



# ATLAS User's Manual

## DEVICE SIMULATION SOFTWARE

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# Introduction

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## Intended Audience

The information presented is based on the assumptions that the reader is (1) familiar with the basic terminology of semiconductor processing and semiconductor device operation, and (2) understands the basic operation of the computer hardware and operating system being employed.

## Introduction

**ATLAS** is a modular and extensible framework for one, two and three dimensional semiconductor device simulation. It is implemented using modern software engineering practices that promote reliability, maintainability, and extensibility. Products that use the ATLAS Framework meet the device simulation needs of all semiconductor application areas.

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## History

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# Technical Support

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When you send us an e-mail message, please:

- Explain the problem or question as fully as possible.
- Include any input files that you have created and error messages that were generated.
- Provide us with the version number of ATLAS, the version numbers of the VWF INTERACTIVE TOOLS that you are using, and the details of the hardware platform on which the problem was encountered.
- Include your company affiliation, business telephone number, and fax number.

You will be contacted promptly and your problem will be resolved as quickly as possible.

Your feedback will help us further develop and improve ATLAS. Please send your comments to our e-mail address.

# How to Read this Manual

| Style Conventions                       |  |  |
|---|--|--|
| Font Style/Convention                   | Description  | Example  |
| •                                       | This represents a list of items or terms.  | <ul style="list-style-type: none"> <li>• Bullet A</li> <li>• Bullet B</li> <li>• Bullet C</li> </ul>   |
| 1.<br>2.<br>3.                          | This represents a set of directions to perform an action.                        | <p>To open a door:</p> <ol style="list-style-type: none"> <li>1. Unlock the door by inserting the key into keyhole.</li> <li>2. Turn key counter-clockwise.</li> <li>3. Pull out the key from the keyhole.</li> <li>4. Grab the doorknob and turn clockwise and pull.</li> </ol> |
| →                                       | This represents a sequence of menu options and GUI buttons to perform an action. | <b>File→Open</b>   |
| Courier                                 | This represents the commands, parameters, and variables syntax.                  | HAPPY BIRTHDAY   |
| <b>New Century Schoolbook Bold</b>      | This represents the menu options and buttons in the GUI.                         | <b>File</b>  |
| <i>New Century Schoolbook Italics</i>   | This represents the equations.   | $abc=xyz$  |
| <u>Note:</u>                            | This represents the additional important information.                            | <u>Note: Make sure you save often while running an experiment.</u>   |
| NEW CENTURY SCHOOLBOOK<br>IN SMALL CAPS | This represents the names of the SILVACO/SIMUCAD AUTOMATION DESIGN Products.     | ATHENA, ATLAS, EXPERT,<br>GATEWAY, HIPEX, SMARTSPICE,<br>STELLAR, and UTMOST.  |

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## 1.1: ATLAS Overview

ATLAS provides general capabilities for physically-based two (2D) and three-dimensional (3D) simulation of semiconductor devices. If you're new to ATLAS, read this chapter and Chapter 2: "Getting Started with ATLAS" to understand how ATLAS works. Chapter 2 is a tutorial for ATLAS. Once you've read these chapters, the remaining chapters can then be referred to for a detailed understanding of the capabilities of each ATLAS product.

Those who have used earlier versions of ATLAS may find it helpful to review the updated version history in Appendix D: "ATLAS Version History".

ATLAS is designed to be used in conjunction with the VWF INTERACTIVE TOOLS. The VWF INTERACTIVE TOOLS, which include DECKBUILD, TONYPLOT, DEVEDIT, MASKVIEWS, and OPTIMIZER, are documented in the VWF INTERACTIVE TOOLS USER MANUALS. See Section 1.3: "Using ATLAS With Other Silvaco Software" for more information about using ATLAS with other Silvaco tools.

If you're new to ATLAS, also read the tutorial chapter in the VWF INTERACTIVE TOOLS USER'S MANUAL to get a basic idea of how the user interface works.

ATLAS is supplied with numerous examples that can be accessed through DECKBUILD. These examples demonstrate most of ATLAS's capabilities. The input files that are provided with the examples are an excellent starting point for developing your own input files. To find out how to access the example, see Chapter 2: "Getting Started with ATLAS", Section 2.4: "Accessing The Examples".

## 1.2: Features And Capabilities of ATLAS

### 1.2.1: Comprehensive Set of Models

ATLAS provides a comprehensive set of physical models, including:

- DC, AC small-signal, and full time-dependency.
- Drift-diffusion transport models.
- Energy balance and Hydrodynamic transport models.
- Lattice heating and heatsinks.
- Graded and abrupt heterojunctions.
- Optoelectronic interactions with general ray tracing.
- Amorphous and polycrystalline materials.
- General circuit environments.
- Stimulated emission and radiation
- Fermi-Dirac and Boltzmann statistics.
- Advanced mobility models.
- Heavy doping effects.
- Full acceptor and donor trap dynamics
- Ohmic, Schottky, and insulating contacts.
- SRH, radiative, Auger, and surface recombination.
- Impact ionization (local and non-local).
- Floating gates.
- Band-to-band and Fowler-Nordheim tunneling.
- Hot carrier injection.
- Quantum transport models
- Thermionic emission currents.

### 1.2.2: Fully Integrated Capabilities

ATLAS works well with other software from SILVACO. For example, ATLAS

- Runs in the DECKBUILD interactive run-time environment.
- Is interfaced to TONYPLOT, the interactive graphics and analysis package.
- Accepts input from the ATHENA and SSUPREM3 process simulators.
- Is interfaced to UTMOST parameter extraction and device modeling software.
- can be used in experiments with the VWF AUTOMATION TOOLS.

### 1.2.3: Sophisticated Numerical Implementation

ATLAS uses powerful numerical techniques, including:

- Accurate and robust discretization techniques.
- Gummel, Newton, and block-Newton nonlinear iteration strategies.
- Efficient solvers, both direct and iterative, for linear subproblems.
- Powerful initial guess strategies.
- Small-signal calculation techniques that converge at all frequencies.
- Stable and accurate time integration.

## 1.3: Using ATLAS With Other Silvaco Software

ATLAS should only be used in conjunction with the VWF INTERACTIVE TOOLS. These include DECKBUILD, TONYPLOT, DEVEDIT, MASKVIEWS, and OPTIMIZER. DECKBUILD provides an interactive run time environment. TONYPLOT supplies scientific visualization capabilities. DEVEDIT is an interactive tool for structure and mesh specification and refinement. MASKVIEWS is an IC Layout Editor. The OPTIMIZER supports black box optimization across multiple simulators.

ATLAS is often used in conjunction with the ATHENA process simulator. ATHENA predicts the physical structures that result from processing steps. The resulting physical structures are used as input by ATLAS, which then predicts the electrical characteristics associated with specified bias conditions. The combination of ATHENA and ATLAS makes it possible to determine the impact of process parameters on device characteristics.

The electrical characteristics predicted by ATLAS can be used as input by the UTMOST device characterization and SPICE modeling software. Compact models based on simulated device characteristics can then be supplied to circuit designers for preliminary circuit design. Combining ATHENA, ATLAS, UTMOST, and SMARTSPICE makes it possible to predict the impact of process parameters on circuit characteristics.

ATLAS can be used as one of the simulators within the VWF AUTOMATION TOOLS. VWF makes it convenient to perform highly automated simulation-based experimentation. VWF is used in a way that reflects experimental research and development procedures using split lots. It therefore links simulation very closely to technology development, resulting in significantly increased benefits from simulation use.

## 1.4: The Nature Of Physically-Based Simulation

ATLAS is a physically-based device simulator. Physically-based device simulation is not a familiar concept for all engineers. This section will briefly describe this type of simulation.

Physically-based device simulators predict the electrical characteristics that are associated with specified physical structures and bias conditions. This is achieved by approximating the operation of a device onto a two or three dimensional grid, consisting of a number of grid points called nodes. By applying a set of differential equations, derived from Maxwells laws, onto this grid you can simulate the transport of carriers through a structure. This means that the electrical performance of a device can now be modeled in DC, AC or transient modes of operation.

There are three physically-based simulation. These are:

- It is predictive.
- It provides insight.
- It conveniently captures and visualizes theoretical knowledge.

Physically-based simulation is different from empirical modeling. The goal of empirical modeling is to obtain analytic formulae that approximate existing data with good accuracy and minimum complexity. Empirical models provide efficient approximation and interpolation. They do not provide insight, or predictive capabilities, or encapsulation of theoretical knowledge.

Physically-based simulation has become very important for two reasons. One, it is almost always much quicker and cheaper than performing experiments. Two, it provides information that is difficult or impossible to measure.

The drawbacks of physically-based simulation are that all the relevant physics must be incorporated into a simulator, and numerical procedures must be implemented to solve the associated equations. These tasks have been taken care of for users of ATLAS.

Those who use physically-based device simulation tools must specify the problem to be simulated. In ATLAS, specify device simulation problems by defining:

- The physical structure to be simulated.
- The physical models to be used.
- The bias conditions for which electrical characteristics are to be simulated.

The subsequent chapters of this manual describe how to perform these steps.

### 2.1: Overview

ATLAS is a physically-based two and three dimensional device simulator. It predicts the electrical behavior of specified semiconductor structures and provides insight into the internal physical mechanisms associated with device operation.

ATLAS can be used standalone or as a core tool in Silvaco's VIRTUAL WAFER FAB simulation environment. In the sequence of predicting the impact of process variables on circuit performance, device simulation fits between process simulation and SPICE model extraction.

This chapter will show you how to use ATLAS effectively. It is a source of useful hints and advice. The organization of topics parallels the steps that you go through to run the program. If you have used earlier versions of ATLAS, you will still find this chapter useful because of the new version.

This chapter concentrates on the core functionality of ATLAS. If you're primarily interested in the specialized capabilities of a particular ATLAS tool, read this chapter first, and then read the chapters that describe the ATLAS tools you wish to use.

## 2.2: ATLAS Inputs and Outputs

Figure 2-1 shows the types of information that flow in and out of ATLAS. Most ATLAS simulations use two input files. The first input file is a text file that contains commands for ATLAS to execute. The second input file is a structure file that defines the structure that will be simulated.

ATLAS produces three types of output files. The first type of output file is the run-time output, which gives you the progress and the error and warning messages as the simulation proceeds. The second type of output file is the log file, which stores all terminal voltages and currents from the device analysis. The third type of output file is the solution file, which stores 2D and 3D data relating to the values of solution variables within the device at a given bias point.

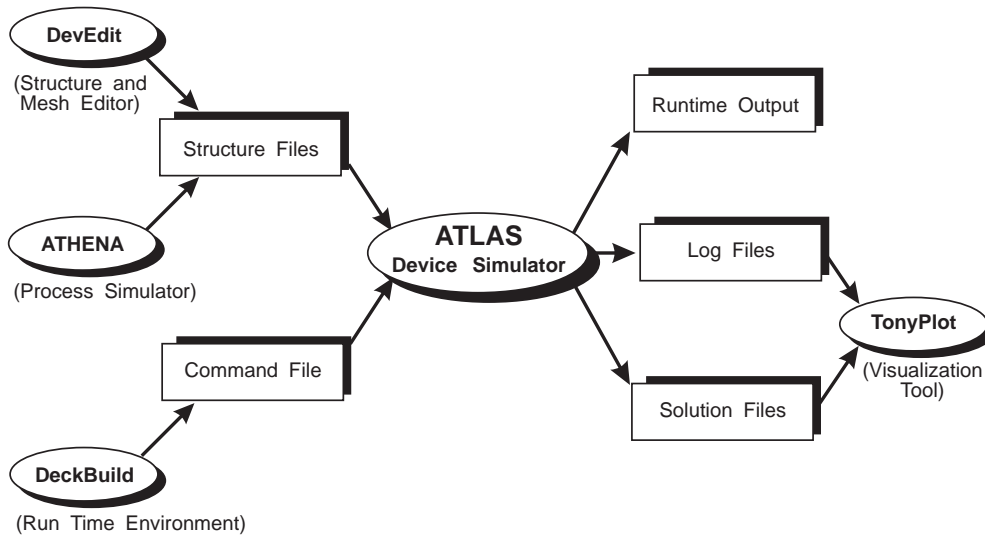


Figure 2-1: ATLAS Inputs and Outputs



## 2.3: Modes of Operation

ATLAS is normally used in conjunction with the DECKBUILD run-time environment, which supports both interactive and batch mode operation. We strongly recommend that you always run ATLAS within DECKBUILD. In this section, we present the basic information you need to run ATLAS in DECKBUILD. The VWF INTERACTIVE TOOLS USER'S MANUALS provides a more detailed description of the features and capabilities of DECKBUILD.

### 2.3.1: Interactive Mode With DeckBuild

To start ATLAS in DECKBUILD, type:

```
deckbuild -as
```

at the UNIX system command prompt. The command line option, `-as`, instructs DECKBUILD to start ATLAS as the default simulator.

If you want to start from an existing input file, start DECKBUILD by typing:

```
deckbuild -as <input filename>
```

The run-time output shows the execution of each ATLAS command and includes error messages, warnings, extracted parameters, and other important output for evaluating each ATLAS run. When ATLAS runs in this mode, the run-time output is sent to the output section of the DeckBuild Window and can be saved as needed. Therefore, you don't need to save the run-time output explicitly. The following command line, however, specifies the name of a file that will be used for storing the run-time output.

```
deckbuild -as <input filename> -outfile <output filename>
```

In this case, the run-time output is sent to the output file and to the output section of the DeckBuild Window.

### 2.3.2: Batch Mode With DeckBuild

To use DECKBUILD in a non-interactive or batch mode, add the `-run` parameter to the command that invokes DECKBUILD. A prepared command file is required for running in batch mode. We advise you to save the run-time output to a file, since error messages in the run-time output would otherwise be lost when the batch job completes. For example:

```
deckbuild -run -as <input filename> -outfile <output filename>
```

Using this command requires a local X-Windows system to be running. The job runs inside a DECKBUILD icon on the terminal and quits automatically when the ATLAS simulation is complete. You can also run DECKBUILD using a remote display. For example:

```
deckbuild -run -as <input file> -outfile <output file> -display<hostname>:0.0
```

### 2.3.3: No Windows Batch Mode With DeckBuild

For completely non-X Windows operation of DECKBUILD, use the `-ascii` parameter. For example:

```
deckbuild -run -ascii -as <input filename> -outfile <output filename>
```

This command directs DECKBUILD to run the ATLAS simulation without any display of the DeckBuild Window or icon. This is useful for remote execution without an X Windows emulator or for replacing UNIX-based ATLAS runs within framework programs.

When using batch mode, use the UNIX command suffix, `&`, to detach the job from the current command shell. To run a remote ATLAS simulation under DECKBUILD without display and then logout from the system, use the UNIX command, `nohup`, before the DECKBUILD command line. For example:

```
nohup deckbuild -run -ascii -as <input filename> -outfile <output filename> &
```

### 2.3.4: Running ATLAS inside Deckbuild

Each ATLAS run inside DECKBUILD should start with the line:

```
go atlas
```

A single input file may contain several ATLAS runs each separated with a `go atlas` line. Input files within DECKBUILD may also contain runs from other programs such as ATHENA or DEVEDIT along with the ATLAS runs.

#### Running a given version number of ATLAS

The `go` statement can be modified to provide parameters for the ATLAS run. To run version 4.3.0.R, the syntax is:

```
go atlas simflags="-V 4.3.0.R"
```

#### Starting Parallel ATLAS

The `-P` option is used to set the number of processors to use in a parallel ATLAS run. If the number set by `-P` is greater than the number of processors available or than the number of parallel thread licenses, the number is automatically reduced to this cap number. To run on 4 processors, use:

```
go atlas simflags="-V 4.3.2.C -P 4"
```

### 2.3.5: Batch Mode Without DeckBuild

You can run ATLAS outside the DECKBUILD environment. But this isn't recommended by Silvaco. If you don't want the overhead of the DeckBuild Window, use the No Windows Mode. Many important features such as variable substitution, automatic interfacing to process simulation, and parameter extraction are not available outside the DECKBUILD environment. To run ATLAS directly under UNIX, use the command:

```
atlas <input filename>
```

To save the run-time output to a file, don't use the UNIX redirect command (`>`). Simply specify the name of the output file. For example:

```
atlas <input filename> -logfile <output filename>
```

---

**Note:** The standard examples supplied with ATLAS will not run correctly outside of DECKBUILD.

---

## 2.4: Accessing The Examples

ATLAS has more than 300 standard examples that demonstrate how the program is used to simulate different technologies. These examples are a good starting point for creating your own simulations. The examples are accessed from the menu system in DECKBUILD. To select and load an example:

1. Start DECKBUILD with ATLAS as the simulator, which is described in the previous section.
2. Use left mouse button to pull down the **Main Control** menu.
3. Select **Examples**. An index will then appear in a Deckbuild Examples Window (see Figure 2-2).

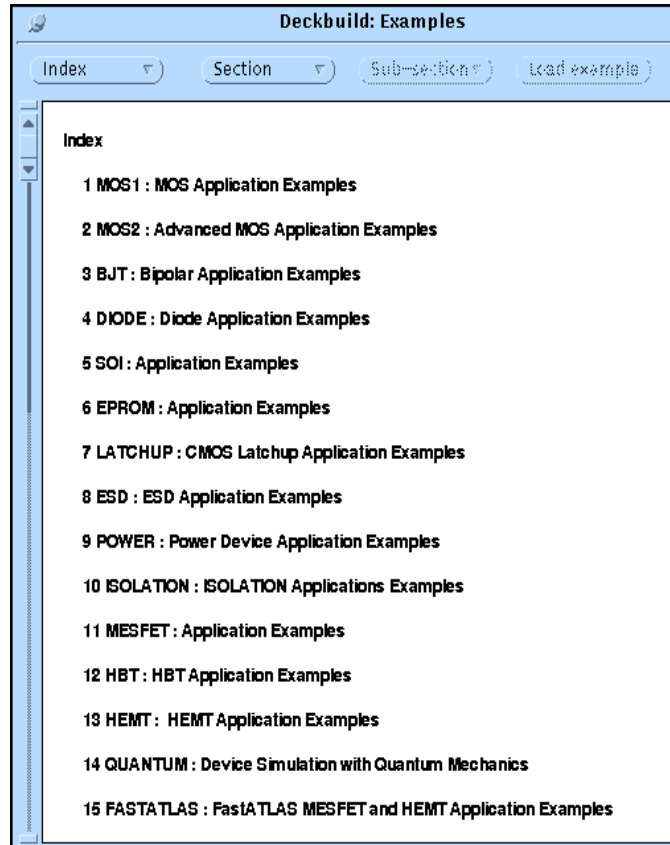


Figure 2-2: Examples Index in DeckBuild

The examples are divided by technology or technology group. For instance, the most common technologies are individually listed (e.g., MOS, BJT), while others are grouped with similar devices (e.g., IGBT and LDMOS are under POWER, and solar cell and photodiode are under OPTOELECTRONICS).

4. Choose the technology by double clicking the left mouse button over that item. A list of examples for that technology will appear. These examples typically illustrate different devices, applications, or types of simulation.

You can also search for an example by selecting the **Index** button. Wildcards can be used in the search.

5. Choose a particular example by double clicking the left mouse button over that item in the list. A text description of the example will appear in the window. This text describes the important physical mechanisms in the simulation, and details of the ATLAS syntax used. You should read this information before proceeding.
6. Press the **Load Example** button. The input command file for the example will be copied into your current working directory together with any associated files. A copy of the command file will be loaded into DECKBUILD. Note that the **Load Example** button remains faded out until this step is performed correctly.
7. Press the **Run** button in the middle frame of the DECKBUILD application window to run the example. Alternatively, most examples are supplied with results that are copied into the current working directory along with the input file. To view the results, select (highlight) the name of the results file and select **Tools-Plot**. Details on using TONYPLOT can be found in the VWF INTERACTIVE TOOLS USER'S MANUALS.

## 2.5: The ATLAS Syntax

An ATLAS command file is a list of commands for ATLAS to execute. This list is stored as an ASCII text file that can be prepared in DECKBUILD or using any text editor. Preparing an input file in DECKBUILD is preferred, which can be made easier by using the DeckBuild Commands menu in the DeckBuild Window.

### 2.5.1: Statements and Parameters

The input file contains a sequence of statements. Each statement consists of a keyword that identifies the statement and a set of parameters. The general format is:

```
<STATEMENT>    <PARAMETER>=<VALUE>
```

With a few exceptions the input syntax is not case sensitive. One important exception is that commands described in this manual as being executed by DECKBUILD rather than ATLAS are case sensitive. These include: EXTRACT, SET, GO, and SYSTEM. Also, filenames for input and output under UNIX are case sensitive.

For any <STATEMENT>, ATLAS may have four different types for the <VALUE> parameter. These are: Real, Integer, Character, and Logical.

An example of a statement line is:

```
DOPING UNIFORM N.TYPE CONCENTRATION=1.0e16 REGION=1 OUTFILE=my.dop
```

The statement is DOPING. All other items are parameters of the DOPING statement. UNIFORM and N.TYPE are logical parameters. Their presence on the line sets their values to true, otherwise they take their default values (usually false). CONCENTRATION is a Real parameter and takes floating point numbers as input values. REGION is an Integer parameter taking only integer numbers as input. OUTFILE is a Character parameter type taking strings as input.

The statement keyword must come first but after this, the order of parameters within a statement is not important.

You only need to use enough letters of any parameter to distinguish it from any other parameter on the same statement. Thus, CONCENTRATION can be shortened to CONC. REGION, but can't be shortened to R, since there's a parameter called RATIO associated with the DOPING statement.

Logical parameters can be explicitly set to false by preceding them with the ^ symbol.

Any line beginning with a # is ignored. These lines are used as comments.

ATLAS can read up to 256 characters on one line. But it is best to spread long input statements over several lines to make the input file more readable. The \ character at the end of a line indicates continuation.

For more information about statements and parameters in ATLAS, see Chapter 18: "Statements".

### 2.5.2: The Order of ATLAS Commands

The order in which statements occur in an ATLAS input file is important. There are five groups of statements that must occur in the correct order (see Figure 2-3). Failure to do so usually causes an error message to appear, which could lead to incorrect operation or termination of the program. For example, if the material parameters or models are set in the wrong order, then they may not be used in the calculations.

The order of statements within the mesh definition, structural definition, and solution groups is also important. Failure to place these statements in proper order may also cause incorrect operation or termination of the program.

| <i>Group</i>                     |      | <i>Statements</i>                          |
|----------------------------------|------|--|
| 1. Structure Specification       | ———— | MESH<br>REGION<br>ELECTRODE<br>DOPING      |
| 2. Material Models Specification | ———— | MATERIAL<br>MODELS<br>CONTACT<br>INTERFACE |
| 3. Numerical Method Selection    | ———— | METHOD                                     |
| 4. Solution Specification        | ———— | LOG<br>SOLVE<br>LOAD<br>SAVE               |
| 5. Results Analysis              | ———— | EXTRACT<br>TONYPLOT                        |

Figure 2-3: ATLAS Command Groups with the Primary Statements in each Group

### 2.5.3: The DeckBuild Command Menu

The DeckBuild Command Menu (Command Menu) can help you to create input files. This menu is found under the **Commands** button on DECKBUILD's main screen. The Commands Menu is configured for ATLAS whenever ATLAS is the currently active simulator in DECKBUILD. When ATLAS is active, which is indicated in the lower bar of the DeckBuild Window, an ATLAS command prompt will appear in the DECKBUILD output section.

The Command Menu gives you access to pop-up windows where you type information. When you select the **Write** button, syntactically correct statements are written to the DECKBUILD text edit region. The DeckBuild Command Menu does not support all possible ATLAS syntax, but aims to cover the most commonly used commands.

### 2.5.4: PISCES-II Quick Start

This section is a quickstart for those who may be familiar with the syntax and use of the Stanford University PISCES-II program or other device simulators derived from this program.

The major differences between ATLAS and PISCES-II are:

- all graphics are handled by a separate interactive graphics program, TONYPLOT. The PISCES-II graphics commands: PLOT.1D, PLOT.2D, CONTOUR, VECTOR, and so on are not required. By using TONYPLOT, it is no longer necessary to run the device simulator simply to plot or alter graphics.
- no need to separate individual ATLAS simulations into separate input files. Multiple runs of ATLAS are possible in the same input file separated by the line `go atlas`. There's also no need to separate process and device simulation runs of Silvaco products into separate input files. A single file containing ATHENA and ATLAS syntax is permitted in DECKBUILD.
- the interface from process to device simulation is handled though a single file format compatible with other programs. The file read by ATLAS is the default output file format of ATHENA. No special file format for the interface is required.

- when defining a grid structure within ATLAS, the `NODE` and `LOCATION` syntax to define exact grid line numbers in `X` and `Y` is not recommended. A more reliable and easier to use syntax using `LOCATION` and `SPACING` is available.
- using the `REGRID` command is not recommended due to the creation of obtuse triangles. A standalone program, such as `DEVEDIT`, can be used as a grid pre-processor for ATLAS.
- all numerical method selection commands and parameters are on the `METHOD` statement. The `SYMBOLIC` statement is not used. Historically, `SYMBOLIC` and `METHOD` were used as a coupled pair of statements, but it is more convenient to use a single statement (`METHOD`) instead. Most of the old parameters of the `SYMBOLIC` statement have the same meaning and names, despite this move to a single statement. One notable change in ATLAS is that numerical methods can be combined together.

See the “Pisces-II Compatibility” section on page 2-40 for more information concerning the translation of PISCES-II numerics statements.

- various general purpose commands are actually part of the `DECKBUILD` user environment. These include: `SET`, `EXTRACT`, `GO`, `SYSTEM`, and `SOURCE`. These commands can be interspersed inside ATLAS syntax.
- Variable substitution is supported for both numerical and string variables using the `SET` statement and `$symbol`. To avoid confusion, the `#` symbol is preferred over the `$symbol` for comment statements.

In addition to these changes, the physical models are generally different in ATLAS. Most of the original PISCES-II models have been preserved but often are not the default or the recommended models to use. See the on-line examples for technology specific information about models.

## 2.6: Defining A Structure

A device structure can be defined in three different ways for use in ATLAS.

The first way is to read an existing structure from a file. The structure is created either by an earlier ATLAS run or another program such as ATHENA or DEVEDIT. A MESH statement loads in the mesh, geometry, electrode positions, and doping of the structure. For example:

```
MESH INFILE=<filename>
```

The second way is to use the **Automatic Interface** feature from DECKBUILD to transfer the input structure from ATHENA or DEVEDIT.

The third way is create a structure by using the ATLAS command language. See Chapter 18: "Statements" for more information about the ATLAS syntax.

### 2.6.1: Interface From ATHENA

When ATHENA and ATLAS are run under DECKBUILD, you can take advantage of an automatic interface between the two programs. Perform the following steps to load the complete mesh, geometry, and doping from ATHENA to ATLAS.

1. Deposit and pattern electrode material in ATHENA
2. Use the ELECTRODE statement in ATHENA to define contact positions. Specify the x and y coordinates as cross-hairs to pin-point a region. The whole region is then turned into electrode. In many cases, only the x coordinate is needed. For example:

```
ELECTRODE NAME=gate X=1.3 [Y=-0.1])
```

There is a special case to specify a contact on the bottom of the structure. For example:

```
ELECTRODE NAME=substrate BACKSIDE
```

3. Save a structure file while ATHENA is still the active simulator. For example:

```
STRUCTURE OUTF=nmos.str
```

4. Start ATLAS with the `go atlas` command written in the same input deck. This will automatically load the most recent structure from ATHENA into ATLAS.

If you need to load the structure saved in step 4 into ATLAS without using the auto-interface capability, use the MESH command. For example:

```
MESH INF=nmos.str
```

ATLAS inherits the grid used most recently by ATHENA. With a careful choice of initial mesh or by using the grid manipulation techniques in ATHENA, you can produce a final mesh from ATHENA that will give good results in ATLAS. But, a grid that is appropriate for process simulation isn't always appropriate for device simulation. If the final ATHENA mesh is inappropriate for ATLAS, use either DEVEDIT to re-mesh the structure or the REGRID command.

---

**Note:** There's no need to specify a MESH command in ATLAS when using the Automatic Interface of Deckbuild.

---



## 2.6.2: Interface From DevEdit

A 2D or 3D structure created by DEVEDIT can be read into ATLAS using the following statement.

```
MESH INF=<structure filename>
```

This statement loads in the mesh, geometry, electrode positions, and doping of the structure. ATLAS will automatically determine whether the mesh is 2D for S-PISCES or BLAZE, or 3D for DEVICE3D or BLAZE3D.

If the structure coming from DEVEDIT were originally created by ATHENA, the electrodes should be defined in ATHENA as described in the previous section. If the structure is created in DEVEDIT, the electrode regions should be defined in the **Region/Add** menu of DEVEDIT.

## 2.6.3: Using The Command Language To Define A Structure

To define a device through the ATLAS command language, you must first define a mesh. This mesh or grid covers the physical simulation domain. The mesh is defined by a series of horizontal and vertical lines and the spacing between them. Then, regions within this mesh are allocated to different materials as required to construct the device. For example, the specification of a MOS device requires the specification of silicon and silicon dioxide regions. After the regions are defined, the location of electrodes is specified. The final step is to specify the doping in each region.

When using the command language to define a structure, the information described in the following four sub-sections must be specified in the order listed.

### Specifying The Initial Mesh

The first statement must be:

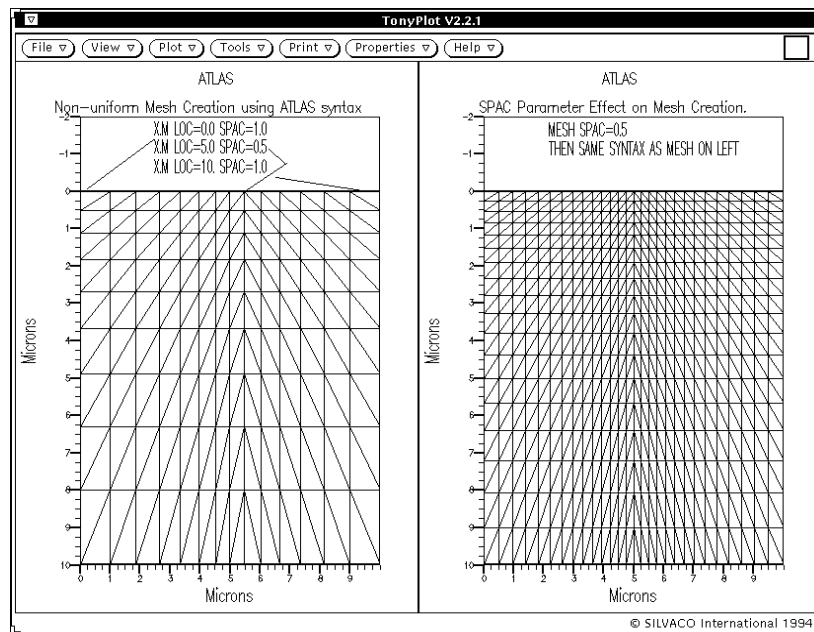
```
MESH SPACE.MULT=<VALUE>
```

This is followed by a series of X.MESH and Y.MESH statements.

```
X.MESH LOCATION=<VALUE> SPACING=<VALUE>
.
Y.MESH LOCATION=<VALUE> SPACING=<VALUE>
.
```

The SPACE.MULT parameter value is used as a scaling factor for the mesh created by the X.MESH and Y.MESH statements. The default value is 1. Values greater than 1 will create a globally coarser mesh for fast simulation. Values less than 1 will create a globally finer mesh for increased accuracy. The X.MESH and Y.MESH statements are used to specify the locations in microns of vertical and horizontal lines, respectively, together with the vertical or horizontal spacing associated with that line. At least two mesh lines must be specified for each direction. ATLAS automatically inserts any new lines required to allow for gradual transitions in the spacing values between any adjacent lines. The X.MESH and Y.MESH statements must be listed in the order of increasing x and y. Both negative and positive values of x and y are allowed.

Figure 2-4 illustrates how these statements work. On the left hand plot, note how the spacing of the vertical lines varies from 1  $\mu\text{m}$  at  $x=0$  and  $x=10 \mu\text{m}$  to 0.5  $\mu\text{m}$  at  $x=5 \mu\text{m}$ . On the right hand plot, note how specifying the SPACE.MULT parameter to have a value of 0.5 has doubled the density of the mesh in both the x- and y-directions.



**Figure 2-4: Non-uniform Mesh Creation using ATLAS Syntax**

After an initial mesh has been defined, you can remove grid lines in specified regions. This is typically done in regions of the device where a coarse grid is expected to be sufficient such as the substrate. The removal of grid lines is accomplished using the `ELIMINATE` statement. The `ELIMINATE` statement removes every second mesh line in the specified direction from within a specified rectangle. For example, the statement:

```
ELIMINATE COLUMNS X.MIN=0 X.MAX=4 Y.MIN=0.0 Y.MAX=3
```

removes every second vertical grid line within the rectangle bounded by  $x=0$ ,  $x=4$ ,  $y=0$  and  $y=3$  microns.

## Specifying Regions And Materials

Once the mesh is specified, every part of it must be assigned a material type. This is done with `REGION` statements. For example:

```
REGION number=<integer> <material_type> <position parameters>
```

Region numbers must start at 1 and are increased for each subsequent region statement. You can have up to 200 different regions in ATLAS. A large number of materials is available. If a composition-dependent material type is defined, the  $x$  and  $y$  composition fractions can also be specified in the `REGION` statement.

The position parameters are specified in microns using the `X.MIN`, `X.MAX`, `Y.MIN`, and `Y.MAX` parameters. If the position parameters of a new statement overlap those of a previous `REGION` statement, the overlapped area is assigned as the material type of the new region. Make sure that materials are assigned to all mesh points in the structure. If this isn't done, error messages will appear and ATLAS won't run successfully.

You can use the `MATERIAL` statement to specify the material properties of the defined regions. But you must complete the entire mesh and doping definition before any `MATERIAL` statements can be used. The specification of material properties is described in Section 2.7.2: "Specifying Material Properties".

## Cylindrical Coordinates

Cylindrical coordinates are often used when simulating discrete power devices. In this mode, ATLAS operates with  $x=0$  as the axis of symmetry around which the cylindrical geometry is placed. Many of the default units change when cylindrical coordinates are used. The calculated current is in Amps rather than the usual Amps per micron. External elements are specified in absolute units (e.g., Farads, not Farads/micron for capacitors).

The MESH statement must be used to specify cylindrical symmetry. The following statement creates a mesh, which contains cylindrical symmetry.

```
MESH NX=20 NY=20 CYLINDRICAL
```

There are 20 mesh nodes along the x-axis and 20 mesh nodes along the y-axis.

The following statement imports a mesh, which contains cylindrical symmetry.

```
MESH INF=mesh0.str CYLINDRICAL
```

---

**Note:** The CYLINDRICAL parameter setting isn't stored in mesh files. Therefore, this parameter must be specified each time a mesh file, which contains cylindrical symmetry, is loaded.

---

## Specifying Electrodes

Once you have specified the regions and materials, define at least one electrode that contacts a semiconductor material. This is done with the ELECTRODE statement. For example:

```
ELECTRODE NAME=<electrode name> <position_parameters>
```

You can specify up to 50 electrodes. The position parameters are specified in microns using the X.MIN, X.MAX, Y.MIN, and Y.MAX parameters. Multiple electrode statements may have the same electrode name. Nodes that are associated with the same electrode name are treated as being electrically connected.

Some shortcuts can be used when defining the location of an electrode. If no y coordinate parameters are specified, the electrode is assumed to be located on the top of the structure. You also can use the RIGHT, LEFT, TOP, and BOTTOM parameters to define the location. For example:

```
ELECTRODE NAME=SOURCE LEFT LENGTH=0.5
```

specifies the source electrode starts at the top left corner of the structure and extends to the right for the distance LENGTH.

## Specifying Doping

You can specify analytical doping distributions, or have ATLAS read in profiles that come from either process simulation or experiment. You specify the doping using the DOPING statement. For example:

```
DOPING <distribution_type> <dopant_type> <position_parameters>
```

### Analytical Doping Profiles

Analytical doping profiles can have uniform or Gaussian forms. The parameters defining the analytical distribution are specified in the DOPING statement. Two examples are shown below with their combined effect shown in Figure 2-5.

```
DOPING UNIFORM CONCENTRATION=1E16 N.TYPE REGION=1
```

```
DOPING GAUSSIAN CONCENTRATION=1E18 CHARACTERISTIC=0.05 P.TYPE \
X.LEFT=0.0 X.RIGHT=1.0 PEAK=0.1
```

The first DOPING statement specifies a uniform n-type doping density of  $10^{16} \text{ cm}^{-3}$  in the region that was previously labelled as region #1. The position parameters: X.MIN, X.MAX, Y.MIN, and Y.MAX can be used instead of a region number.

The second DOPING statement specifies a p-type Gaussian profile with a peak concentration of  $10^{18} \text{ cm}^{-3}$ . This statement specifies that the peak doping is located along a line from  $x = 0$  to  $x = 1$  microns. Perpendicular to the peak line, the doping drops off according to a Gaussian distribution with a standard deviation of 0.05 mm. At  $x < 0$  or  $x > 1$ , the doping drops off laterally with a default standard deviation that is 70% of CHARACTERISTIC. This lateral roll-off can be altered with the RATIO.LATERAL parameter. If a Gaussian profile is being added to an area that was already defined with the opposite dopant type, you can use the JUNCTION parameter to specify the position of the junction depth instead of specifying the standard deviation using the CHARACTERISTIC parameter.

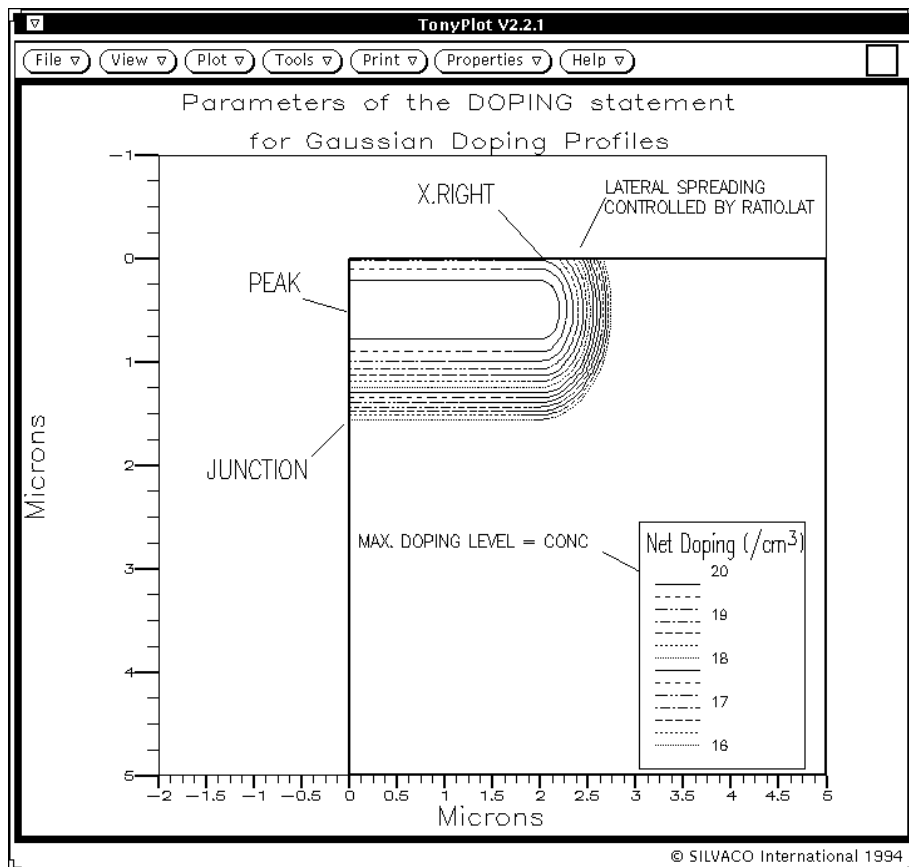


Figure 2-5: Analytical specification of a 2D Profile

## Importing 1D SSUPREM3 Doping Profiles

One-dimensional doping profiles can be read into ATLAS from a SSUPREM3 output file. The doping data must have been saved from SSUPREM3 using the statement:

```
STRUCTURE OUTFILE=<output filename>
```

at the end of the SSUPREM3 run.

In ATLAS, the MASTER parameter of the DOPING statement specifies that a SSUPREM3 file will be read by ATLAS. Since this file will usually contain all the dopants from the SSUPREM3 simulation, the desired dopant type must also be specified. For example, the statement:

```
DOPING MASTER INFILE=mydata.dat BORON REGION=1
```

specifies that the boron profile from the file mydata.dat should be imported and used in region #1. SSUPREM3 profiles are imported into ATLAS one at a time (i.e., one DOPING statement is used for each profile or dopant). The statements:

```
DOPING MASTER INFILE=mydata.dat BORON OUTFILE=doping.dat
DOPING MASTER INFILE=mydata.dat ARSENIC X.RIGHT=0.8 RATIO=0.75
DOPING MASTER INFILE=mydata.dat ARSENIC X.LEFT=2.2 RATIO=0.75
```

offset the arsenic doping from boron to create a 2-D doping profile from a single SSUPREM3 result.

It is advisable to include the OUTFILE parameter on the first DOPING statement to create a 2-D doping file. This file will then be used in the next section to interpolate doping on a refined mesh after a REGRID. This file, however, can't be plotted in TONYPLOT. The position parameters and the RATIO.LATERAL parameter are used in the same manner as for analytical doping profiles to set the extent of the 1-D profile.

### 2.6.4: Automatic Meshing (Auto-meshing) Using The Command Language

Automatic meshing provides a simpler method for defining device structures and meshes than the standard method described in Section 2.6.3: "Using The Command Language To Define A Structure". Auto-meshing is particularly suited for epitaxial structures, especially device structures with many layers (for example, a VCSEL device). Auto-meshing unburdens you from the delicate bookkeeping involved in ensuring that the locations of mesh lines in the Y direction are consistently aligned with the edges of regions. This is done by specifying the locations of Y mesh lines in the REGION statements. The following sections will show how auto-meshing is done, using a few simple examples.

#### Specifying The Mesh And Regions

In the first example, we use a simple device to show you the fundamental concepts of auto-meshing. The first statements in this example are as follows:

```
MESH AUTO
X.MESH LOCATION=-1.0 SPACING=0.1
X.MESH LOCATION=1.0 SPACING=0.1
```

These statements are similar to the ones used in the standard method that described a mesh using the command language as shown in Section 2.6.3: "Using The Command Language To Define A Structure". There are, however, two key differences. The first difference is the inclusion of the AUTO parameter in the MESH statement. You need this parameter to indicate that you want to use auto-meshing. The second and more important difference is that in this example we will not specify any Y.MESH statements. This is because the locations of Y mesh lines will be automatically determined by the parameters of the REGION statements.

You can still specify one or more Y.MESH statements. Such defined mesh lines will be included in the mesh. But including Y.MESH statements is optional in auto-meshing.

In the next few statements of the example, we will show you several new concepts that will explain how auto-meshing works. The following four lines describe the regions in the example device:

```
REGION TOP      THICKNESS=0.02 MATERIAL=GaN    NY=5   DONOR=1E16
REGION BOTTOM   THICKNESS=0.1  MATERIAL=AlGaIn NY=5   DONOR=1E17   X.COMP=0.2
REGION TOP     THICKNESS=0.08 MATERIAL=AlGaIn NY=4   ACCEPTOR=1E17 X.COMP=0.2
REGION BOTTOM   THICKNESS=0.5  MATERIAL=AlGaIn NY=10  DONOR=1E18   X.COMP=0.2
```

### New Concepts

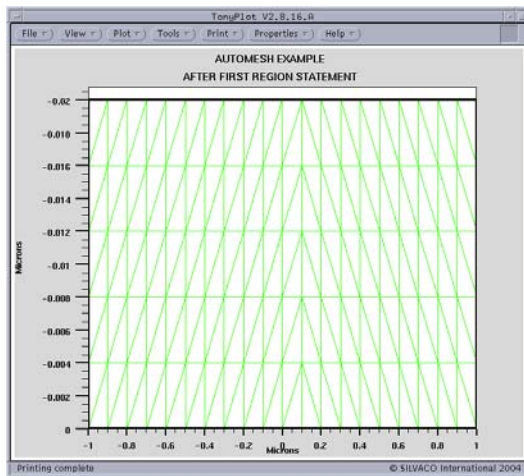
First, it appears that composition and doping are being specified in the REGION statement. This is the case for the DONOR, ACCEPTOR, X.COMPOSITION and Y.COMPOSITION parameters in the REGION statement that specify uniform doping or composition or both over the specified region. These parameters are also available to the standard methods described in Section 2.6.3: "Using The Command Language To Define A Structure", but are more amenable to specification of epitaxial structures such as we are describing in this example.

Next, you should notice several other new parameters. These are the TOP, BOTTOM, THICKNESS and NY parameters. All of these are used to describe the relative locations and thicknesses of the layers as well as the locations of the Y mesh lines. The most intuitive of these parameters is the THICKNESS parameter, which describes the thickness in microns, in the Y direction of each layer. As for the extent in the X direction, in the absence of any specified X.MIN or X.MAX parameters, it is assumed that the region extends over the full range of the X mesh described above in the X.MESH statements.

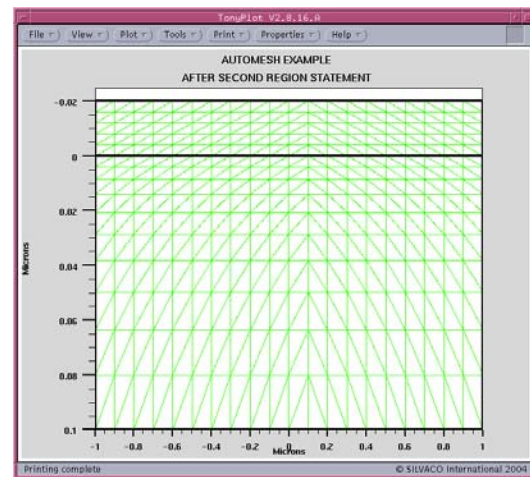
The NY parameter describes how many Y mesh lines are contained in the region so that the Y mesh lines are evenly spaced over the region. You can use the SY parameter instead of NY to specify the spacing in microns between Y mesh lines in the region. Make sure the value of SY does not exceed the value of THICKNESS. Note that in general, the relationship between SY, NY and THICKNESS can be expressed by the following:

$$SY = THICKNESS / NY$$

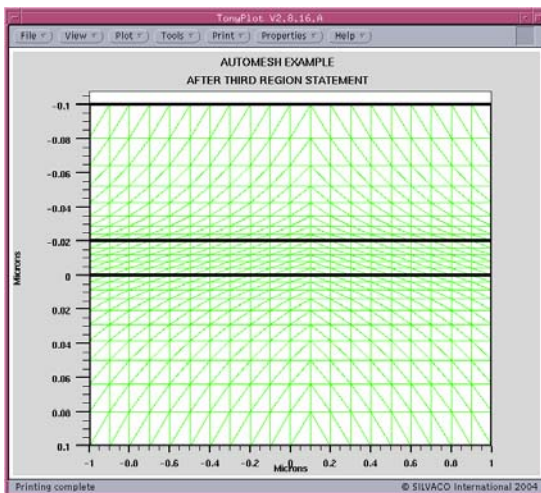
Figure 2-6 shows the meanings of the TOP and BOTTOM parameters.



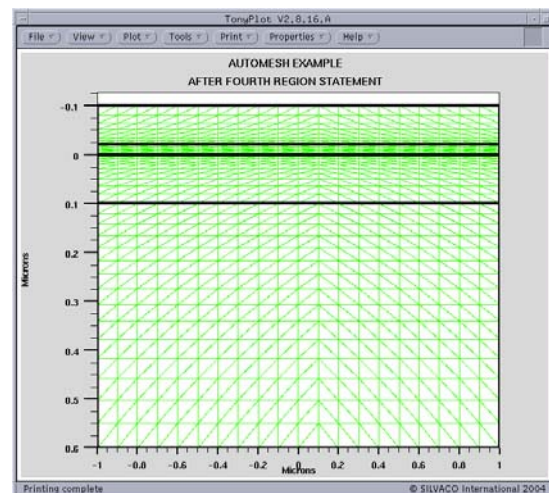
a) Structure after 1st REGION Statement



b) Structure after 2nd REGION Statement



c) Structure after 3rd REGION Statement



d) Structure after 4th REGION Statement

**Figure 2-6: Simple Example of Auto-meshing Showing Sequence of Structure Development.**

This figure shows a progression of representations of how the structure's mesh and region outlines appear after each REGION statement. This figure should give you an intuitive feel of how the regions are alternately placed on the top or bottom of the structure according to the specification of the TOP or BOTTOM parameters. It is important to keep in mind that the ATLAS coordinate convention for the Y axis is that positive Y is directed down into the device. This is similar to using the TOP and BOTTOM parameters of the ELECTRODE statement.

One thing you might notice in this figure is that the number of Y mesh lines in each region does not always match the number specified. This is because at each interface between regions, the Y mesh line spacing is ambiguously defined and the auto-meshing algorithm will always pick the smaller spacing between the two at each interface. Then, the spacing between Y mesh lines varies continuously between subsequent interfaces in a similar way as it does for mesh spacings specified by the LOCATION and SPACING parameters in the X.MESH and Y.MESH statements.

The auto-meshing algorithm maintains the "notion" of the current Y locations of the "top" and "bottom". Let's call these locations " $Y_{top}$ " and " $Y_{bottom}$ ".

Before any REGION statements are processed, "Ytop" and "Ybottom" are both defined to be equal to zero. As the REGION statements are processed, the following cases are addressed:

- If you place the region on the top, as specified by the TOP parameter, the region will extend from "Ytop" to "Ytop"-THICKNESS (remember positive Y points down) and "Ytop" will move to the new location "Ytop"-THICKNESS.
- If you place the region on the bottom, as specified by the BOTTOM parameter, the region will extend from "Ybottom" to "Ybottom"+THICKNESS and "Ybottom" will move to the new location "Ybottom"+THICKNESS.

The auto-meshing algorithm will ensure that all regions are perfectly aligned to their neighboring regions and there are no inconsistencies between the locations of Y mesh lines and the region edges that they resolve.

### Non-uniformity In The X Direction and Auto-meshing

In some cases, you may want to define a device with material discontinuities in the X direction. Such discontinuities may represent etched mesa structures or oxide apertures. There are a couple of ways to do this in auto-meshing. Let's say for example, you want to etch out a region from the structure of the previous example, from X=0 to the right and from Y=0 to the top. You can add the statement

```
REGION MATERIAL=Air X.MIN=0.0 Y.MAX=0.0
```

In this statement, we are not using the auto-meshing features but are using syntax of the standard meshing methods described in Section 2.6.3: "Using The Command Language To Define A Structure". ATLAS supports mixing the standard syntax with auto-meshing but be careful when doing this as we will explain shortly. Figure 2-7 shows the resulting structure and mesh after adding this statement. In this figure, we see that we have obtained the desired result.

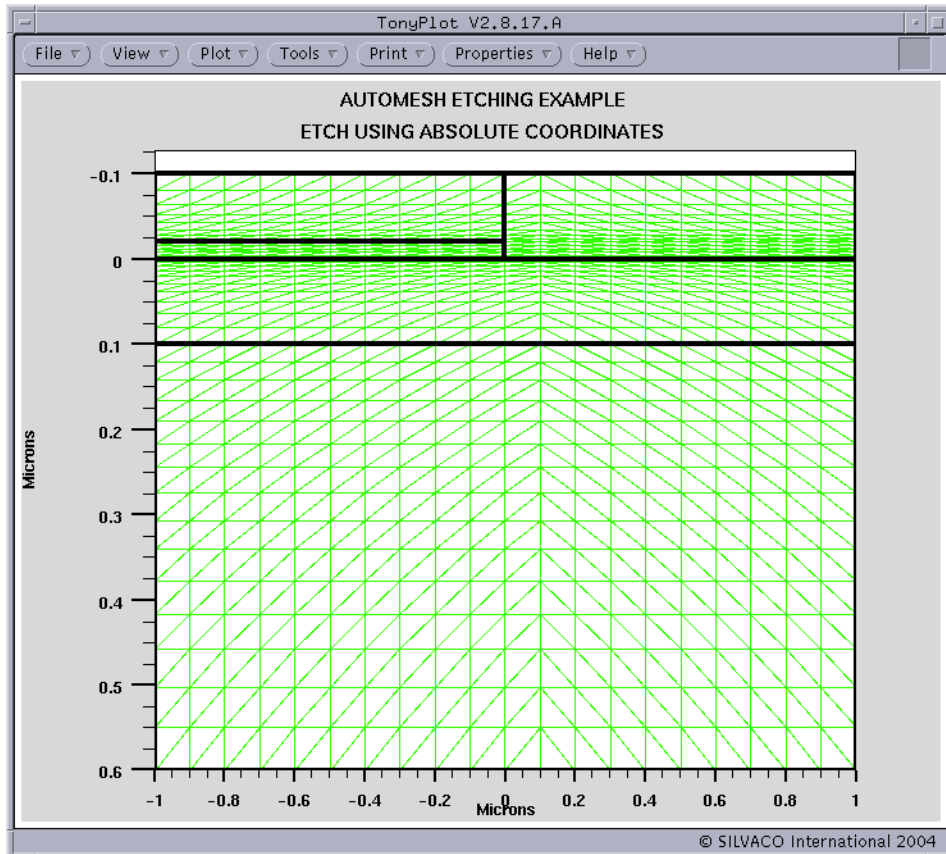


Figure 2-7: Structure Etch Example in Auto-meshing



The potential pitfall in using absolute Y coordinates in auto-meshing is that the location you choose, for example, by summing up thicknesses may not match the location your computer has calculated with its inherent numerical imprecision. The result is not only that the resulting structure may not exactly match what you desire, but more importantly, you may end up accidentally creating a mesh with Y mesh lines closely spaced (usually in the order of the machine precision). This can cause numerical instability (poor convergence) and can overflow or underflow in certain models. What's worse is that this situation is difficult to detect.

There is, however, one situation where we can absolutely predict the location of an edge or Y mesh line. That is at  $Y=0$ . This is exactly what we have done in our example. So if you want to use auto-meshing with specifications of an absolute value of Y, then arrange your device structure so that the specification of Y will be at zero.

This also applies to the location of a recessed electrode. Make sure it is located at  $Y=0$  if you are using auto-meshing.

There is another method of providing for discontinuities in material in the X direction that is absolutely safe from the previously discussed problems. In this approach, we use another parameter called STAY in the REGION statement in conjunction with the TOP or BOTTOM parameters.

The following describes the effect of the STAY parameter in the REGION statement.

- If you place the region on the top, as specified by the TOP parameter, and the STAY parameter is specified, the region will extend from "Ytop" to "Ytop"-THICKNESS and "Ytop" **will remain in its current position**.
- If you place the region on the bottom, as specified by the BOTTOM parameter, and the STAY parameter is specified, the region will extend from "Ybottom" to "Ybottom"+THICKNESS and "Ybottom" **will remain in its current position**.

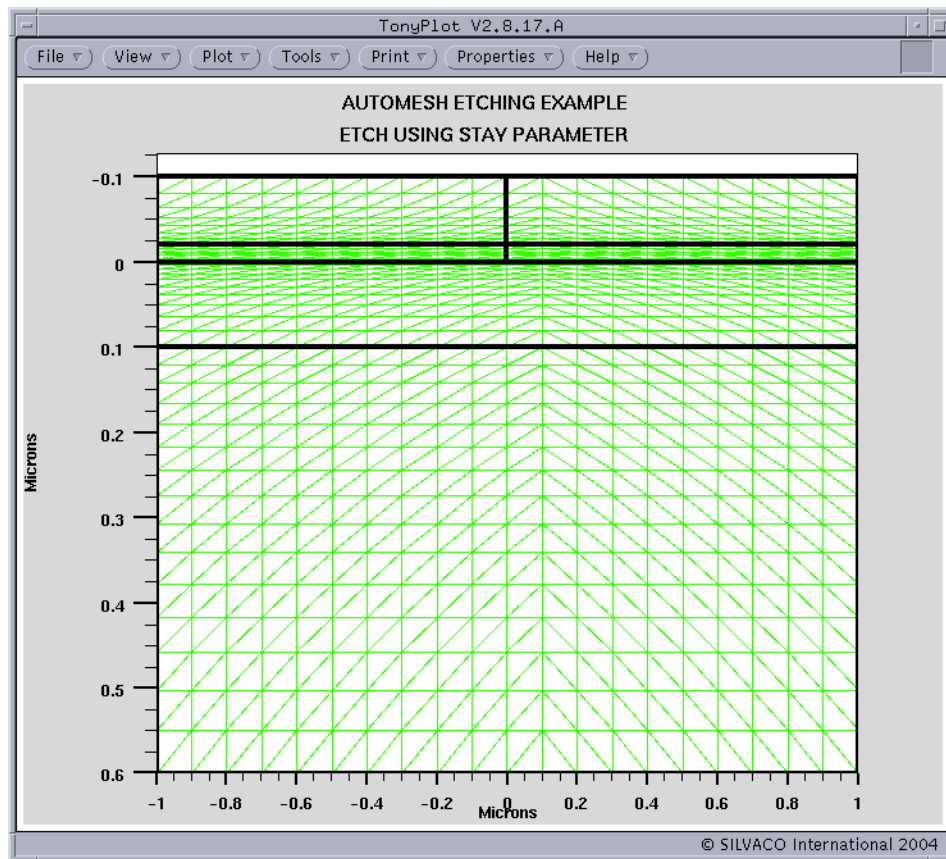
The use of the STAY parameter can best be illustrated by the following example. In this example, we will reproduce the same structure discussed in the last example but this time using only STAY parameters and by not using any specification of absolute Y coordinates. The new REGION specifications are as follows:

```

REGION BOTTOM THICKNESS=0.1 MATERIAL=AlGaIn NY=5 DONOR=1E17 X.COMP=0.2
REGION BOTTOM THICKNESS=0.5 MATERIAL=AlGaIn NY=10 DONOR=1E18 X.COMP=0.2
REGION TOP STAY THICKNESS=0.02 MATERIAL=GaIn NY=5 DONOR=1E16
REGION TOP THICKNESS=0.02 MATERIAL=Air NY=5 X.MIN=0.0
REGION TOP STAY THICKNESS=0.08 MATERIAL=AlGaIn NY=4 ACCEPTOR=1E17 X.COMP=0.2
REGION TOP THICKNESS=0.08 MATERIAL=Air NY=4 X.MIN=0.0

```

In this example, we slightly rearranged the REGION statements for clarity and split one region into two. Figure 2-8 shows the results.



**Figure 2-8: Structure Etching Example Using The STAY Parameter**

The following describes the operation of the STAY parameter in this example:

- The STAY parameter in the third REGION statement means that the fourth REGION will start at the same Y coordinate as the third.
- Since the THICKNESS and NY parameters are the same in the third and fourth regions, they will have the same range of Y values and the same Y mesh.
- The specification of X.MIN in the fourth REGION statement means that the region will not completely overlap the third region but will only overlap to a minimum X value of 0.
- The lack of a STAY parameter in the fourth REGION statement means that the fifth region will lie directly atop the third and fourth regions.
- The STAY parameter in the fifth REGION statement means that the sixth REGION will start at the same Y coordinate as the fifth.
- Since the THICKNESS and NY parameters are the same in the fifth and sixth regions, they will have the same range of Y values and the same Y mesh.
- The specification of X.MIN in the sixth REGION statement means that the region will not completely overlap the fifth region but will only overlap to a minimum X value of 0.

As you can see, using the STAY parameter carefully avoids the problems of specifying values of Y coordinates and the potential problems involved. By doing so, you can specify arbitrary stepped structures.

## Grading of Compositional and Doping

We have provided another method for specifying composition or doping or both in the REGION statement that is available for both auto-meshing and meshing using the standard method described in Section 2.6.3: "Using The Command Language To Define A Structure". This method allows linear grading of rectangular regions. Eight new parameters of the REGION statement support this function. They are ND.TOP, ND.BOTTOM, NA.TOP, NA.BOTTOM, COMPX.TOP, COMPX.BOTTOM, COMPY.TOP, and COMPY.BOTTOM. In the syntax of these parameter names, "TOP" refers to the "top" or extreme Y coordinate in the negative Y direction, and "BOTTOM" refers to the "bottom" or extreme Y coordinate in the positive Y direction. With this in mind, the following rules apply:

- If you specify ND.TOP and ND.BOTTOM in a REGION statement, the donor doping in the region will vary linearly from the value specified by ND.TOP at the "top" of the device to the value specified by ND.BOTTOM at the "bottom" of the device.
- If you specify NA.TOP and NA.BOTTOM in a REGION statement, the acceptor doping in the region will vary linearly from the value specified by NA.TOP at the "top" of the device to the value specified by NA.BOTTOM at the "bottom" of the device.
- If you specify COMPX.TOP and COMPX.BOTTOM in a REGION statement, the X composition fraction in the region will vary linearly from the value specified by COMPX.TOP at the "top" of the device to the value specified by COMPX.BOTTOM at the "bottom" of the device.
- If you specify COMPY.TOP and COMPY.BOTTOM in a REGION statement, the Y composition fraction in the region will vary linearly from the value specified by COMPY.TOP at the "top" of the device to the value specified by COMPY.BOTTOM at the "bottom" of the device.

---

**Note:** Any subsequent DOPING statements will add to the doping specified by the doping related parameters on the REGION statement.

---

## Superlattices and Distributed Bragg Reflectors DBRs

For auto-meshing, we have provided a convenient way of specifying a certain class of superlattices or as they are commonly used distributed Bragg reflectors (DBRs). This class of superlattice includes any superlattice that can be described as integer numbers of repetitions of two different layers. By different, we mean that the two layers may have different thicknesses, material compositions, or dopings, or all. These "conglomerate" structures are specified by the DBR or SUPERLATTICE statement. Actually, SUPERLATTICE is a synonym for DBR. Therefore, in the following discussion we will use the DBR syntax and recognize that SUPERLATTICE and DBR can be used interchangeably.

Most of the syntax of the DBR statement is similar to the syntax of the REGION statement, except the syntax is set up to describe two regions (or two sets of regions). As you will see, we differentiate these regions (or sets of regions) by the indices 1 and 2 in the parameter's name.

The following example should make this concept clear.

```
MESH AUTO
X.MESH LOCATION=-1.0 SPACING=0.1
X.MESH LOCATION=1.0 SPACING=0.1

DBR TOP LAYERS=4 THICK1=0.1 THICK2=0.2 N1=2 N2=3 MAT1=GaAs MAT2=AlGaAs \
X2.COMP=0.4
DBR BOTTOM LAYERS=3 THICK1=0.05 THICK2=0.075 N1=3 N2=3 MAT1=AlGaAs \
MAT2=GaAs X1.COMP=0.4
```

In this example, we can see we are using auto-meshing because of the appearance of the AUTO parameter in the MESH statement. The DBR statements should be familiar since the functionality and syntax are similar to the REGION statement. We will not discuss those similarities here. We will only discuss the important differences. For more information about the similarities, see Chapter 18: "Statements".

The main new parameter is the LAYERS parameter. This parameter specifies the total number of regions added. The region indexed "1" is always added first, then the region indexed "2" is added, and depending on the value of LAYERS, the sequence of regions continues 1, 2, 1, 2, 1, ...

Figure 2-9 shows the functionality of the DBR statement, which gives the resulting structure and mesh from the example.

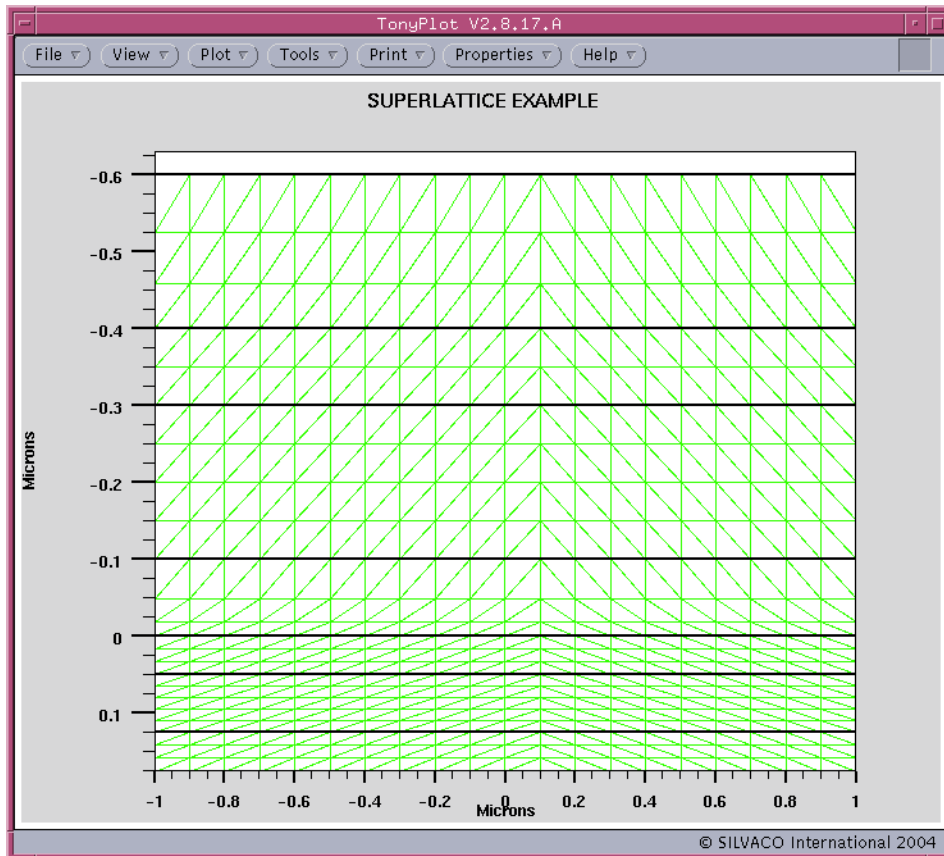


Figure 2-9: Superlattice Example Structure

## 2.6.5: Modifying Imported Regions

If you import a device structure from a file using the INFILE parameter of the MESH statement, you may want to modify some of the characteristics of one or more of the regions in the structure. To do this, specify a REGION statement with the MODIFY parameter and the NUMBER parameter assigned to the region number of interest. You can specify/respecify any of the following REGION statement parameters: DONORS, ACCEPTORS, STRAIN, COMPLEX.TOP, COMPLEX.BOTTOM, NA.TOP, NA.BOTTOM, COMPLY.TOP, COMPLY.BOTTOM, ND.TOP, ND.BOTTOM, WELL.CNBS, WELL.VNBS, WELL.GAIN, POLAR.SCALE, QWELL, LED, WELL.FIELD, and POLARIZATION.

## 2.6.6: Remeshing Using The Command Language

It can be difficult to define a suitable grid when specifying a structure with the command language. The main problem is that the meshes required to resolve 2-D doping profiles and curved junctions are quite complicated and simple rectangular meshes require an excessive number of nodes to resolve such profiles. If a device structure only includes regions of uniform doping, then there's usually no need to regrid. But when realistic 2-D doping profiles are present, a regrid may be necessary.

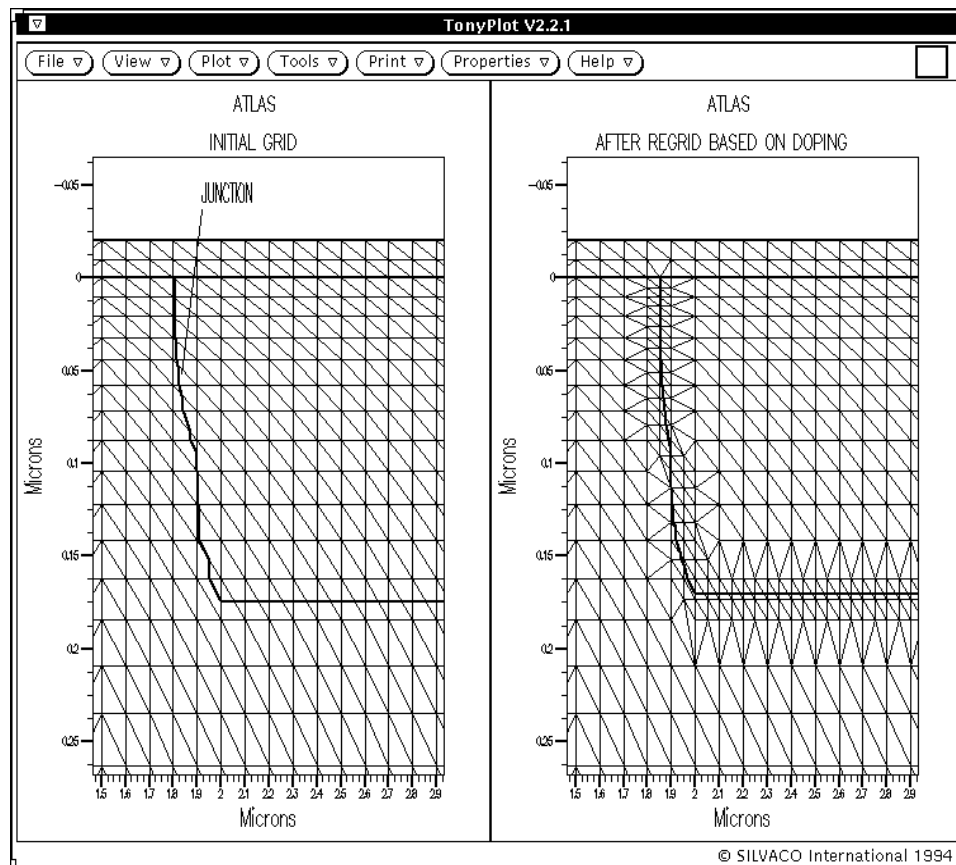
**Note:** The recommended solution for defining complex mesh structures for ATLAS is to use the standalone program, DEVEDIT.

### Regrid On Doping

ATLAS includes a regridding capability that generates a fine mesh only in a localized region. You specify a quantity on which the regrid is to be performed. The mesh is then refined in regions where the specified quantity varies rapidly. Whenever a specified quantity (usually doping) changes quickly, the regridding will automatically grade the mesh accordingly. You can get a regrid on doping before any solutions are obtained. You can do this by using the statement:

```
REGRID LOGARITHM DOPING RATIO=2 SMOOTH.KEY=4 DOPFILE=<filename1> \
  OUTFILE=<filename2>
```

This statement must be used after the MESH, REGION, MATERIAL, ELECTRODE, and DOPING statements described previously. The effects of this REGRID statement on a simple diode structure are shown in Figure 2-10.



**Figure 2-10: Regrid on doping provides improved resolution of junction**

In this statement, the regridding will resolve doping profiles to two orders of magnitude in change.

The doping file, *filename1*, must be specified in the first DOPING statement with the OUTFILE parameter. The results of the regrid are saved in the file, *filename2*. The SMOOTH.KEY parameter value selects a smoothing algorithm. A value of 4 is typically best as this algorithm tends to produce the fewest obtuse triangles. For a complete description of the various smoothing algorithms, see Chapter 17: "Numerical Techniques".

### Regrid Using Solution Variables

The REGRID statement can use a wide range of solution variables as the basis for mesh refinement. Note that regrid on solution variables can only be used after a solution has already been obtained. After a regrid on a solution variable, the solution must be re-solved at the same bias in ATLAS.

For example:

```
REGRID POTENTIAL RATIO=0.2 MAX.LEVEL=1 SMOOTH.K=4 DOPFILE=<filename1>
SOLVE PREV
```

Regrid on potential is often used for high voltage power devices.

---

**Note:** The REGRID statement can be used any number of times on a structure. But we advise you to quit and restart ATLAS between regrids on electrical quantities. You can use the `go atlas` statement to do this. This should be followed by a MESH statement loading the output file of the REGRID command and a re-setting of all material and model parameters.

---

## 2.6.7: Specifying 3D Structures

The syntax for forming 3-D device structures is an extension of the 2-D syntax described in the previous section. The MESH statement should appear as:

```
MESH THREE.D
```

The THREE.D parameter tells ATLAS that a three dimensional grid will be specified. The other statements used to specify 3-D structures and grids are the same as for 2-D with the addition of z direction specifications. The statements:

```
MESH THREE.D X.MESH LOCATION=0 SPACING=0.15
X.MESH LOCATION=3 SPACING=0.15
Y.MESH LOCATION=0 SPACING=0.01
Y.MESH LOCATION=0.4 SPACING=0.01
Y.MESH LOCATION=3 SPACING=0.5
Z.MESH LOCATION=0 SPACING=0.1
Z.MESH LOCATION=3 SPACING=0.1
```

define a 3-D mesh that is uniform in the x and z directions and varies in the y direction.

Position parameters for the z direction (Z.MIN and Z.MAX) are also used on REGION, ELECTRODE, or DOPING statements.

## 2.6.8: General Comments Regarding Grids

Specifying a good grid is a crucial issue in device simulation but there is a trade-off between the requirements of accuracy and numerical efficiency. Accuracy requires a fine grid that resolves the structure in solutions. Numerical efficiency is greater when fewer grid points are used. The critical areas to resolve are difficult to generalize because they depend on the technology and the transport phenomena. The only generalization possible is that most critical areas tend to coincide with reverse-biased metallurgical junctions. Typical critical areas are:

- High electric fields at the drain/channel junction in MOSFETs
- The transverse electric field beneath the MOSFET gate
- Recombination effects around the emitter/base junction in BJTs
- Areas of high impact ionization
- Around heterojunctions in HBT's and HEMTs.

The CPU time required to obtain a solution is typically proportional to  $N^\alpha$ , where  $N$  is the number of nodes and  $\alpha$  varies from 2 to 3 depending on the complexity of the problem. Thus, the most efficient way is to allocate a fine grid only in critical areas, and a coarser grid elsewhere.

The three most important factors to look for in any grid are:

- Ensure adequate mesh density in high field areas
- Avoid obtuse triangles in the current path or high field areas
- Avoid abrupt discontinuities in mesh density

For more information about grids, see Chapter 17: “Numerical Techniques”, Section 17.3: “Meshes”.

## 2.6.9: Maximum Numbers Of Nodes, Regions, and Electrodes

ATLAS sets some limits on the maximum number of grid nodes that can be used. But this shouldn't be viewed as a bottleneck to achieving simulation results. In the default version, 2-D ATLAS simulations have a maximum node limit of 20,000, and 3-D ATLAS simulations have an upper limit of 200,000 nodes with no more than 20,000 in any one plane.

This limit is high enough that for almost all simulations of conventional devices, running out of nodes is never an issue. For most 2-D simulations, accurate results can be obtained with somewhere between 2,000 and 4,000 node points properly located in the structure.

If the node limits are exceeded, error messages will appear and ATLAS will not run successfully. There are two options to deal with this problem. The first option is to decrease the mesh density, because simulations with the maximum nodes take an extremely long time to complete. The second option is to contact your local Silvaco office ([support@silvaco.com](mailto:support@silvaco.com)). Versions of 2-D ATLAS with up to 100,000 nodes have been distributed.

A node point limitation below these values might be seen due to virtual memory constraints on your hardware. For each simulation, ATLAS dynamically allocates the virtual memory. See the Silvaco INSTALLATION GUIDE for information about virtual memory requirements. The virtual memory used by the program depends not only on the number of nodes but also on such items as the models used and the number of equations that are solved.

Also, there is a node limit for the number of nodes in the X or Y directions in 2-D and 3-D ATLAS. In the standard version, this limit is 5,000 nodes. This is applicable to meshes defined in the ATLAS syntax using `X.MESH` and `Y.MESH` statements.

The maximum number of regions defined in both 2-D and 3-D ATLAS is 200. The maximum number of definable electrodes is 50. Again, if it is deemed necessary to include more than the maximum number of regions or electrodes, contact your local Silvaco office ([support@silvaco.com](mailto:support@silvaco.com)).

## 2.7: Defining Material Parameters And Models

Once the mesh, geometry, and doping profiles are defined, you can modify the characteristics of electrodes, change the default material parameters, and choose which physical models ATLAS will use during the device simulation. These actions are accomplished using the `CONTACT`, `MATERIAL`, and `MODELS` statements respectively. Impact ionization models can be enabled using the `IMPACT` statement. Interface properties are set by using the `INTERFACE` statement.

Many parameters are accessible through the SILVACO C-INTERPRETER (SCI), which is further described in Appendix A: “C-Interpreter Functions”. This allows you to define customized equations for some models. For more information about the `INTERFACE` and `MODELS` statements, see Chapter 18: “Statements”, Sections 18.18: “`INTERFACE`” and 18.29: “`MODELS`”.

### 2.7.1: Specifying Contact Characteristics

#### Workfunction for Gates or Schottky Contacts

An electrode in contact with semiconductor material is assumed by default to be ohmic. If a work function is defined, the electrode is treated as a Schottky contact. The `CONTACT` statement is used to specify the metal workfunction of one or more electrodes. The `NAME` parameter is used to identify which electrode will have its properties modified.

The `WORKFUNCTION` parameter sets the workfunction of the electrode. For example, the statement:

```
CONTACT NAME=gate WORKFUNCTION=4.8
```

sets the workfunction of the electrode named `gate` to 4.8eV. The workfunctions of several commonly used contact materials may be specified using the name of the material. Workfunctions for `ALUMINUM`, `N.POLYSILICON`, `P.POLYSILICON`, `TUNGSTEN`, and `TU.DISILICIDE` can be specified in this way. The following statement sets the workfunction for a n-type polysilicon gate contact.

```
CONTACT NAME=gate N.POLYSILICON
```

Aluminum contacts on heavily doped silicon is usually ohmic. For this situation, don't specify a workfunction. For example, MOS devices don't specify:

```
CONTACT NAME=drain ALUMINUM /* wrong */
```

The `CONTACT` statement can also be used to specify barrier and dipole lowering of the Schottky barrier height. Barrier lowering is enabled by specifying the `BARRIER` parameter, while dipole lowering is specified using the `ALPHA` parameter. For example, the statement:

```
CONTACT NAME=anode WORKFUNCTION=4.9 BARRIER ALPHA=1.0e-7`
```

sets the work function of the Schottky contact named `anode` to 4.9eV enables barrier lowering and sets the dipole lowering coefficient to 1 nm.

---

**Note:** When a Schottky barrier is defined at a contact, we recommend that a fine y mesh is present just beneath the contact, inside the semiconductor. This allows the Schottky depletion region to be accurately simulated.

---



## Setting Current Boundary Conditions

The `CONTACT` statement is also used to change an electrode from voltage control to current control. Current controlled electrodes are useful when simulating devices, where the current is highly sensitive to voltage or is a multi-valued function of voltage (e.g., post-breakdown and when there is snap-back).

The statement:

```
CONTACT NAME=drain CURRENT
```

changes the drain electrode to current control. The `BLOCK` or `NEWTON` solution methods are required for all simulations using a current boundary condition. For more information about these methods, see Chapter 17: “Numerical Techniques”, Section 17.5: “Non-Linear Iteration”.

## Defining External Resistors, Capacitors, or Inductors

Lumped resistance, capacitance, and inductance connected to an electrode can be specified using the `RESISTANCE`, `CAPACITANCE`, and `INDUCTANCE` parameters in the `CONTACT` statement. For example, the statement:

```
CONTACT NAME=drain RESISTANCE=50.0 CAPACITANCE=20e-12 INDUCTANCE=1e-6
```

specifies a parallel resistor and capacitor of 50 ohms and 20 pF respectively in series with a 1  $\mu$ H inductor. Note that in 2D simulations, these passive element values are scaled by the width in the third dimension. Since in 2D ATLAS assumes a 1  $\mu$ m width, the resistance becomes 50  $\Omega$ - $\mu$ m.

Distributed contact resistance for an electrode can be specified using the `CON.RESIST` parameter. For example, the statement:

```
CONTACT NAME=source CON.RESISTANCE=0.01
```

specifies that the source contact has a distributed resistance of 0.01  $\Omega$ cm<sup>2</sup>.

---

**Note:** Simulations with external resistors, capacitors, or inductors must be solved using the `BLOCK` or `NEWTON` solution method.

---

## Floating Contacts

The `CONTACT` statement is also used to define a floating electrode. There are two distinctly different situations where floating electrodes are important. The first situation is for floating gate electrodes used in EEPROM and other programmable devices. The second situation is for contacts directly onto semiconductor materials such as floating field plates in power devices.

Floating gates are enabled by specifying the parameter `FLOATING` on the `CONTACT` statement. For example, the statement:

```
CONTACT NAME=fgate FLOATING
```

specifies that the electrode named `fgate` will be floating and that charge boundary conditions will apply.

For contacts directly onto semiconductor, the `FLOATING` parameter cannot be used. This type of floating electrode is best simulated by specifying current boundary conditions on the `CONTACT` statement. For example, the statement:

```
CONTACT NAME=drain CURRENT
```

specifies current boundary conditions for the electrode named `drain`. On subsequent `SOLVE` statements, the drain current boundary condition will default to zero current, therefore floating the contact.

You can also make a floating contact to a semiconductor using a very large resistor attached to the contact instead. For example:

```
CONTACT NAME=drain RESIST=1e20
```

Note that extremely large resistance values must be used to keep the current through the contact insignificant bearing in mind the tolerance on potential will allow the contact voltage to move slightly above zero. For example, if the tolerance is  $10^{-5}\text{V}$  and the defined resistance was only  $10\text{M}\Omega\mu\text{m}$ , then a current of  $10^{-12}\text{A}/\mu\text{m}$  may flow through the contact, which is probably significant in breakdown simulations.

### Shorting Two Contacts Together

It is possible in ATLAS to tie two or more contact together so that voltages on both contacts are equal. This is useful for many technologies for example dual base bipolar transistors. There are several methods for achieving this depending on how the structure was initially defined.

If the structure is defined using ATLAS syntax, you can have multiple `ELECTRODE` statements with the same `NAME` parameter defining separate locations within the device structure. In this case, the areas defined to be electrodes will be considered as having the same applied voltage. A single current will appear combining the current through both `ELECTRODE` areas.

Also, if two separate metal regions in ATHENA are defined using the `ATHENA ELECTRODE` statement to have the same name, then in ATLAS these two electrodes will be considered as shorted together.

If the electrodes are defined with different names the following syntax can be used to link the voltages applied to the two electrodes.

```
CONTACT NAME=base1 COMMON=base
.
SOLVE VBASE=0.1
```

Here, the electrode, `base1`, will be linked to the electrode, `base`. The applied 0.1V on `base` will then appear on `base1`. ATLAS, however, will calculate and store separate currents for both `base` and `base1`. This can be a useful feature but in some cases, such as where functions of the currents are required in `EXTRACT` or `TONYPLOT`, it is undesirable. You can add the `SHORT` parameter to the `CONTACT` statement above to specify so that only a single `base` current will appear combining the currents from `base` and `base1`.

When loading a structure from `ATHENA` or `DEVEDIT` where two defined electrode regions are touching, ATLAS will automatically short these and use the electrode name that was defined first.

## Making an Open Circuit Contact

It is often required to perform a simulation with an open circuit on one of the defined electrodes. There are three different methods to make an open circuit contact. The first method is to entirely deleting an electrode from the structure file. The second method is to add an extremely large lumped resistance. For example,  $10^{20}\Omega$  onto the contact to be made open circuit. The third method is to switch the boundary conditions on the contact to be made open circuit from voltage controlled to current controlled and then specifying a very small or zero current through that electrode.

Each of these methods are feasible but if a floating region is created within the structure, then numerical convergence may be affected. As a result, we normally recommend that you use the second method because it ensures better convergence.

## 2.7.2: Specifying Material Properties

### Semiconductor, Insulator, or Conductor

All materials are split into three classes: semiconductors, insulators and conductors. Each class requires a different set of parameters to be specified. For semiconductors, these properties include electron affinity, band gap, density of states and saturation velocities. There are default parameters for material properties used in device simulation for many materials.

Appendix B: “Material Systems” lists default material parameters and includes a discussion on the differences between specifying parameters for semiconductors, insulators, and conductors.

### Setting Parameters

The `MATERIAL` statement allows you to specify your own values for these basic parameters. Your values can apply to a specified material or a specified region. For example, the statement:

```
MATERIAL MATERIAL=Silicon EG300=1.12 MUN=1100
```

sets the band gap and low field electron mobility in all silicon regions in the device. If the material properties are defined by region, the region is specified using the `REGION` or `NAME` parameters in the `MATERIAL` statement. For example, the statement:

```
MATERIAL REGION=2 TAUN0=2e-7 TAUP0=1e-5
```

sets the electron and hole Shockley-Read-Hall recombination lifetimes for region number two (see Chapter 3: “Physics”, the “Shockley-Read-Hall (SRH) Recombination” section on page 3-63 for more information about this type of recombination). If the name, `base`, has been defined using the `NAME` parameter in the `REGION` statement, then the statement:

```
MATERIAL NAME=base NC300=3e19
```

sets the conduction band density of states at 300 K for the region named `base`.

The description of the `MATERIAL` statement in Chapter 18: “Statements”, Section 18.24: “`MATERIAL`” provides a complete list of all the material parameters that are available.

## Heterojunction Materials

The material properties of heterojunctions can also be modified with the `MATERIAL` statement. In addition to the regular material parameters, composition dependent material parameters can be defined. These include composition dependent band parameters, dielectric constants, saturation velocities, and so on.

For heterojunction material systems, the bandgap difference between the materials is divided between conduction and valence bands. The `ALIGN` parameter specifies the fraction of this difference that is applied to the conduction band edge. This determines the electron and hole barrier height and overrides any electron affinity specification. For example, the statement:

```
MATERIAL MATERIAL=InGaAs ALIGN=0.36
MATERIAL MATERIAL=InP     ALIGN=0.36
```

specifies that 36% of the band gap difference between InGaAs and InP is applied to the conduction band and 64% is applied to the valence band. For example, if the band gap difference ( $\Delta E_g$ ) for this material system is 0.6 eV, then the conduction band barrier height is 0.216 eV and the valence band barrier height is 0.384 eV.

For heterojunction devices, the transport models may be different for each material. These models and their coefficients may be specified for each material using the `MODEL` statement. See Section 2.7.4: “Specifying Physical Models” for a description of this option.

### 2.7.3: Specifying Interface Properties

The `INTERFACE` statement is used to define the interface charge density and surface recombination velocity at interfaces between semiconductors and insulators. For example, the statement:

```
INTERFACE QF=3e10
```

specifies that all interfaces between semiconductors and insulators have a fixed charge of  $3 \cdot 10^{10} \text{cm}^{-2}$ . In many cases, the interface of interest is restricted to a specific region. This can be accomplished with the `X.MIN`, `X.MAX`, `Y.MIN`, and `Y.MAX` parameters on the `INTERFACE` statement. These parameters define a rectangle, where the interface properties apply. For example, the statement:

```
INTERFACE QF=3e10 X.MIN=1.0 X.MAX=2 Y.MIN=0.0 Y.MAX=0.5
```

restricts the interface charge to the semiconductor-insulator boundary within the specified rectangle. In addition to fixed charge, surface recombination velocity and thermionic emission are enabled and defined with the `INTERFACE` statement. For more information about this statement, see Chapter 18: “Statements”, Section 18.18: “INTERFACE”.

### 2.7.4: Specifying Physical Models

Physical models are specified using the `MODELS` and `IMPACT` statements. Parameters for these models appear on many statements including: `MODELS`, `IMPACT`, `MOBILITY`, and `MATERIAL`. The physical models can be grouped into five classes: mobility, recombination, carrier statistics, impact ionization, and tunneling. Chapter 3: “Physics”, Section 3.6: “Physical Models” contains details for each model.

Tables 2-2-1 to 2-2-5 give summary descriptions and recommendations on the use of each model. Table 2-2-6 is a guide for compatibility between models.

All models with the exception of impact ionization are specified on the `MODELS` statement. Impact ionization is specified on the `IMPACT` statement. For example, the statement:

```
MODELS CONMOB FLDMOB SRH FERMIDIRAC
IMPACT SELB
```

specifies that the standard concentration dependent mobility, parallel field mobility, Shockley-Read-Hall recombination with fixed carrier lifetimes, Fermi Dirac statistics and Selberherr impact ionization models should be used.

ATLAS also provides an easy method for selecting the correct models for various technologies. The `MOS`, `BIP`, `PROGRAM`, and `ERASE` parameters for the `MODELS` statement configure a basic set of mobility, recombination, carrier statistics, and tunneling models. The `MOS` and `BIP` parameters enable the models for MOSFET and bipolar devices, while `PROGRAM` and `ERASE` enable the models for programming and erasing programmable devices. For example, the statement:

```
MODELS MOS PRINT
```

enables the `CVT`, `SRH`, and `FERMIDIRAC` models, while the statement:

```
MODELS BIPOLAR PRINT
```

enables the `CONMOB`, `FLDMOB`, `CONSRH`, `AUGER`, and `BGN`.

---

**Note:** The `PRINT` parameter lists to the run time output the models and parameters, which will be used during the simulation. This allows you to verify models and material parameters. We highly recommend that you include the `PRINT` parameter in the `MODEL` statement.

---

Physical models can be enabled on a material by material basis. This is useful for heterojunction device simulation and other simulations where multiple semiconductor regions are defined and may have different characteristics. For example, the statement:

```
MODEL MATERIAL=GaAs FLDMOB EVSATMOD=1 ECRITN=6.0e3 CONMOB
MODEL MATERIAL=InGaAs SRH FLDMOB EVSATMOD=1 \
ECRITN=3.0e3
```

change both the mobility models, and critical electric field used in each material. For devices based on advanced materials, these model parameters should be investigated carefully.

## Energy Balance Models

The conventional drift-diffusion model of charge transport neglects non-local effects such as velocity overshoot and reduced energy dependent impact ionization. ATLAS can model these effects through the use of an energy balance model, which uses a higher order approximation of the Boltzmann Transport Equation (see Chapter 3: “Physics”, Section 3.1.3: “The Transport Equations”). In this equation, transport parameters such as mobility and impact ionization are functions of the local carrier temperature rather than the local electric field.

To enable the energy balance transport model, use the `HCTE`, `HCTE.EL`, or `HCTE.HO` parameters in the `MODELS` statement. These parameters enable the energy transport model for both carriers, electrons only, or holes only respectively. For example, the statement:

```
MODELS MOS HCTE
```

enables the energy balance transport model for both electrons and holes in addition to the default MOSFET models.

## 2.7.5: Summary Of Physical Models

| Table 2-1. Carrier Statistics Models |            |  |
|--------------------------------------|------------|--|
| Model                                | Syntax     | Notes  |
| Boltzmann                            | BOLTZMANN  | Default model  |
| Fermi-Dirac                          | FERMI      | Reduced carrier concentrations in heavily doped regions (statistical approach).    |
| Incomplete Ionization                | INCOMPLETE | Accounts for dopant freeze-out. Typically, it is used at low temperatures.         |
| Silicon Ionization Model             | IONIZ      | Accounts for full ionization for heavily doped Si. Use with INCOMPLETE.            |
| Bandgap Narrowing                    | BGN        | Important in heavily doped regions. Critical for bipolar gain. Use Klaassen Model. |

| Table 2-2. Mobility Models              |          |   |
|---|----------|---|
| Model                                   | Syntax   | Notes   |
| Concentration Dependent                 | CONMOB   | Lookup table valid at 300K for Si and GaAs only. Uses simple power law temperature dependence.  |
| Concentration and Temperature Dependent | ANALYTIC | Caughey-Thomas formula. Tuned for 77-450K.  |
| Arora's Model                           | ARORA    | Alternative to ANALYTIC for Si  |
| Carrier-Carrier Scattering              | CCSMOB   | Dorkel-Leturq Model. Includes n, N and T dependence. Important when carrier concentration is high (e.g., forward bias power devices). |
| Parallel Electric Field Dependence      | FLDMOB   | Si and GaAs models. Required to model any type of velocity saturation effect.   |
| Tasch Model                             | TASCH    | Includes transverse field dependence. Only for planar devices. Needs very fine grid.  |
| Watt Model                              | WATT     | Transverse field model applied to surface nodes only.   |
| Klaassen Model                          | KLA      | Includes N, T, and n dependence. Applies separate mobility to majority and minority carriers. Recommended for bipolar devices         |
| Shirahata Model                         | SHI      | Includes N, $E_{\perp}$ . An alternative surface mobility model that can be combined with KLA.  |

| <b>Table 2-2. Mobility Models</b> |               |   |
|-----------------------------------|---------------|---|
| <b>Model</b>                      | <b>Syntax</b> | <b>Notes</b>  |
| Modified Watt                     | MOD.WATT      | Extension of WATT model to non-surface nodes. Applies constant $E_{\perp}$ effects. Best model for planar MOS devices |
| Lombardi (CVT) Model              | CVT           | Complete model including N, T, $E_{//}$ , and $E_{\perp}$ effects. Good for non-planar devices.                       |
| Yamaguchi Model                   | YAMAGUCHI     | Includes N, $E_{//}$ and $E_{\perp}$ effects. Only calibrated for 300K.   |

| <b>Table 2-3. Recombination Models</b> |               |   |
|--|---------------|---|
| <b>Model</b>                           | <b>Syntax</b> | <b>Notes</b>  |
| Shockley-Read-Hall                     | SRH           | Uses fixed minority carrier lifetimes. Should be used in most simulations.              |
| Concentration Dependent                | CONSRH        | Uses concentration dependent lifetimes. Recommended for Si.                             |
| Auger                                  | AUGER         | Direct transition of three carriers. Important at high current densities.               |
| Optical                                | OPTR          | Band-band recombination. For direct materials only.                                     |
| Surface                                | S.N<br>S.P    | Recombination at semiconductor to insulator interfaces. Set on the INTERFACE statement. |

| <b>Table 2-4. Impact Ionization</b> |                      |  |
|-------------------------------------|----------------------|--|
| <b>Model</b>                        | <b>Syntax</b>        | <b>Notes</b>   |
| Selberherr's Model                  | IMPACT SELB          | Recommended for most cases. Includes temperature dependent parameters.   |
| Grant's Model                       | IMPACT GRANT         | Similar to Selberherr's model but with different coefficients.           |
| Crowell-Sze                         | IMPACT CROWELL       | Uses dependence on carrier scattering length.                            |
| Toyabe Model                        | IMPACT TOYABE        | Non-local model used with Energy Balance. Any IMPACT syntax is accepted. |
| Concannon                           | N.CONCAN<br>P.CONCAN | Non-local model developed in Flash EEPROM technologies.                  |

| Table 2-5. Tunneling Models and Carrier Injection Models |                          |   |
|--|--------------------------|---|
| Model  | Syntax                   | Notes   |
| Fowler-Nordheim (electrons)                              | FNORD                    | Self-consistent calculation of tunneling through insulators. Used in EEPROMs.                               |
| Fowler-Nordheim (holes)                                  | FNHOLES                  | Same as FNORD for holes.  |
| Band-to-Band (standard)                                  | BBT . STD                | For direct transitions. Required with very high fields.   |
| Klaassen Band-to-Band                                    | BBT . KL                 | Includes direct and indirect transitions.   |
| Hot Electron Injection                                   | HEI                      | Models energetic carriers tunneling through insulators. Used for gate current and Flash EEPROM programming. |
| Hot Hole Injection                                       | HHI                      | HHI means hot hole injection.   |
| Concannon Gate Current Model                             | N . CONCAN<br>P . CONCAN | Non-local gate model consistent with Concannon substrate current model.                                     |

**Note:** In the notes in Tables 2-2-1 through 2-2-5, n is electron concentration, p is hole concentration, T is lattice temperature, N is dopant concentration, E<sub>||</sub> is parallel electric field, and E<sub>⊥</sub> is perpendicular electric field.



Table 2-6. Model Compatibility Chart

|                       | CONMOB | FLDMOB          | TFLDMB2         | YAMAGUCHI | CVT    | ARORA | ANALYTIC | CCSMOB | SURMOB | LATTICE H | E.BALANCE |
|-----------------------|--------|-----------------|-----------------|-----------|--------|-------|----------|--------|--------|-----------|-----------|
| <b>CONMOB [CM]</b>    | —      | OK              | OK              | YA        | C<br>V | AR    | AN       | CC     | OK     | OK        | OK        |
| <b>FLDMOB [FM]</b>    | OK     | —               | TF <sup>1</sup> | YA        | C<br>V | OK    | OK       | OK     | OK     | OK        | OK        |
| <b>TFLDMB2 [TF]</b>   | OK     | TF <sup>1</sup> | —               | YA        | C<br>V | OK    | OK       | TF     | TF     | OK        | OK        |
| <b>YAMAGUCHI [YA]</b> | YA     | YA              | YA              | —         | C<br>V | YA    | YA       | YA     | YA     | NO        | NO        |
| <b>CVT [CV]</b>       | CV     | CV              | CV              | CV        | —      | CV    | CV       | CV     | CV     | OK        | OK        |
| <b>ARORA [AR]</b>     | AR     | OK              | OK              | YA        | C<br>V | —     | AR       | CC     | OK     | OK        | OK        |
| <b>ANALYTIC [AN]</b>  | AN     | OK              | OK              | YA        | C<br>V |       | —        | CC     | OK     | OK        | OK        |
| <b>CCSMOB [CC]</b>    | CC     | OK              | TF              | YA        | C<br>V | CC    | CC       | —      | OK     | OK        | OK        |
| <b>SURMOB [SF]</b>    | OK     | OK              | TF              | YA        | C<br>V | OK    | OK       | OK     | —      | OK        | OK        |
| <b>LATTICE H [LH]</b> | OK     | OK              | OK              | NO        | O<br>K | OK    | OK       | OK     | OK     | —         | OK        |
| <b>E.BALANCE [EB]</b> | OK     | OK              | OK              | NO        | O<br>K | OK    | OK       | OK     | OK     | OK        | 2         |

**Key To Table Entries**

MODEL ABBREVIATION = The model that supersedes when a combination is specified. In some cases, but not all, a warning message is issued when a model is ignored.

OK = This combination is allowed.

NO = This combination is not allowed.

**NOTES:**

1. Uses internal model similar to FLDMOB

2. When models including a parallel electric field dependence are used with energy balance the electric field term is replaced by a function of carrier temperature.

## Using the C-Interpreter to Specify Models

One of the ATLAS products is a C language interpreter that allows you to specify many of the models used by ATLAS. To use these functions, implement the model in C as equations in a special file called an *ATLAS lib file*. You can access the default ATLAS template file by typing:

```
atlas -T <filename>
```

at the UNIX command prompt. This creates a default template file with the name specified by the *<filename>* parameter. See Appendix A: "C-Interpreter Functions" for a listing of the default C-INTERPRETER functions. To use the interpreter functions, give the corresponding parameters in the statements containing the name of the C language file with the model given as the parameter value. For example, the statement:

```
MATERIAL NAME=Silicon F.MUNSAT=munsat.lib
```

specifies that the file, *munsat.lib*, contains the C-INTERPRETER function for the specification of the parallel field dependent electron mobility model.

## 2.8: Choosing Numerical Methods

### 2.8.1: Numerical Solution Techniques

Several different numerical methods can be used for calculating the solutions to semiconductor device problems. Numerical methods are given in the `METHOD` statements of the input file. Some guidelines for these methods will be given here, but for full details, see Chapter 17: “Numerical Techniques”.

Different combinations of models will require ATLAS to solve up to six equations. For each of the model types there are basically three types of solution techniques: (a) decoupled (`GUMMEL`), (b) fully coupled (`NEWTON`) and (c) `BLOCK`. The `GUMMEL` method will solve for each unknown in turn keeping the other variables constant, repeating the process until a stable solution is achieved. The `NEWTON` method solve the total system of unknowns together. The `BLOCK` methods will solve some equations fully coupled, while others are de-coupled.

Generally, the `GUMMEL` method is useful where the system of equations is weakly coupled, but has only linear convergence. The `NEWTON` method is useful when the system of equations is strongly coupled and has quadratic convergence. The `NEWTON` method may however spend extra time solving for quantities which are essentially constant or weakly coupled. `NEWTON` also requires a more accurate initial guess to the problem to obtain convergence. Thus, a `BLOCK` method can provide for faster simulations times in these cases over `NEWTON`. `GUMMEL` can often provide better initial guesses to problems. It can be useful to start a solution with a few `GUMMEL` iterations to generate a better guess and then switch to `NEWTON` to complete the solution. Specification of the solution method is carried out as follows:

```
METHOD GUMMEL BLOCK NEWTON
```

The exact meaning of the statement depends on the particular models it is applied to. This will be discussed in the following sections.

#### Basic Drift Diffusion Calculations

The isothermal drift diffusion model requires the solution of three equations for potential, electron concentration, and hole concentration. Specifying `GUMMEL` or `NEWTON` alone will produce simple Gummel or Newton solutions as detailed above. For almost all cases, the `NEWTON` method is preferred and it is the default.

Specifying:

```
METHOD GUMMEL NEWTON
```

will cause the solver to start with `GUMMEL` iterations and then switch to `NEWTON`, if convergence is not achieved. This is a robust, yet a more time consuming way of obtaining solutions for any device. But this method is highly recommended for all simulations with floating regions such as SOI transistors. A floating region is defined as an area of doping which is separated from all electrodes by a pn junction.

`BLOCK` is equivalent to `NEWTON` for all isothermal drift-diffusion simulations.

#### Drift Diffusion Calculations with Lattice Heating

When the lattice heating model is added to drift diffusion, an extra equation is added. The `BLOCK` algorithm solves the three drift diffusion equations as a `NEWTON` solution and follows this with a `GUMMEL` solution of the heat flow equation. The `NEWTON` algorithm solves all four equations in a coupled manner. `NEWTON` is preferred once the temperature is high, however `BLOCK` is quicker for low temperature gradients. Typically, the combination used is:

```
METHOD BLOCK NEWTON
```

## Energy Balance Calculations

The energy balance model requires the solution of up to 5 coupled equations. GUMMEL and NEWTON have the same meanings as with the drift diffusion model (i.e., GUMMEL specifies a de-coupled solution and NEWTON specifies a fully coupled solution).

But BLOCK performs a coupled solution of potential, carrier continuity equations followed by a coupled solution of carrier energy balance, and carrier continuity equations.

It is possible to switch from BLOCK to NEWTON by specifying multiple solution methods on the same line. For example:

```
METHOD BLOCK NEWTON
```

will begin with BLOCK iterations then switch to NEWTON if convergence is still not achieved. This is the most robust approach for many energy balance applications.

The points at which the algorithms switch is predetermined, but can also be changed in the METHOD statement. The default values set by Silvaco work well for most circumstances.

## Energy Balance Calculations with Lattice Heating

When non-isothermal solutions are performed in conjunction with energy balance models, a system of up to six equations must be solved. GUMMEL or NEWTON solve the equations iteratively or fully coupled respectively. BLOCK initially performs the same function as with energy balance calculations, then solves the lattice heating equation in a de-coupled manner.

## Setting the Number Of Carriers

ATLAS can solve both electron and hole continuity equations, or only for one or none. This choice can be made by using the CARRIERS parameter. For example:

```
METHOD CARRIERS=2
```

specifies a solution for both carriers is required. This is the default. With one carrier, the ELEC or HOLE parameter is needed. For example, for hole solutions only:

```
METHOD CARRIERS=1 HOLE
```

To select a solution for potential only specify:

```
METHOD CARRIERS=0
```

---

**Note:** Setting the number of carriers using the syntax, MODEL NUMCARR=<n>, is obsolete and should not be used.

---

## Important Parameters Of the METHOD Statement

You can alter all of the parameters relevant to the numerical solution process. This, however, isn't recommended unless you have expert knowledge of the numerical algorithms. All of these parameters have been assigned optimal values for most solution conditions. For more information about numerical algorithms, see Chapter 17: "Numerical Techniques".

The following parameters, however, are worth noting at this stage:

- `CLIMIT` or `CLIM.DD` specify minimal values of concentrations to be resolved by the solver. Sometimes you need to reduce this value to aid solutions of breakdown characteristics. A value of `CLIMIT=1e-4` is recommended for all simulations of breakdown, where the pre-breakdown current is small. `CLIM.DD` is equivalent to `CLIMIT` but uses the more convenient units of  $\text{cm}^{-3}$  for the critical concentration. `CLIM.DD` and `CLIMIT` are related by the following expression.

$$CLIM.DD = CLIMIT * \sqrt{N_c N_v} \quad 2-1$$

- `DVMAX` controls the maximum update of potential per iteration of Newton's method. The default corresponds to 1V. For power devices requiring large voltages an increased value of `DVMAX` might be needed. `DVMAX=1e8` can improve the speed of high voltage bias ramps.
- `CLIM.EB` controls the cut-off carrier concentration below which the program will not consider the error in the carrier temperature. This is applied in energy balance simulations to avoid excessive calculations of the carrier temperature at locations in the structure, where the carrier concentration is low. But if this parameter is set to too high, where the carrier temperature errors for significant carrier concentrations are being ignored, unpredictable and mostly incorrect results will be seen.

## Restrictions on the Choice of METHOD

The following cases require `METHOD NEWTON CARRIERS=2` to be set for isothermal drift-diffusion simulations:

- current boundary conditions
- distributed or lumped external elements
- AC analysis
- impact ionization

Both `BLOCK` and/or `NEWTON` are permitted for lattice heat and energy balance.

---

**Note:** Simulations using the `GUMMEL` method in these cases may lead to non-convergence or incorrect results.

---

### Pisces-II Compatibility

Previous releases of ATLAS (2.0.0.R) and other PISCES-II based programs, use the SYMBOLIC command to define the solution method and the number of carriers to be included in the solution. In this version of ATLAS, the solution method is specified completely on the METHOD statement.

The COMB parameter, which was available in earlier ATLAS versions, is no longer required. It has been replaced with either the BLOCK method or the combination of GUMMEL and NEWTON parameters. The following table identifies direct translations of old syntax to new.

---

**Note:** These are direct translations and not necessarily the best choices of numerical methods.

---

| Old Syntax (V2.0.0.R)  | New Syntax                        |
|--|-----------------------------------|
| symbolic newton carriers=2                                   | method newton                     |
| symbolic newton carriers=1 elec                              | method newton carriers=1 electron |
| symbolic gummel carriers=0                                   | method gummel carriers=0          |
| symbolic newton carriers=2<br>method comb                    | method gummel newton              |
| models lat.temp<br>symbolic newton carriers=2<br>method comb | models lat.temp<br>method block   |
| models hcte<br>symbolic gummel carriers=2<br>method comb     | models hcte<br>method block       |

## 2.9: Obtaining Solutions

ATLAS can calculate DC, AC small signal, and transient solutions. Obtaining solutions is rather analogous to setting up parametric test equipment for device tests. You usually define the voltages on each of the electrodes in the device. ATLAS then calculates the current through each electrode. ATLAS also calculates internal quantities, such as carrier concentrations and electric fields throughout the device. This is information that is difficult or impossible to measure.

In all simulations, the device starts with zero bias on all electrodes. Solutions are obtained by stepping the biases on electrodes from this initial equilibrium condition. As will be discussed, due to the initial guess strategy, voltage step sizes are limited. This section concentrates on defining solution procedures. Saving results using the LOG or SAVE statements, and analyzing and displaying these results, is described in Section 2.10: “Interpreting The Results”.

### 2.9.1: DC Solutions

In DC solutions, the voltage on each electrode is specified using the SOLVE statement. For example, the statements:

```
SOLVE VGATE=1.0
SOLVE VGATE=2.0
```

solves a single bias point with 1.0V and then 2.0V on the gate electrode. One very important rule in ATLAS is that when the voltage on any electrode is not specified in a given SOLVE statement, the value from the last SOLVE statement is assumed.

In the following case, the second solution is for a drain voltage of 1.0V and a gate voltage of 2.0V.

```
SOLVE VGATE=2.0
SOLVE VDRAIN=1.0
```

When the voltage on a particular electrode is never defined on any SOLVE statement and voltage is zero, you don't need to explicitly state the voltage on all electrodes on all SOLVE statements. For example, in a MOSFET, if VSUBSTRATE is not specified, then  $V_{BS}$  defaults to zero.

### Sweeping The Bias

For most applications, a sweep of one or more electrodes is usually required. The basic DC stepping is inconvenient and a ramped bias should be used. To ramp the base voltage from 0.0V to 1.0V with 0.05V steps with a fixed collector voltage of 2.0V, use the following syntax:

```
SOLVE VCOLLECTOR=2.0
SOLVE VBASE=0.0 VSTEP=0.05 VFINAL=1.0 NAME=base
```

The NAME parameter is required and the electrode name is case-sensitive. Make sure the initial voltage, VSTEP and VFINAL, are consistent. A badly specified ramp from zero to 1.5V in 0.2V steps will finish at 1.4V or 1.6V.

## Generating Families Of Curves

Many applications such as MOSFET Id/Vds and bipolar Ic/Vce simulations require that a family of curves is produced. This is done by obtaining solutions at each of the stepped bias points first, and then solving over the swept bias variable at each stepped point. For example, in MOSFET Id/Vds curves, solutions for each Vgs value are obtained with Vds=0.0V. The output from these solutions are saved in ATLAS solution files. For each gate bias, the solution file is loaded and the ramp of drain voltage performed.

The family of curves for three 1V gate steps and a 3.3V drain sweep would be implemented in ATLAS as follows:

```
SOLVE VGATE=1.0  OUTF=solve_vgate1
SOLVE VGATE=2.0  OUTF=solve_vgate2
SOLVE VGATE=3.0  OUTF=solve_vgate3

LOAD INFILE=solve_vgate1
LOG OUTFILE=mos_drain_sweep1
SOLVE NAME=drain VDRAIN=0 VFINAL=3.3 VSTEP=0.3

LOAD INFILE=solve_vgate2
LOG OUTFILE=mos_drain_sweep2
SOLVE NAME=drain VDRAIN=0 VFINAL=3.3 VSTEP=0.3

LOAD INFILE=solve_vgate3
LOG OUTFILE=mos_drain_sweep3
SOLVE NAME=drain VDRAIN=0 VFINAL=3.3 VSTEP=0.3
```

The LOG statements are used to save the Id/Vds curve from each gate voltage to separate files. We recommend that you save the data in this manner rather than to a single LOG file (see Section 2.10: “Interpreting The Results”).

### 2.9.2: The Importance Of The Initial Guess

To obtain convergence for the equations used, supply a good initial guess for the variables to be evaluated at each bias point. The ATLAS solver uses this initial guess and iterates to a converged solution. For isothermal drift diffusion simulations, the variables are the potential and the two carrier concentrations. If a reasonable grid is used, almost all convergence problems in ATLAS are caused by a poor initial guess to the solution.

During a bias ramp the initial guess for any bias point is provided by a projection of the two previous results. Problems tend to appear near the beginning of the ramp when two previous results are not available. If one previous bias is available, it is used alone. This explains why the following two examples eventually produce the same result. The first will likely have far more convergence problems than the second.

```
1. SOLVE VGATE=1.0 VDRAIN=1.0 VSUBSTRATE=-1.0
2. SOLVE VGATE=1.0
   SOLVE VSUBSTRATE=-1.0
   SOLVE VDRAIN=1.0
```

In the first case, one solution is obtained with all specified electrodes at 1.0V. In the second case, the solution with only the gate voltage at 1.0V is performed first. All other electrodes are at zero bias. Next, with the gate at 1.0V, the substrate potential is raised to -1.0V and another solution is obtained. Finally, with the substrate and the gate biased, the drain potential is added and the system solved again. The advantage of this method over the first case is that the small incremental changes in voltage allow for better initial guesses at each step.



Generally the projection method for the initial guess gives good results when the I-V curve is linear. But it may encounter problems if the IV curve is highly non-linear or if the device operating mode is changing. Typically, this might occur around the threshold or breakdown voltages. At these biases smaller voltage steps are required to obtain convergence. As will be described, ATLAS contains features such as the TRAP parameter and the curve tracer to automatically cut the voltage steps in these highly non-linear area.

Numerical methods are described in Section 2.8: “Choosing Numerical Methods” and Chapter 17: “Numerical Techniques”.

In many cases, these methods are designed to overcome the problems associated with the initial guess. This is particularly important in simulations involving more than the three drift diffusion variables. Generally, coupled solutions require a good initial guess, whereas de-coupled solutions can converge with a poor initial guess.

## The Initial Solution

When no previous solutions exist, the initial guess for potential and carrier concentrations must be made from the doping profile. This is why the initial solution performed must be the zero bias (or thermal equilibrium) case. This is specified by the statement:

```
SOLVE INIT
```

But if this syntax isn't specified, ATLAS automatically evaluates an initial solution before the first SOLVE statement. To aid convergence of this initial guess, the solution is performed in the zero carrier mode solving only for potential.

## The First and Second Non-Zero Bias Solutions

From experience with ATLAS, it is found that the first and second non-zero bias solutions are the most difficult to obtain good convergence. Once these two solutions are obtained, the projection algorithm for the initial guess is available and solutions should all have a good initial guess.

These first two solutions, however, must use the result of the initial solution as the basis of their initial guess. Since the initial solution is at zero bias, it provides a poor initial guess.

The practical result of this is that the first and second non-zero bias solutions should have very small voltage steps. In the following example, the first case will likely converge, whereas the second case may not.

```
1. SOLVE INIT
   SOLVE VDRAIN=0.1
   SOLVE VDRAIN=0.2
   SOLVE VDRAIN=2.0
2. SOLVE INIT
   SOLVE VDRAIN=2.0
```

## The Trap Parameter

Although ATLAS provides several methods to overcome a poor initial guess and other convergence problems, it is important to understand the role of the initial guess in obtaining each solution. The simplest and most effective method to overcome poor convergence is by using:

```
METHOD TRAP
```

This is enabled by default. Its effect is to reduce the bias step if convergence problems are detected. Consider the example from the previous section:

```
SOLVE INIT
SOLVE VDRAIN=2.0
```

If the second SOLVE statement does not converge, TRAP automatically cuts the bias step in half and tries to obtain a solution for  $V_d = 1.0V$ . If this solution does not converge, the bias step will be halved again to solve for  $V_d = 0.5V$ . This procedure is repeated up to a maximum number of tries set by the METHOD parameter MAXTRAPS. Once convergence is obtained, the bias steps are increased again to solve up to  $2.0V$ . The default for MAXTRAPS is four and it is not recommended to increase it since changing the syntax to use smaller bias steps is generally much faster.

This trap facility is very useful during bias ramps in overcoming convergence difficulties around transition points such as the threshold voltage. Consider the following syntax used to extract a MOSFET Id/Vgs curve.

```
SOLVE VGATE=0.0 VSTEP=0.2 VFINAL=5.0 NAME=gate
```

Assume the threshold voltage for the device being simulated is  $0.7V$  and that ATLAS has solved for the gate voltages up to  $0.6V$ . The next solution, at  $0.8V$ , might not converge at first. This is because the initial guess was formed from the two sub-threshold results at  $V_{gs}=0.4V$  and  $0.6V$  and the solution has now become non-linear. The trap facility will detect the problems in the  $0.8V$  solution and cut the bias step in half to  $0.7V$  and try again. This will probably converge. The solution for  $0.8V$  will then be performed and the bias ramp will continue with  $0.2V$  steps.

### 2.9.3: Small-Signal AC Solutions

Specifying AC simulations is a simple extension of the DC solution syntax. AC small signal analysis is performed as a post-processing operation to a DC solution. Two common types of AC simulation in ATLAS are outlined here. The results of AC simulations are the conductance and capacitance between each pair of electrodes. Tips on interpreting these results is described in Section 2.10: "Interpreting The Results".

#### Single Frequency AC Solution During A DC Ramp

The minimum syntax to set an AC signal on an existing DC ramp is just the AC flag and the setting of the small signal frequency. For example:

```
SOLVE VBASE=0.0 VSTEP=0.05 VFINAL=1.0 NAME=base AC FREQ=1.0e6
```

Other AC syntax for setting the signal magnitude and other parameters are generally not needed as the defaults suffice. One exception is in 1D MOS capacitor simulations. To obtain convergence in the inversion/deep depletion region, add the DIRECT parameter to access a more robust solution method.

#### Ramped Frequency At A Single Bias

For some applications, such as determining bipolar gain versus frequency you need to ramp the frequency of the simulation. This is done using the following syntax:

1. SOLVE VBASE=0.7 AC FREQ=1e9 FSTEP=1e9 NFSTEPS=10
2. SOLVE VBASE=0.7 AC FREQ=1e6 FSTEP=2 MULT.F NFSTEPS=10

The first case ramps the frequency from  $1GHz$  to  $11GHz$  in  $1GHz$  steps. A linear ramp of frequency is used and FSTEP is in Hertz. In the second example, a larger frequency range is desired and so a geometrical step of frequency is used. The MULT.F parameter is used to specify that FSTEP is a unitless multiplier for the frequency. This doubles the frequency in successive steps from  $1MHz$  to  $1.024GHz$ .

The syntax described below for ramping the frequency of the AC signal can potentially be combined with that for ramping the bias. The frequency ramps are done at each bias point during the DC ramp.

```
SOLVE VBASE=0.0 VSTEP=0.05 VFINAL=1.0 NAME=base AC FREQ=1.0e6 \  
FSTEP=2 MULT.F NFSTEPS=10
```

## 2.9.4: Transient Solutions

Transient solutions can be obtained for piecewise-linear, exponential, and sinusoidal bias functions. Transient solutions are used when a time dependent test or response is required. To obtain transient solutions for a linear ramp, the `TSTART`, `TSTOP`, `TSTEP`, and `RAMPTIME` parameters should be specified.

Figure 2-11 shows the syntax of the transient voltage ramp. The `TSTART` parameter specifies the time that the linear ramp should start. The `RAMPTIME` specifies the time that the linear ramp should obtain its final value. `TSTOP` specifies the time that solutions will stop. `TSTEP` specifies the initial step size.

Subsequent time steps are calculated automatically by ATLAS. For example, the statement:

```
SOLVE VGATE=1.0 RAMPTIME=1E-9 TSTOP=10e-9 TSTEP=1e-11,
```

specifies that the voltage on the gate electrode will be ramped in the time domain from its present value to 1.0V over a period of 1 nanoseconds.

Time domain solutions are obtained for an additional 9 nanoseconds. An initial time step of 10 picoseconds is specified. It is important to remember that if subsequent transient solutions are specified, don't reset the time to zero.

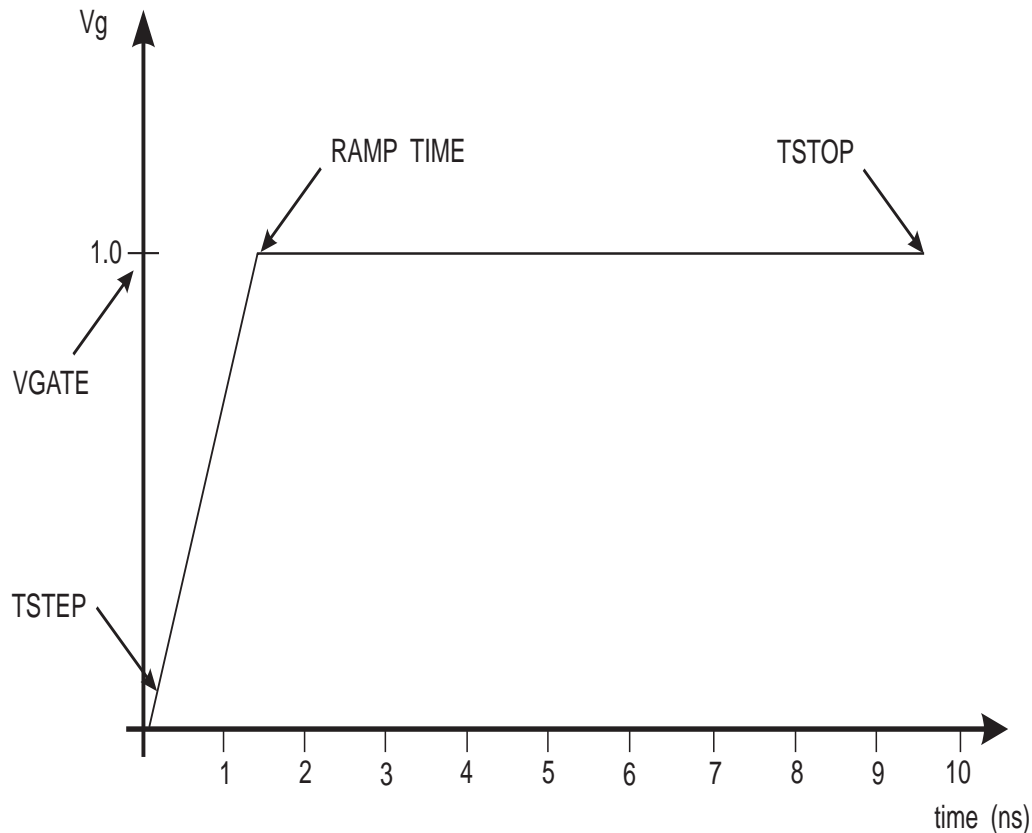


Figure 2-11: Diagram showing syntax of Transient Voltage Ramp in ATLAS

## 2.9.5: Advanced Solution Techniques

### Obtaining Solutions Around The Breakdown Voltage

Obtaining solutions around the breakdown voltage can be difficult using the standard ATLAS approach. It requires special care when choosing voltage steps and interpreting the results. The curve tracer described in “The Curvetrace Capability” section on page 2-47 is the most effective method in many cases.

A MOSFET breakdown simulation might be performed using the following standard syntax for ramping the drain bias. Note that the setting of CLIMIT is recommended for breakdown simulations when the pre-breakdown leakage is low.

```
IMPACT SELB
METHOD CLIMIT=1e-4
SOLVE VDRAIN=1.0 VSTEP=1.0 VFINAL=20.0 NAME=drain
```

If the breakdown were 11.5V, then convergence problems will be expected for biases higher than 11.0V. Although it depends on technology used, it is common for the breakdown curve to be flat up to a voltage very close to breakdown and then almost vertical. The current changes by orders of magnitude for very small bias increments.

This produces some problems for ATLAS using the syntax described above. If the breakdown occurs at 11.5V, there are no solutions for voltages greater than this value. ATLAS is trying to ramp to 20.0V so it is inevitable that ATLAS will fail to converge at some point. This is usually not a problem since by that point the breakdown voltage and curve have been obtained.

Above 11V, bias step reduction will take place due to the TRAP parameter. ATLAS will continually try to increase the drain voltage above 11.5V and those points will fail to converge. But it will solve points asymptotically approaching  $V_{ds}=11.5V$  until the limit set by the MAXTRAPS parameter is reached. If the default of 4 traps is used it is clear that the minimum allowed voltage step is  $1.0 \times (0.5)^4$  or 0.004V. This is normally enough accuracy for determining the breakdown point. But the simulation might not allow the current to reach a sufficiently high level before MAXTRAPS is needed.

Typically in device simulation, the breakdown point is determined once the current is seen to increase above the flat pre-breakdown leakage value by two orders of magnitude in a small voltage increment. If you want to trace the full breakdown curve up to high current values, apply more advanced techniques than the simple voltage ramp. Two of these techniques are described in the following subsections. These methods may use extra CPU time.

### Using Current Boundary Conditions

In all of the examples considered in the basic description of the SOLVE statement, it was assumed that voltages were being forced and currents were being measured. ATLAS also supports the reverse case through current boundary conditions. The current through the electrode is specified in the SOLVE statement and the voltage at the contact is calculated. Current boundary conditions are set using the CONTACT statement as described in Section 2.7: “Defining Material Parameters And Models”.

The syntax of the SOLVE statement is altered once current boundary conditions are specified.

```
SOLVE IBASE=1e-6
```

The syntax above specifies a single solution at a given current.

```
SOLVE IBASE=1e-6 ISTEP=1e-6 IFINAL=5e-6 NAME=base
```

This sets a current ramp similar in syntax to the voltage ramp described earlier.

```
SOLVE IBASE=1e-10 ISTEP=10 IMULT IFINAL=1e-6 NAME=base
```

This is similar to the previous case, but the `IMULT` parameter is used to specify that `ISTEP` should be used as a multiplier for the current rather than a linear addition. This is typical for ramps of current since linear ramps are inconvenient when several orders of magnitude in current may need to be covered.

Important points to remember about current boundary conditions are that the problems of initial guess are more acute when very small (noise level) currents are used. Often it is best to ramp the voltage until the current is above  $1\mu\text{A}/\mu\text{m}$  and then switch to current forcing.

When interpreting the results, it is important to remember the calculated voltage on the electrode with current boundary conditions is stored as the internal bias (i.e., `base int.bias` in `TONYPLOT` or `vint.base` in `DECKBUILD`'s extract syntax).

## The Compliance Parameter

Compliance is a parameter used to limit the current or voltage through or on an electrode during a simulation. An electrode compliance can be set. After it is reached, the bias sweep will stop. This is analogous to parametric device testing when we stop a device from being over stressed or destroyed. The compliance refers to the maximum resultant current or voltage present after a solution is obtained. If an electrode voltage is set, the compliance will then refer to the electrode current. If current boundary conditions are used, then you can set a voltage compliance.

The statements:

```
SOLVE VGATE=1.0
SOLVE NAME=drain VDRAIN=0 VFINAL=2 VSTEP=0.2 COMPL=1E-6 CNAME=drain
```

solve for IV on the gate and then ramps the drain voltage towards 2V in 0.2V steps. The simulation will stop if  $1\mu\text{A}/\mu\text{m}$  of drain current is reached before  $V_d = 2\text{V}$ . Thus, as in parametric testing, a particular level can be defined and the simulation can be set to solve up to that point. Once the compliance limit is reached, ATLAS will simulate the next statement line in the command file.

## The Curvetrace Capability

The automatic curve tracing algorithm can be invoked to enable ATLAS to trace out complex IV curves. The algorithm can automatically switch from voltage to current boundary conditions and vice versa. A single `SOLVE` statement can be used to trace out complex IV curves such as breakdown curves and CMOS latch-up including the snapback region and second breakdown. The algorithm is based upon a dynamic load line approach.

For example, typical `CURVETRACE` and `SOLVE` statements to trace out an IV curve for the breakdown of a diode would look like:

```
CURVETRACE CONTR.NAME=cathode STEP.INIT=0.5 NEXST.RATIO=1.2 \
MINCUR=1e-12 END.VAL=1e-3 CURR.CONT
SOLVE CURVETRACE
```

The name of the electrode, which is to be ramped, is specified using `CONTR.NAME`. `STEP.INIT` specifies the initial voltage step. `NEXST.RATIO` specifies the factor used to increase the voltage step in areas on the IV curve away from turning points. `MINCUR` can be used to set a small current value above which the dynamic load line algorithm is activated. Below the `MINCUR` level, the `STEP.INIT` and `NEXST.RATIO` are used to determine the next solution bias. `END.VAL` is used to stop the tracing if the voltage or current of the ramped electrode equals or exceeds `END.VAL`. Either `VOLT.CONT` or `CURR.CONT` is used to specify whether `END.VAL` is a voltage or current value.

When plotting the log file created by the curve trace statement in `TONYPLOT`, you need to select the internal bias labeled `int.bias` for the ramped electrode instead of plotting the applied bias, which is labeled `Voltage`.

## 2.9.6: Using DeckBuild To Specify SOLVE Statements

The DeckBuild Solve menu can be used generate SOLVE statements. The menu has a spreadsheet style entry. To access this menu, select the **Command/Solutions/Solve...** button in DECKBUILD. To define a test, click the right mouse button in the worksheet and select the **Add new row** option. This will add a new row to the worksheet. This procedure should be repeated once per electrode in your device structure. The entry for each cell can then be edited to construct a SOLVE statement.

Some cells require the selection using a pop menu or the entry of numerical values. The electrode name is specified in the first cell. To edit the electrode name, use a popup menu by pressing the right mouse button on the cell. The second cell specifies whether the electrode will be a voltage (V), current (I) or charge (Q) controlled. The third cell specifies whether the SOLVE statement is to be a single DC solve (CONST), a swept DC variable (VAR 1), a stepped DC variable (VAR2), or a transient solution (PULSE). The remaining cells specify the parameter values that are required for the type of solution desired.

The pop-up window to specify the solution file names are accessed through the **Props...** button. Several SOLVE statements may be constructed to create solve sequences which define a test. This test may be saved in a file and read in using the **Save...** and **Load...** buttons.

## 2.10: Interpreting The Results

As already described in Section 2.2: “ATLAS Inputs and Outputs”, ATLAS produces three different types of output files. These files are also described in the following sections.

### 2.10.1: Run-Time Output

Run-time output is provided at the bottom of the DeckBuild Window. If it’s run as a batch job, the run-time output can be stored to a file.

Errors occurring in the run-time output will be displayed in this window. Note that not all errors will be fatal (as DECKBUILD tries to interpret the file and continue). This may cause a statement to be ignored, leading to unexpected results. We recommend that you check the run-time output of any newly created input file the first time it runs to intercept any errors.

If you specify the PRINT option within the MODELS statement, the details of material parameters and constants and mobility models will be specified at the start of the run-time output. This is a useful way of checking what parameters values and models are being applied in the simulation. We recommend that you always specify MODELS PRINT in input files.

During SOLVE statements the error numbers of each equation at each iteration are displayed (this is a change from the previous ATLAS version.) It isn’t vital for you to understand the iteration information but it can provide important insights in the case of convergence problems.

The output can be interpreted as follows:

```

proj      psi      n      p      psi      n      p
direct    x      x      x      rhs      rhs      rhs

  i      j      m      -5.00*  -5.00*  -5.00*  -26.0*  -17.3*  -17.3*
- - - - -
1      N      -1.932 -2.934 -1.932  -25.2  -10.19 -9.876
2      N      -4.741 -5.64* -4.267  -28.8* -16.67 -15.47
3      A      -11.3* -11.7* -9.63*  -28.8* -16.67 -18.0*

Electrode Va(V)      Jn(A/um)      Jp(A/um)      Jc(A/um)      Jt(A/um)
=====
gate      0.000e+00      -0.000e+00      -0.000e+00      0.000e+00      0.000e+00
source    0.000e+00      -3.138e-13      -1.089e-35      -3.138e-13      -3.138e-13
drain     1.000e-01      3.139e-13      1.076e-23      3.139e-13      3.139e-13
substrate 0.000e+00      -6.469e-19      -8.853e-17      -8.918e-17      -8.918e-17

```

The top left value, `proj`, indicates the initial guess methodology used. The default projection method is used here. Alternatives are `previous`, `local`, or `init`. The second value, `direct`, indicates the solver type. This will either be `direct` or `iterative`.

The first three column headings: `i`, `j`, and `m` indicate the iteration numbers of the solution and the solution method. `i` indicates the outer loop iteration number for decoupled solutions. `j` indicates the inner loop number. `m` indicates the solution method by a single letter, which are:

```

G = gummel
B = block
N = newton
A = newton with autonr
S = coupled Poisson-Schrodinger solution

```

The remaining column headings indicate which column lists the  $XNORM$  and  $RHSNORM$  errors for the equations being solved. See Chapter 17: “Numerical Techniques”, Section 17.5.7: “Error Measures” for a full description of these errors. The values printed in each error column under the hashed line are the logarithm to base 10 of the error. Earlier PISCES versions would print the floating point value. The values printed above the dashed line in each column are the tolerances used.

When the star \* symbol appears as the least significant digit in the number, it means this error measure has met its tolerance.

After convergence is achieved, ATLAS lists the results by electrode. The column,  $V_a$ , lists the voltage at the contact surface. This will differ from the applied voltage if external resistors or the curvetracer are used. All relevant current components are listed. Here, only electron, hole, conduction, and total currents are given. In other modes of simulation, these columns may differ.

The output of AC analysis, MIXEDMODE, and 3-D simulations differ from this standard. See Chapter 12: “MixedMode: Mixed Circuit and Device Simulator” for more information about MIXEDMODE.

ATLAS may produce a very large amount of run-time output for complex simulations. Run-Time output may be saved to a file as shown in Section 2.3: “Modes of Operation”.

## 2.10.2: Log Files

Log files store the terminal characteristics calculated by ATLAS. These are current and voltages for each electrode in DC simulations. In transient simulations, the time is stored. In AC simulations, the small signal frequency and the conductances and capacitances are saved. For example, the statement:

```
LOG OUTF=<FILENAME>
```

is used to open a log file. Terminal characteristics from all SOLVE statements after the LOG statement are then saved to this file along with any results from the PROBE statement.

The only way to stop the terminal characteristics being saved to this file is to use another LOG statement with either a different log filename or the OFF parameter.

Typically, a separate log file should be used for each bias sweep. For example, separate log files are used for each gate bias in a MOS Id/Vds simulation or each base current in a bipolar Ic/Vce simulation. These files are then overlaid in TONYPLOT.

Log files contain only the terminal characteristics. They are typically viewed in TONYPLOT. Parameter extraction of data in log files can be done in DECKBUILD. Log files cannot be loaded into ATLAS to re-initialize the simulation.

### Units Of Currents In Log files

Generally, the units of current written into the log file and therefore seen in TONYPLOT is Amperes per micron. This is because ATLAS is a two-dimensional simulator. It sets the third dimension (or z-direction) to be one micron. Thus, if you compare ATLAS 2D simulation results for a MOSFET versus the measured data from a MOSFET of width 20 micron, you need to multiply the current in the log file by 20.

There are four exceptions:

- In the 3D modules of ATLAS, the width is defined in the 3-D structure and so the units of the current are Amperes.
- In MIXEDMODE, set the width of devices. The current is also in Amperes.
- When cylindrical coordinates are used, the current written to the log file is integrated through the cylinder and is also in Amperes.
- When the WIDTH parameter in the MESH statement is used, the current is scaled by this factor and is in Amperes.



Similar rules apply for the capacitance and conductance produced by AC simulations. These are usually in 1/(ohms.microns) and Farads/micron respectively.

## UTMOST Interface

ATLAS log files can be read directly into the batch mode, UTMOST. The following commands in UTMOST are used to read in a set of IV curves stored in separate log files.

```
INIT INF=<filename> MASTER
INIT INF=<filename> MASTER APPEND
```

The UTMOST statement in ATLAS is no longer recommended for interfacing to UTMOST.

### 2.10.3: Parameter Extraction In DeckBuild

The EXTRACT command is provided within the DECKBUILD environment. It allows you to extract device parameters. The command has a flexible syntax that allows you to construct specific EXTRACT routines. EXTRACT operates on the previous solved curve or structure file. By default, EXTRACT uses the currently open log file. To override this default, supply the name of a file to be used by EXTRACT before the extraction routine. For example:

```
EXTRACT INIT INF="<filename>"
```

A typical example of using EXTRACT is the extraction of the threshold voltage of an MOS transistor. In the following example, the threshold voltage is extracted by calculating the maximum slope of the  $I_d / V_g$  curve, finding the intercept with the x-axis and then subtracting half of the applied drain bias.

```
EXTRACT NAME="nvt" XINTERCEPT(MAXSLOPE(CURVE (V."GATE", (I."DRAIN")))) \
-(AVE(V."DRAIN"))/2.0)
```

The results of the extraction will be displayed in the run-time output and will by default also be stored in the file `results.final`. You can store the results in a different file at the end of EXTRACT command by using the following option:

```
EXTRACT....DATAFILE="<filename>"
```

Cut-off frequency and forward current gain are of particular use as output parameters. These functions can be defined as follows:

```
# MAXIMUM CUTOFF FREQUENCY
EXTRACT NAME="FT_MAX" MAX(G."COLLECTOR" "BASE" / (6.28 * C."BASE" "BASE"))

#FORWARD CURRENT GAIN
EXTRACT NAME="PEAK GAIN" MAX(I."COLLECTOR" / I."BASE")
```

---

**Note:** Over 300 examples are supplied with ATLAS to provide many practical examples of the use of the EXTRACT statement.

---

## AC Parameter Extraction

Basic analysis of the capacitance and conductance matrix produced by ATLAS can be done using DECKBUILD or TONYPLOT. The capacitance between gate and drain will be labeled as Cgate>drain in TONYPLOT or c. "gate" "drain" in DECKBUILD'S EXTRACT.

The total capacitance on any electrode is defined as Celectrode>electrode. Thus, the magnitude of Cgate>gate is the total gate capacitance.

The LOG statement also includes options for small-signal, two-port RF analysis including s-parameter extraction. The solutions are saved into the log file and in the run-time output. The list of options for RF analysis are:

```
s.param, y.param, h.param, z.param, abcd.param gains
```

Terminal impedance and parasitics are accounted for by adding any of the following:

```
impedance=<val>, rin=<val>, rout=<val>, rcommon=<val> or  
rground=<val>, lin=<val>, lout=<val>,  
lcommon=<val> or lground=<val>, width=<val>
```

The width defaults to 1µm and impedance defaults to 50Ω. All parasitics default to zero.

The Stern stability factor, k, is calculated along with current gain (h21), GUm<sub>ax</sub>, and GT<sub>max</sub> when the GAINS option is added to the LOG statement.

The run-time output for AC analysis has been modified to only list the analysis frequency and electrode conductance/capacitance values. If one of the two-port options is added to the LOG statement (e.g., S.PARAM), the two-port parameters are also included in the run-time output.

AC parameter conversion utilities in the UTMOST statement have been discontinued.

## Additional Functions

EXTRACT has two additional important functions. The first function is to provide data for the VWF database (i.e., to store device parameters to the VWF database, they must be evaluated using EXTRACT). The second function is when using the DeckBuild Optimizer to tune parameters, use the EXTRACT statements as the optimization targets.

### 2.10.4: Functions In TonyPlot

The **Functions** Menu in TONYPLOT allows you to specify and plot functions of the terminal characteristics in the **Graph Function** text fields. For example transconductance can be calculated using the following function:

```
dydx (drain current, gate voltage)
```

Current gain can be evaluated as:

```
collector current / base current
```

When creating functions, the key to correct syntax is that the name for any variable in a function is the same as that in the **Y Quantities** list on the **Display** menu.

## 2.10.5: Solution Files

Solution files or structure files provide an image of the device at a particular bias point (DC solution or transient solution point). This gives you the ability to view any evaluated quantity within the device structure in question, from doping profiles and band parameters to electron concentrations and electric fields. These files should be plotted using TONYPLOT.

The syntax used to generate these files is of two forms:

```
(1)  SAVE  OUTFILE=<filename>
(2)  SOLVE .... OUTFILE=<filename>.sta MASTER [ONEFILEONLY]
```

Here in the second form, a file named <filename> will be saved with data from the previously solved bias point.

In this case, a structure file will be saved at each bias point solved in the solve statement. The last letter of the file name will be automatically incremented alphabetically (i.e., \*.sta, \*.stb, \*.stc..., and so on). If the solution for the last bias point is required, you can add the `onefileonly` parameter to the command. The <filename>.sta file will be overwritten at each solution point.

Structure files can be very large (1 - 2 MB), depending on the mesh density and quantities saved. It is recommended that unwanted structure files be deleted.

If many solution files have been written from a long simulation, it is often confusing to find out which solution file belongs to which bias point or transient time. The solution files should be plotted in TONYPLOT. In TONYPLOT, you can create 2-D contour plots and 1-D cutlines. To find out the bias of any solution file in TONYPLOT, select the plot, and press **b** on the keyboard.

### Interpreting Contour Plots

Some quantities saved in the solution files are not evaluated at the node points during solutions. They are evaluated at the center of the sides of each triangle in the mesh. Values of quantities at each node are derived from averaging the values from the sides of triangles connected to that node. The weighting method used to do the averaging can be selected with options in the OUTPUT statement. It is possible that for some meshes, smoother contour plots can be obtained by choosing a non-default averaging method.

When interpreting the contour plots, it's important to remember that the solution file contains values only at each node point. The color fills seen in TONYPLOT are simply interpolations based on the node values. This may lead to occasional strange contour values. In these cases, check the node values using the probe in TONYPLOT.

The primary solution variables (potential, carrier concentration, lattice temperature and carrier temperatures) are calculated on the nodes of the ATLAS mesh and therefore are always correct in TONYPLOT. But since ATLAS doesn't use nodal values of quantities such as electric field and mobility the actual values being used in calculations cannot be determined from TONYPLOT or the structure files. The PROBE statement allows you to directly probe values at given locations in the structure. This provides the most accurate way to determine the actual values used in ATLAS calculations.

### Customizing Solution Files (OUTPUT Statement)

Several quantities are saved by default within a structure file. For example, doping, electron concentration, and potential. You can also specify additional quantities (such as conduction band potential) by using the OUTPUT statement. This must precede the SAVE statement in question. For example, to save the conduction and valence band potentials, the following command would be used at some point before the relevant SAVE.

```
OUTPUT CON.BAND VAL.BAND
```

## Saving Quantities from the Structure at each Bias Point (PROBE statement)

Structure files provide all data from the structure at a single bias point. The log files provide terminal characteristics for a set of bias points. Use the `PROBE` statement to combine these and allow certain structural quantities to be saved at each bias point.

The `PROBE` statement allows you to specify quantities to be saved at given XY locations. There is also a facility to save the maximum or minimum of certain quantities. The value from the `PROBE` at each bias point in DC or timestep in transient mode is saved to the log file. The syntax:

```
PROBE NAME=mycarriers N.CONC X=1 Y=0.1
```

saves the electron concentration at (1, 0.1) for each solution in the log file. When the log file is displayed in `TONYPLOT`, the value will be labelled `mycarriers`. It will be possible to plot `mycarriers` versus terminal bias or current or other probed quantities.

Certain direction dependent quantities, such as electric field and mobility, can be probed. In these cases, a direction for the vector quantity must be specified using the `DIR` parameter.

The `PROBE` statement provides the only way to extract the actual values of quantities that are calculated along the sides of each triangle in `ATLAS`. The `PROBE` statement actually stored the triangle side value closest to the probed location, while taking into account the direction for vector quantities.

---

**Note:** Specifying the probe location exactly at a material or region interface will often lead to erroneous results. It is best to very slightly offset the location of the probe inside the material or region of interest.

---

## Re-initializing ATLAS at a Given Bias Point

Each `SOLVE` statement will begin with the device biased at the previous value solved. If you wish to begin a solution at a previously solved bias point, re-load the structure file saved at that point. This is accomplished in the following manner:

```
LOAD INFILE=<filename> MASTER
```

Information about that solution point will be displayed in the Output Window.

This command is useful for solving a set of I/V curves. For example, to solve a family of  $I_d / V_d$  (at various  $V_g$ ) ramp the gate with zero drain bias. A structure file is then saved at each desired value of  $V_g$ . These structure files can be reloaded in turn while a  $V_d$  sweep is performed.

---

**Note:** An `ATLAS` input file cannot start with a `LOAD` statement. Before loading the structure file, make sure that the device mesh for the same structure has been loaded using the `MESH` statement. Also, the same `MODELS`, `MATERIAL`, and `CONTACT` settings are required when the files are saved by `ATLAS`.

---

## 2.10.6: Technology Specific Issues in ATLAS

This chapter was designed to give an overview to the basic use of ATLAS without regard to the details required for a given technology. Requirements for ATLAS simulation vary considerably. The needs of the sub-micron MOS device engineer, the 1000V power device engineer, and the III-V RF device engineer differ and cannot all be covered in one chapter. Silvaco provides many references to individual technology problems using ATLAS. These are:

- A library of over 500 examples that can be accessed on-line from DECKBUILD. Look at these examples not only for their technology but also related ones. For example, different aspects of high frequency analysis is covered in the MESFET and silicon bipolar example sections.
- The chapters for each ATLAS module in this manual.
- The Simulation Standard, a newsletter distributed by Silvaco. To make sure you're on the mailing list, contact your local Silvaco office or go to [www.silvaco.com](http://www.silvaco.com).
- The Silvaco website also provides detailed information. It contains on-line versions of the articles in our newsletter, on-line searchable index of the examples, links to other TCAD web sites, and a section on solutions to known problems with all Silvaco programs.
- For more information about suggested technology specific strategies, contact your local Silvaco support engineer at [support@silvaco.com](mailto:support@silvaco.com).

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## 3.1: Basic Semiconductor Equations

Years of research into device physics have resulted in a mathematical model that operates on any semiconductor device [1]. This model consists of a set of fundamental equations which link together the electrostatic potential and the carrier densities, within some simulation domain. These equations, which are solved inside any general purpose device simulator, have been derived from Maxwell's laws and consist of Poisson's Equation (see Section 3.1.1: "Poisson's Equation"), the continuity equations (see Section 3.1.2: "Carrier Continuity Equations") and the transport equations (see Section 3.1.3: "The Transport Equations"). Poisson's Equation relates variations in electrostatic potential to local charge densities. The continuity and the transport equations describe the way that the electron and hole densities evolve as a result of transport processes, generation processes, and recombination processes.

This chapter describes the mathematical models implemented in ATLAS. Note that a discretization of the equations is also performed so that they can be applied to the finite element grid used to represent the simulation domain.

### 3.1.1: Poisson's Equation

Poisson's Equation relates the electrostatic potential to the space charge density:

$$\text{div}(\varepsilon \nabla \psi) = -\rho \quad 3-1$$

where  $\psi$  is the electrostatic potential,  $\varepsilon$  is the local permittivity, and  $\rho$  is the local space charge density. The reference potential can be defined in various ways. For ATLAS, this is always the intrinsic Fermi potential  $\psi_i$  which is defined in the next section. The local space charge density is the sum of contributions from all mobile and fixed charges, including electrons, holes, and ionized impurities.

The electric field is obtained from the gradient of the potential (see Equation 3-2).

$$\vec{E} = -\nabla \psi \quad 3-2$$

### 3.1.2: Carrier Continuity Equations

The continuity equations for electrons and holes are defined by equations:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \text{div} \vec{J}_n + G_n - R_n \quad 3-3$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \text{div} \vec{J}_p + G_p - R_p \quad 3-4$$

where  $n$  and  $p$  are the electron and hole concentration,  $\vec{J}_n$  and  $\vec{J}_p$  are the electron and hole current densities,  $G_n$  and  $G_p$  are the generation rates for electrons and holes,  $R_n$  and  $R_p$  are the recombination rates for electrons and holes, and  $q$  is the magnitude of the charge on an electron.

By default ATLAS includes both Equations 3-3 and 3-4. In some circumstances, however, it is sufficient to solve only one carrier continuity equation. The specification of which continuity equations are to be solved is performed in the METHOD statement by turning off any equation that is not to be solved. The syntax, ^ELECTRONS or ^HOLES, turns off the electron continuity equation and the hole continuity equation respectively.

### 3.1.3: The Transport Equations

Equations 3-1, 3-3, and 3-4 provide the general framework for device simulation. But further secondary equations are needed to specify particular physical models for:  $\vec{J}_n$ ,  $\vec{J}_p$ ,  $G_n$ ,  $R_n$ ,  $G_p$  and  $R_p$ .

The current density equations, or charge transport models, are usually obtained by applying approximations and simplifications to the Boltzmann Transport Equation. These assumptions can result in a number of different transport models such as the drift-diffusion model, the Energy Balance Transport Model or the hydrodynamic model. The choice of the charge transport model will then have a major influence on the choice of generation and recombination models.

The simplest model of charge transport that is useful is the Drift-Diffusion Model. This model has the attractive feature that it does not introduce any independent variables in addition to  $\psi$ ,  $n$  and  $p$ . Until recently, the drift-diffusion model was adequate for nearly all devices that were technologically feasible. The drift-diffusion approximation, however, becomes less accurate for smaller feature sizes. More advanced energy balance and hydrodynamic models are therefore becoming popular for simulating deep submicron devices. ATLAS supplies both drift-diffusion and advanced transport models.

The charge transport models and the models for generation and recombination in ATLAS make use of some concepts associated with carrier statistics. These concepts are summarized in a further section of this chapter that deals with the carrier statistics.

#### Drift-Diffusion Transport Model

Derivations based upon the Boltzmann transport theory have shown that the current densities in the continuity equations may be approximated by a drift-diffusion model [2]. In this case, the current densities are expressed in terms of the quasi-Fermi levels  $\phi_n$  and  $\phi_p$  as:

$$\vec{J}_n = -q\mu_n n \nabla \phi_n \quad 3-5$$

$$\vec{J}_p = -q\mu_p p \nabla \phi_p \quad 3-6$$

where  $\mu_n$  and  $\mu_p$  are the electron and hole mobilities. The quasi-Fermi levels are then linked to the carrier concentrations and the potential through the two Boltzmann approximations:

$$n = n_{ie} \exp\left[\frac{q(\psi - \phi_n)}{kT_L}\right] \quad 3-7$$

$$p = n_{ie} \exp\left[\frac{-q(\psi - \phi_p)}{kT_L}\right] \quad 3-8$$

where  $n_{ie}$  is the effective intrinsic concentration and  $T_L$  is the lattice temperature. These two equations may then be re-written to define the quasi-Fermi potentials:

$$\phi_n = \psi - \frac{kT_L}{q} \ln \frac{n}{n_{ie}} \quad 3-9$$

$$\phi_p = \psi + \frac{kT_L}{q} \ln \frac{p}{n_{ie}} \quad 3-10$$



By substituting these equations into the current density expressions, the following adapted current relationships are obtained:

$$\vec{J}_n = qD_n \nabla n - qn\mu_n \nabla \psi - \mu_n n (kT_L \nabla (\ln n_{ie})) \quad 3-11$$

$$\vec{J}_p = -qD_p \nabla p - qp\mu_p \nabla \psi + \mu_p p (kT_L \nabla (\ln n_{ie})) \quad 3-12$$

The final term accounts for the gradient in the effective intrinsic carrier concentration, which takes account of bandgap narrowing effects. Effective electric fields are normally defined whereby:

$$\vec{E}_n = -\nabla \left( \psi + \frac{kT_L}{q} \ln n_{ie} \right) \quad 3-13$$

$$\vec{E}_p = -\nabla \left( \psi - \frac{kT_L}{q} \ln n_{ie} \right) \quad 3-14$$

Which then allows the more conventional formulation of drift-diffusion equations to be written (see Equations 3-15 and 3-16).

$$\vec{J}_n = qn\mu_n \vec{E}_n + qD_n \nabla n \quad 3-15$$

$$\vec{J}_p = qp\mu_p \vec{E}_p - qD_p \nabla p \quad 3-16$$

It should be noted that this derivation of the drift-diffusion model has tacitly assumed that the Einstein relationship holds. In the case of Boltzmann statistics this corresponds to:

$$D_n = \frac{kT_L}{q} \mu_n \quad 3-17$$

$$D_p = \frac{kT_L}{q} \mu_p \quad 3-18$$

If Fermi-Dirac statistics are assumed for electrons, Equation 3-17 becomes:

$$D_n = \frac{\left( \frac{kT_L}{q} \mu_n \right) F_{1/2} \left\{ \frac{1}{kT_L} [\varepsilon_{Fn} - \varepsilon_C] \right\}}{F_{-1/2} \left\{ \frac{1}{kT_L} [\varepsilon_{Fn} - \varepsilon_C] \right\}} \quad 3-19$$

where  $F_\alpha$  is the Fermi-Dirac integral of order  $\alpha$  and  $\varepsilon_{Fn}$  is given by  $-q\phi_n$ . An analogous expression is used for holes with Fermi-Dirac statistics.

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**Note:** See Section 3.2.6: "Bandgap Narrowing" for more information on the effects resulting from bandgap narrowing and their implementation.

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### Energy Balance Transport Model

A higher order solution to the general Boltzmann Transport Equation consists of an additional coupling of the current density to the carrier temperature, or energy. The current density expressions from the drift-diffusion model are modified to include this additional physical relationship. The electron current and energy flux densities are then expressed as:

$$\vec{J}_n = qD_n \nabla n - q\mu_n n \nabla \psi + qnD_n^T \nabla T_n \quad 3-20$$

$$\vec{S}_n = -K_n \nabla T_n - \left( \frac{k\delta_n}{q} \right) \vec{J}_n T_n \quad 3-21$$

$$\vec{J}_p = -qD_p \nabla p - q\mu_p p \nabla \psi - qpD_p^T \nabla T_p \quad 3-22$$

$$\vec{S}_p = -K_p \nabla T_p - \left( \frac{k\delta_p}{q} \right) \vec{J}_p T_p \quad 3-23$$

where  $T_n$  and  $T_p$  represent the electron and hole carrier temperatures and  $S_n$  and  $S_p$  are the flux of energy (or heat) from the carrier to the lattice. The energy balance transport model includes a number of very complex relationships and therefore a later section of this chapter has been devoted to this model.

#### 3.1.4: Displacement Current Equation

For time domain simulation, the displacement current is calculated and included in the structure, log file and the run time output. The expression for displacement current is given as:

$$\vec{J}_{dis} = \varepsilon \left( \frac{\partial \vec{E}}{\partial t} \right) \quad 3-24$$

## 3.2: Basic Theory of Carrier Statistics

### 3.2.1: Fermi-Dirac and Boltzmann Statistics

Electrons in thermal equilibrium at temperature  $T_L$  with a semiconductor lattice obey Fermi-Dirac statistics. That is the probability  $f(\varepsilon)$  that an available electron state with energy  $\varepsilon$  is occupied by an electron is:

$$f(\varepsilon) = \frac{1}{1 + \exp\left(\frac{\varepsilon - E_F}{kT_L}\right)} \quad 3-25$$

where  $E_F$  is a spatially independent reference energy known as the Fermi level and  $k$  is Boltzmann's constant.

In the limit,  $\varepsilon - E_F \gg kT_L$ , Equation 3-25 can be approximated as:

$$f(\varepsilon) = \exp\left(\frac{E_F - \varepsilon}{kT_L}\right) \quad 3-26$$

Statistics based on the use of Equation 3-26 are referred to as Boltzmann statistics [49, 50]. The use of Boltzmann statistics instead of Fermi-Dirac statistics makes subsequent calculations much simpler. The use of Boltzmann statistics is normally justified in semiconductor device theory, but Fermi-Dirac statistics are necessary to account for certain properties of very highly doped (degenerate) materials.

The Fermi-Dirac statistics have been implemented in ATLAS in a similar form to Boltzmann statistics.

The remainder of this section outlines derivations and results for the simpler case of Boltzmann statistics which are the default in ATLAS. You can have ATLAS use Fermi-Dirac statistics by specifying the `FERMIDIRAC` parameter in the `MODEL` statement.

### 3.2.2: Effective Density of States

Integrating the Fermi-Dirac statistics over a parabolic density of states in the conduction and valence bands, whose energy minimum is located at energies  $E_C$  and  $E_V$  respectively, yields the following expressions for the electron and hole concentrations:

$$n = N_C F_{1/2}\left(\frac{E_F - E_C}{kT_L}\right) \quad 3-27$$

$$p = N_V F_{1/2}\left(\frac{E_V - E_F}{kT_L}\right) \quad 3-28$$

where  $F_{1/2}(\eta)$  is referred to as the Fermi-Dirac integral of order  $1/2$ . If Equation 3-26 is a good approximation, then Equations 3-27 and 3-28 can be simplified to

$$n = N_C \exp\left(\frac{E_F - E_C}{kT_L}\right) \quad 3-29$$

$$p = N_V \exp\left(\frac{E_V - E_F}{kT_L}\right) \quad 3-30$$

which are referred to as the Boltzmann approximation.

$N_C$  and  $N_V$  are referred to as the effective density of states for electrons and holes and are given by:

$$N_C(T_L) = 2 \left( \frac{2\pi m_e^* k T_L}{h^2} \right)^{\frac{3}{2}} = \left( \frac{T_L}{300} \right)^{\frac{3}{2}} \text{NC300} \quad 3-31$$

$$N_V(T_L) = 2 \left( \frac{2\pi m_h^* k T_L}{h^2} \right)^{\frac{3}{2}} = \left( \frac{T_L}{300} \right)^{\frac{3}{2}} \text{NV300} \quad 3-32$$

where NC300 and NV300 are user-definable on the MATERIAL statement as shown in Table 3-1.

In some circumstances, the lattice temperature,  $T_L$ , is replaced by the electron temperature,  $T_n$ , in Equation 3-31 and hole temperature,  $T_p$ , in Equation 3-32.

| Table 3-1. User-Definable Parameters for the Density of States |           |                       |                  |
|--|-----------|-----------------------|------------------|
| Statement  | Parameter | Default               | Units            |
| MATERIAL   | NC300     | $2.8 \times 10^{19}$  | $\text{cm}^{-3}$ |
| MATERIAL   | NV300     | $1.04 \times 10^{19}$ | $\text{cm}^{-3}$ |

### 3.2.3: Intrinsic Carrier Concentration

Multiplying Equations 3-29 and 3-30 yields:

$$np = n_{ie}^2 \quad 3-33$$

where  $n_{ie}$  is the intrinsic carrier concentration and is given for Boltzmann statistics by:

$$n_{ie} = \sqrt{N_C N_V} \exp\left(\frac{-E_g}{2kT_L}\right) \quad 3-34$$

$E_g = E_C - E_V$  is the band-gap energy.

For intrinsic (undoped) material,  $p = n$ . By equating Equations 3-29 and 3-30 and solving for  $E_F$  yields:

$$E_F = E_i = -q\psi_i = \frac{E_C + E_V}{2} + \left(-\frac{kT_L}{2}\right) \ln\left(\frac{N_V}{N_C}\right) \quad 3-35$$

where  $E_i$  is the Fermi level for intrinsic doped silicon, and  $\psi_i$  is the intrinsic potential. Equation 3-35 defines the intrinsic potential under non-equilibrium conditions also. As indicated previously, for ATLAS the  $\psi$  used in Equation 3-1 is the intrinsic potential.

The electron and hole concentrations can be expressed in terms of the intrinsic carrier concentration as:

$$n = n_{ie} \exp\left[\frac{q(\psi - \phi_n)}{kT_L}\right] \quad 3-36$$

$$p = n_{ie} \exp\left[\frac{-q(\psi - \phi_p)}{kT_L}\right] \quad 3-37$$

where  $\psi$  is the intrinsic potential and  $\phi$  is the potential corresponding to the Fermi level (i.e.,  $E_F = q\phi$ ).

The expression for intrinsic carrier concentration,  $n_{ie}$ , can be generalized to Fermi-Dirac statistics using Equations 3-27 and 3-28. Specifying the `NI.FERMI` parameter in the `MODELS` statement will cause ATLAS to calculate  $n_{ie}$  using Fermi-Dirac statistics.

### 3.2.4: Evaluation of Fermi-Dirac Integrals

Most programming languages have a built in exponential and logarithmic function, making it straightforward to implement the Boltzmann approximation. Evaluation of the Fermi-Dirac integrals are more problematic. There are simple inaccurate approximations available. ATLAS, however, uses a Rational Chebyshev approximation that gives results close to the exact values. The Fermi-Dirac integrals of order  $\frac{-3}{2}$ ,  $\frac{-1}{2}$ ,  $\frac{1}{2}$ ,  $\frac{3}{2}$  are calculated and at worst differ from the exact values by only 1 part in  $10^{10}$ .

### 3.2.5: The Energy Bandgap

The temperature dependence of the bandgap energy is modeled in ATLAS as follows [9]:

$$E_g(T_L) = E_g(0) - \frac{\text{EGALPHA}(T_L^2)}{T_L + \text{EGBETA}} = \text{EG300} + \text{EGALPHA} \left[ \frac{300^2}{300 + \text{EGBETA}} - \frac{T_L^2}{T_L + \text{EGBETA}} \right] \quad 3-38$$

You can specify `EG300`, `EGALPHA` and `EGBETA` parameters in the `Material` statement (see Table 3-2).

| Table 3-2. User-Specifiable Parameters for Equation 3-38 |           |                       |                  |
|--|-----------|-----------------------|------------------|
| Statement  | Parameter | Default               | Units            |
| MATERIAL   | EG300     | 1.08                  | eV               |
| MATERIAL   | EGALPHA   | $4.73 \times 10^{-4}$ | eV/K             |
| MATERIAL   | EGBETA    | 636                   | K                |
| MATERIAL   | NC300     | $2.8 \times 10^{19}$  | $\text{cm}^{-3}$ |
| MATERIAL   | NV300     | $1.04 \times 10^{19}$ | $\text{cm}^{-3}$ |

The default values are material dependent, which can be found in Appendix B: “Material Systems”. Table 3-2 displays the defaults for Silicon only.

### 3.2.6: Bandgap Narrowing

In the presence of heavy doping, greater than  $10^{18} \text{cm}^{-3}$ , experimental work has shown that the pn product in silicon becomes doping dependent [3]. As the doping level increases, a decrease in the bandgap separation occurs, where the conduction band is lowered by approximately the same amount as the valence band is raised. In ATLAS this is simulated by a spatially varying intrinsic concentration  $n_{ie}$  defined according to Equation 3-39.

$$n_{ie}^2 = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right) \quad 3-39$$

Bandgap narrowing effects in ATLAS are enabled by specifying the BGN parameter of the MODELS statement. These effects may be described by an analytic expression relating the variation in bandgap,  $\Delta E_g$ , to the doping concentration, N. The expression used in ATLAS is from Slotboom and de Graaf [109]:

$$\Delta E_g = \text{BGN} \cdot \mathbf{E} \left\{ \ln \frac{N}{\text{BGN} \cdot \mathbf{N}} + \left[ \left( \ln \frac{N}{\text{BGN} \cdot \mathbf{N}} \right)^2 + \text{BGN} \cdot \mathbf{C} \right]^{\frac{1}{2}} \right\} \quad 3-40$$

You can specify the BGN.E, BGN.N, and BGN.C parameters in the MATERIAL statement. The default values from Slotboom [109] and Klaassen [24] are shown in Table 3-3-3. The Klaassen defaults will be used if you specify the BGN.KLA parameter in the MODELS statement. Otherwise, the Slotboom values will be used (by default). You can select a second set of defaults by specifying BGN.KLASSEN.

| Table 3-3. User-Definable Parameters of Bandgap Narrowing Model |           |                      |                       |                  |
|---|-----------|----------------------|-----------------------|------------------|
| Statement   | Parameter | Defaults (Slotboom)  | Defaults (Klaassen)   | Units            |
| MATERIAL  | BGN.E     | $9.0 \times 10^{-3}$ | $6.92 \times 10^{-3}$ | V                |
| MATERIAL  | BGN.N     | $1.0 \times 10^{17}$ | $1.3 \times 10^{17}$  | $\text{cm}^{-3}$ |
| MATERIAL  | BGN.C     | 0.9                  | 0.5                   | —                |

The variation in bandgap is introduced to the other physical models by subtracting the result of Equation 3-40 from the bandgap,  $E_g$ . In addition an adjustment is also made to the electric field terms in the transport models as described earlier. The adjustment takes the form:

$$\vec{E}_n = -\nabla \left( \psi + \frac{kT_L}{q} \ln n_{ie} \right) \quad 3-41$$

$$\vec{E}_p = -\nabla \left( \psi - \frac{kT_L}{q} \ln n_{ie} \right) \quad 3-42$$

The variation in the energy bandgap is also applied partially to the electron affinity,  $\chi$ . The effective electron affinity,  $\chi_{eff}$  given as follows:

$$\chi_{eff} = \chi + \Delta E_g \times \text{ASYMMETRY} \quad 3-43$$

where ASYMMETRY is a user-specifiable asymmetry factor. You can specify the value of the asymmetry factor using the ASYMMETRY parameter of the MATERIAL statement.

---

**Note:** In addition to this in-built model for bandgap narrowing, ATLAS allows you to use its C-INTERPRETER module. You can write an external file with C-code that defines an equation for bandgap narrowing. The filename is specified with the `F.BGN` parameter in the `MODEL` statement. See Appendix A: "C-Interpreter Functions" for more information on C-INTERPRETER.

---

### 3.2.7: Passler's Model for Temperature Dependent Bandgap

An alternative temperature dependent bandgap model by Passler [158] can be enabled by the `PASSLER` parameter of the `MODELS` statement.

The bandgap is given by

$$E_g(T) = E_g(0) - \frac{A.PASSLER \cdot T.PASSLER}{2} \tag{3-44}$$

$$\left\{ \left[ \left( \frac{2 \cdot T}{T.PASSLER} \right)^{1/P.PASSLER} + 1 \right]^{P.PASSLER} - 1 \right\}$$

where  $E_g(T)$  is the lattice temperature dependent bandgap,  $T$  is the lattice temperature, `A.PASSLER`, `T.PASSLER` and `P.PASSLER` are user-specified parameters on the `MATERIAL` statement and  $E_g(0)$  is given by

$$E_g(0) = EG300 - \frac{A.PASSLER \cdot T.PASSLER}{2} \tag{3-45}$$

$$\left\{ \left[ \left( \frac{2 \cdot 300}{T.PASSLER} \right)^{1/P.PASSLER} + 1 \right]^{P.PASSLER} - 1 \right\}$$

where `EG300` is a user specified parameter on the `MATERIAL` statement.

### 3.3: Space Charge from Incomplete Ionization, Traps, and Defects

Poisson's Equation (Equation 3-1) including the carrier concentrations, the ionized donor and acceptor impurity concentrations  $N_D^+$  and  $N_A^-$ , charge due to traps and defects,  $Q_T$ , has the form:

$$\text{div}(\epsilon \nabla \psi) = q(n - p - N_D^+ + N_A^-) + Q_T \quad 3-46$$

In ATLAS the default is to assume full impurity ionization (i.e.,  $N_D^+ = N_{D, \text{total}}$  and  $N_A^- = N_{A, \text{total}}$ ), and to set  $Q_T$  equal to zero.

ATLAS also provides the options of accounting for incomplete ionization of impurities and accounting for additional charge associated with traps and defects.

#### 3.3.1: Incomplete Ionization of Impurities

ATLAS can account for impurity freeze-out [4] with appropriate degeneracy factors GCB and GVB for conduction and valence bands. The ionized donor and acceptor impurity concentrations are then given by:

$$N_D^+ = \frac{N_D}{1 + \text{GCB} \exp\left(\frac{\epsilon_F - (E_C + \text{EDB})}{kT_L}\right)} \quad 3-47$$

$$N_A^- = \frac{N_A}{1 + \text{GVB} \exp\left(\frac{E_V + \text{EAB} - \epsilon_F}{kT_L}\right)} \quad 3-48$$

where EDB is the donor energy level, EAB is the acceptor energy level and  $N_D$  and  $N_A$  are net compensated n-type and p-type doping, respectively. Net compensated doping is defined as follows:

If

$$N_{\text{total}} \equiv (N_{D, \text{total}} - N_{A, \text{total}}) > 0 \quad 3-49$$

then

$$N_D = |N_{\text{total}}| \text{ and } N_A = 0 \quad 3-50$$

Otherwise

$$N_D = 0 \text{ and } N_A = |N_{\text{total}}| \quad 3-51$$

The INCOMPLETE parameter of the MODELS statement is used to select incomplete ionization and the parameters.



| Table 3-4. User-Specifiable Parameters for Equations 3-47 and 3-48 |           |       |
|--|-----------|-------|
| Statement  | Parameter | Units |
| MATERIAL   | GCB       |       |
| MATERIAL   | EDB       | eV    |
| MATERIAL   | GVB       |       |
| MATERIAL   | EAB       | eV    |

To properly handle incomplete ionization in silicon for high doping levels, a new incomplete ionization model has been added.

The models that form incomplete ionization of impurities given by Equations 3-47 and 3-48 give good physical results for low to moderately doped semiconductors. For heavily (greater than  $3 \times 10^{18}/\text{cm}^3$ ) doped semiconductors, these models fail to predict experimental results of complete ionization. For silicon, an optional model has been introduced that better matches experimental results. This model is set by the IONIZ parameter of the MODELS statement.

In this model, the activation energies of the dopants in Equations 3-47 and 3-48 have been modified for doping dependence as given in the following equations:

$$EDB \text{ (eV)} = 0.044 - 3.6 \times 10^{-8} N_D^{1/3} \quad (N_D < 10^{18}) \quad 3-52$$

$$EAB \text{ (eV)} = 0.0438 - 3.037 \times 10^{-5} N_A^{1/3} \quad (N_D < 10^{18}) \quad 3-53$$

At doping concentrations above  $3 \times 10^{18} \text{ cm}^{-3}$ , the model predicts complete ionization. At doping concentrations between  $10^{18} \text{ cm}^{-3}$  and  $3 \times 10^{18} \text{ cm}^{-3}$ , the model predicts a linearly interpolated value between the above expressions and complete ionization.

### 3.3.2: Low Temperature Simulations

In conjunction with Fermi-Dirac statistics and impurity freeze-out, ATLAS simulates device behavior under low operating temperatures. In general, simulations can be performed at temperatures as low as 50K without loss of quadratic convergence. Below this temperature, carrier and ionization statistics develop sharp transitions which cause slower convergence. Since many more iterations will probably be required if temperatures below 50K are specified, the ITLIMIT parameter of the METHOD statement should be increased.

Due to the limited exponent range on some machines, ATLAS can have trouble calculating the quasi-Fermi level of minority carriers. As the temperature decreases, the intrinsic carrier concentration also decreases. In quasi-neutral regions, the minority carrier concentration can easily underflow. Such situations were handled in the past by setting these concentrations to zero. This method does not allow an accurate subsequent calculation of minority carrier quasi-Fermi levels. In order to accurately

calculate quasi-Fermi levels, majority carrier concentration and the relation,  $np = n_i^2$  is used to obtain minority carrier concentrations in case of an underflow. Despite these efforts, spurious glitches are occasionally observed at low temperatures in the minority quasi-Fermi levels.

### 3.3.3: Traps and Defects

Semiconductor materials exhibit crystal flaws which can be caused by dangling bonds at interfaces or by the presence of impurities in the substrate. The presence of these defect centers, or traps, in semiconductor substrates may significantly influence the electrical characteristics of the device. Trap centers, whose associated energy lies in a forbidden gap, exchange charge with the conduction and valence bands through the emission and recombination of electrons. The trap centers change the density of space charge in semiconductor bulk and influence the recombination statistics.

Device physics has established the existence of three different mechanism which add to the space charge term in Poissons' equation, in addition to the ionized donor and acceptor impurities. These are interface trapped charge, interface trap states and bulk trap states. Interface trapped charge is modelled as a sheet of charge at the interface and therefore is controlled by the interface boundary condition. Interface traps and bulk traps will add space charge directly into the right hand side of Poisson's equation. This section describes the definition of bulk trap states and the implementation of these bulk trap states into ATLAS for both steady state and transient conditions.

Semiconductor flaws have two possible states which are called "empty" and "filled". When empty a flaw has a particular cross-section for capturing an electron. A flaw can only either emit or capture an electron. When the charge on the center has been changed by  $-q$  by addition of an electron, a flaw is filled, and has a new cross section for hole capture. Two basic types of trap have been found to exist. These are donor-like and acceptor-like traps. The charge contained within each type of trap will depend upon whether or not an electron or hole fills the trap.

A donor-type trap can be either positive or neutral like the donor. An acceptor-type trap can be either negative or neutral like the acceptor. A donor-like trap is positively charged (ionized) when empty and neutral when filled (with an electron). An empty donor-type trap, which is positive, can capture an electron or emit a hole. A filled donor-type trap, which is neutral, can emit an electron or capture a hole. An acceptor-like trap is neutral when empty and negatively charged (ionized) when filled (with an electron). A filled acceptor-like trap can emit an electron or capture a hole. An empty acceptor-like trap can capture an electron or emit a hole. Unlike the donor, donor-like traps usually lie near the valence band. Likewise, acceptor-like traps usually lie near the conduction band.

Figure 3-1 shows the terminology used within ATLAS to define the type of trap. The position of the trap is defined relative to the conduction or valence bands using `E.LEVEL` so for instance, an acceptor trap at 0.4eV would be 0.4eV below the conduction band.

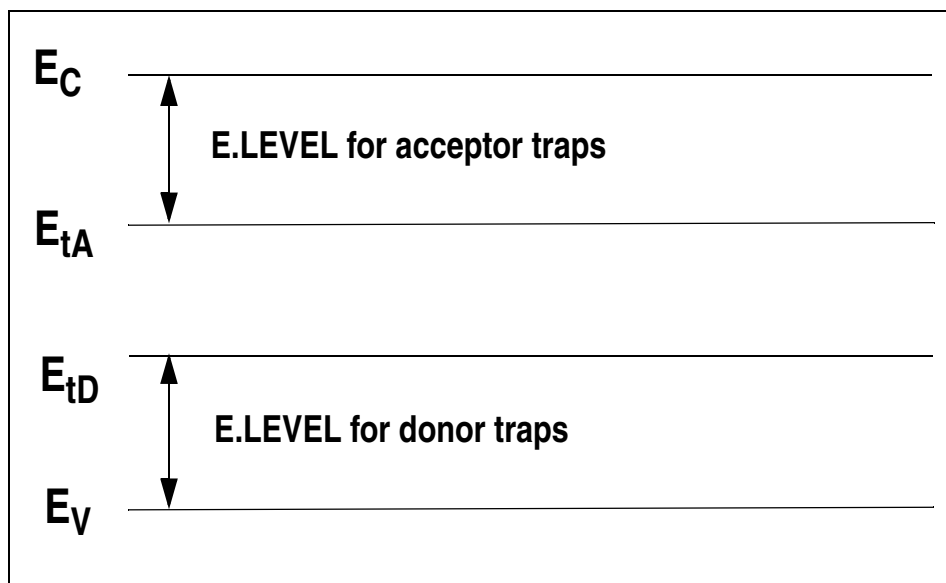


Figure 3-1: Definition of the trap energy level for acceptor and donor traps in reference to the conduction and valence band edges.

### Calculation of Trapped Charge in Poisson's Equation

The total charge caused by the presence of traps is added into the right hand side of Poisson's equation. The total charge value is defined by:

$$Q_T = q(p_t - n_t) \tag{3-54}$$

where  $n_t$  and  $p_t$  are the densities of trapped charge for donor-like and acceptor-like traps respectively. The trapped charge depends upon the trap density DENSITY and its probability of occupation,  $F_{n,p}$ . For donor-like and acceptor-like traps, respectively, the trapped charge is calculated by the equations:

$$n_t = \text{DENSITY} \times F_n \tag{3-55}$$

$$p_t = \text{DENSITY} \times F_p \tag{3-56}$$

In the case where multiple traps at multiple trap energy levels are defined the total charge becomes:

$$n_t = \sum_{\alpha=1}^k n_{t\alpha}, \quad p_t = \sum_{\beta=1}^m p_{t\beta} \tag{3-57}$$

where k is the number of acceptor-like traps and m is the number of donor-like traps.

The probability of occupation assumes that the capture cross sections are constant for all energies in a given band and follows the analysis developed by Simmons and Taylor [5]. The probability of occupation is defined by the following equations for donor and acceptor-like traps.

$$F_n = \frac{v_n \text{SIGN}_{n+e_p}}{v_n \text{SIGN}_{n+v_p} \text{SIGP}_{p+e_n+e_p}} \tag{3-58}$$

$$F_p = \frac{v_p \mathbf{SIGP}_{p+e_n}}{v_n \mathbf{SIGN}_{n+v_p} \mathbf{SIGP}_{p+e_n+e_p}} \tag{3-59}$$

where SIGN and SIGP are the carrier capture cross sections for electrons and holes respectively,  $v_n$  and  $v_p$  are the thermal velocities for electrons and holes and the electron and hole emission rates,  $e_n$  and  $e_p$ , are defined by:

$$e_n = \mathbf{DEGEN.FAC} v_n \mathbf{SIGN}_{n_i} \exp\left(\frac{\mathbf{E.LEVEL} - E_i}{kT_L}\right) \tag{3-60}$$

$$e_p = \frac{1}{\mathbf{DEGEN.FAC}} v_p \mathbf{SIGP}_{n_i} \exp\left(\frac{E_i - \mathbf{E.LEVEL}}{kT_L}\right) \tag{3-61}$$

where  $E_i$  is the intrinsic Fermi level position, E.LEVEL is the energy level in the bandgap of each discrete trap center and DEGEN.FAC is the degeneracy factor of the trap center. The latter term takes into account that spin degeneracy will exist, that is the “empty” and “filled” conditions of a flaw will normally have different spin and orbital degeneracy choices.

**Table 3-5. User-Specifiable Parameters for Equations 3-55 to 3-61**

| Statement | Parameter | Units            |
|-----------|-----------|------------------|
| TRAP      | E.LEVEL   | eV               |
| TRAP      | DENSITY   | cm <sup>-3</sup> |
| TRAP      | DEGEN.FAC |                  |
| TRAP      | SIGN      | cm <sup>2</sup>  |
| TRAP      | SIGP      | cm <sup>2</sup>  |

### Trap Implementation into Recombination Models

To maintain self-consistency, you need to take into account that electrons are being emitted or captured by the donor and acceptor-like traps. Therefore, the concentration of carriers will be affected. This is accounted for by modifying the recombination rate in the carrier continuity equations.

The standard SRH recombination term (see “Shockley-Read-Hall (SRH) Recombination” section on page 3-63) is modified as follows:

$$R = \sum_{\alpha=1}^l R_{n_\alpha} + \sum_{\beta=1}^m R_{p_\beta} \tag{3-62}$$

where  $l$  is the number of donor-like traps,  $m$  is the number of acceptor-like traps, and the function  $R$  is:

$$R_{n,p} = \frac{pn - n_{ie}^2}{\mathbf{TAUN} \left[ p + \frac{1}{\mathbf{DEGEN.FAC}} n_{ie} \exp\left(\frac{E_i - \mathbf{E.LEVEL}}{kT_L}\right) \right] + \mathbf{TAUP} \left[ n + \mathbf{DEGEN.FAC} n_{ie} \exp\left(\frac{\mathbf{E.LEVEL} - E_i}{kT_L}\right) \right]} \tag{3-63}$$

The electron and hole lifetimes TAUN and TAUP are related to the carrier capture cross sections SIGN and SIGP through the equations:

$$\mathbf{TAUN} = \frac{1}{\mathbf{SIGN} v_n \mathbf{DENSITY}} \quad 3-64$$

$$\mathbf{TAUP} = \frac{1}{\mathbf{SIGP} v_p \mathbf{DENSITY}} \quad 3-65$$

The thermal velocities  $v_n$  and  $v_p$  are calculated from the following electron and hole effective masses.

$$v_n = (3kT/m_e)^{1/2} \quad 3-66$$

$$v_p = (3kT/m_n)^{1/2} \quad 3-67$$

To specify the effective masses directly, use the M.VTHN and M.VTHP parameters from the MATERIAL statement. If M.VTHN or M.VTHP or both are not specified, the density of states effective mass is extracted from the density of states ( $N_c$  or  $N_v$ ) using Equations 3-31 and 3-32. In the case of silicon if M.VTHN or M.VTHP are not specified, the effective masses are calculated from:

$$m_e = 1.045 + 4.5 \times 10^{-4} T \quad 3-68$$

$$m_n = 0.523 + 1.4 \times 10^{-3} T - 1.48 \times 10^{-6} T^2 \quad 3-69$$

where  $T$  is the lattice temperature.

| Table 3-6. User-Specifiable Parameters for Equations 3-63- 3-65 |           |       |
|---|-----------|-------|
| Statement   | Parameter | Units |
| TRAP  | TAUN      | s     |
| TRAP  | TAUP      | s     |

The TRAP statement activates the model and is used to:

- Specify the trap type DONOR or ACCEPTOR
- Specify the energy level E.LEVEL parameter
- Specify the density of the trap centers DENSITY
- Specify the degeneracy factor DEGEN.FAC
- Specify either the cross sections, SIGN and SIGP, or the electron and hole lifetimes TAUN and TAUP

### Trap-Assisted Tunneling

Trap-Assisted Tunneling models the trap-to-band phonon-assisted tunneling effects for Dirac wells. At high electric fields, tunneling of electrons from the valence band to the conduction band through trap or defect states can have an important effect on the current.

Trap-assisted tunneling is modeled by including field-effect enhancement terms [113] ( $\Gamma_n^{DIRAC}$  and  $\Gamma_p^{DIRAC}$ ) in the trap lifetimes in Equation 3-63. These enhancement terms modify the lifetimes so that they include the effects of phonon-assisted tunneling on the emission of electrons and holes from a trap. This model is enabled by specifying TRAP . TUNNEL in the MODELS statement.

The recombination term for traps becomes:

$$R_{n,p} = \frac{p_n - n_{ie}^2}{\frac{TAUN}{1 + \Gamma_n^{DIRAC}} \left[ p + \frac{1}{DEGEN.FAC} n_{ie} \exp\left(\frac{E_i - E.LEVEL}{kT_L}\right) \right] + \frac{TAUP}{1 + \Gamma_p^{DIRAC}} \left[ n + DEGEN.FAC n_{ie} \exp\left(\frac{E.LEVEL}{kT_L}\right) \right]} \quad 3-70$$

The field-effect enhancement term for electrons is given by:

$$\Gamma_n^{DIRAC} = \frac{1}{kT_L} \int_0^{\Delta E_n} \exp\left(\frac{\Delta E_n}{KT_L} u - k_n u^{3/2}\right) du \quad 3-71$$

While the field-effect enhancement term for hole is:

$$\Gamma_p^{DIRAC} = \frac{1}{kT_L} \int_0^{\Delta E_p} \exp\left(\frac{\Delta E_p}{KT_L} u - k_p u^{3/2}\right) du \quad 3-72$$

where  $u$  is the integration variable,  $\Delta E_n$  is the energy range where tunneling can occur for electrons,  $\Delta E_p$  is the tunneling energy range for holes, and  $K_n$  and  $K_p$  are defined as:

$$k_n = \frac{4\sqrt{2m_0 \text{MASS.TUNNEL} \Delta E_n^3}}{3q\hbar|E|} \quad 3-73$$

$$k_p = \frac{4\sqrt{2m_0 \text{MASS.TUNNEL} \Delta E_p^3}}{3q\hbar|E|} \quad 3-74$$

$\hbar$  is the reduced Planck's constant,  $m_0$  is the rest mass of an electron and MASS . TUNNEL is the effective mass You can specify MASS . TUNNEL by setting the MASS . TUNNEL parameter in the MODELS statement.

Table 3-7 shows the user-specifiable parameter for Equations 3-73 and 3-74.

| Table 3-7. User-Specifiable Parameters for Equations 3-73 and 3-74 |               |         |       |
|--|---------------|---------|-------|
| Statement  | Parameter     | Default | Units |
| MATERIAL   | MASS . TUNNEL | 0.25    |       |

### Poole-Frenkel Barrier Lowering for Coulombic Wells

The Poole-Frenkel barrier lowering effect enhances the emission rate for trap-to-band phonon-assisted tunneling as well as pure thermal emissions at low electric fields. The Poole-Frenkel effect occurs when the Coulombic potential barrier is lowered due to the electric field and only occurs in traps with a Coulombic potential (such as traps that are neutral when filled).

The following interactions are Coulombic.

- Between an empty (positive) donor-type trap and an electron.
- Between a filled (negative) acceptor-type trap and a hole.

The following interactions are short-range (Dirac).

Between a filled (neutral) donor-type trap and a hole.

Between an empty (neutral) acceptor-type trap and an electron.

The Poole-Frenkel effect is modeled by including field-effect enhancement terms for Coulombic wells ( $\Gamma_n^{CONC}$  and  $\Gamma_p^{CONC}$ ) and thermal emission ( $\chi_F$ ) [135] in the trap lifetimes in Equation 3-63. The model also includes the trap-assisted tunneling effects in the Dirac wells. To enable this model, specify TRAP.COULOMBIC in the MODELS statement.

The recombination term for traps now becomes:

$$R_n = \frac{p_n - n_{ie}^2}{\chi_F + \Gamma_n^{COUL} \left[ p + \frac{1}{DEGEN.FAC} n_{ie} \exp\left(\frac{E_i - E.LEVEL}{kT_L}\right) \right] + \frac{TAUN}{1 + \Gamma_p^{DIRAC}} \left[ n + DEGEN.FAC n_{ie} \exp\left(\frac{E.LEVEL}{kT_L}\right) \right]} \quad 3-75$$

$$R_p = \frac{p_n - n_{ie}^2}{\frac{TAUN}{1 + \Gamma_n^{DIRAC}} \left[ p + \frac{1}{DEGEN.FAC} n_{ie} \exp\left(\frac{E_i - E.LEVEL}{kT_L}\right) \right] + \frac{TAUP}{\chi_F + \Gamma_p^{COUL}} \left[ n + DEGEN.FAC n_{ie} \exp\left(\frac{E.LEVEL}{kT_L}\right) \right]} \quad 3-76$$

where the Poole-Frenkel thermal emission enhancement factor,  $\chi_F$ , is defined as:

$$\chi_F = \exp\left(\frac{\Delta E_{fp}}{kT_L}\right) \quad 3-77$$

$\Delta E_{fp}$  is the barrier lowering term for a Coulombic well (see Equation 3-78).

$$\Delta E_{fp} = \sqrt{\frac{q|E|}{\pi\epsilon}} \quad 3-78$$

The Coulombic field-enhancement terms,  $\Gamma_n^{COUL}$  and  $\Gamma_p^{COUL}$ , are defined as:

$$\Gamma_n^{COUL} = \frac{\Delta E_n}{kT_L} \int_{\frac{\Delta E_{fp}}{\Delta E_n}}^1 \exp\left(\frac{\Delta E_n}{KT_L} u - k_p u^{3/2} \left[ 1 - \left(\frac{\Delta E_{fp}}{u \Delta E_n}\right)^{5/3} \right]\right) du \quad 3-79$$

$$I_p^{COUL} = \frac{\Delta E_p}{kT_L} \int_{\frac{\Delta E_{fp}}{\Delta E_n}}^1 \exp\left(\frac{\Delta E_p}{kT_L} u - k_p u^{3/2} \left[1 - \left(\frac{\Delta E_{fp}}{u \Delta E_p}\right)^{5/3}\right]\right) du \quad 3-80$$

### Transient Traps

In the time domain the acceptor and donor traps do not reach equilibrium instantaneously but require time for electrons to be emitted or captured. This is taken account of inside ATLAS by solving an additional differential rate equation whenever a transient simulation is performed. The probability of occupation becomes linked to the time dependent emission of electrons through the following rate equation [52]:

$$\frac{d}{dt}(\text{DENSITY } F_{n,p}) = R_n(t) - R_p(t) \quad 3-81$$

where  $R_n(t)$  and  $R_p(t)$  are the recombination rates of electrons and holes respectively. The terms describing the emission and capture processes  $R_n$  and  $R_p$  take form:

$$R_n = \text{DENSITY } v_n \text{ SIGN} \left[ n (1 - F_n) - F_n \text{ DEGEN.FAC } n_i \exp\left(\frac{\mathbf{E.LEVEL} - E_i}{kT_L}\right) \right] \quad 3-82$$

$$R_p = \text{DENSITY } v_p \text{ SIGP} \left[ p F_p - (1 - F_p) \frac{1}{\text{DEGEN.FAC}} n_i \exp\left(\frac{E_i - \mathbf{E.LEVEL}}{kT_L}\right) \right] \quad 3-83$$

A transient trap simulation using this model is more time consuming than using the static model but gives a much more accurate description of the device physics. It may sometimes be acceptable to perform transient calculations using the static trap distribution and assume that traps reach equilibrium instantaneously. If this is the case, a flag (FAST) on the TRAP statement will neglect the trap rate equation from the simulation.



### 3.4: The Energy Balance Transport Model

The conventional drift-diffusion model of charge transport neglects non-local transport effects such as velocity overshoot, diffusion associated with the carrier temperature and the dependence of impact ionization rates on carrier energy distributions. These phenomena can have a significant effect on the terminal properties of submicron devices. As a result ATLAS offers two non-local models of charge transport, the energy balance, and hydrodynamic models.

The Energy Balance Transport Model follows the derivation by Stratton [77,85] which is derived starting from the Boltzmann Transport Equation. By applying certain assumptions this model decomposes into the hydrodynamic model [115,138, 139].

The Energy Balance Transport Model adds continuity equations for the carrier temperatures, and treats mobilities and impact ionization coefficients as functions of the carrier temperatures rather than functions of the local electric field.

#### 3.4.1: The Energy Balance Equations

The Energy Balance Transport Model introduces two new independent variables  $T_n$  and  $T_p$ , the carrier temperature for electrons and holes. The energy balance equations consist of an energy balance equation with the associated equations for current density and energy flux  $S_{n,p}$ .

For electrons the Energy Balance Transport Model consists of:

$$\text{div} \vec{S}_n = \frac{1}{q} \vec{J}_n \cdot \vec{E} - W_n - \frac{3k}{2} \frac{\partial}{\partial t} (\lambda_n^* n T_n) \quad 3-84$$

$$\vec{J}_n = q D_n \nabla n - q \mu_n n \nabla \psi + q n D_n^T \nabla T_n \quad 3-85$$

$$\vec{S}_n = -K_n \nabla T_n - \left( \frac{k \delta_n}{q} \right) \vec{J}_n T_n \quad 3-86$$

and for holes:

$$\text{div} \vec{S}_p = \frac{1}{q} \vec{J}_p \cdot \vec{E} - W_p - \frac{3k}{2} \frac{\partial}{\partial t} (\lambda_p^* p T_p) \quad 3-87$$

$$\vec{J}_p = -q D_p \nabla p - q \mu_p p \nabla \psi - q p D_p^T \nabla T_p \quad 3-88$$

$$\vec{S}_p = -K_p \nabla T_p - \left( \frac{k \delta_p}{q} \right) \vec{J}_p T_p \quad 3-89$$

where  $\vec{S}_n$  and  $\vec{S}_p$  are the energy flux densities associated with electrons and holes, and  $\mu_n$  and  $\mu_p$  are the electron and hole mobilities.

The remaining terms,  $D_n$  and  $D_p$ , are the thermal diffusivities for electrons and holes as defined in Equations 3-90 and 3-97 respectively.  $W_n$  and  $W_p$  are the energy density loss rates for electrons and holes as defined in Equations 3-113 and 3-114 respectively.  $K_n$  and  $K_p$  are the thermal conductivities of electrons and holes as defined in Equations 3-94 and 3-101 respectively.

$$D_n = \frac{\mu_n k T_n}{q} \lambda_n^* \quad 3-90$$

$$\lambda_n^* = \frac{F_{1/2}(\eta_n)}{F_{-1/2}(\eta_n)}, \quad \eta_n = \frac{\varepsilon F_n - \varepsilon c}{k T_n} = F_{1/2}^{-1}\left(\frac{n}{N_c}\right) \quad 3-91$$

$$D_n^T = \left(\mu_{2n} - \frac{3}{2} \lambda_n^* \mu_n\right) \frac{k}{q} \quad 3-92$$

$$\mu_{2n} = \mu_n \left(\frac{5}{2} + \xi_n\right) \frac{F_{\xi_n} + 3/2(\eta_n)}{F_{\xi_n} + 1/2(\eta_n)} \quad 3-93$$

$$K_n = q n \mu_n \left(\frac{k}{q}\right)^2 \Delta_n T_n \quad 3-94$$

$$\Delta_n = \delta_n \left[ \left(\xi_n + \frac{7}{2}\right) \frac{F_{\xi_n} + 5/2(\eta_n)}{F_{\xi_n} + 3/2(\eta_n)} - \left(\xi_n + \frac{5}{2}\right) \frac{F_{\xi_n} + 3/2(\eta_n)}{F_{\xi_n} + 1/2(\eta_n)} \right] \quad 3-95$$

$$\delta_n = \frac{\mu_{2n}}{\mu_n} \quad 3-96$$

Similar expressions for holes are as follows:

$$D_p = \frac{\mu_p k T_p}{q} \lambda_p^* \quad 3-97$$

$$\lambda_p^* = \frac{F_{1/2}(\eta_p)}{F_{-1/2}(\eta_p)}, \quad \eta_p = \frac{\varepsilon_v - \varepsilon_f}{k T_p} = F_{1/2}^{-1}\left(\frac{p}{N_V}\right) \quad 3-98$$

$$D_p^T = \left(\mu_{2p} - \frac{3}{2} \lambda_p^* \mu_p\right) \frac{k}{q} \quad 3-99$$

$$\mu_{2p} = \mu_p \left(\frac{5}{2} + \xi_p\right) \frac{F_{\xi_p} + 3/2(\eta_p)}{F_{\xi_p} + 1/2(\eta_p)} \quad 3-100$$

$$K_p = q p \mu_p \left(\frac{k}{q}\right)^2 \Delta_p T_p \quad 3-101$$

$$\Delta_p = \delta_p \left[ \left( \xi_p + \frac{7}{2} \right) \frac{F_{\xi_p} + 5/2(\eta_p)}{F_{\xi_p} + 3/2(\eta_p)} - \left( \xi_p + \frac{5}{2} \right) \frac{F_{\xi_p} + 3/2(\eta_p)}{F_{\xi_p} + 1/2(\eta_p)} \right] \quad 3-102$$

$$\delta_p = \frac{\mu_{2p}}{\mu_p} \quad 3-103$$

If Boltzmann statistics are used in preference to Fermi statistics, the above equations simplify to:

$$\lambda_n^* = \lambda_p^* = 1 \quad 3-104$$

$$\Delta_n = \delta_n = \left( \frac{5}{2} + \xi_n \right) \quad 3-105$$

$$\Delta_p = \delta_p = \left( \frac{5}{2} + \xi_p \right) \quad 3-106$$

$$\xi_n = \frac{d(\ln \mu_n)}{d(\ln T_n)} = \frac{T_n}{\mu_n} \frac{\partial \mu_n}{\partial T_n} \quad 3-107$$

$$\xi_p = \frac{d(\ln \mu_p)}{d(\ln T_p)} = \frac{T_p}{\mu_p} \frac{\partial \mu_p}{\partial T_p} \quad 3-108$$

The parameters  $\xi_n$  and  $\xi_p$  are dependent on the carrier temperatures. Different assumptions concerning  $\xi_n$  and  $\xi_p$  correspond to different non-local models. In the high-field saturated-velocity limit, that corresponds to velocity saturation, the carrier mobilities are inversely proportional to the carrier temperatures.

$$\xi_n = \xi_p = -1 \quad 3-109$$

and this corresponds to the Energy Balance Transport Model.

If instead the choice  $\xi_n = \xi_p = 0$  was chosen this would correspond to the simplified Hydrodynamic Model. The parameters,  $\xi_n$  and  $\xi_p$ , can be specified using the KSN and KSP parameters on the MODELS statement.

Boundary conditions for n, p, and  $\psi$  are the same as for the drift diffusion model. Energy balance equations are solved only in the semiconductor region. Electron and hole temperatures are set equal to the lattice temperature on the contacts. On the other part of the boundary, the normal components of the energy fluxes vanish.

Hot carrier transport equations are activated by the MODELS statement parameters: HCTE.EL (electron temperature), HCTE.HO (hole temperature), and HCTE (both carrier temperatures).

### 3.4.2: Density of States

The calculation of the effective density of states is modified for the Energy Balance Transport Model. The electron and hole temperatures replace the lattice temperature in Equations 3-31 and 3-32. For example:

$$N_c = \left( \frac{2\pi m_e^* k T_n}{h^2} \right)^{\frac{3}{2}} = \left( \frac{T_n}{300} \right)^{\frac{3}{2}} NC(300) \quad 3-110$$

$$N_v = \left( \frac{2\pi m_n^* k T_p}{h^2} \right)^{\frac{3}{2}} = \left( \frac{T_p}{300} \right)^{\frac{3}{2}} NV(300) \quad 3-111$$

### 3.4.3: Energy Density Loss Rates

The energy density loss rates define physical mechanisms by which carriers exchange energy with the surrounding lattice environment. These mechanisms include carrier heating with increasing lattice temperature as well as energy exchange through recombination processes (SRH and Auger) and generation processes (impact ionization). If the net generation-recombination rate is written in the form:

$$U = R_{srh} + R_n^A + R_p^A - G_n - G_p \quad 3-112$$

where  $R_{srh}$  is the SRH recombination rate,  $R_n^A$  and  $R_p^A$  Auger recombination rates related to electrons and holes,  $G_n$  and  $G_p$  are impact ionization rates, then the energy density loss rates in Equations 3-84 and 3-87 can be written in the following form:

$$W_n = \frac{3}{2} n \frac{k(T_n - T_L)}{\text{TAUREL} \cdot \text{EL}} \lambda_n + \frac{3}{2} k T_n \lambda_n R_{SRH} + E_g (G_n - R_n^A) \quad 3-113$$

$$W_p = \frac{3}{2} p \frac{k(T_p - T_L)}{\text{TAUREL} \cdot \text{HO}} \lambda_p + \frac{3}{2} k T_p \lambda_p R_{SRH} + E_g (G_p - R_p^A) \quad 3-114$$

where

$$\lambda_n = F_{\frac{3}{2}}(\eta_n) / F_{\frac{1}{2}}(\eta_n) \quad 3-115$$

$$\lambda_p = F_{\frac{3}{2}}(\eta_p) / F_{\frac{1}{2}}(\eta_p) \quad 3-116$$

(and are equal to 1 for Boltzmann statistics), `TAUREL.EL` and `TAUREL.HO` are the electron and hole energy relaxation times,  $E_g$  is the bandgap energy of the semiconductor. The relaxation parameters are user-definable on the `MATERIAL` statement, which have their defaults shown in Table 3-8.

The relaxation times are extremely important as they determine the time constant for the rate of energy exchange and therefore precise values are required if the model is to be accurate. But, this is an unmeasurable parameter and Monte Carlo analysis is the favored method through which values can be extracted for the relaxation time.

It's also important to take into consideration that different materials will have different values for the energy relaxation time but within ATLAS, the relaxation time will always default to the value for silicon.

| Statement | Parameter | Default               | Units |
|-----------|-----------|-----------------------|-------|
| MATERIAL  | TAUREL.EL | $2.5 \times 10^{-13}$ | s     |
| MATERIAL  | TAUREL.HO | $2.5 \times 10^{-13}$ | s     |

### 3.4.4: Temperature Dependence of Relaxation Times

ATLAS doesn't provide an explicit default model for the temperature dependence of energy relaxation times. Two methods exist, however, to make the relaxation time a function of carrier energy.

For the first method, use a built-in model by specifying the `TRE.T1`, `TRE.T2`, `TRE.T3`, `TRE.W1`, `TRE.W2`, and `TRE.W3` parameters in the `MATERIAL` statement. Then, activate the electron temperature (electron energy) dependent energy relaxation time by using `E.TAUR.VAR` in the `MODELS` statement. Electron energy relaxation time will then be:

$$\tau_e = \begin{cases} \mathbf{TRE.T1}, & W < \mathbf{TRE.W1} \\ \mathbf{TRE.T2}, & W = \mathbf{TRE.W2} \\ \mathbf{TRE.T3}, & W > \mathbf{TRE.W3} \end{cases} \quad 3-117$$

where:

$$W = \frac{3}{2}kT_n \quad 3-118$$

For  $TRE.W1 < W < TRE.W2$  the energy relaxation time varies quadratically between `TRE.T1` and `TRE.T2`. For  $TRE.W2 < W < TRE.W3$  energy relaxation time varies quadratically between `TRE.T2` and `TRE.T3`. The corresponding parameter for hole energy relaxation time in the `MODELS` statement is `H.TAUR.VAR`. Other parameters are listed in Table 3-9.

| Statement | Parameter | Default                | Units |
|-----------|-----------|------------------------|-------|
| MATERIAL  | TRE.T1    | $8 \times 10^{-13}$    | s     |
| MATERIAL  | TRE.T2    | $1.92 \times 10^{-12}$ | s     |
| MATERIAL  | TRE.T3    | $1 \times 10^{-12}$    | s     |
| MATERIAL  | TRE.W1    | 0.06                   | eV    |
| MATERIAL  | TRE.W2    | 0.3                    | eV    |
| MATERIAL  | TRE.W3    | 0.45                   | eV    |

| <b>Statement</b> | <b>Parameter</b> | <b>Default</b>      | <b>Units</b> |
|------------------|------------------|---------------------|--------------|
| MATERIAL         | TRH.T1           | $1 \times 10^{-12}$ | s            |
| MATERIAL         | TRH.T2           | $1 \times 10^{-12}$ | s            |
| MATERIAL         | TRH.T3           | $1 \times 10^{-12}$ | s            |
| MATERIAL         | TRH.W1           | $1 \times 10^{10}$  | eV           |
| MATERIAL         | TRH.W2           | $1 \times 10^{10}$  | eV           |
| MATERIAL         | TRH.W3           | $1 \times 10^{10}$  | eV           |

For the second method, use the C-INTERPRETER to apply a user-defined model for energy relaxation time as a function of carrier energy. In the MODELS statement, assign the F.TAURN and F.TAURP parameters with the names of external files that contain the user-defined C-INTERPRETER function for the energy relaxation time. You should also specify E.TAUR.VAR and H.TAUR.VAR flags in the MODELS statement when using C-INTERPRETER functions for the energy relaxation times.

### 3.4.5: Energy Dependent Mobilities

The Energy Balance Transport Model requires the carrier mobility to be related to the carrier energy. This has been achieved through the homogeneous steady state energy balance relationship that pertains in the saturated velocity limit. This allows an effective electric field to be calculated, which causes the carriers in a homogeneous sample to attain the same temperature as at the node point in the device. The effective electric fields,  $E_{eff,n}$  and  $E_{eff,p}$ , are calculated by solving the equations:

$$q\mu_n(E_{eff,n})E_{eff,n}^2 = \frac{3}{2} \frac{k(T_n - T_L)}{TAUMOB.EL} \quad 3-119$$

$$q\mu_p(E_{eff,p})E_{eff,p}^2 = \frac{3}{2} \frac{k(T_p - T_L)}{TAUMOB.HO} \quad 3-120$$

for  $E_{eff,n}$  and  $E_{eff,p}$ . These equations are derived from the energy balance equations by stripping out all spatially varying terms. The effective electric fields are then introduced into the relevant field dependent mobility model. A full description of the available models is given in Section 3.6.1: "Mobility Modeling".

ATLAS2D provides a general C-interpretter function allowing you to specify carrier mobility as a function of Perpendicular field, carrier temperature, Lattice temperature, carrier concentration and donor and acceptor concentrations.

For electron mobility, the parameter is F.ENMUN, which can be set in either the MATERIAL or MOBILITY statement. The corresponding parameter for hole mobility is F.ENMUP, which can be set in either the MATERIAL or MOBILITY statement. The respective C-functions are endepmun() and endepmup(). The examples of these functions are provided in ATLAS.

## 3.5: Boundary Physics

ATLAS supports several boundary conditions: Ohmic contacts, Schottky contacts, insulated contacts, and Neumann (reflective) boundaries. Voltage boundary conditions are normally specified at contacts. Current boundary conditions can also be specified. Additional boundary conditions have been implemented to address the needs of specific applications. You can connect lumped elements between applied biases and semiconductor device contacts. A true distributed contact resistance is included to account for the finite resistivity of semiconductor contacts.

### 3.5.1: Ohmic Contacts

Ohmic contacts are implemented as simple Dirichlet boundary conditions, where surface potential, electron concentration, and hole concentrations ( $\psi_s, n_s, p_s$ ) are fixed. Minority and majority carrier quasi-Fermi potentials are equal to the applied bias of the electrode (i.e.,  $\phi_n = \phi_p = V_{\text{applied}}$ ). The potential  $\psi_s$  is fixed at a value that is consistent with space charge neutrality. For example:

$$n_s + N_A^- = p_s + N_D^+ \quad 3-121$$

Equation 3-121 can be solved for  $\psi_s, n_s$ , and  $p_s$ , since  $\phi_n$  and  $\phi_p$  are known. If Boltzmann statistics are used, the substitution of Equations 3-36 and 3-37 into Equation 3-121 will yield:

$$n_s = \frac{1}{2} \left[ \left( N_D^+ - N_A^- \right) + \sqrt{\left( N_D^+ - N_A^- \right)^2 + 4n_{ie}^2} \right] \quad 3-122$$

$$p_s = \frac{n_{ie}}{n_s} \quad 3-123$$

$$\psi_s = \phi_n + \frac{kT_L}{q} \ln \frac{n_s}{n_{ie}} = \phi_p - \frac{kT_L}{q} \ln \frac{p_s}{n_{ie}} \quad 3-124$$

---

**Note:** If you don't specify a work function, the contacts will be Ohmic regardless of its material.

---

### 3.5.2: Schottky Contacts

ATLAS allows you to model Schottky contacts in two different ways [99]. You can either define the work function of the electrode metal or specify a finite surface recombination velocity at the electrode.

The work function method defines the surface potential at a Schottky contact according to:

$$\psi_s = \mathbf{AFFINITY} + \frac{E_g}{2q} + \frac{kT_L}{2q} \ln \frac{N_C}{N_V} - \mathbf{WORKFUN} + V_{\text{applied}} \quad 3-125$$

where **AFFINITY** is the electron affinity of the semiconductor material,  $E_g$  is the bandgap,  $N_C$  is the conduction band density of states,  $N_V$  is the valence band density of states, and  $T_L$  is the ambient temperature. This model is turned on by setting the **WORKFUN** parameter equal to some value on the **CONTACT** statement. In practice, this value is defined as:

$$\mathbf{WORKFUN} = \mathbf{AFFINITY} + \phi_B \quad 3-126$$

where  $\phi_B$  is the barrier height at the metal-semiconductor interface in eV.

| Table 3-10. User-Specifiable Parameters for Equation 3-126 |           |       |
|--|-----------|-------|
| Statement  | Parameter | Units |
| CONTACT  | WORKFUN   | eV    |
| MATERIAL   | AFFINITY  | eV    |

For example, if the Schottky contact were aluminum with a workfunction difference to the silicon of 4.2 eV and a barrier height of 0.7eV, then you would define the Schottky contact with the statement:

```
CONTACT NAME=GATE WORKFUN=4.9
```

The Finite Surface Recombination Velocity Method of defining a Schottky contact can be used at a contact by specifying the SURF.REC parameter on the CONTACT statement. In this case, the quasi-Fermi levels,  $\phi_n$  and  $\phi_p$ , are no longer equal to  $V_{applied}$ . Instead, these parameters are defined by a current boundary conditions at the surface [8]:

$$J_{sn} = qVSURFN(n_s - n_{eq})exp\left(\frac{\Delta\phi_b}{kT}\right) \tag{3-127}$$

$$J_{sp} = qVSURFP(p_s - p_{eq})exp\left(\frac{\Delta\phi_b}{kT}\right) \tag{3-128}$$

| Table 3-11. User-Specifiable Parameters for Equations 3-127 to 3-128 |           |       |
|--|-----------|-------|
| Statement  | Parameter | Units |
| CONTACT  | VSURFN    | cm/s  |
| CONTACT  | VSURFP    | cm/s  |

where  $J_{sn}$  and  $J_{sp}$  are the electron and hole currents at the contact,  $n_s$ , is the surface electron concentration and  $p_s$  is the surface hole concentrations. The terms,  $n_{eq}$  and  $p_{eq}$ , are the equilibrium electron and hole concentrations assuming infinite surface recombination velocity ( $\phi_n = \phi_p = V_{applied}$ ). If VSURFN and VSURFP aren't specified on the CONTACT statement, their values will be calculated using:

$$VSURFN = \frac{ARICHN T_L^2}{q N_C} \tag{3-129}$$

$$VSURNP = \frac{ARICHP T_L^2}{q N_V} \tag{3-130}$$



**Table 3-12. User-Specifiable Parameters for Equations 3-129 to 3-130**

| Statement | Parameter | Default | Units                             |
|-----------|-----------|---------|-----------------------------------|
| MATERIAL  | ARICHN    | 110     | A/cm <sup>2</sup> /K <sup>2</sup> |
| MATERIAL  | ARICHP    | 30      | A/cm <sup>2</sup> /K <sup>2</sup> |

Here, ARICHN and ARICHP are the effective Richardson constants for electrons and holes, taking account of quantum mechanical reflections and tunneling,  $N_C$  and  $N_V$  are the conduction and valence band density of states. The ARICHN and ARICHP parameters are user-definable as shown in Table 3-12 and  $N_C$  and  $N_V$  are functions of the lattice temperature,  $T_L$ , according to Equations 3-31 and 3-32.

The Surface Recombination Schottky Model also accounts for field-dependent barrier-lowering mechanisms. These mechanisms are caused by image forces and possible static dipole layers at the metal-semiconductor interface [9.]. If the barrier height is defined as:

$$\phi_{bn} = \mathbf{WORKFUN} - \mathbf{AFFINITY} \quad 3-131$$

$$\phi_{bp} = \mathbf{AFFINITY} + \frac{E}{q} - \mathbf{WORKFUN} \quad 3-132$$

With barrier lowering, the amount of energy by which these barrier heights are lowered is defined by:

$$\Delta\phi_b = \left[ \frac{q}{4\pi\epsilon_s} \right]^{\frac{1}{2}} E^{1/2} + \mathbf{ALPHA} \times E \quad 3-133$$

**Table 3-13. User-Specifiable Parameters for Equation 3-133**

| Statement | Parameter | Units |
|-----------|-----------|-------|
| CONTACT   | ALPHA     | cm    |

Here,  $E$  is the magnitude of the electric field at the interface and ALPHA is the linear, dipole barrier lowering coefficient. The Barrier Lowering Model can be turned on with the BARRIER parameter in the CONTACT statement. Typical values of ALPHA may be found in [10]. Note that the term with the square root dependence on electric field corresponds to the image force, while the linear term corresponds to the Dipole Effect [9].

Surface recombination is implemented on a triangle-by-triangle basis, which means using the surface recombination velocity and geometrical data. A recombination component is then calculated for each triangle so that an element of interest is connected. Using the electric field for each triangle, an adjusted recombination term can be computed if barrier lowering is incorporated. This is in contrast to where a single field value for the electrode node is used to compute total recombination value [61].

You can take electron tunneling through the barrier into account by specifying the E.TUNNEL parameter in the CONTACT statement. The electron tunneling current ( $J_{tn}$ ) is given by the Tsu-esaki Model (Equation 3-134) and is applied to the contact as a current boundary condition.

$$J_{tn} = -\frac{4 \pi q \text{ME.TUNNEL } m_0 k T_L}{h^3} \int_0^{\phi_{bn}} P(E_Z)N(E_Z)dE_Z \quad 3-134$$

Here,  $\phi_{bn}$  is the barrier height,  $\text{ME.TUNNEL}$  is the relative effective mass for electrons,  $m_0$  is the electron rest mass,  $h$  is Planck's constant,  $k$  is Boltzmann's constant,  $q$  is the electron charge, and  $N(E_Z)$  is given by:

$$N(E_Z) = \ln \left( \frac{1 + e^{\left(\frac{E_F - E_Z}{kT_L}\right)}}{1 + e^{\left(\frac{E_F - E_Z - qV}{kT_L}\right)}} \right) \quad 3-135$$

The transmission probability  $P(E_Z)$  is given by the *WKB* [9] approximation for a triangular barrier and is expressed as:

$$P(E_Z) = \exp \left( \frac{-8 \pi (2 \text{ME.TUNNEL } m^*)^{\frac{1}{2}} (\phi_{bn} - E_Z)^{\frac{3}{2}}}{3 q h E} \right) \quad 3-136$$

The  $\text{ME.TUNNEL}$  parameter is user-definable in the `CONTACT` statement.

For example, to specify a Thermoinic Emission Schottky Contact with tunneling and barrier lowering, the command would be:

```
CONTACT NAME=GATE SURF.REC E.TUNNEL BARRIER
```

---

**Note:** At room temperature, both methods for Schottky contacts should yield similiar results. If the ambient temperature changes, then you should apply the Thermoinic Emission Model. Also, when applying either Schottky contact model, we recommend that you place a fine grid underneath the contact to model the depletion region and that you specify `FERMI` statistics in the `MODELS` statement.

---



---

**Note:** Tunneling is implemented as an addition to Equations 3-127 and 3-128.

---

### 3.5.3: Floating Contacts

A contact that isn't connected to a current or voltage source and is totally insulated by dielectric is called a floating contact. ATLAS accounts for floating contacts such as floating gates in EPROM devices by using a distributed charge boundary condition, which is applied to all nodes of the floating electrode (see Equation 3-137).

$$\int_s D \, dS = Q_{FG} \quad 3-137$$

where  $D$  is the electric displacement vector,  $s$  represents the external surface of the floating gate, and  $Q_{FG}$  is the injected charge.

ATLAS performs an integration over the entire surface of the electrode and forces the potential on the floating nodes to produce the correct total charge on the electrode. The total charge when performing a simulation is by default zero but can be defined using the `SOLVE` statement. The total charge may change if you activate a Charge Injection Model. For more information about this model, see Section 3.6.5: "Gate Current Models". To define a contact as a floating contact, use:

```
CONTACT NAME=fgate FLOATING
```

---

**Note:** When specifying a floating contact, use the Newton scheme as the numerical technique. See Chapter 17: "Numerical Techniques", Section 17.5.1: "Newton Iteration".

---

### 3.5.4: Current Boundary Conditions

In some devices, the terminal current is a multi-valued function of the applied voltage. This means that for some voltage boundary conditions, the solution that is obtained depends on the initial guess. An example of this is the CMOS latch-up trigger point. At the trigger point the I-V curve changes from being flat to vertical and may exhibit a negative slope. The solution will then have three different solutions of current for one applied bias. The particular solution which the model finishes in will depend upon the initial conditions.

This trigger point is difficult to determine using a simple voltage boundary condition. In addition, it is almost impossible to compute any solutions in the negative resistance regime when using voltage boundary conditions. Some of these problems can be overcome using current boundary conditions.

Calculation of current boundary conditions is activated by the `CURRENT` parameter in the `CONTACT` statement.

The voltage boundary condition should be used in regions where  $dI/dV$  is small. The current boundary condition may be preferable for operating regimes where  $dI/dV$  is large. It is common for the negative resistance regime of a device to have a slope  $dI/dV$  very close to 0. Such behavior should be considered when using a current source to trace out an entire I-V curve. In these cases, use the `CURVETRACE` option in ATLAS.

---

**Note:** When a current boundary condition has been specified, choose the Newton numerical scheme on the `METHOD` statement. You can perform ac small signal analysis with current boundary conditions.

---

### 3.5.5: Insulating Contacts

Insulating contacts are contacts that are completely surrounded by insulator. They may be connected to a voltage source (tied contact) or they may be floating.

Insulating contacts that are connected to a voltage source generally have a work function that dictates a value for  $\psi_s$  similar to that given by Equation . Electron and hole concentrations within the insulator and at the insulating contact are forced to be zero (i.e.,  $n_s=p_s=0$ ).

### 3.5.6: Neumann Boundaries

Along the outer (non-contact) edges of devices, homogeneous (reflecting) Neumann boundary conditions are imposed so that current only flows out of the device through the contacts. In the absence of surface charge along such edges, the normal electric field component becomes zero. Current isn't permitted to flow from the semiconductor into an insulating region except via oxide tunneling models. At the interface between two different materials, the difference between the normal components of the respective electric displacements must be equal to any surface charge according to:

$$\hat{n} \cdot \epsilon_1 \nabla \psi_1 - \hat{n} \cdot \epsilon_2 \nabla \psi_2 = \rho_s \quad 3-138$$

where  $n$  is the unit normal vector,  $\epsilon_1$  and  $\epsilon_2$  are the permittivities of the materials on either side of the interface and  $\rho_s$  is the sheet charge at the interface.

### 3.5.7: Lumped Element Boundaries

ATLAS supports some simple configurations of lumped elements. These are indicated in Figure 3-2.

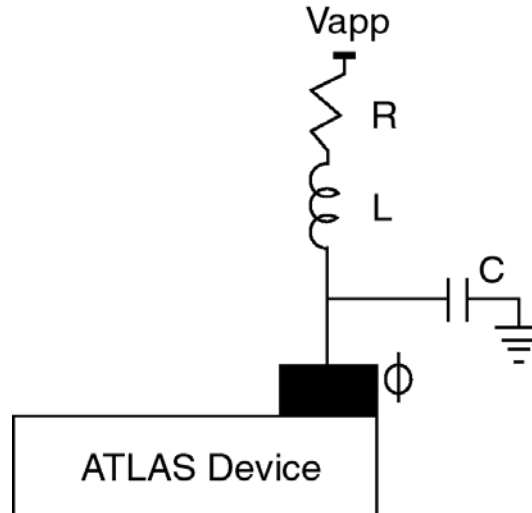


Figure 3-2: The Lumped elements supported by ATLAS

Lumped elements can be extremely useful when simulating CMOS or MOSFET structures. For example, the p-tub contact in the CMOS cross-section might be tens or hundreds of microns away from the active area of an embedded vertical npn bipolar transistor, which may only be 10-20  $\mu\text{m}$  on a side. If the whole structure were simulated, a tremendous number of grid points (probably more than half) are essentially wasted in accounting for a purely resistive region of the device.

In the case of a MOSFET substrate, you would not want to include grid points all the way to the back side of a wafer. In either of these cases, a simple lumped resistance can be substituted [63].

Table 3-14 shows the user-specifiable parameters for Figure 3-2.

**Table 3-14. User-Specifiable Parameters for Figure 3-2.**

| Symbol | Statement | Parameter   | Units               |
|--------|-----------|-------------|---------------------|
| C      | CONTACT   | CAPACITANCE | F / $\mu\text{m}$   |
| R      | CONTACT   | RESISTANCE  | $\Omega\mu\text{m}$ |
| L      | CONTACT   | INDUCTANCE  | H $\mu\text{m}$     |

Resistance is specified in  $\Omega\mu\text{m}$ , capacitance is specified in F/ $\mu\text{m}$ , and inductance is specified in H $\mu\text{m}$ .

The following combinations are possible: resistance only, resistance and capacitance, inductance and resistance and inductance, capacitance and resistance. For the case of inductance or capacitance only, ATLAS adds a small resistance as well. For more complicated circuit configurations, use the MIXEDMODE module of ATLAS.

**Note:** Capacitance increases with device width (into the z-plane) while resistance decreases. Except for the case of extremely large resistances where the arrangement becomes similar to a pure current source, no convergence degradation has been observed for a lumped element boundary in comparison to a simple Ohmic contact. Transient simulation therefore becomes easier and is more well-defined.

You should use the simulator to calculate any resistance (or capacitance) components that might be included as lumped elements. When performing CMOS simulations, you could simulate just the p-tub with Ohmic contacts at either end. From the plot of terminal current (in A/ $\mu\text{m}$ ) versus voltage, resistance can be directly extracted from the slope. Be very careful to consider any three-dimensional effects (e.g., current spreading) before using a resistance value in further simulations.

When looking at the results of simulation with lumped elements it's important to distinguish between the applied voltage ( $V_{app}$ ) and the internal bias ( $\phi$ ) in the log file produced by ATLAS.

**Note:** AC small signal analysis can't be performed when any lumped elements have been specified. AC small signal analysis, however, can be performed when you specify the resistance in the LOG statement. Also, when lumped elements have been defined, use the Newton numerical scheme in the METHOD statement.

### 3.5.8: Distributed Contact Resistance

Since contact materials have finite resistivities, the electrostatic potential isn't always uniform along the metal-semiconductor surface. To account for this effect, a distributed contact resistance can be associated with any electrode. This is in contrast to the lumped contact resistance described in the previous section.

ATLAS implements this distributed contact resistance by assigning a resistance value to each surface element associated with the contact. If each surface element is a different length, a different value for the contact resistance will be assigned. ATLAS calculates a resistance value of  $R_i$  for each surface element from the value of CON.RESIST, as specified on the CONTACT statement. The units of CON.RESIST are  $\Omega\text{cm}^2$  and  $R_i$  calculated as:

$$R_i = \frac{\text{CON.RESIST}}{d_i \cdot \text{WIDTH}}$$

3-139

where  $R_i$  is the resistance at node  $i$ ,  $P_c$  is specified by the `CON.RESIST` parameter,  $d_i$  is the length of the contact surface segment associated with node  $i$  and `WIDTH` is the width of the device. The effect of the resistance,  $R_i$  is to add an extra equation to be satisfied to node  $i$ . This equation is given by:

$$\frac{1}{R_i} \left[ V_{applied} - \left( \psi_i \pm \frac{kT_L}{q} \ln(N/n_{ie}) \right) \right] - (I_n + I_p + I_{disp}) = 0 \tag{3-140}$$

where  $V_{applied}$  is the external applied voltage,  $\Psi_i$  is the surface potential,  $N$  is the net doping,  $n_i$  is the intrinsic electron concentration, and  $I_n$ ,  $I_p$ ,  $I_{disp}$  are the electron, hole and displacement currents at node  $i$ . This equation simply balances the current in and out of the resistor added to each  $i$  node.

As with the case for lumped elements, ATLAS can print out a value of contact resistance for each contact in the run time output. Since the actual value depends on the length of each surface segment for distributed contacts, ATLAS prints out the value of `CON.RESIST/WIDTH` which is the same for all contact surface segments. This runtime output is enabled by adding the `PRINT` option on the `MODELS` statement.

| Table 3-15. User-Specifiable Parameters for Equation 3-139 |            |                      |
|--|------------|----------------------|
| Statement  | Parameter  | Units                |
| CONTACT  | CON.RESIST | $\Omega\text{-cm}^2$ |
| MESH   | WIDTH      | $\mu\text{m}$        |

**Note:** AC small signal analysis cannot be performed when any distributed contact resistance has been specified. Also, only the `NEWTON` numerical scheme should be chosen on the `METHOD` statement.

### 3.5.9: Energy Balance Boundary Conditions

When the Energy Balance Transport Model is applied, special boundary conditions are applied for carrier temperatures. By default at the contacts, Dirichlet boundary conditions are used for carrier temperatures:

$$T_n = T_p = T_L \tag{3-141}$$

You can treat contacts as Neumann (reflective) boundaries with respect to carrier temperature by specifying `REFLECT` on the `CONTACT` statement.

Elsewhere on the boundary, the normal components of the energy fluxes vanish. The boundary conditions for  $(\psi, n, p)$  are the same as for the drift-diffusion model.

## 3.6: Physical Models

### 3.6.1: Mobility Modeling

Electrons and holes are accelerated by electric fields, but lose momentum as a result of various scattering processes. These scattering mechanisms include lattice vibrations (phonons), impurity ions, other carriers, surfaces, and other material imperfections. Since the effects of all of these microscopic phenomena are lumped into the macroscopic mobilities introduced by the transport equations these mobilities are therefore functions of the local electric field, lattice temperature, doping concentration, and so on.

Mobility modeling is normally divided into: (i) low field behavior, (ii) high field behavior, (iii) bulk semiconductor regions and (iv) inversion layers.

The low electric field behavior has carriers almost in equilibrium with the lattice and the mobility has a characteristic low-field value that is commonly denoted by the symbol  $\mu_{n0,p0}$ . The value of this mobility is dependent upon phonon and impurity scattering. Both of which act to decrease the low field mobility.

The high electric field behavior shows that the carrier mobility declines with electric field because the carriers that gain energy can take part in a wider range of scattering processes. The mean drift velocity no longer increases linearly with increasing electric field, but rises more slowly. Eventually, the velocity doesn't increase any more with increasing field but saturates at a constant velocity. This constant velocity is commonly denoted by the symbol  $v_{sat}$ . Impurity scattering is relatively insignificant for energetic carriers, and so  $v_{sat}$  is primarily a function of the lattice temperature.

Modeling mobility in bulk material involves: (i) characterizing  $\mu_{n0}$  and  $\mu_{p0}$  as a function of doping and lattice temperature, (ii) characterizing  $v_{sat}$  as a function of lattice temperature, and (iii) describing the transition between the low field mobility and saturated velocity regions.

Modeling carrier mobilities in inversion layers introduces additional complications. Carriers in inversion layers are subject to surface scattering, extreme carrier-carrier scattering, and quantum mechanical size quantization effects. These effects must be accounted for in order to perform accurate simulation of MOS devices. The transverse electric field is often used as a parameter that indicates the strength of inversion layer phenomena.

You can define multiple non-conflicting mobility models simultaneously. You also need to know which models are over-riding when conflicting models are defined.

#### Low Field Mobility Models

The low field carrier mobility can be defined in five different ways.

The first way is use the MUN and MUP parameters to set constant values for electron and hole mobilities. The second way is by using a look-up table model (CONMOB) to relate the low field mobility at 300K to the impurity concentration. The third way is by choosing the analytic low field mobility models, ANALYTIC and ARORA, to relate the low field carrier mobility to impurity concentration and temperature. The fourth way is by choosing a carrier-carrier scattering model (CCSMOB) that relates the low field mobility to the carrier concentrations and temperature. The fifth way is to use a unified low field mobility model (KLAASSEN) that relates the low field mobility to donor, acceptor, lattice, carrier-carrier scattering, and temperature.

### Constant Low Field Mobility Model

In ATLAS, the choice of mobility model is specified on the MODELS statement. The parameters associated with mobility models are specified on a separate MOBILITY statement. One or more mobility models should always be specified explicitly. The default is to use constant low field mobilities within each region of a device. This default model is independent of doping concentration, carrier densities and electric field. It does account for lattice scattering due to temperature according to:

$$\mu_{n0} = \text{MUN} \left( \frac{T_L}{300} \right)^{-\text{TMUN}} \tag{3-142}$$

$$\mu_{p0} = \text{MUP} \left( \frac{T_L}{300} \right)^{-\text{TMUP}} \tag{3-143}$$

where  $T$  is the lattice temperature. The low field mobility parameters: MUN, MUP, TMUN and TMUP can be specified in the MOBILITY statement with the defaults as shown in Table 3-16.

| Statement | Parameter | Default | Units                   |
|-----------|-----------|---------|-------------------------|
| MOBILITY  | MUN       | 1000    | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MUP       | 500     | cm <sup>2</sup> / (V·s) |
| MOBILITY  | TMUN      | 1.5     |                         |
| MOBILITY  | TMUP      | 1.5     |                         |

### Concentration-Dependent Low Field Mobility Tables

ATLAS provides empirical data for the doping dependent low-field mobilities of electrons and holes in silicon at  $T_L=300K$  only. This data is used if the CONMOB parameter is specified in the MODELS statement. The data that is used is shown in Table 3-17.

| Concentration (cm <sup>-3</sup> ) | Mobility (cm <sup>2</sup> /V·s) |       |
|-----------------------------------|---------------------------------|-------|
|                                   | Electrons                       | Holes |
| 1.0x10 <sup>14</sup>              | 1350.0                          | 495.0 |
| 2.0x10 <sup>14</sup>              | 1345.0                          | 495.0 |
| 4.0x10 <sup>14</sup>              | 1335.0                          | 495.0 |
| 6.0x10 <sup>14</sup>              | 1320.0                          | 495.0 |
| 8.0x10 <sup>14</sup>              | 1310.0                          | 495.0 |
| 1.0x10 <sup>15</sup>              | 1300.0                          | 491.1 |



| Concentration (cm <sup>-3</sup> ) | Mobility (cm <sup>2</sup> /V·s) |        |
|-----------------------------------|---------------------------------|--------|
|                                   | Electrons                       | Holes  |
| 2.0x10 <sup>15</sup>              | 1248.0                          | 487.3  |
| 4.0x10 <sup>15</sup>              | 1200.0                          | 480.1  |
| 6.0x10 <sup>15</sup>              | 1156.0                          | 473.3  |
| 8.0x10 <sup>15</sup>              | 1115.0                          | 466.9  |
| 1.0x10 <sup>16</sup>              | 1076.0                          | 460.9  |
| 2.0x10 <sup>16</sup>              | 960.0                           | 434.8  |
| 4.0x10 <sup>16</sup>              | 845.0                           | 396.5  |
| 6.0x10 <sup>16</sup>              | 760.0                           | 369.2  |
| 8.0x10 <sup>16</sup>              | 720.0                           | 348.3  |
| 1.0x10 <sup>17</sup>              | 675.0                           | 331.5  |
| 2.0x10 <sup>17</sup>              | 524.0                           | 279.0  |
| 4.0x10 <sup>17</sup>              | 385.0                           | 229.8  |
| 6.0x10 <sup>17</sup>              | 321.0                           | 2103.8 |
| 8.0x10 <sup>17</sup>              | 279.0                           | 186.9  |
| 1.0x10 <sup>18</sup>              | 252.0                           | 178.0  |
| 2.0x10 <sup>18</sup>              | 182.5                           | 130.0  |
| 4.0x10 <sup>18</sup>              | 140.6                           | 90.0   |
| 6.0x10 <sup>18</sup>              | 113.6                           | 74.5   |
| 8.0x10 <sup>18</sup>              | 99.5                            | 66.6   |
| 1.0x10 <sup>19</sup>              | 90.5                            | 61.0   |
| 2.0x10 <sup>19</sup>              | 86.9                            | 55.0   |
| 4.0x10 <sup>19</sup>              | 83.4                            | 53.7   |
| 6.0x10 <sup>19</sup>              | 78.8                            | 52.9   |
| 8.0x10 <sup>19</sup>              | 71.6                            | 52.4   |
| 1.0x10 <sup>20</sup>              | 67.8                            | 52.0   |
| 2.0x10 <sup>20</sup>              | 52.0                            | 50.8   |

| Table 3-17. Mobility of Electrons and Holes in Silicon at T=300K |                                 |       |
|--|---------------------------------|-------|
| Concentration (cm <sup>-3</sup> )                                | Mobility (cm <sup>2</sup> /V·s) |       |
|  | Electrons                       | Holes |
| 4.0x10 <sup>20</sup>   | 35.5                            | 49.6  |
| 6.0x10 <sup>20</sup>   | 23.6                            | 48.9  |
| 8.0x10 <sup>20</sup>   | 19.0                            | 48.4  |
| 1.0x10 <sup>21</sup>   | 17.8                            | 48.0  |

### The Analytic Low Field Mobility Model

The following analytic function based upon the work of Caughey and Thomas [11, 54] can be used to specify doping- and temperature-dependent low-field mobilities.

$$\mu_{n0} = \text{MU1N.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{ALPHAN.CAUG}} \tag{3-144}$$

$$+ \frac{\text{MU2N.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{BETAN.CAUG}} - \text{MU1N.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{ALPHAN.CAUG}}}{1 + \left(\frac{T_L}{300\text{K}}\right)^{\text{GAMMAN.CAUG}} \cdot \left(\frac{N}{\text{NCRITN.CAUG}}\right)^{\text{DELTAN.CAUG}}}$$

$$\mu_{p0} = \text{MU1P.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{ALPHAP.CAUG}} \tag{3-145}$$

$$+ \frac{\text{MU2P.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{BETAP.CAUG}} - \text{MU1P.CAUG} \cdot \left(\frac{T_L}{300\text{K}}\right)^{\text{ALPHAP.CAUG}}}{1 + \left(\frac{T_L}{300\text{K}}\right)^{\text{GAMMAP.CAUG}} \cdot \left(\frac{N}{\text{NCRITP.CAUG}}\right)^{\text{DELTAP.CAUG}}}$$

where  $N$  is the local (total) impurity concentration in cm<sup>-3</sup> and  $T_L$  is the temperature in degrees Kelvin.

This model is activated by specifying both the CONMOB and ANALYTIC parameters in the MODELS statement. The parameters of this model are specified in the MOBILITY statement. The default parameters are for silicon at  $T_L = 300\text{K}$ .

**Table 3-18. User-Specifiable Parameters for Equations 3-144 and 3-145**

| Statement | Parameter   | Default                | Units                  |
|-----------|-------------|------------------------|------------------------|
| MOBILITY  | MU1N.CAUG   | 55.24                  | cm <sup>2</sup> /(V·s) |
| MOBILITY  | MU1P.CAUG   | 49.7                   | cm <sup>2</sup> /(V·s) |
| MOBILITY  | MU2N.CAUG   | 1429.23                | cm <sup>2</sup> /(V·s) |
| MOBILITY  | MU2P.CAUG   | 479.37                 | cm <sup>2</sup> /(V·s) |
| MOBILITY  | ALPHAN.CAUG | 0.0                    | arbitrary              |
| MOBILITY  | ALPHAP.CAUG | 0.0                    | arbitrary              |
| MOBILITY  | BETAN.CAUG  | -2.3                   | arbitrary              |
| MOBILITY  | BETAP.CAUG  | -2.2                   | arbitrary              |
| MOBILITY  | GAMMAN.CAUG | -3.8                   | arbitrary              |
| MOBILITY  | GAMMAP.CAUG | -3.7                   | arbitrary              |
| MOBILITY  | DELTAN.CAUG | 0.73                   | arbitrary              |
| MOBILITY  | DELTAP.CAUG | 0.70                   | arbitrary              |
| MOBILITY  | NCRITN.CAUG | 1.072×10 <sup>17</sup> | cm <sup>-3</sup>       |
| MOBILITY  | NCRITP.CAUG | 1.606×10 <sup>17</sup> | cm <sup>-3</sup>       |

### The Arora Model for Low Field Mobility

Another analytic model for the doping and temperature dependence of the low field mobility is available in ATLAS. This model, which is due to Arora [12], has the following form:

$$\mu_{n0} = \text{MU1N.ARORA} \left( \frac{T_L}{300} \right)^{\text{ALPHAN.ARORA}} + \frac{\text{MU2N.ARORA} \left( \frac{T_L}{300} \right)^{\text{BETAN.ARORA}}}{1 + \frac{N}{\text{NCRITN.ARORA} \cdot \left( \frac{T_L}{300} \right)^{\text{GAMMAN.ARORA}}} \quad 3-146$$

$$\mu_{p0} = \text{MU1P.ARORA} \left( \frac{T_L}{300} \right)^{\text{ALPHAP.ARORA}} + \frac{\text{MU2P.ARORA} \left( \frac{T_L}{300} \right)^{\text{BETAP.ARORA}}}{1 + \frac{N}{\text{NCRITP.ARORA} \cdot \left( \frac{T_L}{300} \right)^{\text{GAMMAP.ARORA}}} \quad 3-147$$

This model is used if CONMOB and ARORA are specified in the MODELS statement. The parameters of the model are specified in the MOBILITY statement. The default parameters are for silicon at T<sub>L</sub>=300K.

**Table 3-19. User-Specifiable Parameters for Equations 3-146 and 3-147**

| Statement | Parameter    | Default                | Units                   |
|-----------|--------------|------------------------|-------------------------|
| MOBILITY  | MU1N.ARORA   | 88.0                   | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MU1P.ARORA   | 54.3                   | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MU2N.ARORA   | 1252.0                 | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MU2P.ARORA   | 407.0                  | cm <sup>2</sup> / (V·s) |
| MOBILITY  | ALPHAN.ARORA | -0.57                  |                         |
| MOBILITY  | ALPHAP.ARORA | -0.57                  |                         |
| MOBILITY  | BETAN.ARORA  | -2.33                  |                         |
| MOBILITY  | BETAP.ARORA  | -2.33                  |                         |
| MOBILITY  | GAMMAN.ARORA | 2.546                  |                         |
| MOBILITY  | GAMMAP.ARORA | 2.546                  |                         |
| MOBILITY  | NCRITN.ARORA | 1.432×10 <sup>17</sup> | cm <sup>-3</sup>        |
| MOBILITY  | NCRITP.ARORA | 2.67×10 <sup>17</sup>  | cm <sup>-3</sup>        |

**The Albrecht Model for Low Field Mobility in GaN**

You can choose to model low field mobility following the work of Albrecht et.al (160) by specifying ALBRCT on the MODEL statement or ALBRCT.N or ALBRCT.P or both on the MOBILITY statement for separate control over electrons and holes. This model is described as follows:

$$\frac{1}{\mu(N, T)} = \frac{AN \cdot ALBRCT \cdot N}{NON \cdot ALBRCT} \left( \frac{T}{TON \cdot ALBRCT} \right)^{-3/2} \tag{3-148}$$

$$+ \ln \left[ 1 + 3 \left( \frac{T}{TON \cdot ALBRCT} \right)^2 \left( \frac{N}{NON \cdot ALBRCT} \right)^{-2/3} \right]$$

$$+ BN \cdot ALBRCT \cdot N \left( \frac{T}{TON \cdot ALBRCT} \right)^{3/2}$$

$$+ \frac{CN \cdot ALBRCT}{\exp(TIN \cdot ALBRCT / T) - 1}$$

where  $\mu(N, T)$  is the mobility as a function of doping and lattice temperature,  $N$  is the total doping concentration, and  $T$  is the lattice temperature. AN.ALBRCT, BN.ALBRCT, CN.ALBRCT, NON.ALBRCT, TON.ALBRCT and TIN.ALBRCT are user-specifiable parameters on the MOBILITY statement. You can use a similar expression for holes with the user-defined parameters AP.ALBRCT, BP.ALBRCT, CP.ALBRCT, NOP.ALBRCT, TOP.ALBRCT and T1P.ALBRCT.

### The Carrier-Carrier Scattering Model For Low Field Mobility

The Dorkel and Leturcq Model [13] for low field mobility includes the dependence on temperature, doping, and carrier-carrier scattering. This model is activated by specifying the CCSMOB parameter of the MODELS statement. The parameters of the model are specified in the MOBILITY statement. This model has the form:

$$\mu_{n0,p0} = \mu_{n,p}^L \left( \frac{1.025}{1 + \left[ 1.126 \left( \frac{\mu_{n,p}^L}{IC} \right) \right]^{0.715}} \right)^{-0.025} \quad 3-149$$

where L is the lattice scattering, I is the ionized impurity scattering, and C is the carrier-carrier scattering. Here,  $\mu_{n,p}^{IC}$  is defined as:

$$\mu_{n,p}^{IC} = \left[ \frac{1}{\mu^C} + \frac{1}{\mu_{n,p}^I} \right]^{-1} \quad 3-150$$

where:

$$\mu^C = \frac{1.04 \cdot 10^{21} \left( \frac{T_L}{300} \right)^{3/2}}{\sqrt{np} \ln \left[ 1 + 7.45 \cdot 10^{13} \left( \frac{T_L}{300} \right)^2 (np)^{-1/3} \right]} \quad 3-151$$

$$\mu_n^I = \frac{AN.CCS \left( \frac{T_L}{300} \right)^{3/2}}{N_T} f \left[ \frac{BN.CCS \left( \frac{T_L}{300} \right)^2}{n+p} \right] \quad 3-152$$

$$\mu_p^I = \frac{AP.CCS \left( \frac{T_L}{300} \right)^{3/2}}{N_T} f \left[ \frac{BP.CCS \left( \frac{T_L}{300} \right)^2}{n+p} \right] \quad 3-153$$

Here,  $N_T$  is the total concentration,  $T_L$  is the lattice temperature and  $n,p$  are the electron and hole carrier concentrations respectively.

$$f(x) = \left[ \ln(1+x) - \frac{x}{1+x} \right]^{-1} \quad 3-154$$

The values of the lattice scattering terms,  $\mu_{N,P}^L$  are defined by Equations 3-142 and 3-143.

**Table 3-20. User-Specifiable Parameters for Equations 3-152 and 3-153**

| Statement | Parameter | Default               | Units            |
|-----------|-----------|-----------------------|------------------|
| MOBILITY  | AN.CCS    | 4.61x10 <sup>17</sup> | cm <sup>-3</sup> |
| MOBILITY  | AP.CCS    | 1.0x10 <sup>17</sup>  | cm <sup>-3</sup> |
| MOBILITY  | BN.CCS    | 1.52x10 <sup>15</sup> | cm <sup>-3</sup> |
| MOBILITY  | BP.CCS    | 6.25x10 <sup>14</sup> | cm <sup>-3</sup> |

**Klaassen’s Unified Low Field Mobility Model**

The model by D. B. M. Klaassen [14, 15], provides a unified description of majority and minority carrier mobilities. In so doing, it includes the effects of lattice scattering, impurity scattering (with screening from charged carriers), carrier-carrier scattering, and impurity clustering effects at high concentration. The model shows excellent agreement between the modeled and empirical data for:

- majority electron mobility as a function of donor concentration over the range of 10<sup>14</sup> cm<sup>-3</sup> to 10<sup>22</sup> cm<sup>-3</sup>
- minority electron mobility as a function of acceptor concentration over the range of 10<sup>17</sup> cm<sup>3</sup> to 10<sup>20</sup> cm<sup>-3</sup>
- minority hole mobility as a function of donor concentration from 10<sup>17</sup> cm<sup>-3</sup> to 10<sup>20</sup> cm<sup>-3</sup>
- temperature dependence over the range of 70 K to 500 K

The Klaassen Model accounts for a broader set of effects and has been calibrated over a wider range of conditions than any other of the low field bulk mobility models. This is the recommended model for both MOS and bipolar simulation and is the default model for silicon when you set MOS2 or BIPOLAR2 in the MODELS statement. You can enable or disable the model by using the KLA parameter in0 the MODELS statement, or independently for electrons and holes by the KLA.N and KLA.P parameters of the MOBILITY statement.

The total mobility can be described by its components using Matthiessen’s rule as:

$$\mu_{n0}^{-1} = \mu_{nL}^{-1} + \mu_{nDAP}^{-1} \tag{3-155}$$

$$\mu_{p0}^{-1} = \mu_{pL}^{-1} + \mu_{pDAP}^{-1} \tag{3-156}$$

$\mu_n$  and  $\mu_p$  are the total low field electron and hole mobilities,  $\mu_{nL}$  and  $\mu_{pL}$  are the electron and hole mobilities due to lattice scattering,  $\mu_{nDAP}$  and  $\mu_{pDAP}$  are the electron and hole mobilities due to donor (D), acceptor (A), screening (P) and carrier-carrier scattering.

The lattice scattering components,  $\mu_{nL}$  and  $\mu_{pL}$  are given as:

$$\mu_{nL} = \mathbf{MUMAXN.KLA} \left( \frac{300}{T_L} \right)^{\mathbf{THETAN.KLA}} \tag{3-157}$$

$$\mu_{pL} = \text{MUMAXP.KLA} \left( \frac{300}{T_L} \right)^{\text{THETAP.KLA}} \quad 3-158$$

where  $T_L$  is the temperature in degrees Kelvin. MUMAXN.KLA, MUMAXP.KLA, THETAN.KLA, and THETAP.KLA are user-definable model parameters which can be specified as shown in Table 3-21.

| Table 3-21. User-Specifiable Parameters for Equations 3-157 and 3-158 |            |         |                         |
|---|------------|---------|-------------------------|
| Statement   | Parameter  | Default | Units                   |
| MOBILITY  | MUMAXN.KLA | 1417.0  | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MUMAXP.KLA | 470.5   | cm <sup>2</sup> / (V·s) |
| MOBILITY  | THETAN.KLA | 2.285   |                         |
| MOBILITY  | THETAP.KLA | 2.247   |                         |

The impurity-carrier scattering components of the total mobility are given by:

$$\mu_{nDAP} = \mu_{N,n} \frac{N_{ncs}}{N_{nsc,eff}} \left( \frac{\text{NREF1N.KLA}}{N_{nsc}} \right)^{\text{ALPHA1N.KLA}} + \mu_{nc} \left( \frac{n+p}{N_{nsc,eff}} \right) \quad 3-159$$

$$\mu_{pDAP} = \mu_{N,p} \frac{N_{psc}}{N_{psc,eff}} \left( \frac{\text{NREF1P.KLA}}{N_{psc}} \right)^{\text{ALPHA1P.KLA}} + \mu_{pc} \left( \frac{n+p}{N_{psc,eff}} \right) \quad 3-160$$

| Table 3-22. User-Specifiable Parameters for Equations 3-159 and 3-160 |             |                       |                 |
|---|-------------|-----------------------|-----------------|
| Statement   | Parameter   | Default               | Units           |
| MOBILITY  | ALPHA1N.KLA | 0.68                  |                 |
| MOBILITY  | ALPHA1P.KLA | 0.719                 |                 |
| MOBILITY  | NREF1N.KLA  | 9.68x10 <sup>16</sup> | cm <sup>3</sup> |
| MOBILITY  | NREF1P.KLA  | 2.23x10 <sup>17</sup> | cm <sup>3</sup> |

The impurity scattering components,  $\mu_{N,n}$  and  $\mu_{N,p}$ , are given by:

$$\mu_{N,n} = \frac{\text{MUMAXN.KLA}^2}{\text{MUMAXN.KLA} - \text{MUMINN.KLA}} \left( \frac{T_L}{300} \right)^{3\text{ALPHA1N.KLA} - 1.5} \quad 3-161$$

$$\mu_{N,p} = \frac{\text{MUMAXP.KLA}^2}{\text{MUMAXP.KLA} - \text{MUMINP.KLA}} \left( \frac{T_L}{300} \right)^{3\text{ALPHA1P.KLA} - 1.5} \quad 3-162$$

where  $T_L$  is the temperature in degrees Kelvin. MUMINN.KLA and MUMINP.KLA are user-defined parameters shown in Table 3-23, and the other parameters are as described in Tables 3-3-21 and Table 3-22.

Table 3-23. User-Specifiable Parameters for Equations 3-161 and 3-162

| Statement | Parameter  | Default | Units                 |
|-----------|------------|---------|-----------------------|
| MOBILITY  | MUMINN.KLA | 52.2    | cm <sup>2</sup> (V·s) |
| MOBILITY  | MUMINP.KLA | 44.9    | cm <sup>2</sup> (V·s) |

The carrier-carrier scattering components,  $\mu_{nc}$  and  $\mu_{pc}$ , are given by:

$$\mu_{nc} = \frac{\text{MUMINN.KLA} \times \text{MUMAXN.KLA}}{\text{MUMAXN.KLA} - \text{MUMINN.KLA}} \left( \frac{300}{T_L} \right)^{0.5} \quad 3-163$$

$$\mu_{pc} = \frac{\text{MUMINP.KLA} \times \text{MUMAXP.KLA}}{\text{MUMAXP.KLA} - \text{MUMINP.KLA}} \left( \frac{300}{T_L} \right)^{0.5} \quad 3-164$$

The  $N_{nsc}$  and  $N_{psc}$  parameters of Equations 3-159 and 3-160 are given by:

$$N_{nsc} = N_D + N_A + p \quad 3-165$$

$$N_{psc} = N_D + N_A + n \quad 3-166$$

where  $N_D$  is the donor concentration in cm<sup>-3</sup>,  $N_A$  is the acceptor concentration in cm<sup>-3</sup>,  $n$  is the electron concentration in cm<sup>-3</sup> and  $p$  is the hole concentration in cm<sup>-3</sup>.

The parameters of Equations 3-161 and 3-162 are given by:

$$N_{nsc, eff} = N_D + G(P_n)N_A + \left( \frac{p}{F(P_n)} \right) \quad 3-167$$

$$N_{psc, eff} = N_A + G(P_p)N_D + \left( \frac{n}{F(P_p)} \right) \quad 3-168$$

where  $N_D$  is the donor concentration in cm<sup>-3</sup>,  $N_A$  is the acceptor concentration in cm<sup>-3</sup> and  $n$  is the hole electron concentration in cm<sup>-3</sup> and  $p$  is the hole concentration in cm<sup>-3</sup>. The two functions,  $G(P)$  and  $F(P)$ , are functions of the screening factors,  $P_n$  and  $P_p$ , for electrons and holes. The function,  $G(P)$ , in Equations 3-167 and 3-168 are given by:

$$G(P_n) = 1 - \frac{\text{S1.KLA}}{\left[ \text{S2.KLA} + P_{BH, n} \left( \frac{m_e T_L}{m_e 300} \right) \right] \text{S4.KLA} \text{S3.KLA}} + \frac{\text{S5.KLA}}{\left[ P_{BH, n} \left( \frac{m_e 300}{m_e T_L} \right) \right] \text{S7.KLA} \text{S6.KLA}} \quad 3-169$$

$$G(P_p) = 1 - \frac{\text{S1.KLA}}{\left[ \text{S2.KLA} + P_{BH, p} \left( \frac{m_o T_L}{m_h 300} \right) \right] \text{S4.KLA} \text{S3.KLA}} + \frac{\text{S5.KLA}}{\left[ P_{BH, p} \left( \frac{m_o 300}{m_h T_L} \right) \right] \text{S7.KLA} \text{S6.KLA}} \quad 3-170$$

Here,  $T_L$  is the temperature in degrees Kelvin,  $m_e$  and  $m_h$  are the electron and hole masses and the parameters S1.KLA through S7.KLA are user-specifiable model parameters as shown in Table 3-24.



**Table 3-24. User-Specifiable Parameters for Equations 3-169 and 3-170**

| Statement | Parameter | Default  | Units |
|-----------|-----------|----------|-------|
| MOBILITY  | S1.KLA    | 0.89233  |       |
| MOBILITY  | S2.KLA    | 0.41372  |       |
| MOBILITY  | S3.KLA    | 0.19778  |       |
| MOBILITY  | S4.KLA    | 0.28227  |       |
| MOBILITY  | S5.KLA    | 0.005978 |       |
| MOBILITY  | S6.KLA    | 1.80618  |       |
| MOBILITY  | S7.KLA    | 0.72169  |       |

The functions,  $F(P_n)$  and  $F(P_p)$ , in Equations 3-167 and 3-168 are given by:

$$F(P_n) = \frac{\mathbf{R1.KLA} P_n^{\mathbf{R6.KLA}} + \mathbf{R2.KLA} + \mathbf{R3.KLA} \frac{m_e}{m_h}}{P_n^{\mathbf{R6.KLA}} + \mathbf{R4.KLA} + \mathbf{R5.KLA} \frac{m_e}{m_h}} \quad 3-171$$

$$F(P_p) = \frac{\mathbf{R1.KLA} P_p^{\mathbf{R6.KLA}} + \mathbf{R2.KLA} + \mathbf{R3.KLA} \frac{m_h}{m_e}}{P_p^{\mathbf{R6.KLA}} + \mathbf{R4.KLA} + \mathbf{R5.KLA} \frac{m_h}{m_e}} \quad 3-172$$

where the parameters, R1.KLA through R6.KLA, are user-specifiable as shown in Table 3-25.

**Table 3-25. User-Specifiable Parameters for Equations 3-171 and 3-172**

| Statement | Parameter | Default | Units |
|-----------|-----------|---------|-------|
| MOBILITY  | R1.KLA    | 0.7463  |       |
| MOBILITY  | R2.KLA    | 2.2999  |       |
| MOBILITY  | R3.KLA    | 6.5502  |       |
| MOBILITY  | R4.KLA    | 2.3670  |       |
| MOBILITY  | R5.KLA    | -0.8552 |       |
| MOBILITY  | R6.KLA    | 0.6478  |       |

The screening parameters,  $P_n$  and  $P_p$ , used in Equations 3-171 and 3-172 are given by:

$$P_n = \left[ \frac{\mathbf{FCW.KLA}}{P_{CW,n}} + \frac{\mathbf{FBH.KLA}}{P_{BH,n}} \right]^{-1} \quad 3-173$$

$$P_p = \left[ \frac{\mathbf{FCW.KLA}}{P_{CW,p}} + \frac{\mathbf{FBH.KLA}}{P_{BH,p}} \right]^{-1} \quad 3-174$$

Here, the FCW.KLA and FBH.KLA parameters are user-specifiable model parameters as shown in Table 3-26.

| Table 3-26. User-Specifiable Parameters for Equations 3-173 and 3-174 |           |         |       |
|---|-----------|---------|-------|
| Statement   | Parameter | Default | Units |
| MOBILITY  | FCW.KLA   | 2.459   |       |
| MOBILITY  | FBH.KLA   | 3.828   |       |

The functions,  $P_{BH,n}$  and  $P_{BH,p}$ ,  $P_{CW,n}$ , and  $P_{CW,p}$  are given by the following equations:

$$P_{BH,n} = \frac{1.36 \times 10^{20}}{n} \left( \frac{m_e}{m_0} \right) \left( \frac{T_L}{300} \right)^2 \quad 3-175$$

$$P_{BH,p} = \frac{1.36 \times 10^{20}}{p} \left( \frac{m_h}{m_0} \right) \left( \frac{T_L}{300} \right)^2 \quad 3-176$$

$$P_{CW,n} = 3.97 \times 10^{13} \left\{ \frac{1}{Z_n^3 N_D} \left( \frac{T_L}{300} \right)^3 \right\}^{\frac{2}{3}} \quad 3-177$$

$$P_{CW,p} = 3.97 \times 10^{13} \left\{ \frac{1}{Z_p^3 N_A} \left( \frac{T_L}{300} \right)^3 \right\}^{\frac{2}{3}} \quad 3-178$$

where  $T_L$  is the temperature in degrees Kelvin,  $m_e/m_0$  and  $m_h/m_0$  are the normalized carrier effective masses, and  $n$  and  $p$  are the electron and hole concentrations in  $\text{cm}^{-3}$ .

Also here,  $N_D$  and  $N_A$  are the donor and acceptor concentrations in  $\text{cm}^{-3}$ ,  $T_L$  is the temperature in degrees Kelvin, and  $Z_n$  and  $Z_p$  are clustering functions given by:

$$Z_n = 1 + \frac{1}{\mathbf{CD.KLA} + \left( \frac{\mathbf{NREFD.KLA}}{N_D} \right)^2} \quad 3-179$$

$$Z_p = 1 + \frac{1}{\mathbf{CA.KLA} + \left( \frac{\mathbf{NREFA.KLA}}{N_A} \right)^2} \quad 3-180$$

where  $N_D$  and  $N_A$  are the donor and acceptor concentrations in  $\text{cm}^{-3}$  and `CD.KLA`, `CA.KLA`, `NREFD.KLA`, and `NREFA.KLA` are user-definable parameters as given in Table 3-27.

| Statement | Parameter | Default              | Units         |
|-----------|-----------|----------------------|---------------|
| MOBILITY  | CD.KLA    | 0.21                 |               |
| MOBILITY  | CA.KLA    | 0.50                 |               |
| MOBILITY  | NREFD.KLA | $4.0 \times 10^{20}$ | $\text{cm}^3$ |
| MOBILITY  | NREFA.KLA | $7.2 \times 10^{20}$ | $\text{cm}^3$ |

**Note:** When the Klaassen low field mobility is used, remember that it has been calibrated to work with Klaassen's models for bandgap narrowing, `KLAAUG` recombination, and `KLASRH` recombination. These models are described in the Section 3.6.3: "Carrier Generation-Recombination Models".

### Inversion Layer Mobility Models

To obtain accurate results for MOSFET simulations, you need to account for the mobility degradation that occurs inside inversion layers. The degradation normally occurs as a result of the substantially higher surface scattering near the semiconductor to insulator interface.

This effect is handled within ATLAS by three distinct methods:

- a surface degradation model `SURFMOB`
- a transverse electric field model `SHIRAHATA`
- specific inversion layer mobility models `CVT`, `YAMAGUCHI`, and `TASCH`

The `CVT`, `YAMAGUCHI`, and `TASCH` models are designed as stand-alone models which incorporate all the effects required for simulating the carrier mobility.

#### Lombardi CVT Model

The inversion layer model from Lombardi [16] is selected by setting `CVT` on the `MODEL` statement. This model overrides any other mobility models which may be specified on the `MODELS` statement. In the `CVT` model, the transverse field, doping dependent and temperature dependent parts of the mobility are given by three components that are combined using Matthiessen's rule. These components are  $\mu_{AC}$ ,  $\mu_{sr}$  and  $\mu_b$  and are combined using Matthiessen's rule as follows:

$$\mu_T^{-1} = \mu_{AC}^{-1} + \mu_b^{-1} + \mu_{sr}^{-1} \quad 3-181$$

The first component,  $\mu_{AC}$ , is the surface mobility limited by scattering with acoustic phonons:

$$\mu_{AC, n} = \frac{BN.CVT}{E_{\perp} EN.CVT} + \frac{CN.CVT N TAU.CVT}{T_L E_{\perp} DN.CVT} \quad 3-182$$

$$\mu_{AC,p} = \frac{BP.CVT}{E_{\perp}} + \frac{CP.CVT N TAUP.CVT}{T_L E_{\perp} DP.CVT} \quad 3-183$$

where  $T_L$  is the temperature,  $E_{\perp}$  is the perpendicular electric field, and  $N$  is the total doping concentration. You can define the parameters BN.CVT, BP.CVT, CN.CVT, CP.CVT, DN.CVT, DP.CVT, TAUN.CVT, and TAUP.CVT in the MOBILITY statement (see Table 3-28 for their defaults).

The second component,  $\mu_{sr}$  is the surface roughness factor and is given by:

$$\mu_{sr,n} = \frac{DELN.CVT}{KN.CVT} E_{\perp} \quad 3-184$$

$$\mu_{sr,p} = \frac{DELP.CVT}{KP.CVT} E_{\perp} \quad 3-185$$

The KN.CVT, KP.CVT, DELN.CVT, and DELP.CVT parameters are user-definable in the MOBILITY statement (see Table 3-28 for their defaults).

The third mobility component,  $\mu_b$ , is the mobility limited by scattering with optical intervalley phonons. This component is given by:

$$\mu_{b,n} = MU0N.CVT \exp\left(\frac{-PCN.CVT}{N}\right) + \frac{\left[ MUMAXN.CVT \left(\frac{T_L}{300}\right)^{-GAMN.CVT} - MU0N.CVT \right]}{1 + \left(\frac{N}{CRN.CVT}\right) ALPHN.CVT} - \frac{MU1N.CVT}{1 + \left(\frac{CSN.CVT}{N}\right) BETAN.CVT} \quad 3-186$$

$$\mu_{b,p} = MU0P.CVT \exp\left(\frac{-PCP.CVT}{N}\right) + \frac{\left[ MUMAXP.CVT \left(\frac{T_L}{300}\right)^{-GAMP.CVT} - MU0P.CVT \right]}{1 + \left(\frac{N}{CRP.CVT}\right) ALPHP.CVT} - \frac{MU1P.CVT}{1 + \left(\frac{CSP.CVT}{N}\right) BETAP.CVT} \quad 3-187$$

Here,  $N$  is the total density of impurities and  $T_L$  is the temperature in degrees Kelvin.

| Table 3-28. User-Specifiable Parameters for Equations 3-182 to 3-187 |           |                     |        |
|--|-----------|---------------------|--------|
| Statement  | Parameter | Default             | Units  |
| MOBILITY   | BN.CVT    | $4.75 \times 10^7$  | cm/(s) |
| MOBILITY   | BP.CVT    | $9.925 \times 10^6$ | cm/(s) |
| MOBILITY   | CN.CVT    | $1.74 \times 10^5$  |        |

**Table 3-28. User-Specifiable Parameters for Equations 3-182 to 3-187**

| Statement | Parameter  | Default                 | Units                                     |
|-----------|------------|-------------------------|---|
| MOBILITY  | CP.CVT     | $8.842 \times 10^5$     |   |
| MOBILITY  | DN.CVT     | 0.333                   |   |
| MOBILITY  | DP.CVT     | 0.333                   |   |
| MOBILITY  | KN.CVT     | 2.0                     |   |
| MOBILITY  | KP.CVT     | 2.0                     |   |
| MOBILITY  | TAUN.CVT   | 0.125                   |   |
| MOBILITY  | TAUP.CVT   | 0.0317                  |   |
| MOBILITY  | GAMN.CVT   | 2.5                     |   |
| MOBILITY  | GAMP.CVT   | 2.2                     |   |
| MOBILITY  | MU0N.CVT   | 52.2                    | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | MU0P.CVT   | 44.9                    | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | MU1N.CVT   | 43.4                    | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | MU1P.CVT   | 29.0                    | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | MUMAXN.CVT | 1417.0                  | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | MUMAXP.CVT | 470.5                   | $\text{cm}^2 / (\text{V} \cdot \text{s})$ |
| MOBILITY  | CRN.CVT    | $9.68 \times 10^{16}$   | $\text{cm}^{-3}$                          |
| MOBILITY  | CRP.CVT    | $2.23 \times 10^{17}$   | $\text{cm}^{-3}$                          |
| MOBILITY  | CSN.CVT    | $3.43 \times 10^{20}$   | $\text{cm}^{-3}$                          |
| MOBILITY  | CSP.CVT    | $6.10 \times 10^{20}$   | $\text{cm}^{-3}$                          |
| MOBILITY  | ALPHN.CVT  | 0.680                   |   |
| MOBILITY  | ALPHP.CVT  | 0.71                    |   |
| MOBILITY  | BETAN.CVT  | 2.00                    |   |
| MOBILITY  | BETAP.CVT  | 2.00                    |   |
| MOBILITY  | PCN.CVT    | 0.0                     | $\text{cm}^{-3}$                          |
| MOBILITY  | PCP.CVT    | $9.23 \times 10^{16}$   | $\text{cm}^{-3}$                          |
| MOBILITY  | DELN.CVT   | $5.82 \times 10^{14}$   | $\text{V/s}$                              |
| MOBILITY  | DELP.CVT   | $2.0546 \times 10^{14}$ | $\text{V}^2/\text{s}$                     |

**Note:** The CVT model when activated will also, by default, apply the Parallel Electric Field Mobility Model which is described in the “Parallel Electric Field-Dependent Mobility” section on page 3-58. In this model, the low field mobility is supplied from the CVT model.

### Extended CVT Model

The CVT model already described has been successfully used in many device simulations. Lately, an improved version of this model has been proposed by Darwish et al. [17] where two modifications have been implemented. The first modification is the bulk mobility that is calculated using Klaassen’s model (see “Klaassen’s Unified Low Field Mobility Model” section on page 3-40) to take into account coulomb screening effects. The second modification is a new expression for surface roughness is used.

The new model for surface roughness replaces Equations 3-184 and 3-185 with:

$$\mu_{sr, n} = \frac{DELN.CVT}{E^{\gamma_{n\perp}}} \tag{3-188}$$

$$\mu_{sr, p} = \frac{DELP.CVT}{E^{\gamma_{p\perp}}} \tag{3-189}$$

where:

$$\gamma_n = AN.CVT + \frac{ALN.CVT \times N}{ETAN.CVT N_{TOT}} \tag{3-190}$$

$$\gamma_p = AP.CVT + \frac{ALP.CVT \times N}{ETAP.CVT N_{TOT}} \tag{3-191}$$

Here,  $N_{TOT}$  is the total doping density ( $N_D + N_A$ ) and  $N$  is the total carrier concentration ( $n+p$ ).

The Extended CVT Model has been implemented so that the two additional effects can be enabled independently. By setting both CVT and KLA parameters in the MODELS statement, the CVT model is enabled with the bulk impurity model of Klaassen and with the original surface roughness model of CVT. To enable the new surface roughness calculation from Equations 3-190 and 3-191, set the NEWCVT.N and NEWCVT.P parameters in the MOBILITY statement.

Table 3-29 shows the default parameters for the new equations.

| Table 3-29. Default parameters for the surface roughness components of new CVT model. |      |                        |       |
|---|------|------------------------|-------|
| Parameter   | Type | Default                | Units |
| AN.CVT  | Real | 2.58                   |       |
| AP.CVT  | Real | 2.18                   |       |
| ALN.CVT   | Real | $6.85 \times 10^{-21}$ |       |

| Parameter | Type | Default                | Units |
|-----------|------|------------------------|-------|
| ALP.CVT   | Real | $7.82 \times 10^{-21}$ |       |
| ETAN.CVT  | Real | 0.0767                 |       |
| ETAP.CVT  | Real | 0.123                  |       |

### Yamaguchi Model

The Yamaguchi Model [18] is selected by setting YAMAGUCHI in the MODELS statement. This model overrides any mobility model specifications other than the CVT model. The model consists of calculating the low field, doping dependent mobility. Surface degradation is then accounted for based upon the transverse electric field before including the parallel electric field dependence.

The low field part of the Yamaguchi Model is given as follows:

$$\mu_{n0} = \mathbf{MULN.YAMA} \left[ 1 + \frac{N_i}{\frac{N_i}{\mathbf{SN.YAMA}} + \mathbf{NREFP.YAMA}} \right]^{-\frac{1}{2}} \quad 3-192$$

$$\mu_{p0} = \mathbf{MULP.YAMA} \left[ 1 + \frac{N_i}{\frac{N_i}{\mathbf{SP.YAMA}} + \mathbf{NREFP.YAMA}} \right]^{-\frac{1}{2}} \quad 3-193$$

where  $N_i$  is the net impurity concentration. The equation parameters:  $\mathbf{MULN.YAMA}$ ,  $\mathbf{MULP.YAMA}$ ,  $\mathbf{SN.YAMA}$ ,  $\mathbf{SP.YAMA}$ ,  $\mathbf{NREFP.YAMA}$ , and  $\mathbf{NREFP.YAMA}$  are user-definable in the MOBILITY statement (see Table 3-30 for their defaults).

The transverse electric field dependence is accounted for as follows:

$$\mu_{s,n} = \mu_{n0} (1 + \mathbf{ASN.YAMA} E_{\perp})^{-\frac{1}{2}} \quad 3-194$$

$$\mu_{s,p} = \mu_{p0} (1 + \mathbf{ASP.YAMA} E_{\perp})^{-\frac{1}{2}} \quad 3-195$$

where  $E_{\perp}$  is the perpendicular electric field and the equation parameters,  $\mathbf{ASN.YAMA}$  and  $\mathbf{ASP.YAMA}$ , are user-definable in the MOBILITY statement (see Table 3-30 for their defaults).

The final calculation of mobility takes into account the parallel electric field dependence which takes the form:

$$\mu_n = \mu_{s,n} \left[ 1 + \left( \frac{\mu_{s,n} E}{\mathbf{ULN.YAMA}} \right)^2 \left( \mathbf{GN.YAMA} + \frac{\mu_{s,n} E}{\mathbf{ULN.YAMA}} \right)^{-1} + \left( \frac{\mu_{s,n} E}{\mathbf{VSN.YAMA}} \right)^2 \right]^{-\frac{1}{2}} \quad 3-196$$

$$\mu_p = \mu_{s,p} \left[ 1 + \left( \frac{\mu_{s,p} E}{ULP.YAMA} \right)^2 \left( GP.YAMA + \frac{\mu_{s,p} E}{ULP.YAMA} \right)^{-1} + \left( \frac{\mu_{s,p} E}{VSP.YAMA} \right)^2 \right]^{-\frac{1}{2}} \quad 3-197$$

where E is the parallel electric field and the equation parameters: ULN.YAMA, ULP.YAMA, VSN.YAMA, VSP.YAMA, GN.YAMA, and GP.YAMA are user-definable in the MOBILITY statement (see Table 3-30 for their defaults).

| Table 3-30. User-Specifiable Parameters for Equations 3-192 to 3-197 |            |                       |                         |
|--|------------|-----------------------|-------------------------|
| Statement  | Parameter  | Default               | Units                   |
| MOBILITY   | SN.YAMA    | 350.0                 |                         |
| MOBILITY   | SP.YAMA    | 81.0                  |                         |
| MOBILITY   | NREFP.YAMA | 3.0×10 <sup>16</sup>  | cm <sup>-3</sup>        |
| MOBILITY   | NREFP.YAMA | 4.0×10 <sup>16</sup>  | cm <sup>-3</sup>        |
| MOBILITY   | MULN.YAMA  | 1400.0                | cm <sup>2</sup> / (V·s) |
| MOBILITY   | MULP.YAMA  | 480.0                 | cm <sup>2</sup> / (V·s) |
| MOBILITY   | ASN.YAMA   | 1.54×10 <sup>-5</sup> | cm/V                    |
| MOBILITY   | ASP.YAMA   | 5.35×10 <sup>-5</sup> | cm/V                    |
| MOBILITY   | VSN.YAMA   | 1.036×10 <sup>7</sup> | cm/s                    |
| MOBILITY   | VSP.YAMA   | 1.2×10 <sup>7</sup>   | cm/s                    |
| MOBILITY   | ULN.YAMA   | 4.9×10 <sup>6</sup>   | cm/s                    |
| MOBILITY   | ULP.YAMA   | 2.928×10 <sup>6</sup> | cm/s                    |
| MOBILITY   | GN.YAMA    | 8.8                   |                         |
| MOBILITY   | GP.YAMA    | 1.6                   |                         |

### The Tasch Model

S-PISCES includes an improved local field-dependent mobility model. This model, which was originally derived and published by Tasch et. al [44,46] has been designed explicitly for MOSFETs. It defines the mobility as a function of the perpendicular and parallel electric fields, the interface charge, the lattice temperature and the doping concentration. To activate this model, is activated use the TASCH parameter on the MODELS statement. This mobility model is given by the following expressions:

$$\mu_n = \Gamma_n + (E_{perp} - E_0) \frac{d\Gamma_n}{dE_{perp}} \quad 3-198$$

$$\mu_p = \Gamma_p + (E_{perp} - E_0) \frac{d\Gamma_p}{dE_{perp}} \quad 3-199$$



where  $E_{perp}$  is the transverse electric field and  $E_0$  is the transverse electric field at the edge of the inversion layer. The functions  $\Gamma_{n,p}$  are defined as:

$$\Gamma_n = \frac{\mu_{eff,n}}{\left(1 + \left(\frac{\mu_{eff,n} E_{\parallel}}{\mathbf{VSATN}}\right)^{\mathbf{BETAN}}\right)^{1/\mathbf{BETAN}}} \quad 3-200$$

$$\Gamma_p = \frac{\mu_{eff,p}}{\left(1 + \left(\frac{\mu_{eff,p} E_{\parallel}}{\mathbf{VSATP}}\right)^{\mathbf{BETAP}}\right)^{1/\mathbf{BETAP}}} \quad 3-201$$

The carrier mobilities  $\mu_{eff,n}$  and  $\mu_{eff,p}$  are defined by three components  $\mu_{ph}$ ,  $\mu_{sr}$  and  $\mu_c$  which are combined by Mathiessen's rule according to:

$$\mu_{eff} = \left[ \frac{1}{\mu_{ph}} + \frac{1}{\mu_{sr}} + \frac{1}{\mu_c} \right]^{-1} \quad 3-202$$

The term  $\mu_{ph}$  takes account of the degradation in mobility due to acoustic phonon scattering through the expressions:

$$\mu_{ph,n}^{-1} = \left( \mathbf{MUBN.TAS} \left( \frac{T_L}{300} \right)^{-\mathbf{TMUBN.TAS}} \right)^{-1} + \left( Z_n / \mathbf{DN.TAS} Y_n \left( \frac{T_L}{300} \right)^{1/2} \right)^{-1} \quad 3-203$$

$$\mu_{ph,p}^{-1} = \left( \mathbf{MUBP.TAS} \left( \frac{T_L}{300} \right)^{-\mathbf{TMUBP.TAS}} \right)^{-1} + \left( Z_p / \mathbf{DP.TAS} Y_p \left( \frac{T_L}{300} \right)^{1/2} \right)^{-1} \quad 3-204$$

The function,  $Z_{n,p}$ , is defined as:

$$Z_n = \mathbf{Z11N.TAS} \left( \frac{T_L}{300} \right) E_{eff,n}^{-1} + \mathbf{Z22N.TAS} E_{eff,n}^{-\frac{1}{3}} \quad 3-205$$

$$Z_p = \mathbf{Z11P.TAS} \left( \frac{T_L}{300} \right) E_{eff,p}^{-1} + \mathbf{Z22P.TAS} E_{eff,p}^{-\frac{1}{3}} \quad 3-206$$

where:

$$E_{eff,n} = \frac{(E_{perp} + (\mathbf{RN.TAS} - 1) \cdot E_0)}{\mathbf{RN.TAS}} \quad 3-207$$

$$E_{eff,p} = \frac{(E_{perp} + (\mathbf{RP.TAS} - 1) \cdot E_0)}{\mathbf{RP.TAS}} \quad 3-208$$

Also, the function  $Y_{n,p}$  is defined as:

$$Y_n = \mathbf{P1N.TAS} \left( \frac{T_L}{300} \right)^{\mathbf{B1N.TAS}} + \mathbf{P2N.TAS} n + \mathbf{B2N.TAS} \left( \frac{T_L}{300} \right)^{-1} N_f \quad 3-209$$

$$Y_p = P1P.TAS \left(\frac{T_L}{300}\right)^{B1P.TAS} + P2P.TAS_p + B2P.TAS \left(\frac{T_L}{300}\right)^{-1} N_f \quad 3-210$$

Mobility degradation due to surface roughness is accounted for by the term  $\mu_{sr}$  which is calculated according to:

$$\mu_{sr,n} = \left(\frac{ESRN.TAS}{E_{eff,n}}\right)^{BETAN.TAS} \quad 3-211$$

$$\mu_{sr,p} = \left(\frac{ESRP.TAS}{E_{eff,p}}\right)^{BETAP.TAS} \quad 3-212$$

The final term,  $\mu_C$ , models Coulombic scattering with the expressions:

$$\mu_{C,n} = \frac{N2N.TAS \cdot \left(\frac{T_L}{300}\right)^{1.5}}{N_A \ln(1 + \gamma_{BH,n}) - \frac{\gamma_{BH,n}}{(1 + \gamma_{BH,n})}} \quad 3-213$$

$$\mu_{C,p} = \frac{N2P.TAS \cdot \left(\frac{T_L}{300}\right)^{1.5}}{N_D \ln(1 + \gamma_{BH,p}) - \frac{\gamma_{BH,p}}{(1 + \gamma_{BH,p})}} \quad 3-214$$

Here:

$$\gamma_{BH,n} = \frac{N1N.TAS}{n} \cdot \left(\frac{T_L}{300}\right)^{ALPHAN.TAS} \quad 3-215$$

$$\gamma_{BH,p} = \frac{N1P.TAS}{p} \cdot \left(\frac{T_L}{300}\right)^{ALPHAP.TAS} \quad 3-216$$

$T_L$  is the lattice temperature in degrees Kelvin,  $N_f$  is the fixed interface charge at the gate dielectric-silicon interface ( $\text{cm}^{-2}$ ),  $N_A$  is the channel acceptor doping concentration in  $\text{cm}^{-3}$ ,  $N_D$  is the channel donor doping concentration in  $\text{cm}^{-3}$ ,  $n$  and  $p$  are the electron and hole concentrations per unit volume in the inversion layer ( $\text{cm}^{-3}$ ). The default parameters within each equation is defined in the MOBILITY statement. The default parameters are shown in Table 3-30.

| Table 3-31. Parameters for Equations 3-198 through 3-216 |           |         |       |
|--|-----------|---------|-------|
| Statement  | Parameter | Default | Units |
| MOBILITY   | RN.TAS    | 2       |       |
| MOBILITY   | RP.TAS    | 3       |       |
| MOBILITY   | BETAN     | 2       |       |
| MOBILITY   | BETAP     | 1       |       |

Table 3-31. Parameters for Equations 3-198 through 3-216

| Statement | Parameter  | Default               | Units |
|-----------|------------|-----------------------|-------|
| MOBILITY  | MUBN.TAS   | 1150                  |       |
| MOBILITY  | MUBP.TAS   | 270                   |       |
| MOBILITY  | TMUBN.TAS  | 2.5                   |       |
| MOBILITY  | TMUBP.TAS  | 1.4                   |       |
| MOBILITY  | DN.TAS     | $3.2 \times 10^{-9}$  |       |
| MOBILITY  | DP.TAS     | $2.35 \times 10^{-9}$ |       |
| MOBILITY  | P1N.TAS    | 0.09                  |       |
| MOBILITY  | P1P.TAS    | 0.334                 |       |
| MOBILITY  | B1N.TAS    | 1.75                  |       |
| MOBILITY  | B1P.TAS    | 1.5                   |       |
| MOBILITY  | P2N.TAS    | $4.53 \times 10^{-8}$ |       |
| MOBILITY  | PEP.TAS    | $3.14 \times 10^{-7}$ |       |
| MOBILITY  | B2N.TAS    | -0.25                 |       |
| MOBILITY  | B2P.TAS    | -0.3                  |       |
| MOBILITY  | Z11N.TAS   | 0.0388                |       |
| MOBILITY  | Z11P.TAS   | 0.039                 |       |
| MOBILITY  | Z22N.TAS   | $1.73 \times 10^{-5}$ |       |
| MOBILITY  | Z22P.TAS   | $1.51 \times 10^{-5}$ |       |
| MOBILITY  | ESRN.TAS   | $2.449 \times 10^7$   |       |
| MOBILITY  | ESRP.TAS   | $1.0 \times 10^8$     |       |
| MOBILITY  | BETAN.TAS  | 2                     |       |
| MOBILITY  | BETAP.TAS  | 1                     |       |
| MOBILITY  | N2N.TAS    | $1.1 \times 10^{21}$  |       |
| MOBILITY  | N2P.TAS    | $1.4 \times 10^{18}$  |       |
| MOBILITY  | N1N.TAS    | $2.0 \times 10^{19}$  |       |
| MOBILITY  | N1P.TAS    | $8.4 \times 10^{16}$  |       |
| MOBILITY  | ALPHAN.TAS | 2                     |       |
| MOBILITY  | ALPHAP.TAS | 3.4                   |       |

## Perpendicular Electric Field-Dependent Mobility

### The Watt Model

A surface mobility model derived by J.T.Watt [19] is available in ATLAS. This mobility model is activated when the parameter SURFMOB is specified on the MODELS statement. The default model parameters are tuned to describe the measured mobilities in silicon at 300K. You can modify model parameters by using the MOBILITY statement.

The Watt model takes into consideration the following primary scattering mechanisms in the inversion layer:

1. Phonon scattering which results primarily from the interaction between two-dimensional inversion layer carriers and bulk phonons.
2. Surface roughness scattering caused by the interaction between inversion layer carriers and deviations from ideal planarity at the interface.
3. Charged impurity scattering caused by the interaction between inversion layer carriers and ions located in the oxide, at the interface, or in the bulk

The phonon and surface roughness components are functions of effective electric field. The charged impurity component is a function of the channel doping density.

The effective mobilities for electrons and holes are given by Equations 3-217 and 3-218.

$$\begin{aligned} \frac{1}{\mu_{eff,n}} = & \frac{1}{MREF1N.WATT} \left( \frac{1}{E_{eff,n}} \right)^{AL1N.WATT} & 3-217 \\ & + \frac{1}{MREF2N.WATT} \left( \frac{1}{E_{eff,n}} \right)^{AL2N.WATT} \\ & + \frac{1}{MREF3N.WATT} \left( \frac{1}{N_B} \right)^{-1} \left( \frac{1}{N_i} \right)^{AL3N.WATT} \end{aligned}$$

$$\begin{aligned} \frac{1}{\mu_{eff,p}} = & \frac{1}{MREF1P.WATT} \left( \frac{1}{E_{eff,p}} \right)^{AL1P.WATT} & 3-218 \\ & + \frac{1}{MREF2P.WATT} \left( \frac{1}{E_{eff,p}} \right)^{AL2P.WATT} \\ & + \frac{1}{MREF3P.WATT} \left( \frac{1}{N_B} \right)^{-1} \left( \frac{1}{N_i} \right)^{AL3N.WATT} \end{aligned}$$

Here,  $N_B$  is the surface trapped charge density,  $N_i$  is the inversion layer charge density and  $E_{eff}$  is the effective electric field given by:

$$E_{eff,n} = E_{\perp} + ETAN.WATT(E_0 - E_{\perp}) \quad 3-219$$

$$E_{eff,p} = E_{\perp} + ETAP.WATT(E_0 - E_{\perp}) \quad 3-220$$

Here,  $E_{\perp}$  is the electric field perpendicular to the current flow and  $E_0$  is the perpendicular electric field at the insulator-semiconductor interface. The equation parameters and their defaults are listed in Table 3-32.

The terms on the right side of Equations 3-217 and 3-218, describe (in order) the three scattering mechanisms previously discussed. Each component contains two constants: a pre-exponential factor and the exponent of the principal independent parameter. The charge impurity scattering component is assumed to be inversely proportional to doping density.

The expression for effective mobility contains a number of normalizing constants. These normalizing constants are included to allow easy comparison of constants. The first two terms in this mobility model are dependent on  $E_{eff}$  and represent the universal mobility-field relationship. The third term accounts for deviation from the universal relationship resulting from charged impurity scattering.

| <b>Table 3-32. User-Specifiable Parameters for Equations 3-217 - 3-220</b> |                  |                |                        |
|--|------------------|----------------|------------------------|
| <b>Statement</b>   | <b>Parameter</b> | <b>Default</b> | <b>Units</b>           |
| MOBILITY   | ETAN.WATT        | 0.50           |                        |
| MOBILITY   | ETAP.WATT        | 0.33           |                        |
| MOBILITY   | MREF1N.WATT      | 481.0          | cm <sup>2</sup> /(V·s) |
| MOBILITY   | MREF1P.WATT      | 92.8           | cm <sup>2</sup> /(V·s) |
| MOBILITY   | MREF2N.WATT      | 591.0          | cm <sup>2</sup> /(V·s) |
| MOBILITY   | MREF2P.WATT      | 124.0          | cm <sup>2</sup> /(V·s) |
| MOBILITY   | MREF3N.WATT      | 1270.0         | cm <sup>2</sup> /(V·s) |
| MOBILITY   | MREF3P.WATT      | 534.0          | cm <sup>2</sup> /(V·s) |
| MOBILITY   | AL1N.WATT        | -0.16          |                        |
| MOBILITY   | AL1P.WATT        | -0.296         |                        |
| MOBILITY   | AL2N.WATT        | -2.17          |                        |
| MOBILITY   | AL2P.WATT        | -1.62          |                        |
| MOBILITY   | AL3N.WATT        | 1.07           |                        |
| MOBILITY   | AL3P.WATT        | 1.02           |                        |

### Modifications to the Watt's Model

By default the Watt mobility model is a surface model that applies, only to those grid points on the silicon/oxide interface. A modification has been added that now applies the Watt model to points below the interface. This extension to the Watt model is enabled using the MOD.WATT.N and MOD.WATT.P parameters of the MOBILITY statement.

The distance over which the model is applied can be controlled by using the YMAXN.WATT and the YMAXP.WATT parameters of the MOBILITY statement. These parameters specify the maximum value of the y-coordinate over which the model is applied below the interface for electrons and holes respectively.

The XMINN.WATT, XMINP.WATT, XMAXN.WATT and XMAXP.WATT of the MOBILITY statement can be used to limit the range of the model in the x-direction, to prevent the model from applying to the source and drain regions. The MIN.SURF parameter of the MODELS statement can also be used for this purpose. When enabled, the MIN.SURF parameter will ensure that the Watt model will only apply to minority regions.

The logical parameters `EXP.WATT.N` and `EXP.WATT.P` of the `MOBILITY` statement can also be used to enable an additional modification to the Watt model. When these parameters are enabled the effective normal electric field becomes a function of the depth beneath the silicon/oxide interface according to:

$$E_{\perp,n} = E_y \exp \frac{-(y - y_{int})}{\mathbf{YCHARN.WATT}} \tag{3-221}$$

$$E_{\perp,p} = E_y \exp \frac{-(y - y_{int})}{\mathbf{YCHARP.WATT}} \tag{3-222}$$

where  $E_{\perp}$  is the perpendicular electric field,  $E_y$  is the perpendicular electric field at the interface,  $y$  is the local  $y$ -coordinate and  $y_{int}$  is the  $y$ -coordinate of the silicon/oxide interface. The `YCHARN.WATT` and `YCHARP.WATT` parameters are user-definable in the `MOBILITY` statement.

| Table 3-33. User-Specifiable Parameters for Equations 3-194 and 3-195 |             |                       |         |
|---|-------------|-----------------------|---------|
| Statement   | Parameter   | Default               | Units   |
| MOBILITY  | XMINN.WATT  | -1.0x10 <sup>32</sup> | microns |
| MOBILITY  | XMAXN.WATT  | 1.0x10 <sup>32</sup>  | microns |
| MOBILITY  | YMAXN.WATT  | -1.0x10 <sup>32</sup> | microns |
| MOBILITY  | XMINP.WATT  | -1.0x10 <sup>32</sup> | microns |
| MOBILITY  | XMAXP.WATT  | 1.0x10 <sup>32</sup>  | microns |
| MOBILITY  | YMAXP.WATT  | -1.0x10 <sup>32</sup> | microns |
| MOBILITY  | YCHARN.WATT | 1.0x10 <sup>32</sup>  | microns |
| MOBILITY  | YCHARP.WATT | 1.0x10 <sup>32</sup>  | microns |

### Shirahata's Mobility Model

The Shirahata Mobility Model [20] is a general purpose MOS mobility model that takes into account screening effects in the inversion layer as well as improved perpendicular field dependence for thin gate oxides. In the original paper, the authors present the model as a combination of portions of Klaassen's model for low field mobility contributions and an empirically fit expression for the perpendicular field dependent mobility in the inversion layer. In this implementation, for any given location the lesser of the low field mobility and the mobility due to the Shirahata Mobility Model is used. If the Klaassen Low-Field Model is used with the Shirahata model, the lattice scattering term in the Klaassen model is omitted.

The Shirahata Mobility Model is enabled by the `SHI` parameter of the `MODELS` statement or can be enabled individually for electrons and holes using the `SHI.N` and `SHI.P` parameters of the `MOBILITY` statement.

The Shirahata models for electrons and holes are given by:

$$\mu_n = \frac{\mathbf{MU0N.SHI} \left(\frac{T_L}{300}\right)^{-\mathbf{THETAN.SHI}}}{\left[1 + \frac{|E_{\perp}|}{\mathbf{E1N.SHI}}\right]^{\mathbf{P1N.SHI}} + \left[\frac{|E_{\perp}|}{\mathbf{E2N.SHI}}\right]^{\mathbf{P2N.SHI}}} \tag{3-223}$$

$$\mu_p = \frac{MU0P.SHI \left(\frac{T_L}{300}\right)^{-THETAP.SHI}}{\left[1 + \frac{|E_{\perp}|}{E1P.SHI}\right]^{P1P.SHI} + \left[\frac{|E_{\perp}|}{E2P.SHI}\right]^{P2P.SHI}}$$

3-224

where  $E_{\perp}$  is the perpendicular electric and the equation parameters: MU0N.SHI, MU0P.SHI, E1N.SHI, E1P.SHI, E2N.SHI, E2P.SHI, P1N.SHI, P1P.SHI, P2N.SHI, P2P.SHI, THETAN.SHI and THETAP.SHI are user-definable in the MOBILITY statement (see Table 3-34 for their defaults).

| Statement | Parameter  | Default              | Units                   |
|-----------|------------|----------------------|-------------------------|
| MOBILITY  | MU0N.SHI   | 1430.0               | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MU0P.SHI   | 500.0                | cm <sup>2</sup> / (V·s) |
| MOBILITY  | E1N.SHI    | 6.3x10 <sup>3</sup>  | V/cm                    |
| MOBILITY  | E1P.SHI    | 8.0x10 <sup>3</sup>  | V/cm                    |
| MOBILITY  | E2N.SHI    | 0.77x10 <sup>6</sup> | V/cm                    |
| MOBILITY  | E2P.SHI    | 3.9x10 <sup>5</sup>  | V/cm                    |
| MOBILITY  | P1N.SHI    | 0.28                 |                         |
| MOBILITY  | P1P.SHI    | 0.3                  |                         |
| MOBILITY  | P2N.SHI    | 2.9                  |                         |
| MOBILITY  | P2P.SHI    | 1.0                  |                         |
| MOBILITY  | THETAN.SHI | 2.285                |                         |
| MOBILITY  | THETAP.SHI | 2.247                |                         |

**Note:** If the maximum low field mobility has been user-defined, then it's important to also define this value inside the Shirahata model with the MU0N.SHI and MU0P.SHI parameters in the MOBILITY statement.

## Parallel Electric Field-Dependent Mobility

As carriers are accelerated in an electric field their velocity will begin to saturate when the electric field magnitude becomes significant. This effect has to be accounted for by a reduction of the effective mobility since the magnitude of the drift velocity is the product of the mobility and the electric field component in the direction of the current flow. The following Caughey and Thomas Expression [11] is used to implement a field-dependent mobility. This provides a smooth transition between low-field and high field behavior where:

$$\mu_n(E) = \mu_{n0} \left[ \frac{1}{1 + \left( \frac{\mu_{n0} E}{VSATN} \right)^{BETAN}} \right]^{\frac{1}{BETAN}} \quad 3-225$$

$$\mu_p(E) = \mu_{p0} \left[ \frac{1}{1 + \left( \frac{\mu_{p0} E}{VSATP} \right)^{BETAP}} \right]^{\frac{1}{BETAP}} \quad 3-226$$

Here,  $E$  is the parallel electric field and  $\mu_{n0}$  and  $\mu_{p0}$  are the low field electron and hole mobilities respectively. The low field mobilities are either set explicitly in the `MOBILITY` statement or calculated by one of the low field mobility models. The `BETAN` and `BETAP` parameters are user-definable in the `MOBILITY` statement (see Table 3-35 for their defaults).

The saturation velocities are calculated by default from the temperature-dependent models [43]:

$$VSATN = \frac{ALPHAN.FLD}{1 + THETAN.FLD \exp\left(\frac{T_L}{TNOMN.FLD}\right)} \quad 3-227$$

$$VSATP = \frac{ALPHAP.FLD}{1 + THETAP.FLD \exp\left(\frac{T_L}{TNOMP.FLD}\right)} \quad 3-228$$

but can be set to constant values on the `MOBILITY` statement using the `VSATN` and `VSATP` parameters. In this case, no temperature dependence is implemented. Specifying the `FLDMOB` parameter on the `MODELS` statement invokes the field-dependent mobility. `FLDMOB` should always be specified unless one of the inversion layer mobility models (which incorporate their own dependence on the parallel field) are specified.

You can invoke a `C-INTERPRETER` function for the saturation velocities. The `F.VSATN` and `F.VSATP` parameters in the `MATERIAL` statement can be set to provide the filenames of two text files containing the particular functions. These functions allow you to include the temperature dependence. See Appendix A: "C-Interpreter Functions" for more details.



| Table 3-35. User-Definable Parameters in the Field-Dependent Mobility Model |            |                   |       |
|---|------------|-------------------|-------|
| Statement   | Parameter  | Default           | Units |
| MOBILITY  | BETAN      | 2.0               |       |
| MOBILITY  | BETAP      | 1.0               |       |
| MOBILITY  | VSATN      |                   | cm/s  |
| MOBILITY  | VSATP      |                   | cm/s  |
| MOBILITY  | ALPHAN.FLD | $2.4 \times 10^7$ | cm/s  |
| MOBILITY  | ALPHAP.FLD | $2.4 \times 10^7$ | cm/s  |
| MOBILITY  | THETAN.FLD | 0.8               |       |
| MOBILITY  | THETAP.FLD | 0.8               |       |
| MOBILITY  | TNOMN.FLD  | 600.0             | K     |
| MOBILITY  | TNOMP.FLD  | 600.0             | K     |

**Note:** Equation 3-228, which was derived for the drift-diffusion approximation, ensures that velocity overshoot cannot occur. To model velocity overshoot in silicon, apply the Energy Balance Transport Model. This model follows the above implementation but with the electric field term replaced by a new “effective” field calculated from the carrier temperature see the following section for more details.

**Note:** BLAZE includes a different field dependent mobility model that does simulate velocity overshoot in GaAs. See Chapter 5: “Blaze: Compound Material 2D Simulator” for more information.

### Carrier Temperature Dependent Mobility

The Energy Balance Transport Model allows the carrier mobility to be related to the carrier energy. This has been achieved through the homogeneous steady state energy balance relationship that pertains in the saturated velocity limit. This allows an effective electric field to be calculated, which is the uniform electric field value that causes the carriers in a homogeneous sample to attain the same temperature as at the node point in the device. The effective electric fields,  $E_{eff,n}$  and  $E_{eff,p}$ , are calculated by solving the equations:

$$q\mu_n(E_{eff,n})E_{eff,n}^2 = \frac{3}{2} \frac{k(T_n - T_L)}{TAUMOB.EL} \quad 3-229$$

$$q\mu_p(E_{eff,p})E_{eff,p}^2 = \frac{3}{2} \frac{k(T_p - T_L)}{TAUMOB.HO} \quad 3-230$$

for  $E_{eff,n}$  and  $E_{eff,p}$ . These equations are derived from the energy balance equations by stripping out all spatially varying terms. The effective electric fields are then introduced into the relevant field

dependent mobility model. The TAUMOB.EL and TAUMOB.HO parameters can be set on the MODELS statement and have the default values shown in Table 3-36.

**Note:** The TAUMOB.EL and TAUMOB.HO parameters are distinct from the energy balance relaxation time parameters: TAUREL.EL and TAUREL.HO. But, if the E.TAUR.VAR and H.TAUR.VAR parameters are set on the MODELS statement, then TAUREL.EL and TAUREL.HO are used in place of TAUMOB.EL and TAUMOB.HO.

| Table 3-36. User-Specifiable Parameters for Equations 3-229 and 3-230 |           |                       |       |
|---|-----------|-----------------------|-------|
| Statement   | Parameter | Default               | Units |
| MODELS  | TAUMOB.EL | $2.5 \times 10^{-13}$ | s     |
| MODELS  | TAUMOB.HO | $2.5 \times 10^{-13}$ | s     |

Four different models have been implemented into the ATLAS Energy Balance Transport Model which can be chosen by the parameter EVSATMOD on the MODELS statement. These models shall be described next.

Setting EVSATMOD=0 implements, the default model for silicon based upon the Caughey-Thomas field-dependent mobility model in Equation 3-225. The resultant relationship between the carrier mobility and the carrier temperature is in the forms:

$$\mu_n = \frac{\mu_{n0}}{(1 + X_n^{BETAN})^{BETAN}} \tag{3-231}$$

$$\mu_p = \frac{\mu_{p0}}{(1 + X_p^{BETAP})^{BETAP}} \tag{3-232}$$

$$X_n^{BETAN} = \frac{\frac{1}{2}(\alpha_n^{BETAN}(T_n - T_L)^{BETAN} + \sqrt{\alpha_n^{2BETAN}(T_n - T_L)^{2BETAN} - 4\alpha_n^{BETAN}(T_n - T_L)^{BETAN}})}{1} \tag{3-233}$$

$$X_p^{BETAP} = \frac{\frac{1}{2}(\alpha_p^{BETAP}(T_p - T_L)^{BETAP} + \sqrt{\alpha_p^{2BETAP}(T_p - T_L)^{2BETAP} - 4\alpha_p^{BETAP}(T_p - T_L)^{BETAP}})}{1} \tag{3-234}$$

$$\alpha_n = \frac{3}{2} \frac{k_B \mu_{n0}}{q VSATN^2 TAUREL \bullet EL} \tag{3-235}$$

$$\alpha_p = \frac{3}{2} \frac{k_B \mu_{p0}}{q \text{VSATP}^2 \text{TAUREL} \cdot \text{HO}} \quad 3-236$$

where  $\mu_{n0}$  and  $\mu_{p0}$  are the low field carrier mobilities and VSATN and VSATP are the saturated velocities for electrons and holes. The VSATN, VSATP, BETAN, and BETAP parameters are user-definable in the MOBILITY statement. The terms, TAUREL.EL and TAUREL.HO, are the energy relaxation times for electrons and holes and can be defined in the MATERIAL statement.

Setting EVSATMOD=0 with the additional parameter, MOBTEM.SIMPL, allows you to apply a simplified form of the above model. This form is:

$$\mu_n = \frac{\mu_{n0}}{\sqrt{1 + \alpha_n^2 (T_n - T_L)^2}} \quad 3-237$$

$$\mu_p = \frac{\mu_{p0}}{\sqrt{1 + \alpha_p^2 (T_p - T_L)^2}} \quad 3-238$$

where  $\mu_{n0}$  and  $\mu_{p0}$  are again the low field carrier mobilities and  $\alpha_{n,p}$  are as defined above.

Setting EVSATMOD=1 implements the GaAs carrier temperature dependent mobility model. See Chapter 5: “Blaze: Compound Material 2D Simulator” for more information about this model.

Setting EVSATMOD=2 will apply the simple velocity limiting model based upon the electric field. In other words, the temperature dependent mobility is turned off and the standard electric field based mobility model is applied.

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**Note:** If the YAMAGUCHI or TASCH mobility models are chosen in the MODEL statement, then no energy dependence is applied. No energy dependence is included in any perpendicular electric field model, such as SHIRAHATA or SURFMOB.

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**Table 3-37. User-Specifiable Parameters for Equations 3-231– 3-238**

| Statement | Parameter | Units                   |
|-----------|-----------|-------------------------|
| MOBILITY  | MUN       | cm <sup>2</sup> / (V·s) |
| MOBILITY  | MUP       | cm <sup>2</sup> / (V·s) |
| MATERIAL  | VSATN     | cm/s                    |
| MATERIAL  | VSATP     | cm/s                    |

### 3.6.2: Mobility Model Summary

Tables 3-3-38 and 3-3-39 shows a brief description of the mobility models.

| Model                                   | Syntax    | Notes   |
|---|-----------|---|
| Concentration Dependent                 | CONMOB    | Lookup table valid at 300K for Si and GaAs only. Uses simple power law temperature dependence.  |
| Concentration and Temperature Dependent | ANALYTIC  | Caughey-Thomas formula. Tuned for 77-450K.  |
| Arora's Model                           | ARORA     | Alternative to ANALYTIC for Si.   |
| Carrier-Carrier Scattering              | CCSMOB    | Dorkel-Leturq Model. Includes n, N and T dependence. Important when carrier concentration is high (e.g., forward bias power devices). |
| Parallel Electric Field Dependence      | FLDMOB    | Si and GaAs models. Required to model any type of velocity saturation effect.   |
| Tasch Model                             | TASCH     | Includes transverse field dependence. Only for planar devices. Needs very fine grid.  |
| Watt Model                              | WATT      | Transverse field model applied to surface nodes only.   |
| Klaassen Model                          | KLA       | Includes N, T, and n dependence. Applies separate mobility to majority and minority carriers. Recommended for bipolar devices         |
| Shirahata Model                         | SHI       | Includes N, $E_{\perp}$ . An alternative surface mobility model that can be combined with KLA.  |
| Modified Watt                           | MOD.WATT  | Extension of WATT model to non-surface nodes. Applies constant $E_{\perp}$ effects. Best model for planar MOS devices                 |
| Lombardi (CVT) Model                    | CVT       | Complete model including N, T, E// and $E_{\perp}$ effects. Good for non-planar devices.  |
| Yamaguchi Model                         | YAMAGUCHI | Includes N, E// and $E_{\perp}$ effects. Only for 300K.   |

|                | CONMOB | FLDMOB          | TFLDMB2         | YAMAGUCHI | CVT | ARORA | ANALYTIC | CCSMOB | SURFACE | LATTICE H | E.BALANCE |
|----------------|--------|-----------------|-----------------|-----------|-----|-------|----------|--------|---------|-----------|-----------|
| CONMOB [CM]    | —      | OK              | OK              | YA        | CV  | AR    | AN       | CC     | OK      | OK        | OK        |
| FLDMOB [FM]    | OK     | —               | TF <sup>1</sup> | YA        | CV  | OK    | OK       | OK     | OK      | OK        | OK        |
| TFLDMB2 [TF]   | OK     | TF <sup>1</sup> | —               | YA        | CV  | OK    | OK       | TF     | TF      | OK        | OK        |
| YAMAGUCHI [YA] | YA     | YA              | YA              | —         | CV  | YA    | YA       | YA     | YA      | NO        | NO        |
| CVT [CV]       | CV     | CV              | CV              | CV        | —   | CV    | CV       | CV     | CV      | OK        | OK        |
| ARORA [AR]     | AR     | OK              | OK              | YA        | CV  | —     | AR       | CC     | OK      | OK        | OK        |
| ANALYTIC [AN]  | AN     | OK              | OK              | YA        | CV  |       | —        | CC     | OK      | OK        | OK        |
| CCSMOB [CC]    | CC     | OK              | TF              | YA        | CV  | CC    | CC       | —      | OK      | OK        | OK        |
| SURFMOB [SF]   | OK     | OK              | TF              | YA        | CV  | OK    | OK       | OK     | —       | OK        | OK        |
| LATTICE H [LH] | OK     | OK              | OK              | NO        | OK  | OK    | OK       | OK     | OK      | —         | OK        |
| E.BALANCE [EB] | OK     | OK              | OK              | NO        | OK  | OK    | OK       | OK     | OK      | OK        | 2         |

Table 3-39. Mobility Models Summary

|  | CONMOB | FLDMOB | TFLDMB2 | YAMAGUCHI | CVT | ARORA | ANALYTIC | CCSMOB | SURFACE | LATTICE H | E.BALANCE |
|--|--------|--------|---------|-----------|-----|-------|----------|--------|---------|-----------|-----------|
|--|--------|--------|---------|-----------|-----|-------|----------|--------|---------|-----------|-----------|

**Key to Table Entries:**

MODEL ABBREVIATION = The model that supersedes when a combination is specified. In some cases, but not all, a warning message is issued when a model is ignored.

OK = This combination is allowed.

NO = This combination isn't allowed.

**NOTES:**

1. Uses internal model similar to FLDMOB
2. When models including a parallel electric field dependence are used with energy balance the electric field term is replaced by a function of carrier temperature.

**3.6.3: Carrier Generation-Recombination Models**

Carrier generation-recombination is the process through which the semiconductor material attempts to return to equilibrium after being disturbed from it. If we consider a homogeneously doped semiconductor with carrier concentrations  $n$  and  $p$  to the equilibrium concentrations  $n_0$  and  $p_0$  then at equilibrium a steady state balance exists according to:

$$n_0 p_0 = n_i^2 \quad 3-239$$

Semiconductors, however, are under continual excitation whereby  $n$  and  $p$  are disturbed from their equilibrium states:  $n_0$  and  $p_0$ . For instance, light shining on the surface of a p type semiconductor causes generation of electron-hole pairs, disturbing greatly the minority carrier concentration. A net recombination results which attempts to return the semiconductor to equilibrium. The processes responsible for generation-recombination are known to fall into six main categories:

- phonon transitions
- photon transitions
- Auger transitions
- surface recombination
- impact ionization
- tunneling

The following sections describes the models implemented into ATLAS that attempts the simulation of these six types of generation-recombination mechanisms.

**Shockley-Read-Hall (SRH) Recombination**

Phonon transitions occur in the presence of a trap (or defect) within the forbidden gap of the semiconductor. This is essentially a two step process, the theory of which was first derived by Shockley and Read [21.] and then by Hall [124]. The Shockley-Read-Hall recombination is modeled as follows:

$$R_{SRH} = \frac{pn - n_i^2}{TAUPO \left[ n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) \right] + TAUNO \left[ p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right]} \quad 3-240$$

where  $ETRAP$  is the difference between the trap energy level and the intrinsic Fermi level,  $T_L$  is the lattice temperature in degrees Kelvin and  $TAUNO$  and  $TAUPO$  are the electron and hole lifetimes. This model is activated by using the  $SRH$  parameter of the  $MODELS$  statement. The electron and hole

lifetime parameters, TAUN0 and TAUP0, are user-definable in the MATERIAL statement. The default values for carrier lifetimes are shown in Table 3-40. Materials other than silicon will have different defaults. A full description of these parameters are given in Appendix B: "Material Systems".

| Table 3-40. User-Specifiable Parameters for Equation 3-240 |           |                    |       |
|--|-----------|--------------------|-------|
| Statement  | Parameter | Default            | Units |
| MATERIAL   | ETRAP     | 0                  | eV    |
| MATERIAL   | TAUN0     | 1x10 <sup>-7</sup> | s     |
| MATERIAL   | TAUP0     | 1x10 <sup>-7</sup> | s     |

**Note:** This model only presumes one trap level which, by default, is ETRAP=0 and it corresponds to the most efficient recombination centre. If the TRAP statement is used to define specific trap physics then separate SRH statistics are implemented as described earlier in "Trap Implementation into Recombination Models" section on page 3-14.

### SRH Concentration-Dependent Lifetime Model

The constant carrier lifetimes that are used in the SRH recombination model above can be made a function of impurity concentration [22,93,110] using the following equation:

$$R_{SRH} = \frac{pn - n_{ie}^2}{\tau_p \left[ n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) \right] + \tau_n \left[ p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right]} \quad 3-241$$

where:

$$\tau_n = \frac{TAUN0}{1 + N/(NSRHN)} \quad 3-242$$

$$\tau_p = \frac{TAUP0}{1 + N/(NSRHP)} \quad 3-243$$

Here, N is the local (total) impurity concentration. The TAUN0, TAUP0, NSRHN, and NSRHP parameters can be defined on the MATERIAL statement (see Table 3-41 for their default values). This model is activated with the CONSRH parameter of the MODELS statement.

| Table 3-41. User-Specifiable Parameters for Equations 3-241 to 3-243 |           |                      |                  |
|--|-----------|----------------------|------------------|
| Statement  | Parameter | Default              | Units            |
| MATERIAL   | TAUN0     | 1.0x10 <sup>-7</sup> | s                |
| MATERIAL   | NSRHN     | 5.0x10 <sup>16</sup> | cm <sup>-3</sup> |
| MATERIAL   | TAUP0     | 1.0x10 <sup>-7</sup> | s                |
| MATERIAL   | NSRHP     | 5.0x10 <sup>16</sup> | cm <sup>-3</sup> |

### Klaassen's Concentration Dependent Lifetime Model

The Klaassen Concentration and Temperature-dependent SRH Lifetime Model [15.] is enabled by setting the `KLASRH` logical parameter in the `MODELS` statement. The lifetimes for electrons and holes in this model are given by the equations:

$$\mathbf{TAUN0}^{-1} = (\mathbf{KSRHTN}^{-1} + \mathbf{KSRHCN} \times N) \left( \frac{300}{T_L} \right) \mathbf{KSRHGN} \quad 3-244$$

$$\mathbf{TAUPO}^{-1} = (\mathbf{KSRHTP}^{-1} + \mathbf{KSRHCP} \times N) \left( \frac{300}{T_L} \right) \mathbf{KSRHGP} \quad 3-245$$

Here,  $N$  is the local (total) impurity concentration. You can define the `KSRHTN`, `KSRHTP`, `KSRHCN`, `KSRHCP`, `KSRHGN`, and `KSRHGP` parameters in the `MATERIAL` statement. Their default values are given in Table 3-42.

| Table 3-42. User-Specifiable Parameters for Equations 3-244 to 3-245 |           |                         |                        |
|--|-----------|-------------------------|------------------------|
| Statement  | Parameter | Default                 | Units                  |
| MATERIAL   | KSRHTN    | $2.5 \times 10^{-3}$    | s                      |
| MATERIAL   | KSRHTP    | $2.5 \times 10^{-3}$    | s                      |
| MATERIAL   | KSRHCN    | $3.0 \times 10^{-13}$   | $\text{cm}^3/\text{s}$ |
| MATERIAL   | KSRHCP    | $11.76 \times 10^{-13}$ | $\text{cm}^3/\text{s}$ |
| MATERIAL   | KSRHGN    | 1.77                    |                        |
| MATERIAL   | KSRHGP    | 0.57                    |                        |

### Trap-Assisted Tunneling

In a strong electric field, electrons can tunnel through the bandgap via trap states. This trap-assisted tunneling mechanism is enabled by specifying `TRAP.TUNNEL` on the `MODELS` statement and is accounted for by modifying the Shockley-Read-Hall recombination model.

$$R_{SRH} = \frac{pn - n_{ie}^2}{\frac{\mathbf{TAUPO}}{1 + \Gamma_p^{DIRAC}} \left[ n + n_{ie} \exp\left(\frac{\mathbf{ETRAP}}{kT_L}\right) \right] + \frac{\mathbf{TAUNO}}{1 + \Gamma_n^{DIRAC}} \left[ p + n_{ie} \exp\left(\frac{-\mathbf{ETRAP}}{kT_L}\right) \right]} \quad 3-246$$

Here,  $\Gamma_n^{DIRAC}$  is the electron field-effect enhancement term for Dirac wells, and  $\Gamma_p^{DIRAC}$  is the hole field-effect enhancement term for Dirac wells.  $\Gamma_n^{DIRAC}$  and  $\Gamma_p^{DIRAC}$  are defined in Equations 3-71 and 3-72.

### Poole-Frenkel Barrier Lowering for Coulombic Wells

The Poole-Frenkel effect can enhance the emission rate for Coulombic wells. If the `TRAP.COULOMBIC` parameter is specified in the `MODELS` statement, the Shockley-Read-Hall electron and hole recombination model becomes:

$$R_{n, SRH} = \frac{p_n - n_{ie}^2}{\frac{TAUP0}{1 + \Gamma_p^{DIRAC}} \left[ n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) + \frac{TAUN0}{\chi_F + \Gamma_n^{COUL}} \left[ p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right] \right]} \quad 3-247$$

$$R_{p, SRH} = \frac{p_n - n_{ie}^2}{\frac{TAUN0}{\chi_F + \Gamma_n^{COUL}} \left[ n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) + \frac{TAUP0}{1 + \Gamma_p^{DIRAC}} \left[ p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right] \right]} \quad 3-248$$

The Poole-Frenkel thermal emission factor,  $\chi_F$ , is defined in Equation 3-77. The Coulombic field-enhancement terms,  $\Gamma_n^{COUL}$  and  $\Gamma_p^{COUL}$  are defined in Equations 3-79 and 3-80.

### Optical Generation/Radiative Recombination

The next physical mechanisms we have to consider for generation/recombination are photon transition. This mechanism occurs primarily in one step and is therefore a direct generation/recombination mechanism. There are two partial processes involved. For radiative recombination, an electron loses energy on the order of the band gap and moves from the conduction band to the valence band. For optical generation, an electron moves from the valence band to the conduction. In silicon, band to band generation/recombination is insignificant. This effect, however, is important for narrow gap semiconductors and semiconductors whose specific band structure allows direct transitions. By assuming a capture rate  $C_c^{OPT}$  and an emission rate  $C_e^{OPT}$ , the involved partial processes can be written as

$$R_{np}^{OPT} = C_c^{OPT} n_{np}, \quad 3-249$$

for recombination and

$$G_{np}^{OPT} = C_e^{OPT} \quad 3-250$$

for generation.

These rates must be equal in thermal equilibrium so that

$$C_{np}^{OPT} = C_c^{OPT} n_{ie}^2 \quad 3-251$$

The total band to band generation/recombination is the difference of the partial rates, which equates to

$$R_{np}^{OPT} = C_c^{OPT} (np - n_{ie}^2) \quad 3-252$$



In ATLAS, COPT is used express  $C_c^{OPT}$  and can be defined away from default values on the materials statement or implemented using a C-Interpreter routine. To turn on the optical recombination/generation model, define the OPTR keyword on the MODELS statement.

## Auger Recombination

Auger recombination occurs through a three particle transition whereby a mobile carrier is either captured or emitted. The underlying physics for such processes is unclear and normally a more qualitative understanding is sufficient [2].

### Standard Auger Model

Auger Recombination is commonly modeled using the expression [111]:

$$R_{Auger} = \mathbf{AUGN} \left( pn^2 - nn_{ie}^2 \right) + \mathbf{AUGP} \left( np^2 - pn_{ie}^2 \right) \quad 3-253$$

where the model parameters AUGN and AUGP are user-definable in the MATERIAL statement (see Table 3-43 for its default value). You can activate this model with the AUGER parameter from the MODELS statement.

| Table 3-43. User-Specifiable Parameters for Equation 3-253 |           |                       |                        |
|--|-----------|-----------------------|------------------------|
| Statement  | Parameter | Default               | Units                  |
| MATERIAL   | AUGN      | $8.3 \times 10^{-32}$ | $\text{cm}^6/\text{s}$ |
| MATERIAL   | AUGP      | $1.8 \times 10^{-31}$ | $\text{cm}^6/\text{s}$ |

### Klaassen's Temperature-Dependent Auger Model

The Klaassen Auger Recombination Model [24] is activated by specifying the KLAAUG parameter of the MODELS statement. The form of this model is:

$$R_{Auger} = C_n \left( pn^2 - nn_{ie}^2 \right) + C_p \left( np^2 - pn_{ie}^2 \right) \quad 3-254$$

where the Auger coefficients are temperature dependent according to:

$$C_n = \mathbf{KAUGC N} \left( \frac{T_L}{300} \right) \mathbf{KAUGDN} \quad 3-255$$

$$C_p = \mathbf{KAUGC P} \left( \frac{T_L}{300} \right) \mathbf{KAUGDP} \quad 3-256$$

Here, the KAUGC N, KAUGC P, KAUGDN, and KAUGDP parameters are user-definable in the MATERIAL statement and have the defaults shown in Table 3-44.

**Table 3-44. User-Specifiable Parameters for Equation 3-255 and 3-256**

| Statement | Parameter | Default                | Units                  |
|-----------|-----------|------------------------|------------------------|
| MATERIAL  | KAUGCN    | $1.83 \times 10^{-31}$ | $\text{cm}^6/\text{s}$ |
| MATERIAL  | KAUGCP    | $2.78 \times 10^{-31}$ | $\text{cm}^6/\text{s}$ |
| MATERIAL  | KAUGDN    | 1.18                   |                        |
| MATERIAL  | KAUGDP    | 0.72                   |                        |

### Narrow Bandgap Auger Model

An alternative model for the Auger recombination coefficients that is more suitable for modelling Auger processes in narrow bandgap semiconductors can be enabled by setting the parameters AUGKN and AUGKP on the MODELS statement. The model in ATLAS is a simplification of that by Beattie [125] and takes the form:

$$R_{Auger} = C_n(pn^2 - nn_{ie}^2) + C_p(np^2 - pn_{ie}^2) \tag{3-257}$$

where the Auger coefficients are concentration dependent according to:

$$C_n = \frac{AUGN}{1 + AUGKN n} \tag{3-258}$$

$$C_p = \frac{AUGP}{1 + AUGKP p} \tag{3-259}$$

Here, n and p are the electron and hole carrier concentrations and the new parameters, AUGKN and AUGKP, are user-definable on the MODELS statement.

### Surface Recombination

In addition to generation-recombination within the bulk of the semiconductor, electrons or holes may recombine or be generated at interfaces. The rate of surface recombination may be even greater than within the bulk. The standard method is to model interface recombination in a similar manner as the bulk generation-recombination rate [48] where:

$$R_{surf} = \frac{pn - n_{ie}^2}{\tau_p^{eff} \left[ n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) \right] + \tau_n^{eff} \left[ p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right]} \tag{3-260}$$

Here:

$$\frac{1}{\tau_n^{eff}} = \frac{1}{\tau_n} + \frac{d_i}{A_i} \mathbf{S} \cdot \mathbf{N} \tag{3-261}$$

and

$$\frac{1}{\tau_p^{eff}} = \frac{1}{\tau_i} + \frac{d_i}{A_i} \mathbf{S.P} \quad 3-262$$

$\tau_n^i$  is the bulk lifetime calculated at node  $i$  along the interface and which may be a function of the impurity concentration as well. The  $d_i$  and  $A_i$  parameters are the length and area of the interface for node  $i$ . The  $S.N$  and  $S.P$  parameters are the recombination velocities for electrons and holes respectively, which are user-definable in the `INTERFACE` statement. The `X.MIN`, `X.MAX`, `Y.MIN`, and `Y.MAX` parameters can also be set in the `INTERFACE` statement to define the region, where the specified values of the surface recombination velocities apply. This model is activated by the presence of the recombination velocities in the `INTERFACE` statement.

**Table 3-45. User-Specifiable Parameters for Equations 3-261 to 3-262**

| Statement | Parameter | Default | Units |
|-----------|-----------|---------|-------|
| INTERFACE | S.N       | 0       | cm/s  |
| INTERFACE | S.P       | 0       | cm/s  |

### 3.6.4: Impact Ionization Models

In any space charge region with a sufficiently high reverse bias, the electric field will be high enough to accelerate free carriers up to a point where they will have acquired sufficient energy to generate more free carriers when in collision with the atoms of the crystal. In order to acquire sufficient energy, two principle conditions must be met.

First, the electric field must be sufficiently high. Then, the distance between the collisions of the free carrier must be enough to allow acceleration to a sufficiently high velocity

In other words, the carrier must gain the ionization energy  $E_i$  between collisions. If the generation rate of these free carriers is sufficiently high this process will eventually lead to avalanche breakdown.

The general impact ionization process is described by the Equation 3-263.

$$G = \alpha_n |\vec{J}|_n + \alpha_p |\vec{J}|_p \quad 3-263$$

Here,  $G$  is the local generation rate of electron-hole pairs,  $\alpha_{n,p}$  are the ionization coefficient for electrons and holes and  $J_{n,p}$  are their current densities. The ionization coefficient represents the number of electron-hole pairs generated by a carrier per unit distance travelled. The accurate calculation of this parameter has been researched because it is vital if the effects related to impact ionization, such as substrate current and device breakdown, are to be simulated. These models can be classified into two main types: local and non-local models.

The former assume that ionization at any particular point within the device is a function only of the electric field at that position. Non-local models, however, perform a more rigorous approach by taking into account the energy that the carrier gains.

## Geometrical Considerations for Impact Ionization Models

In all the available models discussed in the following sections, the ionization coefficients are dependent on electric field. There are several different ways to consider the interaction between electric field and current implied by Equation 3-263.

During simulation, currents and fields are calculated both as scalar values on the edges of triangles and as vector quantities on the triangles themselves. ATLAS allows three different ways of looking at Equation 3-263.

The first model uses Equation 3-264.

$$G = \alpha_n(|E_{tri}|)J_{ntri} + \alpha_p(|E_{tri}|)J_{ptri} \quad 3-264$$

Here,  $E_{tri}$  is the vector field on the triangle,  $J_{ntri}$  is the electron current vector on the triangle, and  $J_{ptri}$  is the hole current vector on the triangle. In ATLAS3D, electric field is combined with the z-component of the field at each corner of the prism to give an overall field modules at each node. To select this model, specify `E.VECTOR` of the `IMPACT` statement.

A simpler model can be selected by specifying `E.DIR` on the `IMPACT` statement (see Equation 3-265).

$$G = \alpha_n(|E_{side}|)J_{nside} + \alpha_p(|E_{side}|)J_{pside} \quad 3-265$$

Here,  $E_{side}$  is the scalar field along the side of a triangle,  $J_{nside}$  is the electron current along the side and  $J_{pside}$  is the hole current along the side. This model is the most non-physical but has the advantages of better robustness and calculation speed and is compatible with older device simulators. This model is only supported in ATLAS2D.

The most complex and physically sound model is selected by specifying `E.DIR` on the `IMPACT` statement (see Equation 3-266).

$$G = \alpha_n\left(\frac{E_{tri} \cdot J_{ntri}}{J_{ntri}}\right)J_{ntri} + \alpha_p\left(\frac{E_{tri} \cdot J_{ntri}}{J_{ntri}}\right)J_{ntri} \quad 3-266$$

In this model, the ionization coefficients are a function of the field in the direction of the current. If the dot product of  $E$  and  $J$  is negative, then the field component is taken as 0. Consequently, impact ionization may only occur when a current is dominated by the drift term. This model is the most physically sound and is the default model for the field dependance of the impact ionization coefficients.

## Local Electric Field Models for Impact Ionization

### Selberherr's Impact Ionization Model

The ionization rate model proposed by Selberherr [2.] is a variation of the classical Chynoweth model [26.]. Activate this model by using the `SELB` parameter of the `IMPACT` statement, which is based upon the following expressions [51]:

$$\alpha_n = AN \exp\left[-\left(\frac{BN}{E}\right)^{BETAN}\right] \quad 3-267$$

$$\alpha_p = AP \exp\left[-\left(\frac{BP}{E}\right)^{BETAP}\right] \quad 3-268$$

Here,  $E$  is the electric field in the direction of current flow at a particular position in the structure and the parameters  $AN$ ,  $AP$ ,  $BN$ ,  $BP$ ,  $BETAN$ , and  $BETAP$  are defined on the `IMPACT` statement and have the default values shown in Table 3-46. In the case of  $AN$ ,  $AP$ ,  $BN$ , and  $BP$  you can define a value of electric field,  $EGRAN$  V/cm, where for electric fields,  $>EGRAN$  V/cm, the parameters are:  $AN1$ ,  $AP1$ ,  $BN1$ ,  $BP1$ , while for electric fields,  $<EGRAN$  V/cm, the parameters become  $AN2$ ,  $AP2$ ,  $BN2$ , and  $BP2$ .

The  $AN$  and  $BN$  parameters are also a function of the lattice temperature in this model [87]. The temperature dependence of these coefficients is defined as follows:

$$AN = AN_{1,2} \left( 1 + A.NT \left[ \left( \frac{T_L}{300} \right)^{M.ANT} - 1 \right] \right) \quad 3-269$$

$$AP = AP_{1,2} \left( 1 + A.PT \left[ \left( \frac{T_L}{300} \right)^{M.APT} - 1 \right] \right) \quad 3-270$$

$$BN = BN_{1,2} \left( 1 + B.NT \left[ \left( \frac{T_L}{300} \right)^{M.BNT} - 1 \right] \right) \quad 3-271$$

$$BP = BP_{1,2} \left( 1 + B.PT \left[ \left( \frac{T_L}{300} \right)^{M.BPT} - 1 \right] \right) \quad 3-272$$

The parameters associated with these equations are shown in Table 3-46.

| Table 3-46. User-Definable Parameters in the Selberherr Impact Ionization Model |           |                                    |
|---|-----------|------------------------------------|
| Statement   | Parameter | Default                            |
| IMPACT  | AN1       | $7.03 \times 10^5 \text{ cm}^{-1}$ |
| IMPACT  | AN2       | $7.03 \times 10^5 \text{ cm}^{-1}$ |
| IMPACT  | AP1       | $6.71 \times 10^5 \text{ cm}^{-1}$ |
| IMPACT  | AP2       | $1.58 \times 10^6 \text{ cm}^{-1}$ |
| IMPACT  | BN1       | $1.231 \times 10^6 \text{ V/cm}$   |
| IMPACT  | BN2       | $1.231 \times 10^6 \text{ V/cm}$   |
| IMPACT  | BP1       | $1.693 \times 10^6 \text{ V/cm}$   |
| IMPACT  | BP2       | $2.036 \times 10^6 \text{ V/cm}$   |
| IMPACT  | BETAN     | 1.0                                |
| IMPACT  | BETAP     | 1.0                                |
| IMPACT  | EGRAN     | $4 \times 10^5 \text{ V/cm}$       |

| Table 3-47. Temperature Coefficient Parameters of the Selberherr Impact Ionization Model for Silicon in Equations 3-269 to 3-272 |           |         |
|--|-----------|---------|
| Statement  | Parameter | Default |
| IMPACT   | A.NT      | 0.588   |
| IMPACT   | B.NT      | 0.248   |
| IMPACT   | A.PT      | 0.588   |
| IMPACT   | B.PT      | 0.248   |
| IMPACT   | M.ANT     | 1.0     |
| IMPACT   | M.BNT     | 1.0     |
| IMPACT   | M.APT     | 1.0     |
| IMPACT   | M.BPT     | 1.0     |

**Valdinoci Impact Ionization Model**

Valdinoci et al. [27] reported on a measurement technique to calibrate the temperature dependence of impact ionization models and proposed a new model based on their study. Their model of both electron and hole ionization coefficients was calibrated for silicon for temperature ranging from 25 to 400°C. This model is based on the following:

$$\alpha_{n,p} = \frac{E}{a_{n,p}(T_L) + b_{n,p}(T_L) \exp[d_{n,p}(T_L)/(E + c_{n,p}(T_L))]} \tag{3-273}$$

where  $E$  is the electric field along the current flow lines. The parameters in Equation 3-273 depend on temperature as follows:

$$a_n(T_L) = VAL.AN0 + \left( VAL.AN1 \cdot T_L^{VAL.AN2} \right)$$

$$b_n(T_L) = VAL.BN0 \exp(VAL.BN1 \cdot T_L)$$

$$c_n(T_L) = VAL.CN0 + \left( VAL.CN1 \cdot T_L^{VAL.CN2} \right) + VAL.CN3 \cdot T_L^2$$

$$d_n(T_L) = VAL.DN0 + VAL.DN1 \cdot T_L + VAL.DN2 \cdot T_L^2$$
3-274

$$a_p(T_L) = \text{VAL.AP0} + \left( \text{VAL.AP1} \cdot T_L + \frac{\text{VAL.AP2}}{2} \cdot T_L^2 \right)$$

$$b_p(T_L) = \text{VAL.BP0} \exp(\text{VAL.BP1} \cdot T_L)$$

3-275

$$c_p(T_L) = \text{VAL.CP0} + \left( \text{VAL.CP1} \cdot T_L + \frac{\text{VAL.CP2}}{2} \cdot T_L^2 \right) + \text{VAL.CP3} \cdot T_L^3$$

$$d_p(T_L) = \text{VAL.DP0} + \text{VAL.DP1} \cdot T_L + \text{VAL.DP2} \cdot T_L^2$$

Our default parameters for silicon are shown in Table 3-48. These parameters are also taken from Valdinoci et al. [27]. To enable this model, specify the logical parameter, VALDINOCI, in the IMPACT statement.

| Table 3-48. Default Parameters for Valdinoci Impact Ionization Model |           |      |            |       |
|--|-----------|------|------------|-------|
| Statement  | Parameter | Type | Default    | Units |
| IMPACT   | VAL.AN0   | Real | 4.3383     |       |
| IMPACT   | VAL.AN1   | Real | -2.42e-12  |       |
| IMPACT   | VAL.AN2   | Real | 4.1233     |       |
| IMPACT   | VAL.BN0   | Real | 0.235      |       |
| IMPACT   | VAL.BN1   | Real | 0.0        |       |
| IMPACT   | VAL.CN0   | Real | 1.6831e4   |       |
| IMPACT   | VAL.CN1   | Real | 4.3796     |       |
| IMPACT   | VAL.CN2   | Real | 1.0        |       |
| IMPACT   | VAL.CN3   | Real | 0.13005    |       |
| IMPACT   | VAL.DN0   | Real | 1.233735e6 |       |
| IMPACT   | VAL.DN1   | Real | 1.2039e3   |       |
| IMPACT   | VAL.DN2   | Real | 0.56703    |       |
| IMPACT   | VAL.AP0   | Real | 2.376      |       |
| IMPACT   | VAL.AP1   | Real | 0.01033    |       |
| IMPACT   | VAL.AP2   | Real | 1.0        |       |
| IMPACT   | VAL.BP0   | Real | 0.17714    |       |
| IMPACT   | VAL.BP1   | Real | -0.002178  |       |
| IMPACT   | VAL.CP0   | Real | 0.0        |       |

**Table 3-48. Default Parameters for Valdinoci Impact Ionization Model**

| Statement | Parameter | Type | Default  | Units |
|-----------|-----------|------|----------|-------|
| IMPACT    | VAL.CP1   | Real | 0.00947  |       |
| IMPACT    | VAL.CP2   | Real | 2.4924   |       |
| IMPACT    | VAL.CP3   | Real | 0.0      |       |
| IMPACT    | VAL.DP0   | Real | 1.4043e6 |       |
| IMPACT    | VAL.DP1   | Real | 2.9744e3 |       |
| IMPACT    | VAL.DP2   | Real | 1.4829   |       |

**Grant's Impact Ionization Model**

The second ionization model has the same form as the Selberherr model but a simpler implementation where:

$$\alpha_n = AN \exp\left[-\left(\frac{BN}{E}\right)\right] \tag{3-276}$$

$$\alpha_p = AP \exp\left[-\left(\frac{BP}{E}\right)\right] \tag{3-277}$$

This implementation has three key differences:

- The model has a low field, an intermediate field and a high field region.
- The coefficients for silicon are different.
- There is no temperature dependence.

This model was developed after investigations by Baraff [28] suggested the existence of a low, intermediate and high field response region for electron and hole ionization rates. The coefficients implemented into this model match the experimental data of Grant [29], which suggested that the three different regions existed.

This model is activated with the GRANT parameter of the IMPACT statement. The model parameters: AN, AP, BN, and BP aren't user-definable. Instead, the three electric field regions have in-built values as follows:

1) **Low Electric Field**  $E < 2.4 \times 10^5 \text{ V/cm}$  3-278

$$AN = 2.6 \times 10^6 \quad AP = 2.0 \times 10^6$$

$$BN = 1.43 \times 10^6 \quad BP = 1.97 \times 10^6$$

2) **Intermediate Electric Field**  $2.4 \times 10^5 > E > 5.3 \times 10^5 \text{ V/cm}$  3-279

$$AN = 6.2 \times 10^5 \quad AP = 2.0 \times 10^6$$

$$BN = 1.08 \times 10^6 \quad BP = 1.97 \times 10^6$$

3) **High Electric Field**  $E > 5.3 \times 10^5 \text{ V/cm}$  3-280

$$AN = 5.0 \times 10^5 \quad AP = 5.6 \times 10^5$$

$$BN = 9.9 \times 10^6 \quad BP = 1.32 \times 10^6$$



### Crowell-Sze Impact Ionization Model

Crowell and Sze [30] have proposed a more physical relationship between the electric field and the ionization rates. This model represents ionization coefficients as follows:

$$\alpha_{n,p} = \frac{1}{\lambda_{n,p}} \exp \left[ C_0(r) + C_1(r)x + C_2(r)x^2 \right] \quad 3-281$$

$$C_0 = -1.92 + 75.5r - 75.7r^2 \quad 3-282$$

$$C_1(r) = -1.75 \times 10^{-2} - 11.9r + 46r^2 \quad 3-283$$

$$C_2(r) = 3.9 \times 10^{-4} - 1.17r + 11.5r^2 \quad 3-284$$

where:

$$r = \frac{E_r}{E_i}; \quad x = \frac{E_i}{q\lambda_{n,p}E} \quad 3-285$$

$$E_r = 0.063 \text{ eV} \quad 3-286$$

$$E_i = \begin{cases} 1.1\text{eV} & \text{for electrons} \\ 1.8\text{eV} & \text{for holes} \end{cases} \quad 3-287$$

$$\lambda_n^o = \text{LAMD AE} \frac{\tanh[qE_r/2kT_L]}{\tanh[qE_r/2k300]} \quad 3-288$$

$$\lambda_n^o = \text{LMDAH} \frac{\tanh[qE_r/2kT_L]}{\tanh[qE_r/2k300]} \quad 3-289$$

The Crowell-Sze Model for impact ionization is selected by setting the CROWELL parameter of the IMPACT statement.

| Table 3-49. Crowell-Sze Impact Ionization Model Parameters. |           |                         |
|---|-----------|-------------------------|
| Statement   | Parameter | Default                 |
| IMPACT  | LAMDAE    | $6.2 \times 10^{-7}$ cm |
| IMPACT  | LMDAH     | $3.8 \times 10^{-7}$ cm |

## Non-Local Carrier Energy Models for Impact Ionization

All local electric field based models will normally overestimate the rate of impact ionization. This occurs because lucky electron theory inherently assumes that a carrier is traveling through a constant electric field  $E$ . As a result it will predict a distance  $\Delta x = E_i/qE$  over which the carrier will gain the ionization energy  $E_i$ . In real devices, however, the electric field is never constant but is normally sharply peaked at metallurgical junctions. Therefore, as a carrier passes through the peaked electric field the lucky electron model will predict the ionization distance  $\Delta x$  to be too small. As a result the ionization rate is overestimated. The effect of this is that all the simulated breakdown voltages will be underestimated and substrate currents overestimated.

The Energy Balance Transport Model can be used to improve the simulation of impact ionization by implementing ionization models based upon the carrier temperature instead of the electric field. The carrier temperature is a more meaningful basis as the velocity-field relationship is more closely modeled. This allows a non-local dependence on the electric field within the impact ionization model. Energy Balance Transport Models will therefore result in more accurate simulations of breakdown voltage and substrate current. Two different impact ionization models have been implemented into ATLAS, the first is based upon the classical Chynoweth relationship, modified to include carrier temperature, but the second is a more advanced non-Maxwellian approach based upon carrier temperatures.

When the energy balance transport model is applied, only two impact ionization models are available. These are the Toyabe model and the Concannon model.

### Toyabe Impact Ionization Model

The temperature dependent impact ionization model is founded on the Selberherr model and is similar to that suggested by Toyabe [80]. The carrier temperature is used to calculate an effective electric field based upon the homogeneous temperature-field relation. To maintain self-consistency within the Energy Balance Transport Model this is the same relationship used for the effective electric field within the carrier temperature dependent mobility. This model is the default model for impact ionization with energy balance transport and is activated with the TOYABE or SELB parameters on the IMPACT statement. The ionization rates now have the form:

$$\alpha_n = AN \exp\left(\frac{-BN}{E_{eff, n}}\right) \quad 3-290$$

$$\alpha_p = AP \exp\left(\frac{-BP}{E_{eff, p}}\right) \quad 3-291$$

where the model parameters: AN, AP, BN, and BP are user-definable in the IMPACT statement (see Table 3-46 for their default values). The effective electric field is calculated according to:

$$E_{eff, n} = \frac{3}{2q} \frac{kT_n}{LREL.EL} \quad 3-292$$

$$E_{eff, p} = \frac{3}{2q} \frac{kT_p}{LREL.HO} \quad 3-293$$

where the energy relaxation lengths, LREL.EL and LREL.HO, can be explicitly defined in the IMPACT statement, or can be calculated according to:

$$LREL.EL = VSATN * TAUSN \quad 3-294$$

$$LREL.HO = VSATP * TAUSP \quad 3-295$$

VSATN and VSATP are the saturation velocities for electrons and holes, and TAUSN and TAUSP correspond to the electron energy relaxation times (TAUREL.EL and TAUREL.HO) in Equations 3-235 and 3-236. You must set the LENGTH.REL flag to use the values of LREL.EL and LREL.HO specified in the IMPACT statement.

| Table 3-50. User-Specifiable Parameters for Equations 3-292-3-295 |           |       |
|---|-----------|-------|
| Statement   | Parameter | Units |
| IMPACT  | LREL.EL   | μm    |
| IMPACT  | LREL.HO   | μm    |
| MATERIAL  | VSAT      | cm/s  |
| MATERIAL  | VSATN     | cm/s  |
| MATERIAL  | VSATP     | cm/s  |
| IMPACT  | TAUSN     | s     |
| IMPACT  | TAUSP     | s     |

**Note:** As an added level of flexibility, the relaxation times used for the energy balance equation and those used in the impact ionization model are separated into two user-definable parameters. In contrast to TAUREL.EL and TAUREL.HO, which are used in different formulae, the TAUSN and TAUSP parameters are only applicable in the impact ionization expression in Equations 3-291 and 3-292. By default, TAUREL.EL=TAUSN and TAUREL.HO=TAUSP.

It can also be argued that the AN, AP, BN, and BP parameters should also be a function of the carrier temperature. But, no clear theoretical basis for this has been proposed and accepted. Instead, the C-INTERPRETER within ATLAS has been extended to include two C-INTERPRETER functions. These functions are specified via the F.EDIIN and F.EDIIP parameters of the IMPACT statement. These parameters specify the filename of a text file containing a C-INTERPRETER function that describes the dependence of the model parameters AN, AP, BN and BP as a function of the carrier temperatures. These values will then be used within Toyabe's energy dependent impact ionization model.

### Concannon's Impact Ionization Model

The previous non-local impact ionization model inherently assumes a Maxwellian shape to the distribution of hot carriers. Recent work by Fiegna et. al. [32] using Monte Carlo simulations suggests a non-Maxwellian high energy tail to the energy distribution function. To accurately model these effects, a non-Maxwellian based model from Concannon [33] has been implemented. Based upon this energy distribution the model calculates the probability of a carrier having sufficient energy to cause impact ionization. The model results show good agreement with measured results for a 0.9μm flash EPROM device [33].

To enable the Concannon substrate current for the electron and hole continuity equations, specify the N.CONCANNON and P.CONCANNON parameters in the IMPACT statement.

The generation rate is a function of the carrier temperature and concentration is given by:

$$G_n(x, y) = \mathbf{CSUB.N} \times n \int_0^{\infty} F(\varepsilon, T_n(x, y)) d\varepsilon \quad \mathbf{ETH.N} \quad 3-296$$

$$G_p(x, y) = \mathbf{CSUB.P} \times p \int_{\mathbf{ETH.P}}^{\infty} F(\varepsilon, T_p(x, y)) d\varepsilon \quad 3-297$$

where  $n(x,y)$  and  $p(x,y)$  are the electron and hole carrier concentrations within the semiconductor,  $\varepsilon$  is energy,  $T_n(x,y)$  and  $T_p(x,y)$  are the electron and hole carrier temperatures in the semiconductor,  $F$  is given in Equation 3-228,  $\mathbf{CSUB.N}$ ,  $\mathbf{CSUB.P}$ ,  $\mathbf{ETH.N}$ , and  $\mathbf{ETH.P}$  are user-specifiable parameters as given in Table 3-51.

| Table 3-51. User-Specifiable Parameters for Equations 3-296 and 3-297 |                   |                      |       |
|---|-------------------|----------------------|-------|
| Statement   | Parameter         | Default              | Units |
| IMPACT  | $\mathbf{CSUB.N}$ | $2.0 \times 10^{14}$ |       |
| IMPACT  | $\mathbf{CSUB.P}$ | $4.0 \times 10^{14}$ |       |
| IMPACT  | $\mathbf{ETH.N}$  | 1.8                  | eV    |
| IMPACT  | $\mathbf{ETH.P}$  | 3.5                  | eV    |

The function,  $F(\varepsilon,T)$ , in Equations 3-296 and 3-297 is given by the product of the density of states function,  $g(\varepsilon)$ , and the energy distribution function  $f(\varepsilon)$  as:

$$F = \frac{g(\varepsilon)f(\varepsilon)}{\int_0^{\infty} g(\varepsilon)f(\varepsilon)} \quad 3-298$$

The density of states function is given by:

$$g(\varepsilon) = \varepsilon^{1.25} \quad 3-299$$

The energy distribution functions for electrons and holes are:

$$f_n(\varepsilon) = \left[ \exp\left(\frac{-\mathbf{CHIA} \varepsilon^3}{T_n^{1.5}}\right) + \mathbf{C0} \exp\left(\frac{-\mathbf{CHIB} \varepsilon^3}{T_n^{1.5}}\right) \right] \quad 3-300$$

$$f_p(\varepsilon) = \exp\left(\frac{-\mathbf{CHI.HOLES} \varepsilon^3}{T_p^{1.5}}\right) \quad 3-301$$

Here,  $\varepsilon$  is energy,  $T_{n,p}$  are the carrier temperatures,  $\mathbf{CHIA}$ ,  $\mathbf{CHIB}$ , and  $\mathbf{C0}$  are user-specifiable parameters (see Table 3-52).

**Table 3-52. User-Definable Parameters for the Energy Distribution Functions**

| Statement | Parameter  | Default               | Units |
|-----------|------------|-----------------------|-------|
| IMPACT    | CHIA       | $3.0 \times 10^5$     |       |
| IMPACT    | CHIB       | $5.0 \times 10^4$     |       |
| IMPACT    | CO         | $2.5 \times 10^{-10}$ |       |
| IMPACT    | CHI .HOLES | $4.6 \times 10^4$     |       |

Two other parameters in the IMPACT statement are user-definable, which may affect the result of the numeric integration. The ENERGY .STEP parameter specifies the energy step size in eV used during the numeric integration. The default step size is 25 meV. The INFINITY parameter sets the upper limit of the integration and specifies ratio of the increment added to the integral divided by the current value of the integral. The default value of the INFINITY parameter is 0.001.

**Note:** To maintain self-consistent results, implement this model if the Concannon model is being used for the simulation of gate current.

## Band-to-Band Tunneling

If a sufficiently high electric field exists within a device local band bending may be sufficient to allow electrons to tunnel, by internal field emission, from the valence band into the conduction band. An additional electron is therefore generated in the conduction band and a hole in the valence band. This generation mechanism is implemented into the right-hand side of the continuity equations. The tunneling generation rate is [6,89, 144] as:

$$G_{BBT} = BB.A E^{BB.GAMMA} \exp\left(-\frac{BB.B}{E}\right) \quad 3-302$$

where  $E$  is the magnitude of an electric field and BB.A, BB.B, and BB.GAMMA are user-definable parameters. In ATLAS there are three different sets of values that may be applied to the model parameters.

The model parameters can be set to the standard model [35] by specifying BBT.STD on the MODELS statement. The parameter defaults for the standard model are as follows:

$$BB.A = 9.6615e18 \text{ V/cm} \quad BB.B = 3.0e7 \quad BB.GAMMA = 2.0$$

The model parameters may also be set to the Klaassen Model [6,89,144] by specifying BBT.KL on the MODELS statement. The parameter defaults for the Klaassen model are as follows:

$$BB.A = 4.00e14 \text{ V/cm} \quad BB.B = 1.9e7 \quad BB.GAMMA = 2.5$$

In application, use the standard model with direct transistors while using the “klaassen” model with indirect transistors.

You can modify the basic band-to-band tunneling given in Equation 3-302 by the generation rate GBBT with the D factor as suggested in [6]. The D factor is given by:

$$D = (\exp[\phi_p - q\psi / KT] + 1)^{-1} - (\exp[\phi_n - q\psi / KT] + 1)^{-1} \quad 3-303$$

where  $\phi_n$  and  $\phi_p$  are the electron and hole quasi-Fermi levels as given in Equations 3-9 and 3-10 and  $\psi$  is the electrostatic potential. To enable this modification, specify `BBT.HURKX` in the `MODELS` statement.

Another modification allows these model parameters to be calculated from the first principles by specifying the `AUTOBBT` parameter in the `MODELS` statement. In this case, the parameters are calculated according to:

$$BB.A = \frac{q^2 \sqrt{(2 \times MASS.TUNNEL m_0)}}{h^2 \sqrt{EG300}} \tag{3-304}$$

$$BB.B = \frac{\pi^2 EG300^{\frac{3}{2}} \sqrt{\frac{MASS.TUNNEL m_0}{2}}}{qh} \tag{3-305}$$

Here:

$$BB.GAMMA = 2 \tag{3-306}$$

where  $q$  is the electronic charge,  $h$  is Planck's constant,  $E_g$  is the energy bandgap,  $m_0$  is the rest mass of an electron and `MASS.TUNNEL` is the effective mass. The parameter `MASS.TUNNEL` may be set on the `MODELS` statement and the bandgap at 300K, `EG300`, is defined on the `MATERIAL` statement.

**Table 3-53. User-Definable Parameters in the Band-to-Band Tunneling Model**

| Statement | Parameter | Default              | Units                   |
|-----------|-----------|----------------------|-------------------------|
| MODEL     | BB.A      | $4.0 \times 10^{14}$ | $V^{-2} s^{-1} cm^{-1}$ |
| MODEL     | BB.B      | $1.9 \times 10^7$    | V/cm                    |
| MODEL     | BB.GAMMA  | 2.5                  |                         |

### 3.6.5: Gate Current Models

In devices that have a metal-insulator-semiconductor (MIS) formation, the conductance of the insulating film would ideally be considered as zero. But, for the sub 0.5um generation of MOS devices there is now considerable conductance being measured on the gate contacts. This gate current has resulted in two major consequences, one negative and one positive.

On the negative side, the gate current is responsible for the degradation in device operating characteristics with time. This reliability issue is important because the lifetime of electronic parts has to be guaranteed. You can simulate reliability within the Silvaco suite of tools for device level reliability which are described in a later chapter.

On the positive side, the existence of this gate current has caused the proliferation of the non-volatile memory market. These devices use the existence of gate current to program and erase the charge on a "floating" contact. This concept has resulted in a variety of different devices such as `FLASH`, `FLOTOX`, and `EEPROM`. All such devices rely on the physics of the gate current process for their existence.

There are a variety of different conduction mechanisms within an insulating layer [9], but in the case of nonvolatile memory, only two mechanism are relevant: Fowler-Nordheim tunneling and hot carrier injection. Models for these two injection processes are described in the following sections. In the case of

hot electron injection, two models are available: the lucky electron model and the Concannon gate current model.

### Fowler-Nordheim Tunneling

If the electric field across an insulator is sufficiently high, then it may cause tunneling of electrons from the semiconductor (or metal) Fermi level into the insulator conduction band. This process is strongly dependent on the applied electric field but is independent of the ambient temperature.

The Fowler-Nordheim Equation [37] expresses tunnel current density through the oxide as:

$$J_{FN} = F.AE E^2 \exp\left(-\frac{F.BE}{E}\right) \quad 3-307$$

$$J_{FP} = F.AH E^2 \exp\left(-\frac{F.BH}{E}\right) \quad 3-308$$

where  $E$  specifies the magnitude of the electric field in the oxide. The model parameters:  $F.AE$ ,  $F.AH$ ,  $F.BE$ , and  $F.BH$  can be defined on the `MODELS` statement. The default values for these parameters, obtained from Keeney, Piccini, and Morelli [35], are shown in Table 3-54.

| Table 3-54. User-Specifiable Parameters for Equations 3-307 and 3-308 |           |           |                       |
|---|-----------|-----------|-----------------------|
| Symbol  | Statement | Parameter | Default Values        |
| $A_{FN}$  | MODELS    | $F.AE$    | $1.82 \times 10^{-7}$ |
| $B_{FN}$  | MODELS    | $F.BE$    | $1.90 \times 10^8$    |
| $A_{FH}$  | MODELS    | $F.AH$    | $1.82 \times 10^{-7}$ |
| $B_{FH}$  | MODELS    | $F.BH$    | $1.90 \times 10^8$    |

The Fowler-Nordheim model in ATLAS has been implemented as either a post processing function or as a self-consistent scheme with the other equations. The post processing option may be chosen by specifying the parameter, `FNPP`, on the `MODEL` statement. The self-consistent scheme is activated by specifying the parameter, `FNORD`, on the `MODEL` statement.

For either model, the implementation scheme is the same. Each electrode-insulator and insulator-semiconductor interface is divided into discrete segments which are based upon the mesh. For each insulator-semiconductor segment, the Fowler-Nordheim current is calculated as described above. This current is then added to a segment on the electrode-insulator boundary. Two schemes have been implemented to find out to which segment this current should be added.

The default model that calculates which electrode segment receives the Fowler-Nordheim current follows the path of the electric field vector at the semiconductor-insulator interface. The first electrode-insulator segment that is found along this trajectory, provided no other semiconductors or metals are found along the trajectory, receives the Fowler-Nordheim current.

A second model may be chosen using the `NEARFLG` parameter of the `MODEL` statement. In this case, the electrode-insulator segment found closest to the semiconductor-insulator segment receives the Fowler-Nordheim current.

The total current on the gate electrode is then the sum of the currents from all the individual segments around the electrode boundary.

**Note:** Since Fowler-Nordheim tunneling current is responsible for EPROM and EEPROM cell erasure, this model should always be specified when performing erasure simulation. We also recommend that you model the band-to-band tunneling model if you model Fowler-Norheim tunneling.

**Note:** When simulating EPROM erasure in a transient analysis with this model, the floating contact charge becomes a function of the gate current. In this case, the total current flowing into the floating electrode is multiplied by the time step to calculate the charge added to the electrode during that time step. The new value of the charge is then used as the boundary condition for the next time step.

### Lucky Electron Hot Carrier Injection Model

In the Lucky-Electron Hot Carrier Injection Model it is proposed that an electron is emitted into the oxide by first gaining enough energy from the electric field in the channel to surmount the insulator/semiconductor barrier. Once the required energy to surmount the barrier has been obtained the electrons are redirected towards the insulator/semiconductor interface by some form of phonon scattering. When these conditions are met, the carrier travelling towards the interface will then have an additional probability that it will not suffer any additional collision through which energy could be lost.

The model implemented into ATLAS is a modified version of the model proposed by Tam [38] and is activated by the parameters HEI and HHI, for electron and hole injection respectively, on the MODELS statement. The gate electrode-insulator interface is subdivided into a number of discrete segments which are defined by the mesh. For each segment the lucky electron model is used to calculate the injected current into that segment. The total gate current is then the sum of all of the discrete values.

If we consider a discrete point on the gate electrode-insulator boundary we can write a mathematical formula for the current injected from the semiconductor. The formula calculates the injected gate current contribution from every node point within the semiconductor according to:

$$I_{inj} = \iint P_n(x, y) |\vec{J}_n(x, y)| dx dy + \iint P_p(x, y) |\vec{J}_p(x, y)| dx dy \quad 3-309$$

where  $J_{n,p}(x,y)$  are the electron and hole current densities at a point  $(x,y)$  within the semiconductor, and  $P_{n,p}(x,y)$  are the probabilities that a fraction of this current reaches the gate oxide and is injected across into the gate electrode. The total probability  $P_{n,p}(x,y)$  is defined by:

$$P_n(x, y) = P_{\phi B, n} P_{1, n} P_{2, n} / \mathbf{IG.ELINR} \quad 3-310$$

$$P_p(x, y) = P_{\phi B, p} P_{1, p} P_{2, p} / \mathbf{IG.HLINR} \quad 3-311$$

where  $E$  is the electric field parallel to the current flow,  $\mathbf{IG.ELINR}$  and  $\mathbf{IG.HLINR}$  are the electron and hole mean free path lengths between redirecting collisions. The three probability factors will now be described.

The probability  $P_{\phi B}$  is the probability of a carrier gaining the energy  $\phi_B$  by moving in, and parallel to, an electric field  $E$ , without suffering energy loss by optical phonon scattering and is given by:

$$P_{\phi B, n} = 0.25 \left( \frac{E \mathbf{IG.ELINF}}{\phi_{B, n}} \right) \exp \left( -\frac{\phi_{B, n}}{E \mathbf{IG.ELINF}} \right) \quad 3-312$$



$$P_{\phi_{B,p}} = 0.25 \left( \frac{E \text{ IG.HLINF}}{\phi_{B,p}} \right) \exp \left( - \frac{\phi_{B,p}}{E \text{ IG.HLINF}} \right) \quad 3-313$$

where  $\text{IG.ELINF}$  and  $\text{IG.HLINF}$  are the mean free path lengths of electrons and holes for scattering by optical phonons. The barrier heights  $\phi_{Bn,p}$  are defined according to:

$$\phi_{B,n} = \text{IG.EB0} - \text{IG.EBETA} \sqrt{E_{\perp}} - \text{IG.EETA} E_{\perp}^{2/3} - \Delta\psi(x, y) \quad 3-314$$

$$\phi_{B,p} = \text{IG.HB0} - \text{IG.HBETA} \sqrt{E_{\perp}} - \text{IG.HETA} E_{\perp}^{2/3} - \Delta\psi(x, y) \quad 3-315$$

where  $E_{\perp}$  is the electric field perpendicular to the semiconductor-insulator interface. The traditional barrier heights,  $\text{IG.EB0}$  and  $\text{IG.HB0}$ , are reduced to take account of three effects. The first effect is due to Schottky barrier lowering which depends on the perpendicular electric field at the semiconductor-insulator interface. The second effect takes account of tunneling through the gate oxide by reducing the barrier height. The third effect takes into account that a potential difference exists between the semiconductor-insulator interface and the starting position of the hot carrier. By default, this last effect is disabled. But you can enable it by specifying the  $\text{E.BENDING}$  and  $\text{H.BENDING}$  parameters for electrons and holes respectively.

The second probability  $P_1$  is the probability that no energy is lost by optical phonon scattering as the hot carrier travels towards the semiconductor-insulator interface after being redirected, and is given by:

$$P_{1,n} \sim \exp \left( - \frac{r}{\text{IG.ELINF}} \right) \quad 3-316$$

$$P_{1,p} \sim \exp \left( - \frac{r}{\text{IG.HLINF}} \right) \quad 3-317$$

where  $r$  is the distance from point of redirection to the semiconductor-insulator interface.

The final probability  $P_2$  accounts for the probability of scattering in the image force potential well in the gate oxide and is given by:

$$P_{2,n} = \exp \left( - \frac{\sqrt{\frac{q}{16\pi\epsilon_{ox} E_{ox}}}}{\text{PATH.N}} \right) \quad \text{for } \theta > \text{THETA.N} \quad 3-318$$

$$P_{2,n} = 0 \quad \text{for } \theta < \text{THETA.N} \quad 3-319$$

$$P_{2,p} = \exp \left( - \frac{\sqrt{\frac{q}{16\pi\epsilon_{ox} E_{ox}}}}{\text{PATH.P}} \right) \quad \text{for } \theta > \text{THETA.P} \quad 3-320$$

$$P_{2,p} = 0 \quad \text{for } \theta < \text{THETA.P} \quad 3-321$$

Here,  $PATH.N$  and  $PATH.P$  are the electron and hole mean free path lengths within the oxide,  $\epsilon_{ox}$  is the oxide permittivity and  $E_{ox}$  is the electric field in the oxide. The angle  $\theta$  introduces an angle dependence which is based upon the work of Wada [39]. His experiments indicate a critical rejection angle,  $THETA.N$  and  $THETA.P$ , between the angle  $\theta$  formed between the semiconductor-insulator interface and the electric field in the oxide. If the angle  $\theta$  is less than the rejection angle then the electrons are repelled back to the substrate.

Table 3-55 lists the user-definable model parameters that can be set in the MODELS statement, their default values, and their units.

| Table 3-55. User-Definable Parameters in Concannon's Gate Current Model |           |                       |                    |
|---|-----------|-----------------------|--------------------|
| Statement   | Parameter | Default               | Units              |
| MODELS  | IG.EB0    | 3.2                   | eV                 |
| MODELS  | IG.ELINR  | $6.16 \times 10^{-6}$ | cm                 |
| MODELS  | IG.HLINR  | $6.16 \times 10^{-6}$ | cm                 |
| MODELS  | IG.ELINF  | $9.2 \times 10^{-7}$  | cm                 |
| MODELS  | IG.HB0    | 4.0                   | eV                 |
| MODELS  | IG.HLINF  | $9.2 \times 10^{-7}$  | cm                 |
| MODELS  | IG.EBETA  | $2.59 \times 10^{-4}$ | $(Vcm)^{1/2}$      |
| MODELS  | IG.HBETA  | $2.59 \times 10^{-4}$ | $(Vcm)^{1/2}$      |
| MODELS  | IG.EETA   | $2.0 \times 10^{-5}$  | $V^{1/3} cm^{2/3}$ |
| MODELS  | IG.HETA   | $2.0 \times 10^{-5}$  | $V^{1/3} cm^{2/3}$ |
| MODELS  | IG.LRELE  | $3.0 \times 10^{-6}$  | [Q=1] cm           |
| MODELS  | IG.LRELH  | $2.0 \times 10^{-6}$  | [Q=1] cm           |
| MODELS  | PATH.N    | $3.4 \times 10^{-7}$  | cm                 |
| MODELS  | PATH.P    | $2.38 \times 10^{-7}$ | cm                 |
| MODELS  | THETA.N   | 60                    | degrees            |
| MODELS  | THETA.P   | 60                    | degrees            |

The implementation of this model is similar to that for Fowler-Nordheim tunneling. Each electrode-insulator and insulator-semiconductor interface is divided into discrete segments, which are based upon the mesh. For each insulator-semiconductor segment the Fowler-Nordheim current is calculated as described above. This current will then be added to a segment on the electrode-insulator boundary. Two schemes have been implemented to find out to which segment this current should be added.

The default model that calculates which electrode segment receives the hot carrier injected current follows the path of the electric field vector at the semiconductor-insulator interface. The first electrode-insulator segment that is found along this trajectory, provided no other semiconductors or metals are found along the trajectory, will receive the current.

A second model may be chosen using the `NEARFLG` parameter of the `MODELS` statement. In this case, the electrode-insulator segment found closest to the semiconductor-insulator segment will receive the hot carrier injected current.

The total current on the gate electrode is then the sum of the currents from all the individual segments around the electrode boundary.

The lucky electron hot carrier injection model can be used to include the electron or hole carrier temperature in the solution because the carrier temperature does not directly enter the equations.

The one exception is in `ATLAS2D` where the electric field parallel to the current flow is calculated as

$$E = 1.5 K_B T_n / IG.LRELE$$

for electrons if `HCTE.EL` is specified and

$$E = 1.5 K_B T_p / IG.LRELH$$

for holes if `HCTE.HO` is specified.  $K_{\{B\}}$  is Boltzmanns constant in units of eV/Kelvin. If `IG.LRELE` is set to zero then  $E$  will be calculated the same way as if `HCTE.EL` is unspecified. The same is true for `IG.LRELH` and `HCTE.HO`. In `ATLAS3D`, this model is unavailable and  $E$  is calculated the same way regardless if `HCTE` is specified.

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**Note:** When simulating EPROM programming with this model, the floating contact charging is simulated in the transient mode. In this case, the total current flowing into the floating electrode is multiplied by the time step to calculate the charge added to the electrode during that time step. The new value of charge is then used as the boundary condition for the next time step.

---

## Concannon's Injection Model

The implicit assumption in the lucky electron approach is a Maxwellian shape for the energy distribution of the hot carriers. Recent work by Fiegna [32] using Monte Carlo simulations suggests a non-Maxwellian high energy tail to the distribution function. To accurately model these effects, a non-Maxwellian based model from Concannon [33] has been implemented. This model requires the solution to the energy balance equation for the carrier temperatures but has been implemented in a similar manner to the lucky electron model. The Concannon gate injection model may be specified with the parameters `N.CONCANNON` and `P.CONCANNON` on the `MODELS` statement. This choice of parameters automatically activates the Energy Balance Transport Model.

The Concannon injection model has a similar form to the lucky electron model. The injected current is calculated according to:

$$I_{inj} = \iint P_n(x, y) n(x, y) dx dy + \iint P_p(x, y) p(x, y) dx dy \quad 3-322$$

where  $n(x, y)$  and  $p(x, y)$  are the carrier concentrations within the semiconductor. The probability functions  $P_n(x, y)$  and  $P_p(x, y)$  are now defined by:

$$P_n(x, y) = -q \text{CGATE.N} P_{\phi_{B, n}} P_{1, n} P_{2, n} \quad 3-323$$

$$P_p(x, y) = q \text{CGATE.P} P_{\phi_{B, p}} P_{1, p} P_{2, p} \quad 3-324$$

where  $q$  is the electronic charge and the parameters `CGATE.N` and `CGATE.P` are user-definable on the `MODEL` statement. The three probability functions in Equations 3-322 and 3-323 shall now be described.

The probability that a carrier has sufficient energy to surmount the insulator-semiconductor barrier of height  $\phi_B$  is now defined as a function of energy. The probability now has the form:

$$P_{\phi_{B,n}} = \int_{\phi_{B,n}}^{\infty} v_{\perp}(\varepsilon)F(\varepsilon, T_n(x, y))d\varepsilon \quad 3-325$$

$$P_{\phi_{B,p}} = \int_{\phi_{B,p}}^{\infty} v_{\perp}(\varepsilon)F(\varepsilon, T_p(x, y))d\varepsilon \quad 3-326$$

Here,  $v_{\perp}(\varepsilon)$  is the perpendicular velocity of a hot carrier and defines the probability of a hot carrier with an energy  $\varepsilon$  travelling in the direction of the insulator-semiconductor. The barrier heights  $\phi_{Bn,p}$  are defined according to:

$$\phi_{B,n} = \mathbf{PEFF.N} - \mathbf{IG.EBETA} \sqrt{E_{\perp}} - \mathbf{IG.EETA} E_{\perp}^{2/3} - \Delta\psi(x, y) \quad 3-327$$

$$\phi_{B,p} = \mathbf{PEFF.P} - \mathbf{IG.HBETA} \sqrt{E_{\perp}} - \mathbf{IG.HETA} E_{\perp}^{2/3} - \Delta\psi(x, y) \quad 3-328$$

where  $E_{\perp}$  is the electric field perpendicular to the semiconductor-insulator interface. The traditional barrier heights,  $\mathbf{IG.EB0}$  and  $\mathbf{IG.HB0}$ , are reduced to take account of three effects. The first effect is due to Schottky barrier lowering which depends on the perpendicular electric field at the semiconductor-insulator interface. The second effect takes account of tunneling through the gate oxide by reducing the barrier height. The third effect takes into account that a potential difference exists between the semiconductor-insulator interface and the starting position of the hot carrier. By default, this last effect is disabled. But you can enable it by specifying the  $\mathbf{E.BENDING}$  and  $\mathbf{H.BENDING}$  parameters for electrons and holes respectively.

The carrier velocity model follows the approach of Fiegna et. al. [32.] where velocity is proportional to energy according to:

$$v_{\perp} \sim \varepsilon^{0.25} \quad 3-329$$

The function,  $F(\varepsilon, T_{n,p}(x,y))$ , is determined by the density of states and the energy distribution function according to:

$$F(\varepsilon, T_n(x, y)) \sim \frac{g(\varepsilon)f(\varepsilon)}{\int_0^{\infty} g(\varepsilon)f(\varepsilon)d\varepsilon} \quad 3-330$$

The density of states  $g(\varepsilon)$  follows the analysis of Cassi [40] where:

$$g(\varepsilon) \sim \varepsilon^{0.25} \quad 3-331$$

Finally the energy distribution functions for electrons and holes are defined by:

$$f_e(\varepsilon) \sim \left[ \exp\left(\frac{-\mathbf{ETH.N} \varepsilon^3}{T_n^{1.5}}\right) + \mathbf{C0} \exp\left(\frac{-\mathbf{ETH.P} \varepsilon^3}{T_n^{1.5}}\right) \right] \quad 3-332$$

$$f_h(\varepsilon) \sim \exp\left(\frac{-\mathbf{CHI.A} \varepsilon^3}{T_p^{1.5}}\right) \quad 3-333$$

where  $\mathbf{ETH.N}$ ,  $\mathbf{ETH.P}$ ,  $\mathbf{CHI.A}$ , and  $\mathbf{C0}$  are user-definable constants found from fitting to measured data. The terms:  $T_n$  and  $T_p$  are the mean carrier temperatures for electrons and holes, which are calculated from the Energy Balance Transport Model.

Normalization in all of the above equations is accounted for in the combined constants of proportionality,  $\mathbf{CGATE.N}$  and  $\mathbf{CGATE.P}$ .

The second probability  $P_l$  is the probability that no energy is lost by optical phonon scattering as the hot carrier travels towards the semiconductor-insulator interface after being redirected and is given by:

$$P_{1,n} \sim \exp\left(-\frac{r}{\mathbf{IG.ELINF}}\right) \quad 3-334$$

$$P_{1,p} \sim \exp\left(-\frac{r}{\mathbf{IG.HLINF}}\right) \quad 3-335$$

where  $r$  is the distance from point of redirection to the semiconductor-insulator interface.

The final probability  $P_2$  accounts for the probability of scattering in the image force potential well in the gate oxide and is given by:

$$P_{2,n} = \exp\left(\frac{\sqrt{\frac{q}{16\pi\varepsilon_{ox}E_{ox}}}}{\mathbf{PATH.N}}\right) \quad \text{for } \theta > \mathbf{THETA.N} \quad 3-336$$

$$P_{2,n} = 0 \quad \text{for } \theta > \mathbf{THETA.N} \quad 3-337$$

$$P_{2,p} = \exp\left(\frac{\sqrt{\frac{q}{16\pi\varepsilon_{ox}E_{ox}}}}{\mathbf{PATH.P}}\right) \quad \text{for } \theta > \mathbf{THETA.P} \quad 3-338$$

$$P_{2,p} = 0 \quad \text{for } \theta < \mathbf{THETA.P} \quad 3-339$$

Here,  $\mathbf{PATH.N}$  and  $\mathbf{PATH.P}$  are the electron and hole mean free path lengths within the oxide,  $\varepsilon_{ox}$  is the oxide permittivity and  $E_{ox}$  is the electric field in the oxide. The angle  $\theta$  introduces an angle dependence which is based upon the work of Wada [39]. His experiments indicate a critical rejection angle,  $\mathbf{THETA.N}$  and  $\mathbf{THETA.P}$  between the angle  $\theta$  formed between the semiconductor-insulator interface and the electric field in the oxide. If the angle  $\theta$  is less than the rejection angle, then the electrons are repelled back to the substrate.

---

**Note:** The current implementation of the Concannon model for hot carrier injection is that only carriers along the semiconductor-insulator interface are significant and as a result the probability  $P_1$  is assumed unity. This also means that the integration is only applied to those node points along the semiconductor-insulator interface.

---

Two other parameters of the `MODELS` statement that may affect the result of the numeric integration are user-definable. The `ENERGY.STEP` parameter specifies the energy step size in eV used during the numeric integration. The default step size is 25 meV. The `INFINITY` parameter sets the upper limit of the integration and specifies ratio of the increment added to the integral divided by the current value of the integral. The default value of the `INFINITY` parameter is 0.001.

The implementation of this model is similar to that for Fowler-Nordheim tunneling. Each electrode-insulator and insulator-semiconductor interface is divided into discrete segments which are based upon the mesh. For each insulator-semiconductor segment the Fowler-Nordheim current is calculated as described above. This current will then be added to a segment on the electrode-insulator boundary. Two schemes have been implemented to find out to which segment this current should be added.

The default model that calculates which electrode segment receives the hot carrier injected current follows the path of the electric field vector at the semiconductor-insulator interface. The first electrode-insulator segment that is found along this trajectory, provided no other semiconductors or metals are found along the trajectory, will receive the current.

A second model may be chosen using the `NEARFLG` parameter of the `MODELS` statement. In this case the electrode-insulator segment found closest to the semiconductor-insulator segment will receive the hot carrier injected current.

The total current on the gate electrode is then the sum of the currents from all the individual segments around the electrode boundary.

---

**Note:** To maintain self-consistent results, it's important that this model is implemented if the Concannon model is being used for the simulation of substrate current.

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## 3.6.6: Device Level Reliability Modeling

### Hansch MOS Reliability Model

The Hansch Reliability Model [41,100,101] can be used to simulate MOS transistor degradation under stress conditions. The causes of device characteristic degradation are the hot electron (hole) injection into gate oxide, and the trapping of electron (hole) charge on the effective interface acceptor (donor) like traps.

The model calculates hot electron (hole) injection current according to the lucky electron model. The arbitrary position-dependent distributions of acceptor and donor-like traps are specified on the oxide-semiconductor interface with corresponding capture cross sections. The device degradation is calculated as a function of stress time by performing transient calculations. The trap rate equation is solved on every time-step and thus the trapped electron (hole) concentration is calculated. The rate of electron trapping can be described by the equations:

$$\frac{dN_n(x,t)}{dt} = \frac{\text{SIGMAE}}{q} \cdot J_{inj,n}(x,t) \cdot (\text{NTA}(x) - N(x,t)) \quad 3-340$$

$$\frac{dN(x,t)}{dt} = \frac{\text{SIGMAH}}{q} \cdot J_{inj,p}(x,t) \cdot (\text{NTD}(x) - N(x,t)) \quad 3-341$$

where  $N(x,t)$  represents the trapped electron (hole) density, at the interface point  $x$ , at time= $t$  during a transient simulation. The NTA and NTD parameters represent the acceptor and donor-like trap densities at time=0. The  $J_{inj,n}(x,t)$  and  $J_{inj,p}(x,t)$  parameters are the injected electron and hole current densities, SIGMAE and SIGMAH are the capture cross section of electrons and holes.

To activate this model, use the DEVDEG, DEVDEG.E, and DEVDEG.H parameters in the MODELS statement (to account for both hot electron and hole injection, hot electron or hot hole injection, respectively). The model parameters are user-definable on the DEGRADATION statement.

| Statement   | Parameter | Units           |
|-------------|-----------|-----------------|
| DEGRADATION | SIGMAE    | cm <sup>2</sup> |
| DEGRADATION | SIGMAH    | cm <sup>2</sup> |
| DEGRADATION | NTA/F.NTA | cm <sup>2</sup> |
| DEGRADATION | NTD/F.NTD | cm <sup>2</sup> |

The results of stress simulation can be used to calculate the characteristics of the degraded device (the shift of the threshold voltage, transconductance degradation, and so on). You can view the distribution of traps, hot electron (hole) current density, and trapped electron (hole) distribution by using TONYPLOT.

The model parameters: NTA, NTD, SIGMAE, and SIGMAH can also be defined through the C-INTERPRETER functions: F.NTA, F.NTD, F.SIGMAE, and F.SIGMAH. This allows you to define these values as functions of their position (x,y) along the insulator-semiconductor interface. These C-function libraries are also defined on the DEGRADATION statement. More information on the C-INTERPRETER functions can be found in Appendix A: “C-Interpreter Functions”.

### 3.6.7: The Ferroelectric Permittivity Model

Ferroelectric materials exhibit high dielectric constants, polarization and hysteresis. Such materials are finding more and more applications in integrated memory devices. To simulate these effects, a modified version of the ferroelectric model from Miller [117.] has been implemented.

To enable the Ferroelectric Model, set the FERRO parameter in the MODELS statement. In this model the permittivity used in Poisson’s Equation (Equation 3-1) is given the following functional form:

$$\varepsilon(E) = \mathbf{FERRO.EPSF} + \mathbf{FERRO.PS} \cdot 2\delta \cdot \operatorname{sech}^2 \left[ \frac{E - \mathbf{FERRO.EC}}{2\delta} \right] \quad 3-342$$

where FERRO.EPSF is the permittivity,  $E$  is the electric field and  $\delta$  is given as follows:

$$\delta = \mathbf{FERRO.EC} \left[ \log \frac{1 + \mathbf{FERRO.PR}/\mathbf{FERRO.PS}}{1 - \mathbf{FERRO.PR}/\mathbf{FERRO.PS}} \right]^{-1} \quad 3-343$$

The FERRO.EPSF, FERRO.PS, FERRO.PR, and FERRO.EC parameters can be modified in the MATERIAL statement (see Table 3-57).

The permittivity in Equation 3-341 can be replaced with a user-defined expression with the C-INTERPRETER. The F.FERRO parameter of the MATERIAL statement (see Chapter 18: “Statements”, Section 18.24: “MATERIAL”) defines the file that contains the C-function. This function allows the permittivity to be position and field dependent.

For more information about C-Interpreter, see Appendix A: "C-Interpreter Functions".

The derivative of the dipole polarization with respect to electric field is given by:

$$\frac{dP_d}{dE} = \Gamma \frac{dP_{sat}}{dE} \tag{3-344}$$

where  $P_d$  is the position dependent dipole polarization. A numeric integration of this function is carried out in ATLAS to determine the position dependent dipole polarization.

For saturated loop polarization, the  $\Gamma$  function is equal to unity, which corresponds to the default model. If you specify the UNSAT.FERRO parameter in the MODELS statement, the  $\Gamma$  function will take on a more general form suitable for simulation of unsaturated loops. In this case, the  $\Gamma$  function is given by:

$$\Gamma = 1 - \tanh \left[ \left( \frac{P_d - P_{sat}}{\xi P_s - P_d} \right)^{1/2} \right] \tag{3-345}$$

where  $\xi = 1$  for increasing fields and  $\xi = -1$  for decreasing fields.

| Table 3-57. User-Specifiable Parameters for Equations 3-342 to 3-343 |           |         |        |
|--|-----------|---------|--------|
| Statement  | Parameter | Default | Units  |
| MATERIAL   | FERRO.EC  | 0.0     | V/cm   |
| MATERIAL   | FERRO.EPS | 1.0     |        |
| MATERIAL   | FERRO.PS  | 0.0     | C/sqcm |
| MATERIAL   | FERRO.PR  | 0.0     | C/sqcm |

### 3.6.8: Polarization in Wurtzite Materials

Polarization in wurtzite materials is characterized by two components, spontaneous polarization,  $P_{sp}$ , and piezoelectric polarization,  $P_{pi}$ . Therefore, the total polarization,  $P_t$ , is given by:

$$P_t = P_{sp} + P_{pi} \tag{3-346}$$

where  $P_{sp}$  is specified on the MATERIAL statement and specifies the total spontaneous polarization,  $P_{sp}$ , for the given material(s). The piezoelectric polarization,  $P_{pi}$ , is given by:

$$P_{pi} = 2 \frac{a_s - a_0}{a_0} \left( E_{31} - \frac{C_{13}}{C_{33}} E_{33} \right) \tag{3-347}$$

where  $E_{31}$  and  $E_{33}$  are piezoelectric constants, and  $C_{13}$  and  $C_{33}$  are elastic constants all specified in the MATERIAL statement. The  $a_0$  parameter is the lattice constant of the material layer in question, which can be specified by the ALATTICE parameter of the MATERIAL statement. The  $a_s$  parameter is the average value of the lattice constants of the layers directly above and below the layer in question.

To enable the polarization model, specify POLARIZATION in the REGION statement for the region for which you wish to characterize polarization effects. Typically, this will be a quantum well layer or active layer.



The polarization enters into the simulation as a positive and negative fixed charges appearing at the top (most negative Y coordinate) and bottom (most positive Y coordinate) of the layer in question. By default, the positive charge is added at the bottom and the negative charge is added at the top. You can modify the sign and magnitude of this charge by specifying `POLAR.SCALE` in the `REGION` statement. This parameter is multiplied by the polarization determined by Equation 3-346 to obtain the applied charge. The default value for `POLAR.SCALE` is 1.0.

In some cases, the introduction of polarization charges may introduce difficulties with convergence due to problems with initial guess. If these problems arise, you can use the `PIEZSCALE` parameter of the `SOLVE` statement to gradually introduce the effects of polarization. This parameter defaults to 1.0 and is multiplied by the net charge given by the product of the results of Equation 3-347 and the `POLAR.SCALE` parameter.

Table 3-58 shows the parameters of the wurtzite polarization model.

| <b>Table 3-58. User Specifiable Parameters of the Wurtzite Polarization Model</b> |                  |                |                  |
|---|------------------|----------------|------------------|
| <b>Statement</b>  | <b>Parameter</b> | <b>Default</b> | <b>Units</b>     |
| MATERIAL  | PSP              | see Table B-21 | $\text{Cm}^{-2}$ |
| MATERIAL  | ALATTICE         | see Table B-21 | Å                |
| MATERIAL  | E13              | see Table B-21 | $\text{Cm}^{-2}$ |
| MATERIAL  | E33              | see Table B-21 | $\text{Cm}^{-2}$ |
| MATERIAL  | C13              | see Table B-20 | GPa              |
| MATERIAL  | C33              | see Table B-20 | GPa              |

### 3.7: Quasistatic Capacitance - Voltage Profiles

Quasistatic Capacitance is calculated by specifying the `QSCV` parameter in the `SOLVE` statement. The quasistatic capacitance is obtained for the electrode (whose bias is being ramped) by subtracting the electrode charge on the electrode at one bias from that at the adjacent bias and dividing by the Voltage increment. The charge density is calculated by applying Gauss' Flux Theorem to the electrode. This gives the capacitance at the midpoint between the two bias points. ATLAS does not correct the output for this because the voltage increment should be sufficient fine. Therefore, this small shift is negligible. A fine voltage increment will also give a good approximation to the continuous derivative.

`QSCV` will work with `CARRIERS=0, 1` or `2` specified in the `METHOD` statement. If you link electrodes using the `COMMON` parameter of the `CONTACT` statement, then the capacitance for each one and the sum of capacitances will be calculated. If you specify `MULT` and `FACTOR` for a linked electrode, then the capacitance will be calculated for the appropriate bias points, but will be stored as a function of the bias applied to the `COMMON` electrode. In this case, scaling or shifting of the C-V curve may be necessary.

### 3.8: Conductive Materials

In certain cases, it may be advantageous to simulate metal conductivity directly rather than handling electrodes as boundaries. You can define metal regions as “conductive” by specifying the `CONDUCTOR` parameter of the `REGION` statement. This might be useful, for example in simulating self-heating in metal regions.

When the metal is treated as a conductor, the conduction equation for all points in the region are solved as follows:

$$J = \varepsilon / \text{RESISTIVITY} \qquad 3-348$$

where  $J$  is the current density,  $\varepsilon$  is the electric field, and `RESISTIVITY` is the metal resistivity in metal resistivity in  $\mu\Omega/\text{cm}$ . To specify the metal resistivity, use the `RESISTIVITY` parameter from the `MATERIAL` statement. To specify the thermal coefficient of resistivity, use the `DRHODT` parameter from the `MATERIAL` statement.

## 3.9: Optoelectronic Models

This section discusses various physical models used to simulate optoelectronic devices. These models predict fundamental optoelectronic processes, such as absorption and gain and radiative recombination rates versus material composition, temperature and optical wavelength.

These models are based on various band theories and account for the following:

- the existence of multiple valence bands supporting multiple optical transitions,
- asymmetry in conduction band effective masses,
- the effects of strain on the band parameters,
- the effects of quantum confinement on allowable transitions.

In the following paragraphs, we will discuss three optoelectronic models.

With respect to their various principal investigators they are named the Yan model, the Li model and the Chuang model. To activate these models, specify `YAN`, `LI` or `CHUANG` in the `MODELS` statement. Yan and Li's models are applicable to zincblende materials while Chuang's model applies to wurtzite materials. Yan's model is based on a single valence band, Li's is based on two valence bands (light holes and heavy holes), and Chuang's model is based on three valence bands (light holes, heavy holes and crystal split-off holes).

In addition to the band structure based models, there are certain, more general but less physical models that are also mentioned. All of these models are used in the following applications:

- General drift-diffusion to account for radiative recombination for any semiconductor device,
- Laser and VCSEL simulation in both stimulated emission gain and spontaneous emission (see Chapters 8: "Laser: Edge Emitting Simulator" and 9: "VCSEL Simulator"),
- LED light emission (see Chapter 11: "LED: Light Emitting Diode Simulator").

### 3.9.1: The General Radiative Recombination Model

At the most, fundamental level the radiative recombination model described in Equation 3-242 describes all the most salient features of radiative recombination except spectral content. You can, however, use this model in all three applications mentioned above. It has the advantages of being fast, simple and easily calibrated.

To enable the general model, specify `OPTR` in the `MODEL` statement. This will enable radiative recombination using the general model in the drift diffusion part of the simulation. To enable this model in `LASER` or `VCSEL`, disable the default model for `LASER` and `VCSEL` by specifying `^SPONTANEOUS` in the `LASER` statement. To use the general model for `LED`, make sure no other competing mechanisms are enabled. The disadvantage of using this model for any light emission application is that it lacks spectral information.

When used in `LASER` and `VCSEL` the spontaneous recombination rate is given by:

$$r(r, z) = \frac{\text{EMISSION\_FACTOR} \cdot \text{COPT} \cdot (n \cdot p - n_i^2)}{N_l} \quad 3-349$$

where  $n$  and  $p$  are the electron and hole concentrations,  $n_i$  is the intrinsic concentration,  $N_l$  is the number of longitudinal modes, `EMISSION_FACTOR` and `COPT` are user-defined parameters on the `MATERIAL` statement. `COPT` accounts for the radiative rate in all directions and energies. `EMISSION_FACTOR` represents the fraction of energy coupled into the direction of interest and in the energy range of interest. Note that Equation 3-349 contains no spectral information.

### 3.9.2: The Default Radiative Recombination Model

The default spontaneous radiative recombination model is given by

$$r_{sp_m}(r, z) = \mathbf{ESEP} \cdot \mathbf{EMISSION\_FACTOR} \frac{c}{\mathbf{NEFF}} \cdot D(E) \cdot \mathbf{GAIN0} \cdot \sqrt{\frac{\hbar\omega - E_g}{kT}} \cdot f\left(\frac{E_c - E_{fn} + \mathbf{GAMMA}(\hbar\omega - E_g)}{kT}\right) \cdot \left[1 - f\left(\frac{E_v - E_{fp} - (1 - \mathbf{GAMMA})(\hbar\omega - E_g)}{kT}\right)\right] \quad 3-350$$

where:

- $c$  is the speed of light,
- $\hbar$  Planck's constant,
- $k$  Boltzman's constant,
- $E_g$  is the energy bandgap,
- $E_c$  and  $E_v$  are the conduction and valence band edge energies,
- $T$  is the lattice temperature,
- $E_{fn}$  and  $E_{fp}$  are the electron and hole quasi-Fermi energies,
- $\omega$  is the emission frequency that corresponds to the transition energy  $E$ ,
- $D(E)$  is the optical mode density,
- $\mathbf{EMISSION\_FACTOR}$ ,  $\mathbf{GAIN0}$  and  $\mathbf{GAMMA}$  are user defined parameters from the **MATERIAL** statement,
- $\mathbf{ESEP}$  and  $\mathbf{NEFF}$  are user-defined parameters specified from the **LASER** statement.

The optical mode density  $D(E)$  is given by

$$D(E) = \frac{n^3 E^2}{\pi \hbar^3 c^3} \quad 3-351$$

where  $n$  is the index of refraction.

The function  $f(x)$  is given by

$$f(x) = \frac{1}{1 + \exp(x)}. \quad 3-352$$

### 3.9.3: The Standard Gain Model

The standard gain model [104,105] is enabled by specifying **G.STANDARD** in the **MODELS** statement. The standard gain model is given by

$$g(r, z) = \mathbf{GAIN0} \sqrt{\frac{\hbar\omega - E_g}{kT}} \left[ f\left(\frac{E_c - E_{fn} + \mathbf{GAMMA}(\hbar\omega - E_g)}{kT}\right) - f\left(\frac{E_v - E_{fp} - (1 - \mathbf{GAMMA})(\hbar\omega - E_g)}{kT}\right) \right] \quad 3-353$$

where:

- $\hbar$  is Planck's constant,
- $E_g$  is the energy bandgap,
- $k$  is Boltzman's constant,
- $T$  is the lattice temperature,
- $E_{fn}$  and  $E_{fp}$  are the electron and hole quasi-Fermi energies,

- $\omega$  is the emission frequency,
- $E_v$  and  $E_c$  are the valence and conduction band edge energies,
- the function  $f$  is defined in Equation 3-352,
- GAMMA and GAIN0 user-definable parameters specified on the MATERIAL statement.

Table 3-59 describes the user defined parameters of Equation 3-353.

| Table 3-59. User-Specifiable Parameters for Equation 3-353 |           |         |                  |
|--|-----------|---------|------------------|
| Statement  | Parameter | Default | Units            |
| MATERIAL   | GAIN0     | 2000.0  | cm <sup>-1</sup> |
| MATERIAL   | GAMMA     |         |                  |

If GAMMA in Equation 3-353 is not specified, it is automatically calculated from the following expression:

$$GAMMA = \frac{1}{\left(\frac{N_c}{N_v}\right)^{\frac{2}{3}} + 1} \tag{3-354}$$

where  $N_c$  and  $N_v$  are the conduction and valence band densities of states.

### 3.9.4: The Empirical Gain Model

The empirical gain model is enabled by specifying G.EMPIRICAL in the MODELS statement. The model is described by the following expression:

$$g(r, z) = GAIN00 + GAIN1N \cdot n + GAIN1P \cdot p + GAIN2NP \cdot np + GAIN1MIN \cdot \min(n, p) \tag{3-355}$$

where  $n$  and  $p$  are the electron and hole concentrations, and GAIN00, GAIN1N, GAIN1P, GAIN2NP and GAIN1MIN are user-specified parameters from the MATERIAL statement. Note that the empirical model contains no spectral dependency and should not be used for LASER or VCSEL simulations with multiple longitudinal modes. Table 3-60 shows the user-definable parameters for Equation 3-355.

| Table 3-60. User-Specifiable Parameters for Equation 3-355 |           |                       |                  |
|--|-----------|-----------------------|------------------|
| Statement  | Parameter | Default               | Units            |
| MATERIAL   | GAIN00    | -200.0                | cm <sup>-1</sup> |
| MATERIAL   | GAIN1N    | 0                     | cm <sup>2</sup>  |
| MATERIAL   | GAIN2N    | 0                     | cm <sup>2</sup>  |
| MATERIAL   | GAIN1NP   | 0                     | cm <sup>5</sup>  |
| MATERIAL   | GAIN1MIN  | 3.0x10 <sup>-16</sup> | cm <sup>2</sup>  |

### 3.9.5: Tayamaya's Gain Model

Tayamaya's gain model [128] is enabled by specifying TAYAMAYA in the MODELS statement. Tayamaya's model is described by the following expression:

$$\begin{aligned}
 g(r, z) &= \mathbf{GN1}(n(r, z) - \mathbf{NTRANSPARENT}) & n > \mathbf{NTRANSPARENT} \\
 g(r, z) &= \mathbf{GN2}(n(r, z) - \mathbf{NTRANSPARENT}) & n \leq \mathbf{NTRANSPARENT}
 \end{aligned}
 \tag{3-356}$$

where  $n$  is the electron concentration and GN1, GN2 and NTRANSPARENT are user-specified parameters from the MATERIAL statement. As in the empirical gain model, this model contains no spectral dependency and should not be used to simulate multiple longitudinal modes in LASER or VCSEL. Table 3-61 shows the user definable parameters for Equation 3-356.

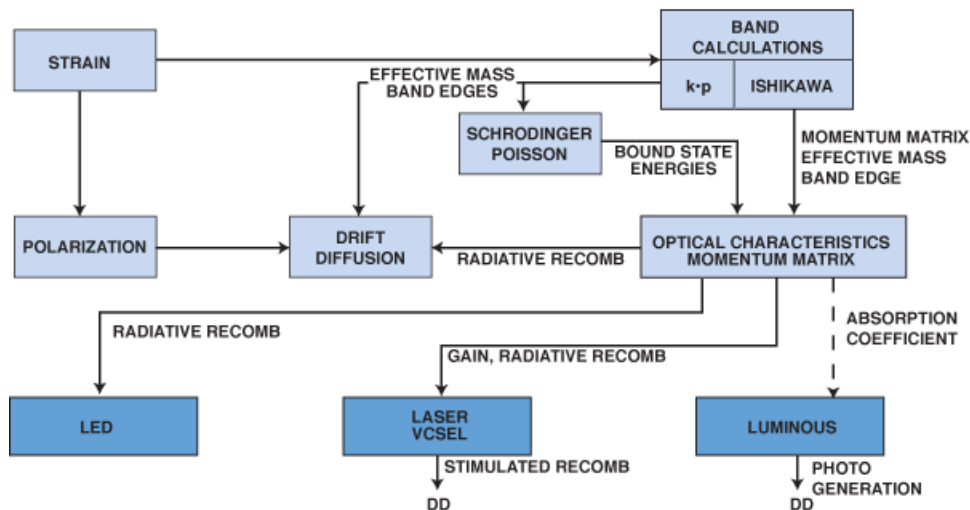
| Statement | Parameter    | Default               | Units            |
|-----------|--------------|-----------------------|------------------|
| MATERIAL  | GN1          | $3.0 \times 10^{-16}$ | $\text{cm}^2$    |
| MATERIAL  | GN2          | $4.0 \times 10^{-15}$ | $\text{cm}^2$    |
| MATERIAL  | NTRANSPARENT | $2.0 \times 10^{18}$  | $\text{cm}^{-3}$ |

### 3.9.6: Band Structure Dependent Optoelectronic Models

Although the simple models described in Sections 3.9.1: “The General Radiative Recombination Model” through 3.9.5: “Tayamaya's Gain Model” are useful for modeling the principal effects, they suffer from one or more of the following drawbacks:

- they lack spectral dependencies,
- they are not generally calibrated to all tools,
- they do not account for effects of strain,
- they do not account for the effects of quantum confinement,
- the lack physical basis.

The following sections will describe more physically based models. Figure 3-3 illustrates the simulation flow for these models.



**Figure 3-3: Simulation Flow For Physically Based Optoelectronic Models**

First, strain is introduced either directly or calculated from lattice mismatch and used to calculate the strain effects on band calculations. The strain is also introduced to polarization calculations that enter directly into the drift diffusion calculations as polarization fields.

Next, the band parameters (band edges and effective masses) are used directly in the drift diffusion simulations as well as feeding into the solutions of Schrodinger's equations to calculate the bound state energies. The band parameters and bound state energies are then used to calculate gain, radiative recombination rate and optical absorption.

### 3.9.7: Yan's and Li's Models for Gain and Radiative Recombination in Zincblende Materials

You can select one of two models for optical gain and spontaneous recombination. If the LI parameter is specified, the model by Li [136] will be used. If the YAN parameter is specified the model by Yan [137] will be used. The difference between the models is that in the YAN Model only one valence band is accounted for, whereas the LI Model accounts for both light and heavy holes in the valence band.

The first step in calculating the gain and radiative recombination is to calculate the bound state energies. The band edge energies and effective masses are used to calculate the quantum well bound state energies through the Schrodinger's Equation (See Chapter 13: "Quantum: Quantum Effect Simulator", Equations 13-1 and 13-2). This calculation is performed in the same manner as the Self-Consistent Coupled Schrodinger Poisson Model. The calculation of the bound state energies is performed over a discrete domain that isn't the same as the device simulation mesh. The discrete domain is specified by the WELL.NX and WELL.NY parameters in the REGION statement.

The WELL.NX and WELL.NY parameters specify the number of uniform mesh locations in the bounding box where the solution of Schrodinger's Equation is performed to extract bound state energies. Typically, WELL.NY should be set to a large number so that there will be several samples per well. WELL.NX should be comparable to the number of grid lines in the device mesh over the same extent in the X direction.



Once the bound state energies are calculated, the bulk momentum matrix element is calculated as shown in Equation 3-357.

$$|M_{avg}|^2 = \frac{m_0}{6} \left( \frac{m_0}{m^*} - 1 \right) \frac{E_g (E_g + \text{WELL.DELTA})}{\left( E_g + \frac{2}{3} \text{WELL.DELTA} \right)} \quad 3-357$$

where  $m^*$  is the effective mass,  $E_g$  is the bandgap, and `WELL.DELTA` is the user-specifiable spin-orbital splitting energy as described in Table 3-62.

| Table 3-62. User-Specifiable parameters for Equation 3-357 |            |         |       |
|--|------------|---------|-------|
| Statement  | Parameter  | Default | Units |
| MATERIAL   | WELL.DELTA | 0.341   | eV    |

Next, the bulk momentum matrix element is used to calculate the quantum well matrix element. If the YAN Model is specified, Equation 3-358 will be used to calculate the quantum well momentum matrix element.

$$|M_{qw}|^2 = \frac{3}{4} |M_{avg}|^2 \quad 3-358$$

If the LI Model is specified the matrix elements for light and heavy holes are given by Equation 3-359.

$$\begin{aligned} M_{hh} &= A_{hh} M_{avg} \\ M_{lh} &= A_{lh} M_{avg} \end{aligned} \quad 3-359$$

where  $A_{hh}$  and  $A_{lh}$  are anisotropy factors for heavy and light holes.

The anisotropy factors depend upon whether TM or TE modes are the dominant modes [136]. The dominant mode is user-specifiable by using the `TE.MODES` parameter of the `MATERIAL` statement. When this parameter is `true` (default), the TE mode models are used and when `false` the TM mode model is used.

For TE modes, the values of the anisotropy factors are given by Equation 3-360.

$$\begin{aligned} A_{hh} &= \frac{3 + 3E_{ij}/E}{4}, & A_{lh} &= \frac{5 - 3E_{ij}/E}{4} & \text{for}(E > E_{ij}) \\ A_{hh} &= 3/2, & A_{lh} &= 1/2 & \text{for}(E \leq E_{ij}) \end{aligned} \quad 3-360$$

For TM modes, the values of the anisotropy factors are given by Equation 3-361.

$$\begin{aligned} A_{hh} &= \frac{3 - 3E_{ij}/E}{2}, & A_{hh} &= \frac{1 + 3E_{ij}/E}{2} & \text{for}(E > E_{ij}) \\ A_{hh} &= 0, & A_{lh} &= 2 & \text{for}(E < E_{ij}) \end{aligned} \quad 3-361$$

where  $E$  is the transition energy and  $E_{ij}$  is the energy difference between the  $i$ th conduction bound state and the  $j$ th valence band state.

The bound state energies and effective masses are then used to calculate the Fermi functions given in Equation 3-362.

$$f_i^{\prime} = \left\{ 1 + \exp \left[ \left( E_i - \frac{m_{ij}}{m_i} (E - E_{ij}) - E_{fp} \right) / kT \right] \right\}^{-1}$$

$$f_j^{\prime} = \left\{ 1 + \exp \left[ \left( E_j - \frac{m_{ij}}{m_j} (E - E_{ij}) - E_{fn} \right) / kT \right] \right\}^{-1}$$
3-362

where  $E_{fp}$  is the hole Fermi level,  $E_{fn}$  is the electron Fermi level,  $E_i$  is the valence band energy, and  $E_j$  is the conduction band energy.

Next, the reduced effective masses are used to calculate the 2D density of states as in Equation 3-363.

$$\rho = \frac{m}{\pi \hbar^2 t}$$
3-363

where  $t$  is the quantum well width.

Next, the optical mode density is calculated as given by Equation 3-364.

$$D(E) = \frac{n^3 E^2}{\pi^2 \hbar^3 c^3}$$
3-364

### Optical Gain Models

For the LI Model, the optical gain is given by Equation 3-365.

$$g_{ij}(E_{ij}^0) = \left( \frac{2\pi}{\hbar} \right) |H_{ij}|^2 (f_j^{\prime} - f_i^{\prime}) \left( \frac{\epsilon_1}{nc} \right) \rho \cdot \mathbf{WELL.GAIN}$$

$$|H_{ij}|^2 = \left( \frac{q}{m_0} \right)^2 \left( \frac{2\hbar\omega}{4\epsilon_1 \epsilon_0 \omega^2} \right) M_{ij}^2$$
3-365

where  $H_{ij}$  is the Hamiltonian matrix element,  $\omega$  is the frequency, and  $M_{ij}$  is either  $M_{hh}$  or  $M_{eh}$  and  $\mathbf{WELL.GAIN}$  is a user-specifiable scale factor on the `REGION` statement.

For the YAN Model, the optical gain is given by Equation 3-366.

$$g(E) = \left( \frac{\pi e^2 \hbar}{\epsilon_0 n c m_0^2 E} \right) |M_{qw}|^2 \rho \cdot D(E) (f_j^{\prime} - f_i^{\prime})$$
3-366

### Spontaneous Recombination Models

For the LI Model, the spontaneous recombination is given by Equation 3-367.

$$r_{sp}(E) = \sum_{i,j} \left( \frac{2\pi}{\hbar} \right) |H_{ij}|^2 f_j^{\prime} (1 - f_i^{\prime}) D(E) \rho$$
3-367

For the YAN Model, the spontaneous recombination is given by Equation 3-368.

$$r_{sp}(E) = \left( \frac{2\pi}{\hbar} \right) \left( \frac{e}{m_0} \right)^2 \left( \frac{2\hbar\omega/\epsilon}{4\omega^2} \right) |M_{qw}|^2 \rho \cdot D(E) \cdot f_j^{\prime} (1 - f_i^{\prime})$$
3-368

### 3.9.8: Chuang's Three Band Model for Gain and Radiative Recombination in Wurtzite Materials

Chuang's model [148] is derived from the  $k^*p$  method for three valence bands in wurtzite crystalline structure. Given the assumptions of parabolic bands, no valence band mixing and momentum approaching zero, the following approach can be used. First, we solve the strain tensor as given in Equations 3-369 through 3-371

$$\varepsilon_{xx} = \varepsilon_{yy} = \frac{a_s - a_0}{a_0} \quad 3-369$$

$$\varepsilon_{zz} = -2 \frac{C_{13}}{C_{33}} \varepsilon_{xx} \quad 3-370$$

$$\varepsilon_{xy} = \varepsilon_{yz} = \varepsilon_{zx} = 0 \quad 3-371$$

where  $a_s$  is the lattice constant in the strained layer,  $a_0$  is the bulk layer lattice constant,  $C_{13}$  and  $C_{33}$  are elastic constants and  $\varepsilon_{xx}$ ,  $\varepsilon_{yy}$ ,  $\varepsilon_{zz}$ ,  $\varepsilon_{xy}$ ,  $\varepsilon_{yz}$  and  $\varepsilon_{zx}$  are the strain tensor.

Next, we calculate the parameters  $\theta_\varepsilon$  and  $\lambda_\varepsilon$  from Equations 3-372 and 3-373

$$\theta_\varepsilon = D_3 \varepsilon_{zz} + D_4 (\varepsilon_{xx} + \varepsilon_{yy}) \quad 3-372$$

$$\lambda_\varepsilon = D_1 \varepsilon_{zz} + D_2 (\varepsilon_{xx} + \varepsilon_{yy}) \quad 3-373$$

where  $D_1$ ,  $D_2$ ,  $D_3$  and  $D_4$  are shear deformation potentials. Next, we can calculate the valence band energies from Equations 3-374 through 3-376

$$E_{hh}^0 = E_v^0 + \Delta_1 + \Delta_2 + \theta_\varepsilon + \lambda_\varepsilon \quad 3-374$$

$$E_{lh}^0 = E_v^0 + \frac{\Delta_1 - \Delta_2 + \theta_\varepsilon}{2} + \lambda_\varepsilon + \sqrt{\left(\frac{\Delta_1 - \Delta_2 + \theta_\varepsilon}{2}\right)^2} + 2\Delta_3^2 \quad 3-375$$

$$E_{ch}^0 = E_v^0 + \frac{\Delta_1 - \Delta_2 + \theta_\varepsilon}{2} + \lambda_\varepsilon + \sqrt{\left(\frac{\Delta_1 - \Delta_2 + \theta_\varepsilon}{2}\right)^2} + 2\Delta_3^2 \quad 3-376$$

where  $\Delta_1$ ,  $\Delta_2$  and  $\Delta_3$  are split energies and  $E_v$  is the valence band reference level. Next, we can calculate the hydrostatic energy shift from Equation 3-377

$$P_{c\varepsilon} = a_{cz} \varepsilon_{zz} + a_{ct} (\varepsilon_{xx} + \varepsilon_{yy}) \quad 3-377$$

where  $a_{cz}$  and  $a_{ct}$  are hydrostatic deformation potentials. From which we can calculate the conduction band energy as given in Equation 3-378

$$E_c^0 = E_v^0 + \Delta_1 + \Delta_2 + E_g + P_{c\varepsilon} \quad 3-378$$

where  $E_g$  is the energy bandgap.

Next, we can calculate the effective masses in the various bands using the expressions in Equations 3-379 through 3-384

$$m_{hh}^z = -m_0(A_1 + A_3)^{-1} \quad 3-379$$

$$m_{hh}^t = -m_0(A_2 + A_4)^{-1} \quad 3-380$$

$$m_{lh}^z = -m_0 \left[ A_1 + \left( \frac{E_{lh}^0 - \lambda_\varepsilon}{E_{lh}^0 - E_{ch}^0} \right) A_3 \right]^{-1} \quad 3-381$$

$$m_{lh}^t = -m_0 \left[ A_2 + \left( \frac{E_{lh}^0 - \lambda_\varepsilon}{E_{lh}^0 - E_{ch}^0} \right) A_4 \right]^{-1} \quad 3-382$$

$$m_{ch}^z = -m_0 \left[ A_1 + \left( \frac{E_{ch}^0 - \lambda_\varepsilon}{E_{ch}^0 - E_{lh}^0} \right) A_3 \right]^{-1} \quad 3-383$$

$$m_{ch}^t = -m_0 \left[ A_2 + \left( \frac{E_{lh}^0 - \lambda_\varepsilon}{E_{lh}^0 - E_{ch}^0} \right) A_4 \right]^{-1} \quad 3-384$$

where  $m_\phi$  is the free space mass of an electron,  $m_{hh}^z$ ,  $m_{hh}^t$ ,  $m_{lh}^z$ ,  $m_{lh}^t$ ,  $m_{ch}^z$  and  $m_{ch}^t$  are the effective masses for heavy holes, light holes and crystal split off holes in the axial and transverse directions and  $A_1, A_2, A_3$  and  $A_4$  are hole effective mass parameters.

The momentum matrix elements for the various transitions can be calculated by Equations 3-397 through 3-399

$$m_{hh}^{11} = 0 \quad 3-385$$

$$m_{hh}^{11} = b^2 \left( \frac{m_0}{2} E_{pz} \right) \quad 3-386$$

$$m_{ch}^{11} = a^2 \left( \frac{m_0}{2} E_{pz} \right) \quad 3-387$$

$$m_{hh}^\perp = \frac{m_0}{4} E_{px} \quad 3-388$$

$$m_{lh}^\perp = a^2 \left( \frac{m_0}{4} \right) E_{px} \quad 3-389$$

$$m_{ch}^\perp = b^2 \left( \frac{m_0}{4} \right) E_{px} \quad 3-390$$

where  $E_{px}$  and  $E_{pz}$  are given by Equations 3-391 and 3-392,  $a^2$  and  $b^2$  are given by Equations 3-395 and 3-396. The values of  $P_1^2$  and  $P_2^2$  are given by Equations 3-393 and 3-394.

$$E_{px} = \left(2m_0/\hbar^2\right)P_2^2 \quad 3-391$$

$$E_{pz} = \left(2m_0/\hbar^2\right)P_1^2 \quad 3-392$$

$$P_1^2 = \frac{\hbar^2}{2m_0} \left(\frac{m_0}{m_e^z} - 1\right) \frac{(E_g + \Delta_2 + \Delta_2)(E_g + 2\Delta_2) - 2\Delta_3^2}{(E_g + 2\Delta_2)} \quad 3-393$$

$$P_2^2 = \frac{\hbar^2}{2m_0} \left(\frac{m_0}{m_e^t} - 1\right) \frac{E_g [(E_g + \Delta_1 + \Delta_2)(E_g + 2\Delta_2) - 2\Delta_3^2]}{(E_g + \Delta_1 + \Delta_2)(E_g + \Delta_2) - \Delta_3^2} \quad 3-394$$

$$a^2 = \left(\frac{E_{lh}^0 - \lambda_\varepsilon}{E_{lh}^0 - E_{ch}^0}\right) \quad 3-395$$

$$b^2 = \left(\frac{E_{ch}^0 - \lambda_\varepsilon}{E_{ch}^0 - E_{lh}^0}\right) \quad 3-396$$

In Equations 3-391 through 3-396,  $m_e^t$  and  $m_e^z$  are the transverse and axial conduction band effective masses.

The default values for the parameters of Equations 3-369 through 3-396 are shown in Appendix B: “Material Systems”, Section B.8: “Material Defaults for GaN/InN/AlN System”.

### 3.9.9: Lorentzian Gain Broadening

Gain broadening due to intra-band scattering can be introduced by specifying LORENTZ in the MODEL statement. The following equation describes gain broadening when it's applied.

$$g = \int \frac{g(E)}{\mathbf{WELL.GAMMA0}} L[(E - E_{ij})/\mathbf{WELL.GAMMA0}] dE \quad 3-397$$

The Lorentzian shape function is given by Equation 3-398.

$$L(E - E_{ij}) = \frac{1}{\pi} \cdot \frac{\mathbf{WELL.GAMMA0}}{(E - E_{ij})^2 + \mathbf{WELL.GAMMA0}^2} \quad 3-398$$

where  $\mathbf{WELL.GAMMA0}$  is user-specifiable in the MATERIAL statement.

### 3.9.10: Ishikawa's Strain Effects Model

The strained layer InGaAsP and InGaAlAs quantum well material models from [133] are implemented in the ATLAS simulator. To enable these models, specify the `ISHIKAWA` parameter in the MQW statement (see Chapter 18: “Statements”, Section 18.30: “MQW”). Strain percentages are specified by the `STRAIN` parameter in the MQW statement. `STRAIN` between a substrate material with lattice constant,  $d_s$ , and an epitaxial material without `STRAIN`, with lattice constant,  $d_e$ , is  $(d_e - d_s) / d_s$ .

When you enable this model, the band edge parameters for materials in the InGaAsP and InGaAlAs systems are calculated using Equations 3-399, 3-400, and 3-401.

#### InGaAs

$$\begin{aligned}
 E_c &= 1.040 - 0.0474\text{STRAIN} + 0.003303\text{STRAIN}^2 \\
 E_{v,HH} &= 0.3331 + 0.05503\text{STRAIN} - 0.002212\text{STRAIN}^2 \\
 E_{v,LH} &= 0.331 - 0.01503\varepsilon - 0.003695\text{STRAIN}^2
 \end{aligned}
 \tag{3-399}$$

#### InGaAsP

$$\begin{aligned}
 &a) \text{STRAIN} < 0 \\
 E_c &= (0.6958 + 0.4836E_g) - 0.03031\text{STRAIN} \\
 E_{v,LH} &= (0.5766 - 0.3439E_g) - 0.3031\text{STRAIN} \\
 &b) \text{STRAIN} > 0 \\
 E_c &= (0.6958 + 0.4836E_g) + 0.003382\text{STRAIN} \\
 E_{v,HH} &= (0.6958 - 0.5164E_g) + 0.003382\text{STRAIN}
 \end{aligned}
 \tag{3-400}$$

#### InGaAlAs

$$\begin{aligned}
 &a) \text{STRAIN} < 0 \\
 E_c &= (0.5766 + 0.6561E_g) - 0.02307\text{STRAIN} \\
 E_{v,LH} &= (0.5766 - 0.3439E_g) - 0.2307\text{STRAIN} \\
 &b) \text{STRAIN} > 0 \\
 E_c &= (0.5766 + 0.06561E_g) + 0.01888\text{STRAIN} \\
 E_{v,HH} &= (0.5766 - 0.3439E_g) + 0.01888\text{STRAIN}
 \end{aligned}
 \tag{3-401}$$

A `STRAIN` parameter has also been added to the `REGION` statement to account for strain in the bulk materials. Note that for the InGaAs material system, the equations ignore composition fraction and variation in the parameters is accounted strictly through strain (see Equation 3-399). The compositional variation can be seen in *Figure 5.a* from [136].

These band edge parameters are used through all subsequent calculations. Most importantly, the band edges are used in solving the Schrodinger's Equation (See Chapter 13: “Quantum: Quantum Effect Simulator”, Equations 13-1 and 13-2) to obtain the bound state energies in multiple quantum wells.

If you enable the Ishikawa Model, this would include the effects of strain in the valence and conduction band effective masses as described in [136]. The effects of strain are introduced in Equation 3-402.

$$\frac{1}{m_{lh}} = \mathbf{ASTR} + \mathbf{BSTRSTRAIN} + \mathbf{CSTRSTRAIN}^2$$

$$\frac{1}{m_{hh}} = \mathbf{DSTR} + \mathbf{ESTRSTRAIN} + \mathbf{FSTRSTRAIN}^2$$

3-402

The ASTR, BSTR, CSTR, DSTR, ESTR, and FSTR parameters are user-definable in the MQW statement. You can also choose the appropriate values for these parameters from Tables 3-3-63 or 3-3-64.

|   | <b>-2.0&lt;Strain(%)&lt;-0.5</b> |         |        | <b>0&lt;Strain(%)&lt;2.0</b> |       |        |
|---|----------------------------------|---------|--------|------------------------------|-------|--------|
|   | ASTR                             | BSTR    | CSTR   | DSTR                         | ESTR  | FSTR   |
| Lattice-matched InGaAsP barrier/InGaAs well     | -4.238                           | -6.913  | -1.687 | 4.260                        | 2.253 | -0.584 |
| InGaAsP (1.6- $\mu$ m) well                     | -0.936                           | -4.825  | -1.754 | 2.986                        | 5.505 | -1.736 |
| Strain-compensated InGaAsP barrier/InGaAs well  | -7.761                           | -13.601 | -5.100 | 4.166                        | 1.933 | -0.558 |
| Lattice-matched InGaAlAs barrier/InGaAs well    | -3.469                           | -6.133  | -1.481 | 3.9134                       | 2.336 | -0.633 |
| InGaAlAs(1.6- $\mu$ m) well                     | -1.297                           | -5.598  | -2.104 | 2.725                        | 6.317 | -1.766 |
| Strain-compensated InGaAlAs barrier/InGaAs well | -5.889                           | -9.467  | -2.730 | 4.193                        | 1.075 | -0.155 |

|   | <b>-2.0&lt;Strain(%)&lt;-0.5</b> |        |        | <b>-0.5&lt;Strain(%)&lt;2.0</b> |       |         |
|---|----------------------------------|--------|--------|---------------------------------|-------|---------|
|   | ASTR                             | BSTR   | CSTR   | DSTR                            | ESTR  | FSTR    |
| Lattice-matched InGaAsP barrier/InGaAs well     | -9.558                           | -8.634 | -1.847 | 4.631                           | 1.249 | -0.313  |
| InGaAsP (1.4- $\mu$ m) well                     | -2.453                           | -4.432 | -1.222 | 3.327                           | 3.425 | -1.542  |
| Strain-compensated InGaAsP barrier/InGaAs well  |                                  |        |        | 4.720                           | 0.421 | -0.014  |
| Lattice-matched InGaAlAs barrier/InGaAs well    | -8.332                           | -8.582 | -2.031 | 3.931                           | 1.760 | -0.543  |
| InGaAlAs(1.4- $\mu$ m) well                     | -3.269                           | -5.559 | -1.594 | 3.164                           | 4.065 | -1.321  |
| Strain-compensated InGaAlAs barrier/InGaAs well |                                  |        |        | 4.078                           | 0.516 | -0.0621 |

To choose these values, use the STABLE parameter in the MQW statement. You can set this parameter to the row number in the tables. The rows are numbered sequentially. For example, the first row in Table 3-63 is selected by specifying STABLE=1. The first row of Table 3-64 is selected by specifying STABLE=7.

You can also choose to specify the effective masses directly. The conduction band effective mass is specified by the MC parameter in the MQW statement. There are two ways to specify the valence band. One way, is to use the MV parameter to specify a net effective mass. The other way, is to use the MLH and MHH parameters to specify the light and heavy hole effective masses individually.

If you don't specify the effective masses by using one of these methods, then the masses will be calculated from the default density of states for the given material as described in Section 3.4.2: "Density of States".

The effective masses described are also used to solve the Schrodinger Equation (see Chapter 13: "Quantum: Quantum Effect Simulator", Equations 13-1 and 13-2).



### 4.1: Overview

S-PISCES is a powerful and accurate two-dimensional device modeling program that simulates the electrical characteristics of silicon based semiconductor devices including MOS, bipolar, SOI, EEPROM, and power device technologies.

S-PISCES calculates the internal distributions of physical parameters and predicts the electrical behavior of devices under either steady-state, transient, or small signal AC conditions. This is performed by solving Poisson's Equation (see Chapter 3: "Physics", Section 3.1.1: "Poisson's Equation") and the electron and hole carrier continuity equations in two dimensions (see Chapter 3: "Physics", Section 3.1.2: "Carrier Continuity Equations").

S-PISCES solves basic semiconductor equations on non-uniform triangular grids. The structure of the simulated device can be completely arbitrary. Doping profiles and the structure of the device may be obtained from analytical functions, experimentally measured data, or from process modeling programs SSUPREM3 and ATHENA.

For more information on semiconductor equations, see Chapter 3: "Physics", Section 3.1: "Basic Semiconductor Equations".

Before reading this chapter any further you should be familiar with ATLAS. If you're not, read Chapter 2: "Getting Started with ATLAS".

## 4.2: Simulating Silicon Devices Using S-PISCES

### 4.2.1: Simulating MOS Technologies

#### Physical Models for MOSFETs

S-PISCES provides special physical models tuned for simulating MOS devices. Most of these models are accessed from the `MODEL` statement. The `MOS` parameter of the `MODEL` statement can be specified to turn on a default set of physical models that are most useful for MOS simulation. The `MOS` parameter enables Shockley-Read-Hall (`SRH`), Fermi Statistics (`FERMI`), and the Lombardi Mobility model (`CVT`) for transverse field dependence. To set the default MOS simulation models, use:

```
MODEL MOS PRINT
```

The transverse field dependent mobility models are of particular importance for simulating MOS devices. S-PISCES currently supports several different transverse field dependent mobility models. The `CVT` parameter selects the Lombardi CVT model. The `YAMA` parameter selects the Yamaguchi model. The `TASCH` parameter selects the Tasch model. The `WATT` parameter selects the Watt Surface Model, which can be operated in a more accurate mode with the extra parameter, `MOD.WATT`, on the `MOBILITY` statement.

You will find that the `MOBILITY` statement can be used to modify some of the parameters of the various models, to apply different models to different regions, or to apply different models to electrons and holes.

#### Meshing for MOS Devices

In device simulation of MOS devices, the key areas for a tight mesh are:

- very small vertical mesh spacing in the channel under the gate. The exact size of mesh required depends on the transverse field or surface mobility model chosen. See Figure 4-1 for an example of the effect of mesh size on drain current.
- lateral mesh spacing along the length of the channel for deep sub-micron devices. This is required to get the correct source-drain resistance and to resolve the channel pinch-off point.
- lateral mesh at the drain/channel junction for breakdown simulations. This is required to resolve the peak of electric field, carrier temperature and impact ionization.
- several vertical grid spacings inside the gate oxide when simulating gate field effects such as gate induced drain leakage (`GIDL`) or using any hot electron or tunneling gate current models

Figures 4-1 and 4-2 show the effect of mesh size in the MOS channel on IV curves. In Figure 4-1, the mesh density in the vertical direction is increased. As the mesh density increases, the resolution of the electric field and carrier concentration is improved. This example uses the `CVT` mobility model. Improvements in transverse electric field resolution lead to a reduced mobility in the channel and a stronger IV roll-off.

But Figure 4-2 shows the effect of surface channel mesh in MOSFETs is model dependent. This result shows the current at  $V_{ds}=3.0V$  and  $V_{gs}=0.1V$  versus the size of the first grid division into the silicon. Results vary for each model but note that for all models a very fine grid is required in order to reduce the grid dependence to acceptable levels.

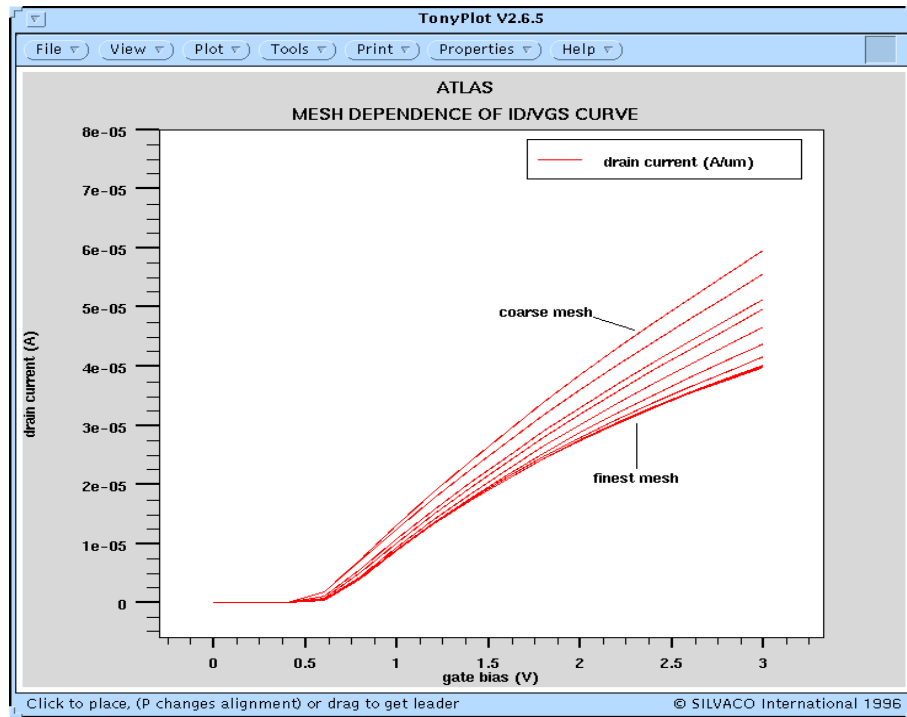


Figure 4-1: Effect on MOS IV curve of progressive refinement of the vertical mesh spacing at the surface of the MOS channel

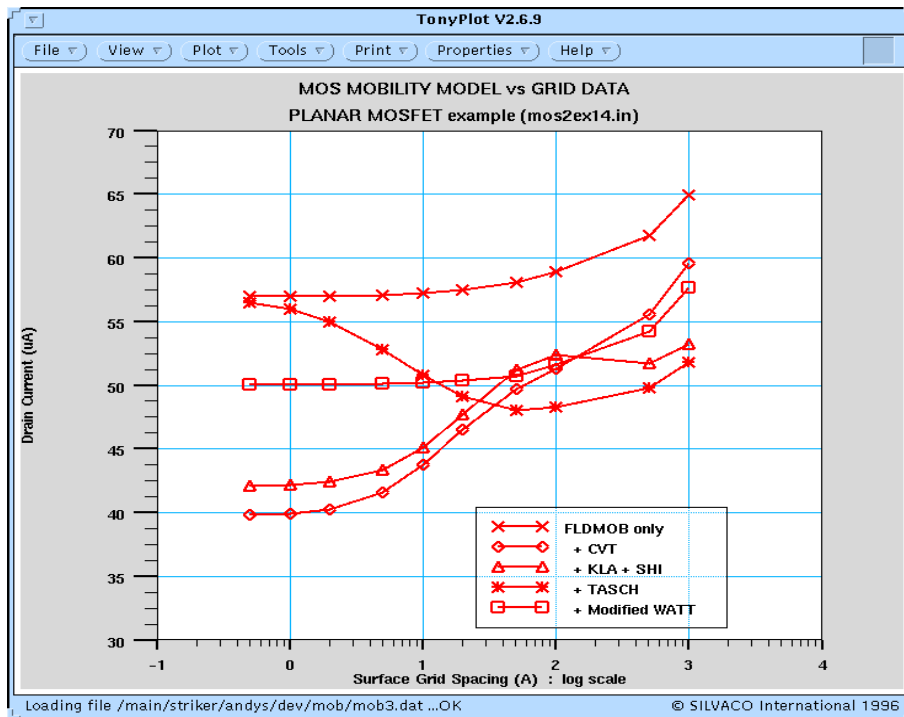


Figure 4-2: Effect of surface mesh spacing on simulated current for several MOS Mobility Models

## MOS Electrode Naming

For MOS simulation, S-PISCES allows you to use standard electrode names to reduce confusion with the use of electrode indices. These names include: source, drain, gate, and substrate. Electrode names can be defined in ATHENA or DEVEDIT or in the ELECTRODE statement in ATLAS. These names can be used in the SOLVE statements for setting bias voltages such as:

```
SOLVE VGATE=1.0 VSTEP=1.0 VFINAL=5.0 NAME=GATE
```

## Gate Workfunction

In MOS simulations, the workfunction of the gate is an important parameter. This must be set in each input deck using the WORK parameter of the CONTACT statement. For example:

```
CONTACT NAME=GATE WORK=4.17
```

would set the workfunction on the gate at 4.17 eV.

Certain material names can also be used to set the workfunction of common gate materials. For example:

```
CONTACT NAME=GATE N.POLY
```

would set the workfunction on the gate to that of n type polysilicon.

---

**Note:** The gate workfunction should be set on a CONTACT statement even though the material or workfunction might be set from ATHENA or DEVEDIT.

---

## Interface Charge

For accurate simulation of MOS devices the interface charge at the oxide, specify semiconductor interface. This can be done by setting the QF parameters for the INTERFACE statement. Typically, a value of  $3 \times 10^{10} \text{ cm}^{-2}$  is representative for the interface charge found in silicon MOS devices. The proper syntax for setting the value for this interface fixed charge is:

```
INTERFACE QF=3e10
```

You can also try to model the fixed charge more directly by using interface traps to simulate the surface states. This can be done by using the INTTRAP statement. But this is rarely done in practice.

## Single Carrier Solutions

Frequently for MOS simulation, you can choose to simulate only the majority carrier. This will significantly speed up simulations where minority carrier effects can be neglected. This can be done by turning off the minority carrier. To do this, use the ATLAS negation character, ^, and one of the carrier parameters (ELECTRONS or HOLES) in the METHOD statement. For example, to simulate electrons only, you can specify one of the following:

```
METHOD CARRIERS=1 ELECTRONS  
METHOD ^HOLES
```

Single carrier solutions should not be performed where impact ionization, any recombination mechanism, lumped element boundaries, or small signal AC analysis are involved.

## Energy Balance Solutions

As MOS devices become smaller and smaller, non-local carrier heating effects becomes important. Accurate simulation of non-local carrier heating effects can be simulated using the energy balance model (EBM). As a general rule, the gate length can be used as a gauge to predict when non-local effects are important. Generally, for drain currents, energy balance should be applied for gate lengths less than 0.5 microns. For substrate currents, energy balance should be applied for gate lengths less than 1.0 micron.

To enable energy balance for electrons/holes, the `HCTE.EL` or `HCTE.HO` parameters should be set on the `MODEL` statement. For example:

```
MODEL HCTE.EL
```

enables the energy balance model for electrons.

## ESD Simulation

In some cases, lattice heating may be important to MOS simulation. This typically occurs in cases with very high currents, just like the case with ESD simulation. In these cases, `GIGA` should be used to simulate the heat-flow in the device. To enable heat flow simulation, set the `LAT.TEMP` parameter of the `MODEL` statement (a license for `GIGA` is required). For example, the statement:

```
MODEL LAT.TEMP
```

enables heat-flow simulation.

## 4.2.2: Simulating Silicon Bipolar Devices

### Physical Models for BJTs

S-PISCES provides special physical models for bipolar device simulation. These models can be selected using the `MODEL` statement. The `BIPOLAR` parameter of the `MODEL` statement enables a reasonable default set of bipolar models. These include: concentration dependent mobility (`CONMOB`), field dependent mobility (`FLDMOB`), bandgap narrowing (`BGN`), concentration-dependent lifetime (`CONSRH`) and Auger recombination (`AUGER`).

For the most accurate bipolar simulations the recommended mobility model is the Klaassen model (`KLA`). This includes doping, temperature and carrier dependence. It applies separate mobility expressions for majority and minority carriers. This model should also be used with Klaassen's Auger model (`KLAAUG`) and Klaassen's concentration dependent SRH model (`KLASRH`). The mobility model should be combined with `FLDMOB` to model velocity saturation. For surface (or lateral) bipolar devices the Shirahata model (`SHI`) can be used to extend the Klaassen model with a transverse electric field dependence. The most accurate and appropriate model statement for bipolar devices is therefore:

```
MODELS KLA FLDMOB KLASRH KLAAUG BGN FERMI PRINT
```

You can choose this set of models by using the `BIPOLAR2` parameter from the `MODEL` statement.

---

**Note:** For a complete syntax including description of models and method for simulating polysilicon emitter bipolar devices, see the BJT directory in the on-line examples.

---

### Meshing Issues for BJTs

The most important areas to resolve in bipolar transistors are the emitter/base and base/collector junctions. Typically, a very fine mesh throughout the base region is required. The gain of the bipolar device is determined primarily by the recombination at the emitter/base junction or inside the emitter. Hence, these regions need to be resolved with a fine mesh.

## BJT Electrode Naming

S-PISCES also provides special electrode names for bipolar simulation that can be used to ease confusion over electrode indices. These electrode names include: “emitter”, “base”, “collector”, “anode”, and “cathode”. Electrode names can be defined in ATHENA or DEVEDIT or in the ELECTRODE statement in ATLAS. The electrode names are used on SOLVE statement for example:

```
SOLVE VBASE=1.0 VSTEP=1.0 VFINAL=5.0 NAME=BASE
```

## Dual Base BJTs

It is possible in S-PISCES to tie two or more contacts together so that voltages on both contacts are equal. This is useful for many technologies for example dual base bipolar transistors. There are several methods for achieving this depending on how the structure was initially defined.

If the structure is defined using ATLAS syntax it is possible to have multiple ELECTRODE statements with the same NAME parameter defining separate locations within the device structure. In this case the areas defined to be electrodes will be considered as having the same applied voltage. A single current will appear combining the current through both ELECTRODE areas.

Similarly if two separate metal regions in ATHENA are defined using the ATHENA ELECTRODE statement to have the same name, then in ATLAS these two electrodes will be considered as shorted together.

If the electrodes are defined with different names, the following syntax can be used to link the voltages applied to the two electrodes.

```
CONTACT NAME=base1 COMMON=base
.
SOLVE VBASE=0.1
```

Here, the electrode, base1, will be linked to the electrode, base. Then, the applied 0.1V on base will also appear on base1. But ATLAS will calculate and store separate currents for both base and base1. This can be a useful feature. In some cases, however, such as where functions of the currents are required in EXTRACT or TONYPLOT, it is undesirable. The SHORT parameter can be added to the CONTACT statement above to specify that only a single base current will appear combining the currents from base and base1.

When loading a structure from ATHENA or DEVEDIT where two defined electrode regions are touching, ATLAS will automatically short these and use the electrode name that was defined first.

## Creating an Open Circuit Electrode

It is often required to perform a simulation with an open circuit, such as for an open-base breakdown voltage simulation, on one of the defined electrodes. There are three different methods that will accomplish this. The first method is to entirely deleting an electrode from the structure file. The second method is to add an extremely large lumped resistance, for example  $10^{20}\Omega$  onto the contact to be made open circuited. The third method is to switch the boundary conditions on the contact to be made open circuited from voltage controlled to current controlled and then specify a very small current through that electrode.

Each of these methods are feasible but if in doing so a floating region is created within the structure, then numerical convergence may be affected. As a result, it is normally recommended to use the second method to ensure that no floating region is created.

## Solution Techniques for BJTs

To obtain bipolar solutions, you almost always need to simulate using two carriers. This is due to the importance of minority carriers to device operation.

In certain cases, non-local carrier heating may be important to accurately simulate bipolar devices. In these cases, use the energy balance model. To model non-local carrier heating for electrons/holes, set the `HCTE.EL` and `HCTE.HO` parameters in the `MODEL` statement. For example, the statement:

```
MODEL HCTE.EL
```

invokes the carrier heating equation for electrons.

### 4.2.3: Simulating Non-Volatile Memory Technologies (EEPROMs, FLASH Memories)

If you want to simulate non-volatile memory devices, first become familiar with the basics of MOSFET simulation (see Section 4.2.1: “Simulating MOS Technologies”).

#### Defining Floating Gates

To simulate non-volatile memory technologies such as EEPROMs or FLASH EEPROMs, it is necessary to specify one or more electrodes as floating gates. This is done by setting the `FLOATING` parameter of the `CONTACT` statement. For example:

```
CONTACT NAME=fgate FLOATING
```

This specifies that the electrode named `fgate` is simulated as a floating gate. This means that the charge on the floating gate is calculated as the integral of the gate current at that gate during a transient simulation.

Modeling the correct coupling capacitance ratio between the floating gate and control gate often requires adding an extra lumped capacitor from the floating gate to the control gate or one of the other device terminals. This is often required since S-PISCES is performing a 2-D simulation whereas the coupling of the gates is often determined by their 3-D geometry. Parameters on the `CONTACT` statement are used to apply these extra lumped capacitances. For example, to add a capacitor of 1fF/mm between the control and floating gates the syntax is:

```
CONTACT NAME=fgate FLOATING FG1.CAP=1.0e-15 EL1.CAP=cgate
```

#### Gate Current Models

The gate currents for the floating gate structure can be supplied by one of three sources: hot electron injection (`HEI` or `N.CONCAN`), hot hole injection (`HHI` or `P.CONCAN`) and Fowler-Nordheim tunneling current (`FNORD`).

These currents are of importance, depending on whether electrons are being moved onto the gate or off the floating gate. In the case of placing electrons on the floating gate hot electron injection and Fowler-Nordheim tunneling should be used. In the case of removal of electrons from the floating gate, hot hole injection and Fowler-Nordheim tunneling should be set.

In drift diffusion simulations hot electron injection is simulated by setting the `HEI` parameter of the `MODELS` statement. Hot hole injection is simulated using the `HHI` parameter of the `MODELS` statement. Fowler-Nordheim tunneling is enabled by setting the `FNORD` parameter of the `MODELS` statement. The following example demonstrated the proper setting for Flash EPROM programming.

```
MODELS MOS HEI PRINT
```

This next example is appropriate for EEPROM erasure.

```
MODELS MOS HHI FNORD PRINT
```

With energy balance simulations, the Concannon Models should be used for EPROM programming and erasing. For more information about these models, see Chapter 3: “Physics”, the “Concannon’s Injection Model” section on 3-85.

---

**Note:** Writing and erasure of floating gate devices should be done using transient simulation.

---

### Gate Current Assignment (NEARFLG)

The actual calculation of floating gate current magnitude is done at the silicon-oxide interface. The question of distribution of oxide currents to the various electrodes near the interface is resolved using one of two models. The actual flow of carriers in oxides is not well known. Accepted physical models of carrier flow in oxides are still under research. As such, S-PISCES provides two heuristic models to choose from. The default is to distribute currents calculated at points along the interface to the electrode in the direction of highest contributing field. This model is somewhat analogous to a purely drift model of oxide carrier transport. The alternative is to set the NEARFLG parameter of the MODEL statement. In this case, the currents calculated at points along the interface are distributed to the geometrically closest electrode. This model is analogous to a purely diffusion model of carrier transport in oxide.

### 4.2.4: Simulating SOI Technologies

Silicon substrates are now being produced that contain an oxide layer buried below the surface of the silicon at some predefined depth. The existence of this buried oxide layer has resulted in a change not only in the fabrication process used to manufacture a device in the surface silicon, but also in the challenges facing device simulation.

All of the issues raised previously about MOS device simulation should also be considered with some extra SOI specific problems.

The most common device technology that uses these SOI substrates is the SOI MOSFET. This section summarizes the simulation requirements for SOI using this particular technology as a reference.

#### Meshing in SOI devices

The mesh requirements for SOI MOSFETs is very similar to that described in the previous section for bulk MOS transistors. In addition to these requirements, there are some additional points to meshing these devices. These are:

- Two channel regions may exist: one underneath the top (front) gate oxide and one above the buried (back gate) oxide.
- Inside the buried oxide layer, the mesh constraints can be relaxed considerably compared with the top gate oxide.
- The active silicon underneath the top gate can act as the base region of a bipolar transistor and as such may require a finer mesh when compared to bulk MOS transistors.



## Physical Models for SOI

SOI MOSFET simulations are based upon the physical operation of the device, which exhibits both MOS and bipolar phenomena. As a result a more complex set of physical models will be required than for either MOS or bipolar technologies. Table 4-1 shows these models.

| <b>Model</b>             | <b>Description</b>   |
|--------------------------|--|
| <b>Mobility</b>          | Klaassens Model (KLA) is recommended to account for lattice scattering, impurity scattering, carrier-carrier scattering and impurity clustering effects at high concentration. The Shirahata Mobility Model (SHI) is needed to take into account surface scattering effects at the silicon/oxide interface which is a function of the transverse electric field. High electric field velocity saturation is modelled through the field dependent mobility model (FLDMOB). You can tune model parameters using the MOBILITY statement syntax. |
| <b>Interface Charge</b>  | In SOI transistors, there exist two active silicon to oxide interfaces on the wafer. The top interface, under the top gate, is similar to MOS technology. The bottom interface is quite different and typically contains significantly more charge. Different interface charges may be set in SPICES using the INTERFACE statement with region specific parameters.  |
| <b>Recombination</b>     | To take account of recombination effects, we recommend the use of the Shockley-Read-Hall (SRH) model. This simulates the leakage currents that exist due to thermal generation. It may also be necessary to simulate the presence of interface traps at the silicon/oxide interface. Then, turn on the Direct Recombination Model (AUGER). The parameters for both models can be tuned in the MOBILITY statement.  |
| <b>Bandgap Narrowing</b> | This model (BGN) is necessary to correctly model the bipolar current gain when the SOI MOSFET behaves like a bipolar transistor. The parameters for this model are specified in the MODELS statement.  |

| <b>Table 4-1: SOI Physical Models</b> |  |
|---------------------------------------|--|
| <b>Model</b>                          | <b>Description</b>   |
| <b>Carrier Generation</b>             | Impact ionization significantly modifies the operation of SOI MOSFETs. To account for this phenomena, switch on the impact ionization model (IMPACT) and calibrate for SOI technology. The calibration parameters are set in the IMPACT statement.   |
| <b>Lattice Heating</b>                | When a device is switched on, there can be significant current density within the silicon. This could generate a significant amount of heat. In bulk MOS devices, the silicon substrates behaves like a good heat conductor and this generated heat is quickly removed. But, this isn't the case with SOI substrates as the buried oxide layer allows this generated heat to be retained. For SOI MOSFETs, this can be a significant amount and can drastically affect the operation of the device. In such cases, take account of this by using the GIGA module. Note that when lattice heating is switched on, by using the LAT.TEMP parameter in the MODELS statement, you also need to specify a thermal boundary condition with the THERMCONTACT statement. See Chapter 7: "Giga: Self-Heating Simulator" for more details. |
| <b>Carrier Heating</b>                | <p>In deep submicron designs, you may need to switch on the additional energy balance equations. These take into account the exchange of energy between carriers and between the carriers and the lattice. See Section 4.2.1: "Simulating MOS Technologies" for more information.</p> <p>An example of a set of typical models for a partially depleted SOI MOSFET could be:</p> <pre style="margin-left: 40px;"> MODEL KLA SHI FLDMOB SRH AUGER BGN LAT.TEMP INTERFACE QF=1e10 Y.MAX=0.05 INTERFACE QF=1e11 Y.MIN=0.05 THERMCONTACT NUM=1 ELEC.NUM=4 EXT.TEMP=300 IMPACT SELB                     </pre>  |

### Numerical Methods for SOI

One important issue with SOI device simulation is the choice of numerical methods. In SOI technology, the potential in the channel (or body) region is commonly referred to as "floating". This occurs because there exists no direct contact to it by any electrode. As a result, when a bias is applied, or increased, on a contact there may be some convergence problem. This occurs because the guess used in the numerical solution scheme for  $(\psi, n, p)$  may be poor, particularly in the "floating" region. This is particularly true if impact ionization is used. To overcome the problem of poor initial guess, the following numerical methods syntax should be used in isothermal drift-diffusion simulations.

```
METHOD GUMMEL NEWTON
```

This method initially performs a GUMMEL iteration to obtain an improved initial guess for the NEWTON solution scheme. Although this method is more robust, this is slower than using the NEWTON scheme alone. For more information on the numerical schemes available, see Chapter 17: "Numerical Techniques".

## SOI Physical Phenomena

The physical models and the numerical schemes described above should allow S-PISCES to study all the important SOI phenomena. These include:

- full or partial depletion effects
- threshold voltage
- subthreshold slopes
- front to back gate coupling effects
- leakage current analysis
- high frequency analysis
- device breakdown
- snapback effects
- the kink effect in the output  $I_{ds}$ - $V_{ds}$  characteristics
- negative differential resistance

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## 5.1: Overview

Before continuing to the sections that follow, become familiar with ATLAS. If not, read Chapter 2: “Getting Started with ATLAS” before proceeding with this chapter.

BLAZE is a general purpose 2-D device simulator for III-V, II-VI materials, and devices with position dependent band structure (i.e., heterojunctions). BLAZE accounts for the effects of positionally dependent band structure by modifications to the charge transport equations. BLAZE is applicable to a broad range of devices including: HBTs, HEMTs, LEDs, heterojunction photodetectors (APDs, solar cells, and so on) and heterojunction diodes.

This chapter is composed of several sections. Section 5.1.1: “Basic Heterojunction Definitions” diagrams the basic heterojunction band parameters and includes a section on heterojunction alignment. Heterojunction charge transport is covered in Section 5.1.3: “The Drift Diffusion Transport Model”. This section includes the details of how BLAZE modifies the basic transport models to simulate heterodevices. Section 5.2: “The Physical Models” covers the physical models unique to BLAZE. Detailed information about the material systems encountered in heterojunction simulation is covered in Section 5.3: “Material Dependent Physical Models”. This includes the relationships between the compound elemental concentrations and bandgap, dielectric constant, low field mobility, and other important material and transport parameters. Finally, Section 5.4: “Simulating Heterojunction Devices with Blaze” covers how to define materials and models for heterojunction devices with BLAZE.

Appendix B: “Material Systems” has the defaults for these parameters.

### 5.1.1: Basic Heterojunction Definitions

Figure 5-1 shows the band diagrams and band parameters for a basic p-n heterojunction device under equilibrium conditions. This diagram illustrates two materials with different bandgaps and electron affinities and a Schottky barrier in contact to the n-type material.

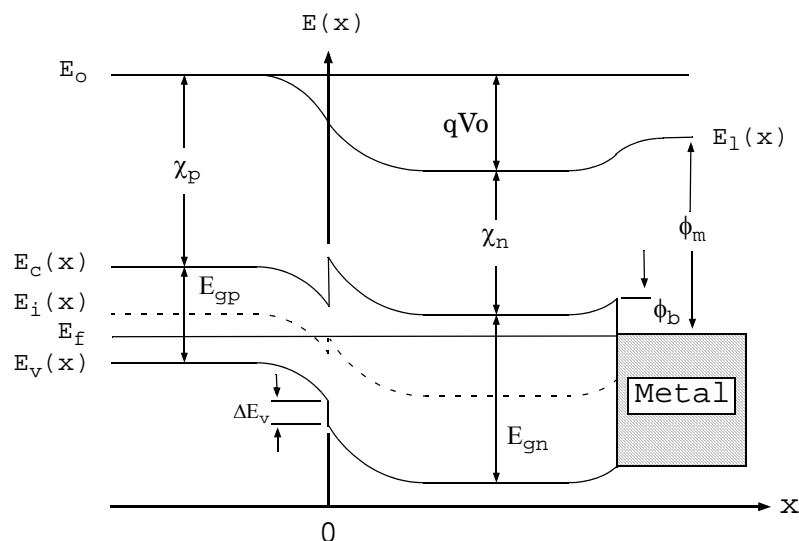


Figure 5-1: Band Diagram of p-n Heterojunction

Referring to Figure 5-1:

- $E_c(x)$ ,  $E_v(x)$  and  $E_i(x)$  are the spatially dependent conduction band, valence band and intrinsic energy levels respectively.
- $E_f$  and  $E_o$  are the Fermi and Vacuum level energies.
- $E_{gp}$  and  $E_{gn}$  are the p-type and n-type material bandgaps.
- $\Delta E_v$  is the portion of the difference between  $E_{gp}$  and  $E_{gn}$  that appears between the valence bands at the heterojunction interface.
- $\Delta E_c$  (not labelled) is the portion of the difference between  $E_{gp}$  and  $E_{gn}$  that appears between the conduction bands at the heterojunction interface.
- $qV_o$  is the built-in potential of the heterojunction.
- $\chi_p$  and  $\chi_n$  are the electron affinities of the p-type and n-type materials.
- $\phi_m$  is the work function of the metal.
- $\phi_b$  is the barrier height between the metal and the semiconductor.

The basic band parameters for defining heterojunctions in BLAZE are bandgap parameter, EG300, electron parameter, AFFINITY, and the conduction and valence band density of states, NC300 and NV300. These parameters are defined for each material using the MATERIAL statement. Other transport parameters relating these basic definitions to compound elemental concentrations (X.COMPOSITION and Y.COMPOSITION) can also be defined.

See the MATERIALS section of this chapter for a description of these relationships for each material system and the Simulating Heterojunction Devices with BLAZE section for their usage. The work function of metals is defined using the CONTACT statement.

## 5.1.2: Alignment

As can be seen from Figure 5-1, the difference in the two material bandgaps creates conduction and valence band discontinuities. How the bandgap difference is distributed between the conduction and valence bands has a large impact on the charge transport in these heterodevices. There are three methods for defining the conduction band alignment for a heterointerface. These methods are: the Affinity Rule, using the ALIGN parameter on the MATERIAL statement, and manually adjusting the material affinities using the AFFINITY parameter on the MATERIAL statement.

### The Affinity Rule

The default method in BLAZE for assigning how much of the bandgap difference appears as the conduction band discontinuity makes use of the affinity rule. The affinity rule assigns the conduction band discontinuity equal to the difference between the two materials electron affinities (AFFINITY on the MATERIAL statement). The affinity rule method is used by default for all materials where the ALIGN parameter has not been defined on the MATERIAL statement.

### Using the ALIGN parameter in the MATERIAL statement

Experimental measurements of the actual band discontinuities can differ from what is assigned using the affinity rule with the standard material electron affinities. Therefore, BLAZE allows  $\Delta E_c$  to be calculated by specifying the ALIGN parameter on the MATERIAL statement. ALIGN specifies the fraction of the bandgap difference which will appear as the conduction band discontinuity. This bandgap difference is between the material for which the ALIGN parameter is specified and the smallest bandgap material in the overall structure (the reference material). Internally, BLAZE creates the desired conduction band offset by modifying the electron affinity of the material for which the ALIGN parameter is specified.

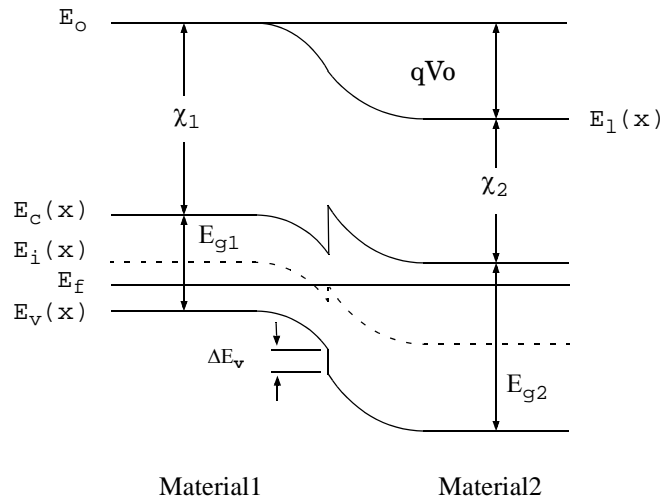
In many applications, the Schottky barriers or more than two different semiconductor materials are present. Keep the reference material bandgap and these assigned affinities in mind when defining offsets for multiple materials or Schottky barrier heights. Examples for multiple materials and Schottky barriers are given in the examples section.

### Manually Adjusting Material Affinity

The `AFFINITY` parameter on the `MATERIAL` statement can be used in conjunction with the default affinity rule alignment method to manually adjust the conduction band offset. In this case, the electron affinity of the larger bandgap material is adjusted so that the difference between the two materials affinity equals the desired conduction band offset. When more than two different materials are present, each material affinity can be adjusted in this manner. This is the easiest method for handling multiple materials and heterojunctions.

The following examples describe the procedure for aligning heterojunctions using these three methods in BLAZE.

#### EXAMPLE 1



**Figure 5-2: Band diagram of heterojunction with band offset.**

Figure 5-2 diagrams a heterojunction consisting of two semiconductors with different bandgaps  $E_{g1}$  and  $E_{g2}$  and electron affinities  $\chi_1$  and  $\chi_2$ . This example is similar to the bandstructure of a HFET or HEMT. For this example,  $E_{g1} < E_{g2}$  and  $\chi_2 < \chi_1$ .

Allocating the conduction band offsets using the affinity rule:

$$\Delta E_c = \chi_1 - \chi_2 \quad 5-1$$

and

$$\Delta E_v = \Delta E_g - \Delta E_c \quad 5-2$$

$\Delta E_c$  is the amount of the conduction band discontinuity at the heterointerface and  $\Delta E_v$  is the amount of the valence band discontinuity.

---

**Note:** Remember the Affinity Rule is used to calculate the conduction band offset for a material, as long as the `ALIGN` parameter is not specified on the `MATERIAL` statement for that material.

---

#### Using the `ALIGN` parameter on the `MATERIAL` statement

Let's assign 80% of the bandgap difference between `Material1` and `Material2` to the conduction band offset. Then, define the `ALIGN` parameter on the `MATERIAL` statement for `Material2` using

```
MATERIAL NAME=Material2 ALIGN=0.80
```

Then:

$$\Delta E_c = (E_{g2} - E_{g1}) \cdot 0.80 \quad 5-3$$

Internally, the affinity of `Material2` is adjusted so that  $\Delta E_c$  equals this value. This value of electron affinity will override any electron affinity specification for `Material2`. This has an impact on any calculation where this materials electron affinity is used and considered when specifying Schottky barriers contacted to this materials. See "EXAMPLE 4" on page 5-10 for more details on Schottky barrier considerations

#### Manually Adjusting Material Affinity

```
MATERIAL NAME=Material2 AFFINITY=VALUE
```

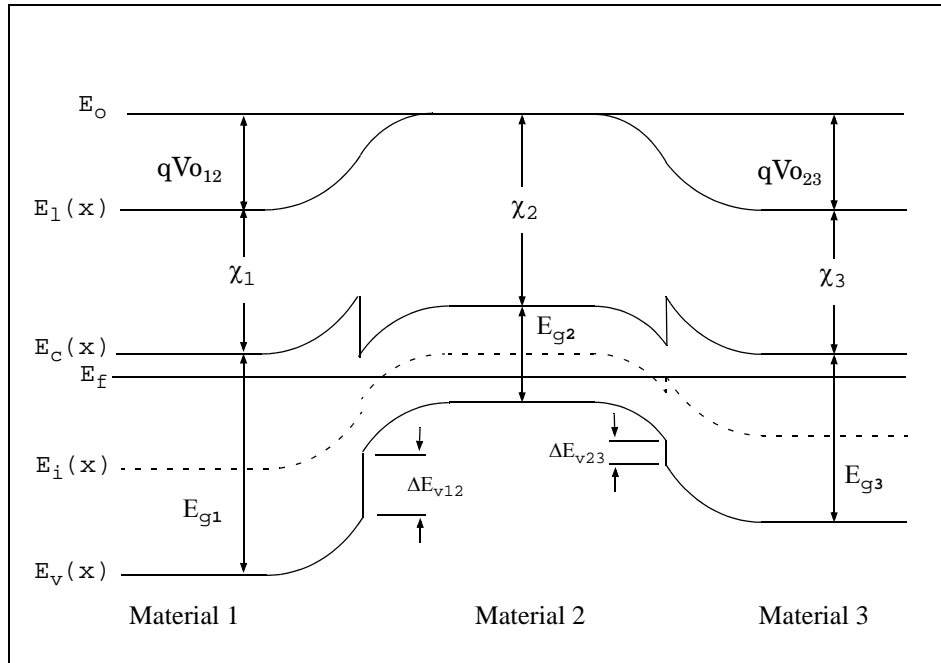
where `VALUE` is adjusted to provide for the desired conduction band offset as calculated by the affinity rule, that is, relative to `Material1`. This value of electron affinity will override any electron affinity specification for `Material2`. This has an impact on any calculation where this materials electron affinity is used and must be considered when specifying Schottky barriers contacted to this materials. See "EXAMPLE 4" on page 5-10 for more details on Schottky barrier considerations

---

**Note:** Remember, if the `ALIGN` parameter is not specified on the `MATERIAL` statement, `BLAZE` will use the Affinity Rule and either the default electron affinity or the affinity assigned using the `AFFINITY` parameter on the `MATERIAL` statement to calculate the conduction band offsets.

---



**EXAMPLE 2**

**Figure 5-3: Band diagram of three material system (lowest  $E_g$  in center)**

Figure 5-3 details a heterostructure device consisting of three semiconductors with different bandgaps  $E_{g1}$ ,  $E_{g2}$  and  $E_{g3}$  and electron affinities  $\chi_1$ ,  $\chi_2$  and  $\chi_3$ . This is similar to the band diagram of a Double Heterojunction Bipolar Transistor. For this example,  $E_{g1} > E_{g2} < E_{g3}$  and  $\chi_1 < \chi_2 > \chi_3$ .

Allocating the conduction band offsets using the affinity rule:

$$\Delta E_{c12} = \chi_2 - \chi_1 \quad 5-4$$

and:

$$\Delta E_{v12} = \Delta E_{g12} - \Delta E_{c12} \quad 5-5$$

for the heterojunction between Material1 and Material2 and:

$$\Delta E_{c23} = \chi_2 - \chi_3 \quad 5-6$$

and:

$$\Delta E_{v23} = \Delta E_{g23} - \Delta E_{c23} \quad 5-7$$

for the heterojunction between Material2 and Material3.

Using the ALIGN parameter on the MATERIAL statement:

Notice that the reference material, the material with the smallest bandgap in this case, Material2, is located between the two larger bandgap materials, Material1, and Material3.

Let's assign 80% of the bandgap difference between Material1 and Material2 to the conduction band offset for this heterojunction. Then, define the ALIGN parameter on the MATERIAL statement for Material 1 using:

```
MATERIAL NAME=Material1 ALIGN=0.8
```

then:

$$\Delta E_{c12} = (E_{g1} - E_{g2}) \cdot 0.80 \quad 5-8$$

Internally, the affinity of Material1 is adjusted so that  $\Delta E_{c12}$  equals this value.

Let's assign 70% of the bandgap difference between Material3 and Material2 to the conduction band offset for this heterojunction. Defining the ALIGN parameter on the MATERIAL statement for Material3 using:

```
MATERIAL NAME=Material3 ALIGN=0.70
```

then:

$$\Delta E_{c23} = (E_{g3} - E_{g2}) \cdot 0.70 \quad 5-9$$

Internally, the affinity of Material3 is adjusted so that  $\Delta E_{c23}$  equals this value.

These new values of electron affinity for Material1 and Material3 will override any electron affinity specification for these materials. This has an impact on any calculation where these materials electron affinity is used and must be considered when specifying Schottky barriers contacted to these materials. See "EXAMPLE 4" on page 5-10 for more details on Schottky barrier considerations.

### Manually Adjusting Material Affinity

Assigning the conduction band offsets for each heterojunction is accomplished by setting the electron affinities for Material1 and Material3 using the AFFINITY parameter on the MATERIAL statement. The electron affinity for Material1 and Material3 are adjusted relative to Material2 by the amount of the desired conduction band offset for each heterojunction. Since Material2 affinity is larger than that for Material1 and Material3, the affinities for Material1 and Material3 are reduced (relative to Material2) to provide the desired conduction band offset.

Let's assume an electron affinity for Material2 of 4eV (~ that of GaAs). Let's decide that between Material1 and Material2, the conduction band offset is 0.3eV and that between Material3 and Material2, the conduction band offset is 0.2eV. Then, for Material1:

```
MATERIAL NAME=Material1 AFFINITY=3.7
```

and for Material3:

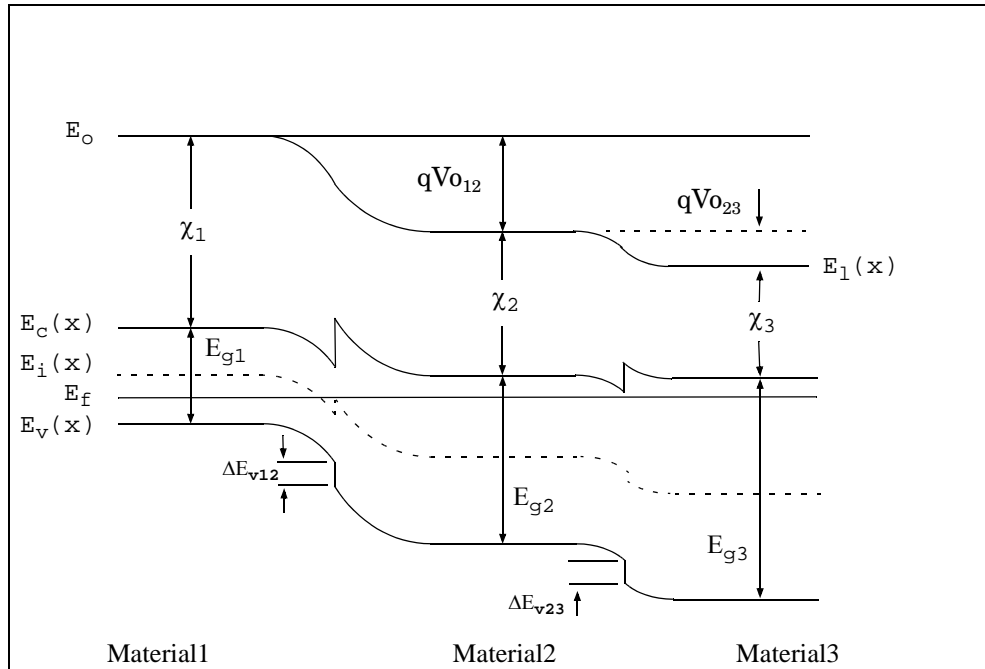
```
MATERIAL NAME=Material3 AFFINITY=3.8
```

This is the easiest method to define the conduction band offsets for multiple materials. This value of electron affinity will override any electron affinity specification. This has an impact on any calculation where this materials electron affinity is used and must be considered when specifying Schottky barriers contacted to this materials. See "EXAMPLE 4" on page 5-10 for more details on Schottky barrier considerations.

---

**Note:** The band offsets are always defined with reference to the conduction band. Therefore, if a specific valence band offset is required, the appropriate conduction band offset should be calculated from the desired valence band offset and the materials bandgap.

---

**EXAMPLE 3**

**Figure 5-4: Band diagram of three material system (lowest  $E_g$  not in center)**

Figure 5-4 details a heterostructure device consisting of three semiconductors with different bandgaps  $E_{g1}$ ,  $E_{g2}$  and  $E_{g3}$  and electron affinities  $\chi_1$ ,  $\chi_2$  and  $\chi_3$ . This is similar to the “EXAMPLE 2” on page 5-5, except that the narrow bandgap material is not located in between the other larger bandgap materials. As will be seen, this adds extra complexity to the conduction and valence band offset calculations. For this example,  $E_{g1} < E_{g2} < E_{g3}$  and  $\chi_3 < \chi_2 < \chi_1$ .

Allocating the conduction band offsets using the affinity rule:

$$\Delta E_{c12} = \chi_1 - \chi_2 \quad 5-10$$

and

$$\Delta E_{v12} = \Delta E_{g12} - \Delta E_{c12} \quad 5-11$$

for the heterojunction between Material1 and Material2 and:

$$\Delta E_{c23} = \chi_2 - \chi_3 \quad 5-12$$

and

$$\Delta E_{v23} = \Delta E_{g23} - \Delta E_{c23} \quad 5-13$$

for the heterojunction between Material2 and Material3.

### Using the ALIGN parameter on the MATERIAL statement

Notice that the reference material, the material with the smallest bandgap in this case, Material1, is not shared between the two larger bandgap materials, Material2, and Material3. This will be important in calculating the conduction band offsets for the heterojunction formed by Material2 and Material3 (the one where the reference material is not present).

Let's assign 80% of the bandgap difference between Material1 and Material2 to the conduction band offset for this heterojunction. Since the reference material is one of the materials of this heterojunction, we can proceed as before. Define the ALIGN parameter in the MATERIAL statement for Material2 using:

```
MATERIAL NAME=Material2 ALIGN=0.8
```

then

$$\Delta E_{c12} = (E_{g2} - E_{g1}) \cdot 0.80 \quad 5-14$$

Internally, the affinity of Material2 is adjusted so that  $\Delta E_{c12}$  equals this value.

Let's assign 70% of the bandgap difference between Material3 and Material2 to the conduction band offset for this heterojunction. Since the reference material is not one of the materials in this heterojunction, another procedure will be used. Since BLAZE always uses the bandgap of the reference material (the smallest bandgap material in overall structure) when calculating the conduction band offset using the ALIGN parameter on the MATERIAL statement, the actual value for the ALIGN parameter needs to be calculated as follows:

$$\text{ALIGN} = (\Delta E_{g32} / \Delta E_{g31}) \cdot \text{FRACTION} \quad 5-15$$

where FRACTION is the desired fraction of the bandgap difference between Material3 and Material2 that will appear in the conduction band.  $\Delta E_{g23}$  is the bandgap difference for the actual heterojunction and  $\Delta E_{g31}$  is the bandgap difference using the reference material. Once calculated, this value for the ALIGN parameter can be used on the MATERIAL statement for Material3. FRACTION and ALIGN will only be equal when the reference material is one of the two materials in the heterojunction. For this example, let's assume that

$$\Delta E_{g32} = 0.2 \quad 5-16$$

and

$$\Delta E_{g31} = 0.4 \quad 5-17$$

then for a desired conduction band offset fraction of 0.70:

$$\text{ALIGN} = (\Delta E_{g32} / \Delta E_{g31}) \cdot \text{FRACTION} = (0.2 / 0.4) \times 0.70 = 0.35 \quad 5-18$$

The proper value of the ALIGN parameter reflecting the desired conduction band offset can be assigned as:

```
MATERIAL NAME=Material3 ALIGN=0.35
```

This assigns 70% of the bandgap difference between Material3 and Material2 as the conduction band offset. Internally, the affinity of Material3 is adjusted so that  $\Delta E_{c23}$  equals this value.

**Note:** Calculating ALIGN in this manner is only necessary when the reference material is not in contact with the material where the ALIGN parameter will be specified.

---

These new values of electron affinity for Material2 (from the first heterojunction band offset calculation) and Material3 (from the second heterojunction band offset calculation) will override any electron affinity specification for these materials. This has an impact on any calculation where these materials electron affinity is used and must be considered when specifying Schottky barriers contacted to these materials. See “EXAMPLE 4” on page 5-10 for more details on Schottky barrier considerations.

### Manually Adjusting Material Affinity

Assigning the conduction band offsets for each heterojunction is accomplished by setting the electron affinities for Material2 and Material3 using the AFFINITY parameter on the MATERIAL statement. The electron affinity for Material2 is adjusted relative to Material1 and Material3 is adjusted relative to Material2 by the amount of the desired conduction band offset for each heterojunction. Since Material1 affinity is larger than that for Material2 and Material2 affinity is larger than that for Material3, the affinities for Material2 and Material3 are reduced to provide the desired conduction band offsets.

Let's assume an electron affinity for Material1 of 4eV (~ that of GaAs). Let's decide that between Material1 and Material2, the conduction band offset is 0.3eV and that between Material2 and Material 3, the conduction band offset is 0.2eV. Then, for Material2:

```
MATERIAL NAME=Material2 AFFINITY=3.7
```

and for Material3:

```
MATERIAL NAME=Material3 AFFINITY=3.5
```

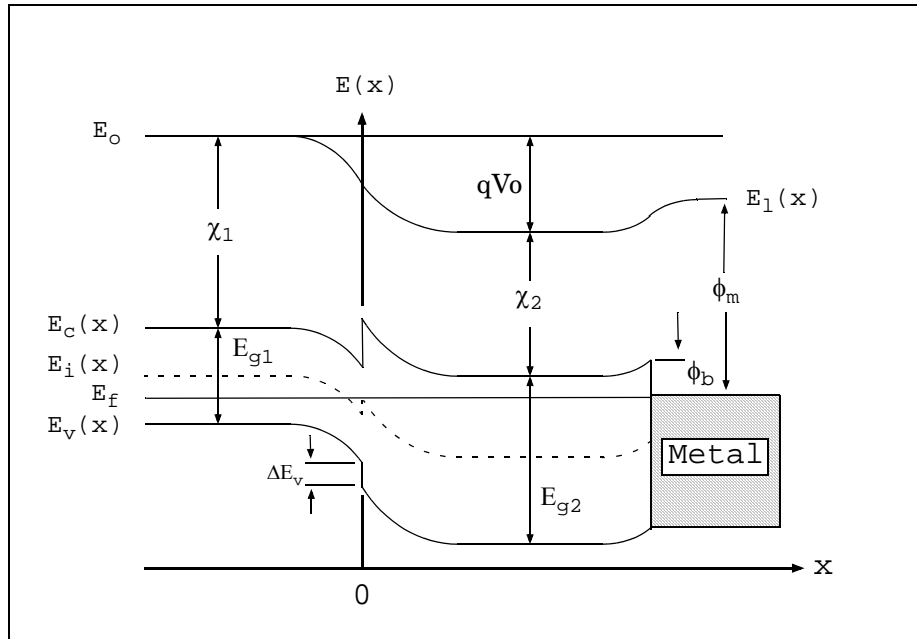
This is the easiest method to define the conduction band offsets for multiple materials. This has an impact on any calculation where this materials electron affinity is used and must be considered when specifying Schottky barriers contacted to this materials. See “EXAMPLE 4” on page 5-10 for more details on Schottky barrier considerations.

---

**Note:** The band offsets are always defined with reference to the conduction band. Therefore, if a specific valence band offset is required, the appropriate conduction band offset should be calculated from the desired valence band offset and the materials bandgap.

---

**EXAMPLE 4**



**Figure 5-5: Schematic band diagram for an abrupt heterojunction**

Figure 5-5 details a heterostructure device consisting of two semiconductors with different bandgaps  $E_{g1}$  and  $E_{g2}$  and electron affinities  $\chi_1$  and  $\chi_2$  and a Schottky barrier. For this example,  $E_{g1} < E_{g2}$  and  $\chi_2 < \chi_1$ .

This example will first define the heterojunction band offsets and then the Schottky barrier height. Schottky contact barrier heights are calculated by BLAZE using the metal work function and the semiconductor electron affinity as:

$$\phi_b = \phi_m - \chi_s \tag{5-19}$$

where  $\phi_b$  is the Schottky barrier height,  $\phi_m$  is the work function of the metal, and  $\chi_s$  is the semiconductor electron affinity.  $\phi_m$  is set using the WORKFUN parameter in the CONTACT statement. Therefore, the semiconductor electron affinity as modified or defined during the heterojunction alignment process plays an important role in determining the value of the metal workfunction needed to provide the desired barrier height. Let's assume for this example that a Schottky barrier height of 0.2eV is desired and calculate the appropriate metal workfunction for each case.

**Using the Affinity rule for the heterojunction**

$$\Delta E_c = \chi_1 - \chi_2 \tag{5-20}$$

and

$$\Delta E_v = \Delta E_g - \Delta E_c \tag{5-21}$$

$\Delta E_c$  is the amount of the conduction band discontinuity at the heterointerface and  $\Delta E_v$  is the amount of the valence band discontinuity.

---

**Note:** Remember the Affinity Rule is used for a material as long as the `ALIGN` parameter is not specified on the `MATERIAL` statement for that material.

---

Let's use an electron affinity for `Material1` of 4eV and for `Material2` of 3.5eV. Since the affinity of the material on which the Schottky barrier is formed was not modified with this method of alignment, the metal work function needed to provide for a Schottky barrier height of 0.2eV is:

$$\phi_m = 3.5 + 0.2 = 3.7 \quad 5-22$$

This value can now be assigned to the `WORKFUN` parameter on the `CONTACT` statement as:

```
CONTACT NUMBER=1 WORKFUN=3.7
```

This produces a Schottky barrier height of 0.2eV between the metal and `Material 2`.

Using the `ALIGN` parameter on the `MATERIAL` statement:

Let's assign 80% of the bandgap difference between `Material1` and `Material2` to the conduction band offset, an electron affinity for `Material1` of 4eV, and  $\Delta E_g$  of 0.2eV. Then, define the `ALIGN` parameter on the `MATERIAL` statement for `Material2` using:

```
MATERIAL NAME=Material2 ALIGN=0.80
```

Then:

$$\Delta E_c = (E_{g2} - E_{g1}) \cdot 0.80 = 0.2 \cdot 0.80 = 0.16 \quad 5-23$$

Internally, the affinity of `Material2` is reduced by 0.16eV so:

$$\chi_2 = \chi_1 - \Delta E_c = (4 - 0.16) = 3.84 \quad 5-24$$

This value of electron affinity can be used to assign the proper value of `WORKFUN` on the `CONTACT` statement to provide for a Schottky barrier height of 0.2eV.

$$\phi_m = 3.84 + 0.2 = 4.04 \quad 5-25$$

This value can now be assigned to the `WORKFUN` parameter on the `CONTACT` statement as:

```
CONTACT NUMBER=1 WORKFUN=4.04
```

producing a Schottky barrier height of 0.2eV between the metal and `Material2`.

### Manually Adjusting Material Affinity

Let's assign a conduction band offset between `Material1` and `Material2` of 0.15eV, an electron affinity for `Material1` of 4eV, and the desired Schottky barrier height of 0.2eV. The affinity for `Material2` is calculated from the affinity of `Material1` and the desired conduction band offset as:

$$\chi_2 = \chi_1 - 0.15 = 4 - 0.15 = 3.85 \quad 5-26$$

This is then used to assign the value of `AFFINITY` using,

```
MATERIAL NAME=Material2 AFFINITY=3.85
```

This value of electron affinity can now be used to calculate the metal workfunction necessary to produce a Schottky barrier height of 0.2eV as:

$$\phi_m = 3.85 + 0.2 = 4.05 \quad 5-27$$

This value can now be assigned to the WORKFUN parameter on the CONTACT statement as:

```
CONTACT NUMBER=1 WORKFUN=4.05
```

This produces a Schottky barrier height of 0.2eV between the metal and Material2.

### 5.1.3: The Drift Diffusion Transport Model

#### Drift-Diffusion with Position Dependent Band Structure

The current continuity equations for electrons and holes, and the Poisson Equation (see Chapter 3: "Physics", Equation 3-1) are the same as for the homogeneous case. Although the changing dielectric constant is taken into account. The current density expressions, however, must be modified to take into account the nonuniform band structure [37]. This procedure starts with the current density expressions:

$$\vec{J}_n = -\mu_n n \nabla \phi_n \quad 5-28$$

$$\vec{J}_p = -\mu_p p \nabla \phi_p \quad 5-29$$

where  $\phi_n$  and  $\phi_p$  are quasi-Fermi potentials.

$$\phi_n = \frac{1}{q} E_{FN} \quad 5-30$$

$$\phi_p = \frac{1}{q} E_{FP} \quad 5-31$$

The conduction and valence band edge energies can be written as:

$$E_c = q(\psi_0 - \psi) - \chi \quad 5-32$$

$$E_v = q(\psi_0 - \psi) - \chi - E_g \quad 5-33$$

where:

- $\psi_0$  is some reference potential.
- $\chi$  is the position-dependent electron affinity.
- $E_g$  is the position-dependent bandgap.
- $\psi_0$  can be selected in the form:

$$\psi_0 = \frac{\chi_r}{q} + \frac{kT_L}{q} \ln \frac{N_{cr}}{n_{ir}} = \frac{\chi_r + E_g}{q} - \frac{kT_L}{q} \ln \frac{N_{vr}}{n_{ir}} \quad 5-34$$

where  $n_{ir}$  is the intrinsic carrier concentration of the arbitrarily selected reference material, and  $r$  is the index that indicates that all of the parameters are taken from reference material.



Fermi energies are expressed in the form:

$$E_{FN} = E_c + kT_L \ln \frac{n}{N_c} - kT_L \ln \gamma_n \quad 5-35$$

$$E_{FP} = E_v + kT_L \ln \frac{n}{N_v} - kT_L \ln \gamma_p \quad 5-36$$

The final terms in Equations 5-35 and 5-36 are due to the influence of Fermi-Dirac statistics. These final terms are defined as follows:

$$\gamma_n = \frac{F_{1/2}(\eta_n)}{e^{\eta_n}}, \quad \eta_n = \frac{E_{FN} - E_c}{kT_L} = F_{1/2}^{-1}\left(\frac{n}{N_c}\right) \quad 5-37$$

$$\gamma_p = \frac{F_{1/2}(\eta_p)}{e^{\eta_p}}, \quad \eta_p = \frac{E_v - E_{FP}}{kT_L} = F_{1/2}^{-1}\left(\frac{p}{N_v}\right) \quad 5-38$$

where  $N_c$  and  $N_v$  are position-dependent and  $\gamma_n = \gamma_p = 1$  for Boltzmann statistics.

By combining Equations 5-28 to 5-38, the following expressions for current densities can be obtained.

$$\vec{J}_n = kT_L \mu_n \nabla n - q \mu_n n \nabla \left( \psi + \frac{kT_L}{q} \ln \gamma_n + \frac{\chi}{q} + \frac{kT_L}{q} \ln \frac{N_c}{n_{ir}} \right) \quad 5-39$$

$$\vec{J}_p = kT_L \mu_p \nabla p - q \mu_p p \nabla \left( \psi + \frac{kT_L}{q} \ln \gamma_p + \frac{\chi + E_g}{q} + \frac{kT_L}{q} \ln \frac{N_v}{p_{ir}} \right) \quad 5-40$$

#### 5.1.4: The Thermionic Emission and Field Emission Transport Model

You can activate alternative current density expressions for electron and hole current [90,126], which take into account thermionic emission dominated current in abrupt heterojunctions. These equation applies only at the node points along the interface of the heterojunction and take the form:

$$\vec{J}_n = q v_n (1 + \delta) \left( n^+ - n^- \exp\left(\frac{-\Delta E_c}{kT_L}\right) \right) \quad 5-41$$

$$\vec{J}_p = (-q) v_p (1 + \delta) \left( p^+ - p^- \exp\left(\frac{-\Delta E_v}{kT_L}\right) \right) \quad 5-42$$

where  $J_n$  and  $J_p$  are the electron and hole current densities from the "-" region to the "+" region

$v_n$  and  $v_p$  are the electron and hole thermal velocities,  $\Delta E_c$  is conduction band energy change going from the "-" region to the "+" region and  $\Delta E_v$  is the valence band energy change going from the "-" region to the "+" region. The  $\delta$  parameter represents the contribution due to thermionic field emission (tunneling).

The thermal velocities  $v_n$  and  $v_p$  are given by:

$$v_n = \frac{A_n^* T_L^2}{q N_C} \tag{5-43}$$

$$v_p = \frac{A_p^* T_L^2}{q N_V} \tag{5-44}$$

where  $T_L$  is the lattice temperature,  $N_C$  is the conduction band density of states,  $N_V$  is the valence band density of states and  $A_n^*$  and  $A_p^*$  are the electron and hole Richardson constants.

The minimum valued Richardson constants from the “-” region or “+” region are used for the calculation of the thermal velocities [126]. You can specify the Richardson constants with the ARICHN and ARICHP parameters of the MATERIAL statement. If the Richardson constants aren't specified, the following expressions will be used:

$$A_n^* = \frac{4 \pi q k^2 m_n^*}{h^3} \tag{5-45}$$

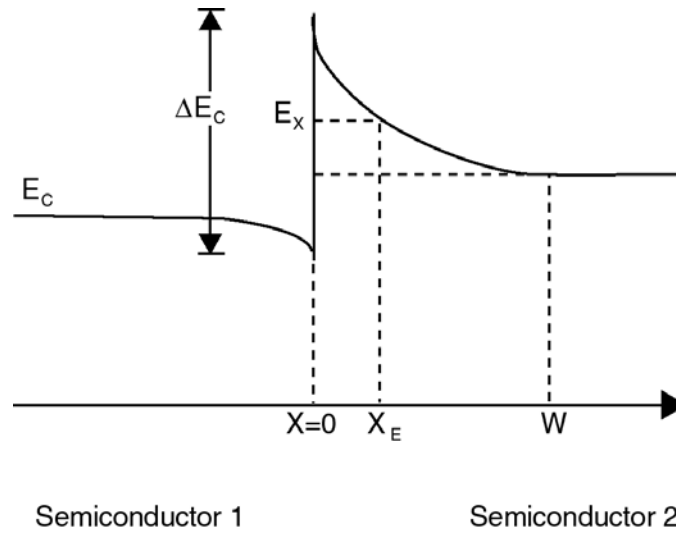
$$A_p^* = \frac{4 \pi q k^2 m_p^*}{h^3} \tag{5-46}$$

where  $m_n^*$  and  $m_p^*$  are the electron and hole effective masses. The electron and hole effective masses can be specified with the M.VTHN and M.VTHP parameters of the MATERIAL statement. If the effective masses aren't specified, then they will be calculated from the conduction and valence band densities of states using Equations 3-31 and 3-32 in Chapter 3: “Physics”.

The tunneling factor  $\delta$  in Equation 5-41 is zero when the tunneling mechanism is neglected. When you account for tunneling by specifying the THERMIONIC parameter in the INTERFACE statement, the tunneling factor,  $\delta$ , is calculated by using the expression:

$$\delta = \frac{1}{kT} \int_{E_{min}}^{E_C^+} \exp\left(\frac{E_C^+ - E_x}{kT}\right) \exp\left(\frac{-4\pi}{h} \int_0^{X_E} [2m_n^*(E_C - E_x)]^{0.5} dx\right) dE_x \tag{5-47}$$

where  $E_x$  is the energy component in the  $x$  direction and  $E_{min} = \max[E_c(0-), E_c(W)]$  as described in Figure 5-6.



**Figure 5-6: Band Diagram of p-n heterojunction**

## 5.2: The Physical Models

Chapter 3: “Physics”, Section 5.2: “The Physical Models” already describes a comprehensive set of physical models for silicon. It is known, however, that for III-V, II-VI, and ternary compounds that special consideration are required such as for mole fraction dependence, material properties, and so on. The following sections describe the material dependent physical models that have been implemented into BLAZE to account for these effects.

First, a description of the common mobility model equations is given. These equations are applicable to all materials unless otherwise stated in the following material sections. Following this are sections describing the physical models on a material-per-material basis. For each material there are descriptions of the models for bandgap narrowing, electron affinity, density of states, dielectric permittivity, and low field mobility.

### 5.2.1: Common Physical Models

#### Low Field Mobility Models

The default low field mobility models used for most materials in BLAZE are given by the following:

$$\mu_{n0}(T_L) = \text{MUN} \left( \frac{T_L}{300} \right)^{\text{TMUN}} \tag{5-48}$$

$$\mu_{p0}(T_L) = \text{MUP} \left( \frac{T_L}{300} \right)^{\text{TMUP}} \tag{5-49}$$

Where  $T_L$  is the temperature in degrees Kelvin and the parameters: MUN, MUP, TMUN and TMUP are user-definable as shown in Table 5-1.

---

**Note:** All the mobility models described in Chapter 3: “Physics”, except for the TASCH model, can be used in BLAZE. But all default coefficients exist only for Silicon and therefore are not suitable for compound materials.

---

| Table 5-1. User-Specifiable Parameters for Equations 5-48 and 5-49 |           |                      |
|--|-----------|----------------------|
| Statement  | Parameter | Units                |
| MOBILITY   | MUN       | cm <sup>2</sup> /V·s |
| MOBILITY   | TMUN      |                      |
| MOBILITY   | MUP       | cm <sup>2</sup> /V·s |
| MOBILITY   | TMUP      |                      |

## Parallel Electric Field-Dependent Mobility Models

There are two types of electric field-dependent mobility models used in ATLAS/BLAZE. These models are called Standard Mobility Model and Negative Differential Mobility Model. Both of these models contain appropriate default values of parameters for different materials. You need to specify which type of mobility will be used for each material and which material parameters you want to alter.

The Standard Mobility Model that takes account of velocity saturation is defined according to:

$$\mu_n(E) = \mu_{n0} \left[ \frac{1}{1 + \left( \frac{\mu_{n0} E}{\text{VSATN}} \right)^{\text{BETAN}}} \right]^{1/\text{BETAN}} \quad 5-50$$

$$\mu_p(E) = \mu_{p0} \left[ \frac{1}{1 + \left( \frac{\mu_{p0} E}{\text{VSATP}} \right)^{\text{BETAP}}} \right]^{1/\text{BETAP}} \quad 5-51$$

where VSATN and VSATP are the saturation velocities for electrons and holes, BETAN and BETAP are constants given in Table 5-2, and  $\mu_{n0,p0}$  are the electron and hole low field mobilities. This model is activated by the FLDMOB or the EVSATMOD=0 parameter in the MODEL statement.

| Table 5-2. User-Specifiable Parameters for Equations 5-50 and 5-51 |           |       |
|--|-----------|-------|
| Statement  | Parameter | Units |
| MOBILITY   | BETAN     |       |
| MOBILITY   | BETAP     |       |
| MOBILITY   | VSATN     | cm/s  |
| MOBILITY   | VSATP     | cm/s  |

The Negative Differential Mobility Model of Barnes et. al. [55] has been implemented to account for certain devices where the carrier drift velocity peaks at some electric field before reducing as the electric field increases. This model takes account of this through the carrier mobility with equations of the form:

$$\mu_n(E) = \frac{\mu_{n0} + \frac{\text{VSATN}}{E} \left( \frac{E}{\text{ECRITN}} \right)^{\text{GAMMAN}}}{1 + \left( \frac{E}{\text{ECRITN}} \right)^{\text{GAMMAN}}} \quad 5-52$$

$$\mu_p(E) = \frac{\mu_{p0} + \frac{\text{VSATP}}{E} \left( \frac{E}{\text{ECRITP}} \right)^{\text{GAMMAP}}}{1 + \left( \frac{E}{\text{ECRITP}} \right)^{\text{GAMMAP}}} \quad 5-53$$

where VSATN and VSATP are the electron and hole saturation velocities,  $E_0$  is a constant, and  $\mu_{n0,p0}$  are the low-field electron and hole mobilities. This mobility model is activated by specifying EVSATMOD=1 in the MODEL statement.

| Table 5-3. User-Specifiable Parameters for Equations 5-52 and 5-53 |           |                   |       |
|--|-----------|-------------------|-------|
| Statement  | Parameter | Default           | Units |
| MOBILITY   | ECRITN    | $4.0 \times 10^3$ | V/cm  |
| MOBILITY   | ECRITP    | $4.0 \times 10^3$ | V/cm  |
| MOBILITY   | GAMMAN    | 4.0               |       |
| MOBILITY   | GAMMAP    | 1.0               |       |

**Note:** The Negative Differential Mobility Model introduces an instability in the solution process and is not recommended for general use. Only activate this model in cases where the device operation directly depends on negative differential mobility (e.g., a Gunn diode).

For both the standard and negative differential models an empirical temperature-dependent model for saturation velocity in GaAs [56] is implemented according to:

$$v_{SATN} = v_{SATP} = 11.3 \times 10^6 - 1.2 \times 10^4 T_L \tag{5-54}$$

where  $v_{SATN}$  and  $v_{SATP}$  are expressed in cm/sec and  $T_L$  is the temperature in degrees Kelvin.

Alternatively, the saturation velocities can be set to constant values using the  $v_{SATN}$  and  $v_{SATP}$  parameters of the MATERIAL statement.

### Velocity Saturation with Energy Balance Transport Model

When the Energy Balance Transport Model is activated the mobility can be made a function of carrier energy. In Chapter 3: “Physics”, Section 3.6.1: “Mobility Modeling” physical models for the dependence of carrier mobility on carrier energy were introduced. The same models are applicable for use within BLAZE with one additional model, which applies when the negative differential mobility model is used.

The carrier temperature dependence is activated when the  $EV_{SATMOD}=1$  parameter is on the MODEL statement. This model can be derived in a similar fashion as in the case of  $EV_{SATMOD}=0$  described in Chapter 3: “Physics”, “Parallel Electric Field-Dependent Mobility” on page 3-58. These expressions, however, require several piecewise approximations, which are too in-depth to show in this manual. To say that these piecewise expressions provide a continuous velocity saturation model for mobility versus carrier temperature are completely like the expressions for drift diffusion given in Equations 3-237 and 3-238 from Chapter 3: “Physics”.

### 5.2.2: Recombination and Generation Models

The recombination and generation models for compound semiconductors are the same as the models previously described in Chapter 3: “Physics”, Section 3.6.3: “Carrier Generation-Recombination Models”. The default parameters for different materials are automatically used, unless new values are specified. The default parameter values are listed in Appendix B: “Material Systems”.

## 5.3: Material Dependent Physical Models

### 5.3.1: Gallium Arsenide (GaAs) Physical Models

#### Bandgap Narrowing

Following Klausmeier-Brown [88], the bandgap narrowing effects are important only for p-type regions. By default, BLAZE uses the bandgap narrowing values shown in Table 5-4.

| Concentration<br>$\text{cm}^{-3}$ | Bandgap Narrowing<br>meV |
|-----------------------------------|--------------------------|
| $1.0 \times 10^{18}$              | 31.0                     |
| $2.0 \times 10^{18}$              | 36.0                     |
| $4.0 \times 10^{18}$              | 44.2                     |
| $6.0 \times 10^{18}$              | 48.5                     |
| $8.0 \times 10^{18}$              | 51.7                     |
| $1.0 \times 10^{19}$              | 54.3                     |
| $2.0 \times 10^{19}$              | 61.1                     |
| $4.0 \times 10^{19}$              | 64.4                     |
| $6.0 \times 10^{19}$              | 61.9                     |
| $8.0 \times 10^{19}$              | 56.9                     |
| $1.0 \times 10^{20}$              | 53.2                     |
| $2.0 \times 10^{20}$              | 18.0                     |

**Note:** This table is only used for GaAs. No data is available at present for other materials. The C-INTERPRETER function for bandgap narrowing, however, allows a user-defined model for bandgap narrowing to be applied for these materials. See Appendix A: "C-Interpreter Functions" for more information about on these functions.

### Low Field Mobility

The mobility in GaAs can be made concentration dependent by setting the CONMOB parameter of the MODEL statement.

In this model, mobility is interpolated from the values in Table 5-5.

| <b>Table 5-5. Default Concentration Dependent Mobility for GaAs</b> |  |              |
|---|--|--------------|
| <b>Concentration(cm-3)</b>  | <b>Mobility in GaAs (cm<sup>2</sup>/v-s)</b> |              |
|   | <b>Electrons</b>                             | <b>Holes</b> |
| 1.0×10 <sup>14</sup>  | 8000.0                                       | 390.0        |
| 2.0×10 <sup>14</sup>  | 7718.0                                       | 380.0        |
| 4.0×10 <sup>14</sup>  | 7445.0                                       | 375.0        |
| 6.0×10 <sup>14</sup>  | 7290.0                                       | 360.0        |
| 8.0×10 <sup>14</sup>  | 7182.0                                       | 350.0        |
| 1.0×10 <sup>15</sup>  | 7300.0                                       | 340.0        |
| 2.0×10 <sup>15</sup>  | 6847.0                                       | 335.0        |
| 4.0×10 <sup>15</sup>  | 6422.0                                       | 320.0        |
| 6.0×10 <sup>15</sup>  | 6185.0                                       | 315.0        |
| 8.0×10 <sup>15</sup>  | 6023.0                                       | 305.0        |
| 1.0×10 <sup>16</sup>  | 5900.0                                       | 302.0        |
| 2.0×10 <sup>16</sup>  | 5474.0                                       | 300.0        |
| 4.0×10 <sup>16</sup>  | 5079.0                                       | 285.0        |
| 6.0×10 <sup>16</sup>  | 4861.0                                       | 270.0        |
| 8.0×10 <sup>16</sup>  | 4712.0                                       | 245.0        |
| 1.0×10 <sup>17</sup>  | 4600.0                                       | 240.0        |
| 2.0×10 <sup>17</sup>  | 3874.0                                       | 210.0        |
| 4.0×10 <sup>17</sup>  | 3263.0                                       | 205.0        |
| 6.0×10 <sup>17</sup>  | 2950.0                                       | 200.0        |
| 8.0×10 <sup>17</sup>  | 2747.0                                       | 186.9        |
| 1.0×10 <sup>18</sup>  | 2600.0                                       | 170.0        |
| 2.0×10 <sup>18</sup>  | 2060.0                                       | 130.0        |



| Concentration(cm-3)  | Mobility in GaAs (cm <sup>2</sup> /v-s) |       |
|----------------------|---|-------|
|                      | Electrons                               | Holes |
| 4.0×10 <sup>18</sup> | 1632.0                                  | 90.0  |
| 6.0×10 <sup>18</sup> | 1424.0                                  | 74.5  |
| 8.0×10 <sup>18</sup> | 1293.0                                  | 66.6  |
| 1.0×10 <sup>20</sup> | 1200.0                                  | 61.0  |

If MODEL ANALYTIC is specified, the program will use [88]:

$$\mu_{n,p} = 940 + \frac{8000 - 940}{1 + \left(\frac{Nt}{2.8 \times 10^{16}}\right)^{0.75}} \quad 5-55$$

where  $Nt$  is the total impurity concentration.

### 5.3.2: Al(x)Ga(1-x)As System

The Al(x)Ga(1-x)As material system is commonly used for the fabrication of heterojunction devices. These materials are available in BLAZE by specifying the material name GaAs, AlGaAs, or AlAs. As a ternary material system, different material properties are obtained by adjusting the molar fraction of Aluminum and Gallium. This mole fraction is represented by the  $x$  as written in Al(x)Ga(1-x)As. GaAs material parameters are identical to the those of AlGaAs with mole the fraction  $x$  set equal to zero. AlAs material parameters are identical to the those of AlGaAs with mole the fraction  $x$  set equal to one. Fundamental in the proper simulation with the AlGaAs material system is the relationship between this mole fraction  $x$ , and the material parameters for that composition. In the following sections, the relationship between mole fraction and material parameters for the AlGaAs material system will be described. You can specify the `x.composition` of a material in the REGION statement with the `X.COMP` parameter.

---

**Note:** Don't use this material system to form GaAs by setting  $x=0$ , specify GaAs as the material instead.

---

#### Bandgap

There are three primary conduction bands in the AlGaAs system that depending on mole fraction, determine the bandgap. These are named Gamma, L, and X. The default bandgaps for each of these conduction band valleys are as follows:

$$E_{g\Gamma} = \mathbf{EG300} + x.comp \cdot (1.155 + 0.37 \cdot X.COMP) \quad 5-56$$

$$E_{gL} = 1.734 + x.comp \cdot (0.574 + 0.055 \cdot X.COMP) \quad 5-57$$

$$E_{gX} = 1.911 + x.comp \cdot (0.005 + 0.245 \cdot X.COMP) \quad 5-58$$

The bandgap used for any given Al concentration is the minimum as calculated from these equations. EG300 is the bandgap at 300K and specified on the material statement. x.composition is the Aluminum mole fraction and may be user-defined on the REGION statement.

The temperature dependence of the bandgap is calculated according to:

$$E_g(T_L) = E_g(300) + EGALPHA \cdot \left[ \frac{300^2}{300 + EGBETA} - \frac{T_L^2}{T_L + EGBETA} \right] \quad 5-59$$

The value of  $E_g(300)$  is taken as the minimum of  $E_{g\Gamma}$ ,  $E_{gx}$ , and  $E_{gL}$ . The default temperature dependent bandgap parameters for AlGaAs are listed in Table 5-6.

| Table 5-6. Default Bandgap Parameters for Al(x)Ga(1-x)As |           |                        |       |
|--|-----------|------------------------|-------|
| Statement  | Parameter | Default                | Units |
| MATERIAL   | EG300     | 1.59                   | eV    |
| MATERIAL   | EGALPHA   | $5.405 \times 10^{-4}$ | eV/K  |
| MATERIAL   | EGBETA    | 204                    | K     |

### Electron Affinity

As indicated in the introduction, the semiconductor electron affinity  $\chi$  is a key parameter for determining the alignment of heterojunctions. For AlGaAs,  $\chi$  is a function of  $E_{g\Gamma}$  and is given by:

$$\chi_{AlGaAs} = 4.07 - 0.85 \cdot (E_{g\Gamma}(X.COMP) - E_{gGaAs}) \quad 5-60$$

### Density of States and Effective Mass

The valence and conduction band densities of states,  $N_C$  and  $N_V$ , are calculated from the effective masses according to the following equations:

$$N_c = 2 \left( \frac{2\pi m_e^* kT_L}{h^2} \right)^{\frac{3}{2}} \quad 5-61$$

$$N_v = 2 \left( \frac{2\pi m_h^* kT_L}{h^2} \right)^{\frac{3}{2}} \quad 5-62$$

For the AlGaAs system the conduction band and valence band effective masses, for electrons and holes, are given by [135]:

$$m_e = \begin{cases} 0.067 + 0.083x & (0 < x < 0.45) \\ 0.85 - 0.14x & (x > 0.45) \end{cases} \quad 5-63$$

$$m_{lh} = 0.087 + 0.063x \quad 5-64$$

$$m_{hh} = 0.62 + 0.14x \quad 5-65$$

$$m_h = (m_{lh}^{3/2} + m_{hh}^{3/2})^{2/3} \quad 5-66$$

### Dielectric Permittivity

The default static dielectric constant for AlGaAs is given by:

$$\varepsilon_{AlGaAs} = 13.18 - 2.9 \cdot x \cdot \text{COMP} \quad 5-67$$

### Low Field Mobility

The default low field electron mobility for AlGaAs is a function of the composition fraction,  $x$ , within the system. The following equations outline this relationship:

| Table 5-7. Low Field Mobility Equations                                |  |
|--|--|
| AlGaAs Low Field Mobility  | Mole Fraction Range                    |
| $\mu_n = 8000 - (1.818 \times 10^4 \cdot x \cdot \text{COMP})$         | $(0 < x \cdot \text{COMP} < 0.429)$    |
| $\mu_n = 90 + 1.1435 \times 10^4 \cdot (x \cdot \text{COMP} - 0.46)^2$ | $(0.429 < x \cdot \text{COMP} < 0.46)$ |
| $\mu_n = 90 + 3.75 \times 10^4 \cdot (x \cdot \text{COMP} - 0.46)^2$   | $(0.46 < x \cdot \text{COMP} < 0.5)$   |
| $\mu_n = 200 - (2 / (x \cdot \text{COMP} - 0.46))$                     | $(0.5 < x \cdot \text{COMP} < 1.0)$    |

### 5.3.3: In(1-x)Ga(x)As(y)P(1-y) System

The In(1-x)Ga(x)As(y)P(1-y) material system is commonly used for the fabrication of heterojunction devices. These include laser diodes, photodiodes, Gunn diodes, and high speed heterostructure transistors. As a quaternary material, two different mole fraction parameters,  $x$  and  $y$ , are necessary to specify any particular combination. This produces a wide array of InGaAsP materials and characteristics. Of particular interest in this system are materials that are lattice matched to InP.

The default material characteristics in BLAZE for the InGaAsP system correspond to composition fractions  $x$  and  $y$  that yield InGaAsP material that is lattice matched to InP. The  $x$ .composition and  $y$ .composition are specified in the REGION statement with the  $x$ .COMP and  $y$ .COMP parameters. The relationship between  $x$  and  $y$  that satisfy this condition is given by:

$$x = \frac{0.1896 \cdot y \cdot \text{COMP}}{0.4176 - (0.0125 \cdot y \cdot \text{COMP})} \quad 0 < y \cdot \text{COMP} < 1 \quad 5-68$$

Many of the parameter models for the In(1-x)Ga(x)As(y)P(1-y) system are functions of the composition fraction  $y$ .composition only. The composition fraction,  $x$ .composition, can be deduced from the preceding relationship. Again, the default material characteristics in BLAZE for the InGaAsP system correspond to composition fractions  $x$  and  $y$  that yield InGaAsP material that is lattice matched to InP.

**Note:** Don't use this material system to form GaAs by setting x=1 and y=1, specify GaAs as the material instead.

## Bandgap

The default energy bandgap for the InP lattice matched In(1-x)Ga(x)As(y)P(1-y) system used in BLAZE is given by:

$$E_g(InGaAsP) = 1.35 + X.COMP \cdot (0.642 + (0.758 \cdot X.COMP)) + (0.101 \cdot Y.COMP - 1.101) \cdot Y.COMP - (0.28 \cdot X.COMP - 0.109 \cdot Y.COMP + 0.159) \cdot X.COMP \cdot Y.COMP \quad 5-69$$

## Electron Affinity

The electron affinities for materials in the InP lattice matched InGaAsP system are derived from conduction band offsets and from the assumption that the affinity of InP is 4.4eV. The default conduction band edge offset between lattice matched InGaAsP and InP is then:

$$\Delta E_c = 0.268 \cdot Y.COMP + 0.003 \cdot (Y.COMP)^2 \quad 5-70$$

## Density of States and Effective Mass

The density of states is defined, as before, as a function of the effective masses of electrons and holes according to Chapter 3: "Physics", Equation 3-31. For the InGaAsP system, the default conduction and valence band effective masses, for electrons and holes, are given by the following.

For the conduction band:

$$m_e^* = 0.08 - (0.116 \cdot Y.COMP) + (0.026 \cdot X.COMP) - 0.059 \cdot (X.COMP \cdot Y.COMP) + (0.064 - 0.02 \cdot Y.COMP) \cdot (X.COMP)^2 + (0.06 + 0.032 \cdot X.COMP) \cdot (Y.COMP)^2 \quad 5-71$$

For the valence band the hole effective mass is defined by:

$$m_h^* = \left( m_{lh}^{1.5} + m_{hh}^{1.5} \right)^{\frac{2}{3}} \quad 5-72$$

where the default light hole effective mass is given by:

$$m_{lh} = 0.120 - (0.116 \cdot Y.COMP) + 0.03 \cdot (X.COMP)^2 \quad 5-73$$

and the default heavy hole effective mass is a constant and is given by:

$$m_{hh} = 0.46 \quad 5-74$$

## Dielectric Permittivity

The default static dielectric constant for lattice matched InGaAsP to InP is given by

$$\epsilon_{InGaAsP} = (14.6 \cdot (1 - X.COMP) \cdot Y.COMP) + 12.5 \cdot (1 - X.COMP) \cdot (1 - Y.COMP) + 13.18 \cdot X.COMP \cdot Y.COMP + 11.11 \cdot X.COMP \cdot (1 - Y.COMP) \quad 5-75$$

## Low Field Mobility

The default low field mobility parameters for electrons and holes for lattice matched InGaAs are given by linear interpolations from the binary compounds GaAs and InP. The following formulas are used:

$$\mu_{n1} = 33000 + (8500 - 33000) \cdot X \cdot \text{COMP} \quad 5-76$$

$$\mu_{p1} = 460 + (400 - 460) \cdot X \cdot \text{COMP} \quad 5-77$$

$$\mu_{n2} = 4600 + (300 - 4600) \cdot X \cdot \text{COMP} \quad 5-78$$

$$\mu_{p2} = 150 + (100 - 150) \cdot X \cdot \text{COMP} \quad 5-79$$

$$\mu_{n0} = \mu_{n1} + (1 - Y \cdot \text{COMP})(\mu_{n2} - \mu_{n1}) \quad 5-80$$

$$\mu_{p0} = \mu_{p1} + (1 - Y \cdot \text{COMP})(\mu_{p2} - \mu_{p1}) \quad 5-81$$

### 5.3.4: The Si(1-x)Ge(x) System

Advances in the growth of Silicon and Si(1-x)Ge(x) alloys have allowed the potential for using bandgap engineering to construct heterojunction devices such as HBTs and HEMTs using these materials. BLAZE supports the SiGe material system by providing composition dependent material parameters. These parameters are accessed by specifying the material name SiGe.

The following sections describe the functional relationship between Ge mole fraction  $x$ , and the SiGe material characteristics necessary for device simulation.

#### Bandgap

Bandgap is one of the most fundamental parameters for any material. For SiGe, the dependence of the bandgap on the Ge mole fraction,  $x$ , *composition*, is divided into ranges as follows:

$$E_g = 1.08 + X \cdot \text{COMP} \cdot (0.945 - 1.08) / 0.245; \quad 5-82$$

for  $x \leq 0.245$

$$E_g = 0.945 + (X \cdot \text{COMP} - 0.245) \cdot (0.87 - 0.945) / (0.35 - 0.245); \quad 5-83$$

for  $0.245 < x \leq 0.35$

$$E_g = 0.87 + (X \cdot \text{COMP} - 0.35) \cdot (0.78 - 0.87) / (0.5 - 0.35); \quad 5-84$$

for  $0.35 < x \leq 0.5$

$$E_g = 0.78 + (X \cdot \text{COMP} - 0.5) \cdot (0.72 - 0.78) / (0.6 - 0.5); \quad 5-85$$

for  $0.5 < x \leq 0.6$

$$E_g = 0.72 + (X \cdot \text{COMP} - 0.6) \cdot (0.69 - 0.72) / (0.675 - 0.6); \quad 5-86$$

for  $0.6 < x \leq 0.675$

$$E_g = 0.69 + (X.COMP - 0.675) \cdot (0.67 - 0.69) / (0.735 - 0.675); \quad 5-87$$

for  $0.675 < x \leq 0.735$

$$E_g = 0.67; \quad 5-88$$

for  $0.735 < x \leq 1$

The temperature dependence of the bandgap of SiGe is calculated the same as for Silicon using except that EGALPHA and EGBETA are a function of Ge mole fraction x as follows:

$$E_g(T_L) = E_g + \mathbf{EGALPHA} \left[ \frac{300^2}{300 + \mathbf{EGBETA}} - \frac{T_L^2}{T_L + \mathbf{EGBETA}} \right] \quad 5-89$$

$$\mathbf{EGALPHA} = (4.73 + X.COMP \cdot (4.77 - 4.73)) \times 10^4 \quad 5-90$$

$$\mathbf{EGBETA} = 626 + X.COMP \cdot (235 - 636) \quad 5-91$$

where  $E_g$  is dependent upon the mole fraction as above.

### Electron Affinity

The electron affinity  $\chi$  of SiGe is taken to be constant with respect to composition.

### Density of States

The density of states for SiGe is defined differently compared to the previous materials by not being a function of the effective masses. Instead the density of states have been made to depend upon the Ge mole fraction, *x.composition*, according to:

$$N_c = 2.8 \times 10^{19} + X.COMP \cdot (1.04 \times 10^{19} - 2.8 \times 10^{19}) \quad 5-92$$

$$N_v = 1.04 \times 10^{19} + X.COMP \cdot (6.0 \times 10^{18} - 1.04 \times 10^{19}) \quad 5-93$$

### Dielectric Function

The compositional dependence of the static dielectric constant of SiGe is given by

$$\epsilon = 11.8 + 4.2 \cdot X.COMP \quad 5-94$$

### Low Field Mobility

No specific SiGe low field mobility models have been implemented into BLAZE.

### Velocity Saturation

In SiGe, the temperature dependent velocity saturation, used in the field dependent mobility model is defined by the following equations.

$$v_{SATN} = 1.38 \cdot 10^7 \cdot \sqrt{\left(\tanh\left(\frac{175}{T_L}\right)\right)} \quad 5-95$$

$$v_{SATP} = 9.05 \cdot 10^6 \cdot \sqrt{\left(\tanh\left(\frac{312}{T_L}\right)\right)} \quad 5-96$$

---

**Note:** All other defaults used for SiGe are taken from Silicon

---

### 5.3.5: Silicon Carbide (SiC)

Silicon carbide materials are of interest for high power, high temperature applications. The main characteristics of silicon carbide are that they have a very wide bandgap, high thermal conductivity, high saturation velocity, and high breakdown strength. Silicon carbide is commercially available in three polytypes called 6H-SiC, 3H-SiC, and 4H-SiC. ATLAS supports all three these polytypes. The following paragraphs describe the material defaults for these materials.

#### Band Parameters for SiC

SiC band parameter equations are identical to those used for Silicon but with the values adjusted for 3C-SiC, 4H-SiC, and 6H-SiC. The physical band parameter values are shown in Tables B-18 and B-19 of Appendix B: “Material Systems”.

#### SiC Mobility Parameters

##### Isotropic Mobility

By default mobility is assumed to be entirely isotropic in nature. that is there is no directional component. The default low field mobilities of electrons and holes for 3C-SiC, 4H-SiC, and 6H-SiC are shown in Table 5-8.

| Table 5-8. Silicon Carbide Low Field Mobility Defaults |           |        |        |        |                      |
|--|-----------|--------|--------|--------|----------------------|
| Statement  | Parameter | 6H-SiC | 3C-SiC | 4H-SiC | Units                |
| MOBILITY   | MUN       | 330    | 1000   | 460    | cm <sup>2</sup> /V·s |
| MOBILITY   | MUP       | 60     | 50     | 124    | cm <sup>2</sup> /V·s |

##### Anisotropic Mobility

The mobility behavior within SiC is now known to be anisotropic in nature, which dramatically alters the electrical performance of a device. An isotropic model has been implemented into ATLAS to correctly model this behavior. Following the ideas of Lindefelt [7] and Lades [134], the mobility within the drift diffusion equations has been made a tensor property. As a result the mobility has become:

$$\mu = \begin{bmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_1 & 0 \\ 0 & 0 & \mu_2 \end{bmatrix} \quad 5-97$$

where  $\mu_1$  represents the mobility defined in one plane and  $\mu_2$  the mobility defined in a second plane. In the case of SiC  $\mu_1$  represents the mobility of plane <1100> whilst  $\mu_2$  represents the mobility of plane <1000>. These mobilities are defined for both holes and electrons.

### Defining Anisotropic Mobility in ATLAS

To define a material with anisotropic mobility, specify two MOBILITY statements. In each statement, the N.ANGLE and P.ANGLE parameters are used to specify the direction where that particular mobility is to apply. The following example shows how this is done.

```
# FIRST DEFINE MOBILITY IN PLANE <1100>
#
MOBILITY MATERIAL=3C-SiC VSATN=2E7 VSATP=2E7 BETAN=2 BETAP=2 \
    MU1N.CAUG=10 MU2N.CAUG=410 NCRITN.CAUG=13E17 \
    DELTAN.CAUG=0.6 GAMMAN.CAUG=0.0 \
    ALPHAN.CAUG=-3 BETAN.CAUG=-3 \
    MU1P.CAUG=20 MU2P.CAUG=95 NCRITP.CAUG=1E19 \
    DELTAP.CAUG=0.5 GAMMAP.CAUG=0.0 \
    ALPHAP.CAUG=-3 BETAP.CAUG=-3
#
# NOW DEFINE MOBILITY IN PLANE <1000>
#
MOBILITY MATERIAL=3C-SiC N.ANGLE=90.0 VSATN=2E7 VSATP=2E7 BETAN=2 BETAP=2 \
    MU1N.CAUG=5 MU2N.CAUG=80 NCRITN.CAUG=13E17 \
    DELTAN.CAUG=0.6 GAMMAN.CAUG=0.0 \
    ALPHAN.CAUG=-3 BETAN.CAUG=-3 \
    MU1P.CAUG=2.5 MU2P.CAUG=20 NCRITP.CAUG=1E19 \
    DELTAP.CAUG=0.5 GAMMAP.CAUG=0.0 \
    ALPHAP.CAUG=-3 BETAP.CAUG=-3
```

### Impact Ionization and Thermal Parameters

The equations governing these effects are identical to those for Silicon but with adjusted coefficients. See Appendix B: "Material Systems" for a list of all these parameters.



### 5.3.6: The Al(1-x)Ga(x)N System

The following sections describe the relationship between mole fraction,  $x.COMP$ , and the material parameters of the Al(1-x)Ga(x)N system.

#### Bandgap

Equation 5-98 is used in the calculation of bandgap as a function of composition fraction.

$$E_g = 6.13 * x.COMP + 3.42 * (1 - x.COMP) - x.COMP * (1 - x.COMP) \quad 5-98$$

#### Electron Affinity

Equation 5-99 is used in the calculation of electron affinity as a function of composition fraction.

$$\chi = 4.31 - 0.7 * (E_g - 3.42) \quad 5-99$$

#### Permittivity

Equation 5-100 is used in the calculation of permittivity as a function of composition fraction.

$$\varepsilon = 10.4 - 0.3 * x.COMP \quad 5-100$$

#### Density of States Masses

Equations 5-101 and 5-102 are used to calculate the density of states effective masses of electrons and holes.

$$m_c = 0.228 + (0.314 - 0.228) * x.COMP \quad 5-101$$

$$m_v = 0.259 + (0.417 - 0.259) * x.COMP \quad 5-102$$

### 5.3.7: The Hg(1-x)Cd(x)Te System

The following sections describe the relationship between mole fraction,  $x.COMP$ , and the material parameters of the of the Hg(1-x)Cd(x)Te system. This data has been taken from [141].

#### Bandgap

Equation 5-103 is used in the calculation of bandgap as a function of composition fraction.

$$E_g = -0.302 + 1.93 * x.COMP - 0.810 * x.COMP^2 + 0.832 * x.COMP^3 + 5.354 \times 10^{-4} * (1 - 2 * x.COMP) T_L \quad 5-103$$

Here,  $T_L$  is lattice temperature.

### Electron Affinity

Equation 5-104 is used in the calculation of electron affinity as a function of composition fraction.

$$\chi = 4.23 - 0.813*(EG300 - 0.0083) \quad 5-104$$

### Permittivity

Equation 5-105 is used in the calculation of relative permittivity as a function of composition fraction.

$$\varepsilon = 20.5 - 15.5*X.COMP + 5.7*X.COMP^2 \quad 5-105$$

### Density of States Masses

Equations 5-106 and 5-107 are used to calculate the density of states effective masses of electrons and holes.

$$\frac{m_e}{m_0} = \left[ -0.6 + 6.333*\left(\frac{2}{EG300} + \frac{1}{EG300 + 1}\right) \right]^{-1} \quad 5-106$$

$$\frac{m_e}{m_0} = 0.55 \quad 5-107$$

### Mobility

Equations 5-108 and 5-109 are used to calculate the electron and hole mobilities as functions of composition fraction.

$$\mu_e = 9 \times 10^4 \left( \frac{0.2}{X.COMP} \right) T_L^{7.5} - 0.2*(0.2/X.COMP)^{0.6} \quad 5-108$$

$$\mu_h = 0.01*\mu_e \quad 5-109$$

## 5.4: Simulating Heterojunction Devices with Blaze

### 5.4.1: Defining Material Regions with Positionally-Dependent Band Structure

#### Step Junctions

The easiest way to define a device with positionally dependent band structure is to specify two adjacent semiconductor regions with dissimilar bandgap. In this case, BLAZE would simulate an abrupt heterojunction between the two materials. As an example, suppose you wanted to simulate an abrupt heterojunction parallel to the x-axis at a location of  $y=0.1$  microns. For values of  $y$  greater than 0.1 specify, for example, GaAs. For values of  $y$  less than 0.1, specify AlGaAs with a composition fraction of 0.3. The following statements would specify this situation.

```
REGION Y.MIN=0.1 MATERIAL=GaAs
REGION Y.MAX=0.1 MATERIAL=AlGaAs x.COMP=0.3
```

This fragment specifies that the two regions form an abrupt heterojunction at  $Y=0.1$ . The first region is composed of GaAs while the second is composed of AlGaAs.

These two material names are used by BLAZE to choose default material models for the two regions. For a complete list of the materials available in ATLAS/BLAZE, see Appendix B: “Material Systems”. For the AlGaAs region a composition fraction of 0.3 is specified.

#### Graded Junctions

A grading can be applied to this heterojunction with a simple modification. For example:

```
REGION Y.MIN=0.1 MATERIAL=GaAs
REGION Y.MAX=0.1 MATERIAL=AlGaAs x.COMP=0.3 GRAD.34=0.01
```

specifies that the composition fraction of the AlGaAs region decreases from 0.3 at  $y=0.1$  microns to 0.0 at  $y=0.11$  microns. The GRAD. parameter specifies the distance over which the mole fraction reduces to zero. The GRAD. parameter is indexed such that GRAD.12 corresponds to the Y.MIN side of the region, GRAD.23 corresponds to the x.MAX side of the region, GRAD.34 corresponds to the Y.MAX side of the region, and GRAD.41 corresponds to the x.MIN side of the region. In most cases the GRAD.n parameter acts to increase the size of the region. By default the GRAD.n parameters are set to zero and all heterojunctions are abrupt. It should also be noted that the GRAD. parameter acts just like the other region geometry parameters in that later defined regions overlapping the graded part of the region will overlap the grading. If in the previous example, the grading had been applied to the GaAs region it would be overlapped by the AlGaAs region. This would have produced an abrupt interface. A solution would be to limit Y.MAX in the AlGaAs region to 0.09. Care should always be taken to specify regions in the proper order to avoid such problems.

Along similar lines, the overlapping of regions can be used to an advantage in forming graded heterojunctions between two materials in the same system with different non-zero composition fractions. For example:

```
REGION Y.MIN=0.1 MATERIAL=AlGaAs x.COMP=0.3 GRAD.12=0.02
REGION Y.MAX=0.11 MATERIAL=AlGaAs x.COMP=0.1
```

specifies a graded heterojunction with a composition of 0.3 at  $y = 0.1$  falling to 0.1 at  $y = 0.11$ .

## 5.4.2: Defining Materials and Models

### Materials

For example to set the bandgap for the material, InP, the following syntax should be used:

```
MATERIAL MATERIAL=InP EG300=1.35
```

### Models

BLAZE has two ways of simulating the physical effects of variations in semiconductor composition. For relatively gradual variations in composition the standard modifications to the drift-diffusion equations can be considered adequate for simulation purposes. For abrupt heterojunctions, it has been suggested that thermionic emission may be the dominant factor in the behavior of heterojunction behavior.

Individual material parameters and models can be defined for each material or region. These models are set in the MATERIAL, MODEL, and IMPACT statements.

This statement uses the MATERIAL parameter to select all regions composed of the material "InP". The bandgap in these regions will be set to 1.35. The parameters of a particular region can be set in two ways. The first is by way of the region index, as in:

```
MODEL REGION=1 BGN
```

In this case, the band gap narrowing model is enabled in the region indexed number 1.

The region name may also be used as in the following:

```
IMPACT NAME=substrate SELB
```

This example turns on the Selberherr Impact Ionization Model in the region named "substrate". You can then set the parameters for all regions and materials by omitting the MATERIAL, REGION, or NAME parameters, as in the following:

```
MODEL BGN
```

This statement sets the bandgap narrowing model for all regions and materials

### Parser Functions

To use the C-INTERPRETER functions, you need to know the C programming language. See Appendix A: "C-Interpreter Functions" for a description of the parser functions.

To specify a completely arbitrary spatial variation of varying composition fraction, use a parser function. To define the parser function for composition fraction, write a C function describing the composition fraction as a function of position. A template for the function called COMPOSITION is provided with this release of ATLAS. Once you define the COMPOSITION function, store it in a file. In order to use the function for composition, set the F.COMPOSIT parameter to the file name of the function.

## 6.1: 3D Device Simulation Programs

This chapter aims to highlight the extra information required for 3-D simulation as compared to 2-D. You should be familiar with the equivalent 2-D models before reading this chapter.

This chapter describes the set of ATLAS products that extends 2D simulation models and techniques and applies them to general non-planar 3D structures. The structural definition, models and material parameters settings and solution techniques are similar to 2D. You should be familiar with the simulation techniques described in Chapter 2: “Getting Started with ATLAS” and the equivalent 2D product chapters before reading the sections that follow. The products that form 3D device simulation in ATLAS are:

- DEVICE3D – silicon simulation equivalent to S-PISCES
- BLAZE3D – compound material and heterojunction simulation
- GIGA3D – non-isothermal simulation
- MIXEDMODE3D – mixed device-circuit simulation
- TFT3D – thin film transistor simulation
- QUANTUM3D – quantum effects simulation
- LUMINOUS3D – photodetection simulation

The 3D modules, THERMAL3D, are described in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”.

In a similar manner to the 2D products, GIGA3D, MIXEDMODE3D, LUMINOUS3D and QUANTUM3D should be combined with both DEVICE3D or BLAZE3D depending on the semiconductor materials used.

### 6.1.1: DEVICE3D

Device3D provides semiconductor device simulation of silicon technologies. Its use is analogous to the 2-D simulations in S-PISCES. See Chapter 4: “S-Piscses: Silicon Based 2D Simulator” for more information on S-PISCES.

### 6.1.2: BLAZE3D

BLAZE3D allows you to simulate semiconductor devices with semiconductor compositional variations (i.e., heterojunction devices). BLAZE3D is completely analogous to BLAZE (see Chapter 5: “Blaze: Compound Material 2D Simulator”), with some exceptions. For one thing, the current version of BLAZE3D doesn’t allow or account for compositional variations in the Z direction. It also doesn’t account for thermionic interfaces at abrupt heterojunctions.

### 6.1.3: GIGA3D

GIGA3D is an extension of DEVICE3D or BLAZE3D that accounts for lattice heat flow in 3D devices. GIGA3D has all the functionality of GIGA (see Chapter 7: “Giga: Self-Heating Simulator”) with a few exceptions. One exception is that additional syntax has been added to account for the three dimensional nature of thermal contacts. The Z.MIN and Z.MAX parameters can be specified on the THERMCONTACT statement to describe the extent of the contact in the Z direction. Another exception is that there is no BLOCK method available in the 3D version.

### **6.1.4: TFT3D**

TFT3D is an extension of DEVICE3D that allows you to simulate amorphous and polycrystalline semiconductor materials in three dimensions. TFT3D is completely analogous to the TFT simulator described in Chapter 14: “TFT: Thin-Film Transistor Simulator”. The complete functionality of the TFT simulator is available in TFT3D for three dimensional devices.

### **6.1.5: MIXEDMODE3D**

MIXEDMODE3D is an extension of DEVICE3D or BLAZE3D that allows you to simulate physical devices embedded in lumped element circuits (SPICE circuits). MIXEDMODE3D is completely analogous to the MIXEDMODE simulator, which is described in Chapter 12: “MixedMode: Mixed Circuit and Device Simulator”. The complete functionality of the MIXEDMODE simulator is available in MIXEDMODE3D for three dimensional devices.

### **6.1.6: QUANTUM3D**

QUANTUM3D is an extension of DEVICE3D or BLAZE3D, which allows you to simulate of the effects of quantum confinement using the Quantum Transport Model (Quantum Moments Model). QUANTUM3D is completely analogous to the QUANTUM model, but applies to three dimensional devices. See Chapter 13: “Quantum: Quantum Effect Simulator” for more information on QUANTUM.

### **6.1.7: LUMINOUS3D**

LUMINOUS3D is an extension of DEVICE3D that allows you to simulate photodetection in three dimensions. LUMINOUS3D is analogous to the LUMINOUS simulator, which is described in Chapter 10: “Luminous: Optoelectronic Simulator” with a few significant differences described later in this chapter.

## 6.2: 3D Structure Generation

All 3-D programs in ATLAS supports structures defined on 3D prismatic meshes. Structures may have arbitrary geometries in two dimensions and consist of multiple slices in the third dimension.

There are two methods for creating a 3D structure that can be used with ATLAS. One way is through the command syntax of ATLAS. Another way is through an interface to DEVEDIT3D.

A direct interface from ATHENA to 3D ATLAS isn't possible. But DEVEDIT3D provides the ability to read in 2D structures from ATHENA and extend them non-uniformly to create 3D structures for ATLAS.

### ATLAS Syntax For 3D Structure Generation

#### Mesh generation

Chapter 2: "Getting Started with ATLAS", Section 2.6.3: "Using The Command Language To Define A Structure" covers the generation of 2D and 3D mesh structures using the ATLAS command language. The `Z.MESH` statement and the `NZ` and `THREE.D` parameters of the `MESH` statement are required to extend a 2D mesh into 3D.

Conventionally, slices are made perpendicular to the `Z` axis. The mesh is triangular in `XY` but rectangular in `XZ` or `YZ` planes.

#### Region, Electrode, and Doping definition

Chapter 2: "Getting Started with ATLAS", Section 2.6.3: "Using The Command Language To Define A Structure" also covers the definition of 2D regions, electrodes and doping profiles. To extend the regions into 3D, use the `Z.MIN` and `Z.MAX` parameters. For example:

```
REGION NUM=2 MATERIAL=Silicon X.MIN=0 X.MAX=1 Y.MIN=0 Y.MAX=1 Z.MIN=0
Z.MAX=1
ELECTRODE NAME=gate X.MIN=0 X.MAX=1 Y.MIN=0 Y.MAX=1 Z.MIN=0 Z.MAX=1
DOPING GAUSS N.TYPE CONC=1E20 JUNC=0.2 Z.MIN=0.0 Z.MAX=1.0
```

For 2D regions or electrodes defined with the command language, geometry is limited to rectangular shapes. Similarly, in 3D regions and electrodes are composed of rectangular parallelepipeds.

#### DevEdit3D Interface

DEVEDIT3D is a graphical tool that allows you to draw 3D device structures and create 3D meshes. It can also read 2D structures from ATHENA and extend them into 3D. These structures can be saved from DEVEDIT3D as structure files for ATLAS. Also, save a command file when using DEVEDIT3D. This file is used to recreate the 3D structure inside DEVEDIT3D, which is important, since DEVEDIT3D doesn't read in 3D structure files.

ATLAS can read structures generated by DEVEDIT3D using the command:

```
MESH INF=<filename>
```

The program is able to distinguish automatically between 2D and 3D meshes read in using this command.

#### Defining Devices with Circular Masks

DEVEDIT3D makes a triangular mesh in the `XY` plane and uses `z`-plane slices. This means, that normally the `Y` direction is vertically down into the substrate. But in the case of using circular masks, you need to rotate the device.

With defining devices using circular masks in DEVEDIT3D, the `XY` plane should be the surface of the device and the `Z` direction should be into the substrate.

## 6.3: Model And Material Parameter Selection in 3D

Models and material parameters are chosen in 3-D in common with other 2-D modules using the `MODELS`, `IMPACT`, `MATERIAL`, `MOBILITY`, `INTERFACE`, and `CONTACT` statements.

The models available in 3D device simulation programs are:

### 6.3.1: Mobility

- Table for 300K (`CONMOB`)
- Thomas (`ANALYTIC`)
- Arora's Model (`ARORA`)
- Klaassen's Model (`KLAASSEN`)
- Lombardi's Model (`CVT`)
- Yamaguchi Model (`YAMA`)
- Parallel Field Dependence (`FLDMOB`)
- Parallel Field Dependence with negative differential mobility (`FLDMOB EVSATMOD=1`)

### 6.3.2: Recombination

- Shockley Read Hall (`SRH`)
- Concentration dependent lifetime `SRH` (`CONSRH`)
- Klaassen's concentration dependent lifetime `SRH` (`KLASRH`)
- Auger (`AUGER`)
- Klaassen's concentration dependent Auger recombination model (`KLAAUG`)
- Optical Recombination (`OPTR`)
- Bulk and interface traps (`TRAP`, `INTTRAP`)
- Continuous defect states (`DEFECT`)

### 6.3.3: Generation

- Selberherr Impact Ionization (`IMPACT SELB`)
- Crowell Impact Ionization (`IMPACT CROWELL`)
- Hot Electron Injection (`HEI`)
- Fowler Nordheim Tunneling (`FNORD`)
- Single Event Upset (`SINGLEEVENTUPSET`)

### 6.3.4: Carrier Statistics

- Boltzmann (default)
- Fermi (`FERMI`)
- Band Gap Narrowing (`BGN`)
- Incomplete Ionization (`INCOMPLETE`)
- Quantum Mechanical Effects (`QUANTUM`)

### 6.3.5: Boundary Conditions

- Ohmic and Schottky
- Current Boundary Conditions



- Lumped Element Boundary Conditions
- Distributed Contact Resistance

### 6.3.6: Interface and Bulk Traps (Discrete and Continuous)

- Photogeneration with Ray Tracing (LUMINOUS3D):

All these models, with the exception of `SINGLEEVENTUPSET`, are documented in the Chapter 3: “Physics” or in the 2D product chapters of this manual.

### 6.3.7: Single Event Upset Simulation

The capability of single event upset/photogeneration transient simulation is included in 3D using the `SINGLEEVENTUPSET` statement (see Chapter 18: “Statements”, Section 18.39: “`SINGLEEVENTUPSET`” for more information). It allows you to specify the radial, length, and time dependence of generated charge along tracks. There can be a single particle strike or multiple strikes. Each track is specified by an Entry Point Location ( $x_0, y_0, z_0$ ) and an Exit Point Location ( $x_1, y_1, z_1$ ). This is assumed to be a cylinder with the radius defined with the `RADIUS` parameter.

The entry and exit points are specified by the `ENTRYPOINT` and `EXITPOINT` parameters of the `SINGLEEVENTUPSET` statement. These are character parameters that represent the ordered triplet coordinates of the entry and exit points of the particle track.

The electron/hole pairs generated at any point is a function of the radial distance,  $r$ , from the center of the track to the point, the distance  $l$  along the track and the time,  $t$ . The implementation into ATLAS allows you to define the generation as the number of electron-hole pairs per  $\text{cm}^3$  along the track according to the equation:

$$G(r,l,t) = (\text{DENSITY} * L1(l) + S * B.\text{DENSITY} * L2(l)) * R(r) * T(t) \quad 6-1$$

where `DENSITY` and `B.DENSITY` are defined as the number of generated electron/hole pairs per  $\text{cm}^3$ .

In radiation studies, the ionizing particle is typically described by the linear charge deposition (LCD) value, which defines the actual charge deposited in units of  $\text{pC}/\mu\text{m}$ . You can use this definition within ATLAS by specifying the `PCUNITS` parameter in the `SINGLEEVENTUPSET` statement. If the user-defined parameter, `PCUNITS`, is set in the `SINGLEEVENTUPSET` statement, then `B.DENSITY` is the generated charge, in  $\text{pC}/\mu\text{m}$ , and the scaling factor  $S$  is:

$$S = \frac{1}{q\pi \text{RADIUS}^2} \quad 6-2$$

where `RADIUS` is defined on the `SINGLEEVENTUPSET` statement. If the `PCUNITS` parameter isn't set, then `B.DENSITY` is the number of generated electron/hole pairs in  $\text{cm}^{-3}$ , and the scaling parameter,  $S$ , is unity.

Another common measure of the loss of energy of the SEU particle, as it suffers collisions in a material, is the linear energy transfer (LET) value which is given in units of  $\text{MeV}/\text{mg}/\text{cm}^2$  (or  $\text{MeV}\cdot\text{cm}^2/\text{mg}$ ). In silicon, energy can be converted to charge by considering that approximately 3.6 eV of energy is required to generate an electron-hole pair. The conversion factor from the LET value to the LCD value is then approximately 0.01 for silicon. So, for instance, a LET value of  $25 \text{ MeV}\cdot\text{cm}^2/\text{mg}$  is therefore equivalent to  $0.25 \text{ pC}/\mu\text{m}$  which can then be defined with the `B.DENSITY` and `PCUNITS` parameters.

The factors,  $L1$  and  $L2$ , in Equation 6-1 define the variation of charge or carrier generation along the path of the SEU track. These variations are defined by the equations:

$$L1(l) = A1 + A2 \cdot l + A3 \exp(A4 \cdot l) \quad 6-3$$

$$L2(1) = \mathbf{B1(B2 + 1 \cdot B3)^{B4}}$$

6-4

where the parameters: A1, A2, A3, A4, B1, B2, B3 and B4 are user-definable as shown in Table 6.1.

| Table 6.1. User-Specifiable Parameters for Equations 6-3 and 6-4 |           |         |                  |
|--|-----------|---------|------------------|
| Statement  | Parameter | Default | Units            |
| SINGLEEVENTUPSET   | A1        | 1       |                  |
| SINGLEEVENTUPSET   | A2        | 0       | cm <sup>-1</sup> |
| SINGLEEVENTUPSET   | A3        | 0       |                  |
| SINGLEEVENTUPSET   | A4        | 0       | cm <sup>-1</sup> |
| SINGLEEVENTUPSET   | B1        | 1       |                  |
| SINGLEEVENTUPSET   | B2        | 1       |                  |
| SINGLEEVENTUPSET   | B3        | 0       | cm <sup>-1</sup> |
| SINGLEEVENTUPSET   | B4        | 0       |                  |

**Note:** The default parameters in Table 6.1 were chosen to result in constant carrier or charge generation as a function of distance along the particle track.

The factor R(r) is the radial parameter which is defined by one of two equations. The default is:

$$R(r) = \exp\left(-\frac{r}{\mathbf{RADIUS}}\right) \quad 6-5$$

where r is the radial distance from the centre of the track to the point and RADIUS is a user-definable parameter as shown in Table 6.2. You can choose an alternative expression if the RADIALGAUSS parameter is specified on the SINGLEEVENTUPSET statement. In this case, R(r) is given by:

$$R(r) = \exp\left(-\left(\frac{r}{\mathbf{RADIUS}}\right)^2\right) \quad 6-6$$

The time dependency of the charge generation T(t) is controlled with the TC parameter through two functions.

For TC=0:

$$T(t) = \text{deltafunction}(t - \mathbf{T0}) \quad 6-7$$

For  $TC > 0$ :

$$T(t) = \frac{2e^{-\left(\frac{t-TO}{TC}\right)^2}}{TC\sqrt{\pi}\operatorname{erfc}\left(\frac{-TO}{TC}\right)} \quad 6-8$$

where  $TO$  and  $TC$  are parameters of the `SINGLEEVENTUPSET` statement.

| Statement                     | Parameter              | Default | Units                                       |
|-------------------------------|------------------------|---------|---|
| <code>SINGLEEVENTUPSET</code> | <code>DENSITY</code>   | 0.0     | $\text{cm}^{-3}$                            |
| <code>SINGLEEVENTUPSET</code> | <code>B.DENSITY</code> | 0.0     | $\text{cm}^{-3}$ or $\text{pC}/\mu\text{m}$ |
| <code>SINGLEEVENTUPSET</code> | <code>TO</code>        | 0.0     | s   |
| <code>SINGLEEVENTUPSET</code> | <code>TC</code>        | 0.0     | s   |
| <code>SINGLEEVENTUPSET</code> | <code>RADIUS</code>    | 0.05    | $\mu\text{m}$                               |

The following example shows a particle strike that is perpendicular to the surface along the z-plane, so only the z-coordinates change has a radius of 0.1  $\mu\text{m}$  and a LET value of 20  $\text{MeV}\cdot\text{cm}^2/\text{mg}$  (`B.DENSITY=0.2`). The strike has a delay time of 60 ps and the Gaussian profile has a characteristic time of 10 ps. The generation track for this striking particle is from  $z=0$  to  $z=10 \mu\text{m}$  and carrier generation occurs along its entire length.

```
single entry="5.5,0.0,0.0" exit="5.5,0.0,10" radius=0.1 \
pcunits b.density=0.2 t0=60.e-12 tc=10.e-12
```

### User-defined SEU in 3D

In addition to the model described by the `SINGLEEVENTUPSET` statement, you can use the `C-INTERPRETER` to specify an arbitrary generation profile. This is specified using the syntax:

```
BEAM NUM=1 F3.RADIATE=myseu.c
.
SOLVE B1=1.0 RAMPTIME=1e-12 DT=1e-14 TSTOP=1e-7
```

The `F3.RADIATE` parameter indicates an external c-language subroutine conforming to the template supplied. The file, `myseu.c`, returns a time and position dependent value of carrier generation in 3-D. The value returned by `myseu.c`, is multiplied by the `B1` parameter at each timestep.

For more information about the C-Interpreter, see Appendix A: "C-Interpreter Functions".

## 6.3.8: Boundary Conditions in 3D

### External Passive Elements

You can attach external lumped resistors, capacitors and inductors to any contact. The syntax is the same as for the 2D products, which is:

```
CONTACT NAME=drain RES=1e3 CAP=1e-12 L=1e-6
```

You can also apply distributed resistances to contacts. The algorithm used for estimating contact area for 3D distributed contact resistance multiplies the contact perimeter in a given Z plane by the displacement in the Z direction. This algorithm will only work properly for planar contacts that do not vary in the Z direction. They may however abruptly terminate or start in the Z direction.

The units of lumped external passive elements are ohms for resistors, Farads for capacitors and Henrys for inductors. Distributed contact resistance is defined in ohms.cm<sup>3</sup>.

### Thermal Contacts for GIGA3D

Thermal contacts for non-isothermal simulation in GIGA3D are defined in an analogous manner to the 2D thermal contacts in GIGA. The Z.MIN and Z.MAX parameters are used to define the extent of the thermal contact in the z-plane. The units of the thermal resistance parameter ALPHA are scaled in 3D to W/(cm.K). For more information about GIGA3D, see Chapter 7: “Giga: Self-Heating Simulator”.

## 6.3.9: BLAZE3D Models

Models for simulating III-V materials are supported in BLAZE3D. The material parameters for all compound semiconductors are the same as used in 2-D simulations with BLAZE. Specialized models for III-V materials including heterojunction transport, optical recombination, and negative differential field dependent mobility are described in Chapter 5: “Blaze: Compound Material 2D Simulator”.

## 6.3.10: TFT3D Models

Models for simulating thin-film transistors made from amorphous or polycrystalline semiconductors are supported in TFT3D. The definition of the continuous defect states in the bandgap is performed using the same parameters as in 2D simulations with TFT. The models for continuous defect (or trap) densities are documented in Chapter 14: “TFT: Thin-Film Transistor Simulator”.

## 6.3.11: QUANTUM3D Models

Models for simulating quantum effects semiconductors are supported in QUANTUM3D. The definition of the quantum moments solver is the same as in 2D simulations with QUANTUM. The models for simulating quantum effects and the parameters to control the model are shown in Chapter 13: “Quantum: Quantum Effect Simulator”.

## 6.3.12: LUMINOUS3D Models

Many of the models for simulating photodetection in LUMINOUS3D are similar to those for simulating photodetection in LUMINOUS. For more information about LUMINOUS, see Chapter 10: “Luminous: Optoelectronic Simulator”. This chapter, however, shows several important differences between LUMINOUS and LUMINOUS3D.

### Optical Source Specification

The specification of the optical source in 3D is similar to the specification of the source described in Chapter 10: “Luminous: Optoelectronic Simulator”, Section 10.4.1: “Defining Optical Sources” with a few additions to account for the third dimension.

Figures 6-6-1 and 6-6-2 show the complete specification of the optical source in 3D includes the specification of the three coordinates of the source origin using the X.ORIGIN, Y.ORIGIN, and Z.ORIGIN parameters of the BEAM statement as well as two angles of rotation using the THETA and

PHI parameters. The PHI parameter is analogous to the LUMINOUS parameter, ANGLE, and specifies the direction of propagation relative to the device x axis (see Figure 6-1). In fact, PHI and ANGLE are synonymous. The THETA parameter specifies the rotated angle of propagation relative to the x-y plane (see Figure 6-2).

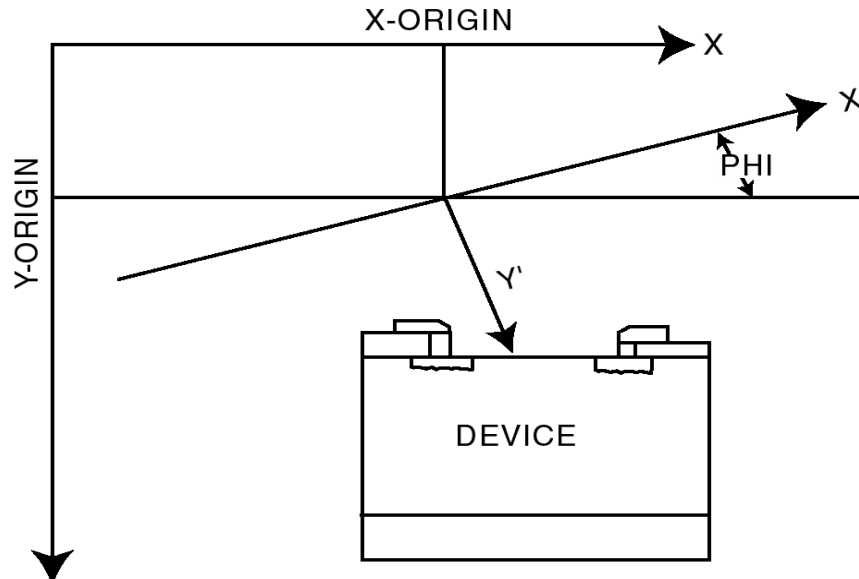


Figure 6-1: Source beam coordinate rotation around Z-axis

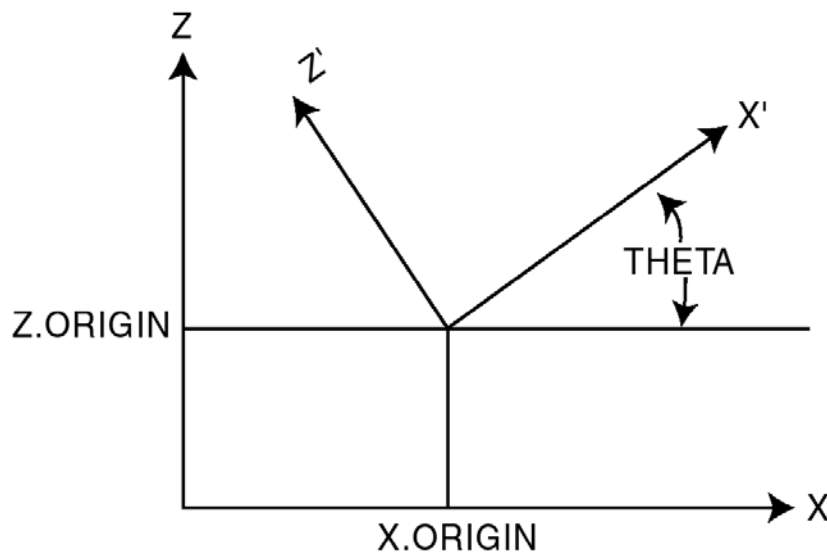
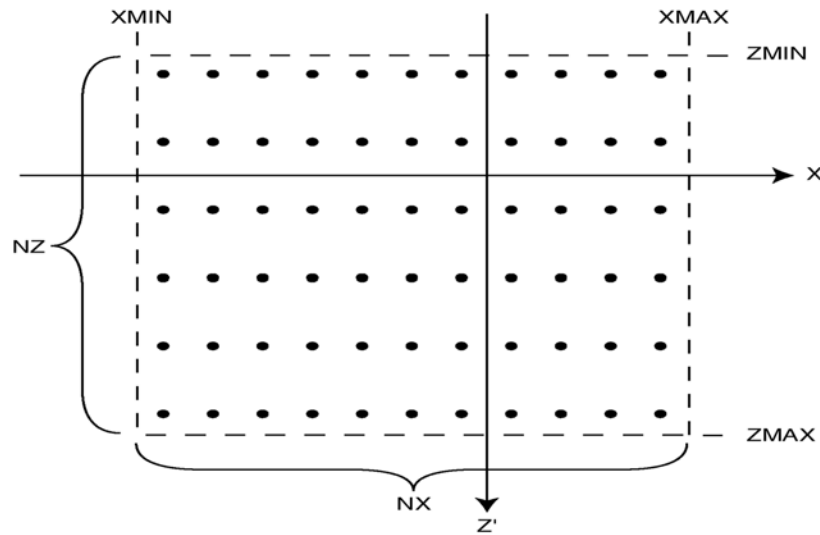


Figure 6-2: Source beam coordinate rotation around Y-axis

### Ray tracing

The discrete sampling of the source beam into rays in LUMINOUS3D is unlike that done in LUMINOUS. In LUMINOUS, the source beam is automatically broken up into a set of rays that resolve the device topology and variations in the interior of the device. In LUMINOUS3D, this process is more complex and is a computational burden. As such in LUMINOUS3D, specify a discrete sampling of the source beam (see Figure 6-3).

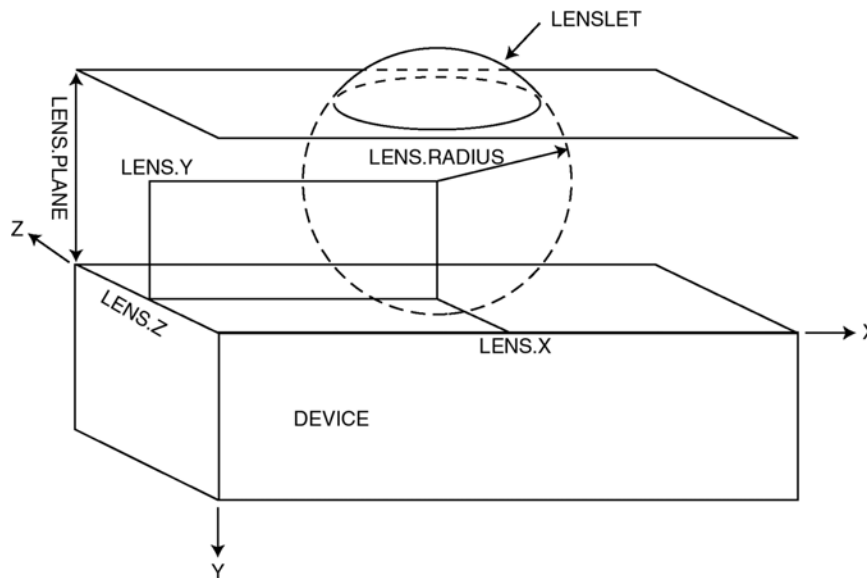


**Figure 6-3: Source beam sampling**

In Figure 6-3, the extent of the source sampling is specified by the XMIN, XMAX, ZMIN and ZMAX parameters of the BEAM statement. Even samples are taken along each of the beam front principal axes. The number of samples in the x and z directions are given by the NX and NZ parameters of the BEAM statement.

**Lenslet specification**

Another significant difference between LUMINOUS and LUMINOUS3D is that in 3-D, you can specify a virtual lenslet (see Figure 6-4) Due to the restriction of prismatic elements in 3D, you can't accurately specify focusing elements using the device mesh.



**Figure 6-4: Luminous3D Lenslet Specification**

As shown in Figure 6-4, the lenslet is represented by a spherical section atop a plane. The center of the sphere is specified by the `LENS . X`, `LENS . Y` and `LENS . Z` parameters of the `BEAM` statement. The radius of the sphere is specified by the `LENS . RADIUS` parameter of the `BEAM` statement. The location of the planar part surrounding the lenslet relative to the  $y=0$  plane is specified by the `LENS . PLANE` parameter. The index of refraction of the lenslet as well as the volume between the lens plane and the device surface is specified by the `LENS . INDEX` parameter of the `BEAM` statement.

Note that the volume associated with the lenslet is not meshed or considered in the solution of the device equations. It is merely used in the ray tracing. Also, you should keep in mind that lenslet can only be specified in planes perpendicular to the  $y$  axis.

#### **Other differences between Luminous and Luminous3D**

`LUMINOUS3D` has several other differences with `LUMINOUS`. For example, in `LUMINOUS` the rays generated during ray tracing are stored in all subsequent structure files. In `LUMINOUS3D`, this isn't the case. To save the rays in `LUMINOUS3D`, set the `RAYTRACE` parameter of the `BEAM` statement to the name of a file where the results of the ray trace are to be stored.

Another difference is that `LUMINOUS3D` has an option to cause all metal regions to act as perfect reflectors. To enable this option, specify `METAL . REFLECT` in the `BEAM` statement.

`LUMINOUS3D` also allows you to simulate periodicity with respect to ray tracing by specifying `PERIODIC` on the `BEAM` statement. This causes rays exiting the sides of the device (perpendicular to the  $x$ - $z$  plane) to re-enter the opposite side of the device.

## 6.4: Numerical Methods for 3D

### 6.4.1: DC Solutions

There are several differences between the default numerical methods applied in 2D ATLAS and those applied in 3D ATLAS. For example, with respect to non-linear iteration strategies, the current version of the 3D simulator does not support the BLOCK method. The NEWTON and GUMMEL iteration strategies are supported for 3D simulations, whereas NEWTON, GUMMEL and BLOCK are all supported for 2D simulations.

In solving the linear subproblem, the default approach in 3D is to use an iterative solver. This is believed to be the most efficient method for general 3D problems. In 2D, the direct solver is used by default. You may find it desirable to use direct methods in 3D problems due to improved convergence of computational efficiency. You can select the direct method by specifying DIRECT in the METHOD statement.

Also, in 3D there are two linear iterative solution methods available. The default is ILUCGS (incomplete lower-upper decomposition conjugate gradient system) and BICGST (bi-conjugate gradient stabilized). Historically, tests have shown that the current implementation of ILUCGS is slightly more stable than BICGST and is the default iterative solver in 3D. You can define the BICGST solver by specifying BICGST in the METHOD statement.

---

**Note:** Iterative solvers are recommended for large problems, typically greater than 5000 node points, due to lower solution times and memory usage.

---

### 6.4.2: Transient Solutions

In transient mode, a semi-implicit scheme is used in addition to the default TR-BDF algorithm [114]. This algorithm is recommended for complex simulations such as Single Event Upset. To select this method, use:

```
METHOD HALFIMPL
```

### 6.4.3: Obtaining Solutions In 3D

ATLAS3D programs can perform DC and transient analysis in an equivalent manner to 2D. The SOLVE statement is used to define the solution procedure. The syntax used is described as that in Chapter 2: "Getting Started with ATLAS", Section 2.9: "Obtaining Solutions".

### 6.4.4: Interpreting the Results From 3D

The log files produced by 3D ATLAS can be plotted in TONYPLOT exactly as those that result from S-PISCES or BLAZE. The only difference is the units of the currents produced. Log files from 3D simulations save current in Amperes, whereas the 2D simulations use Amperes/micron.

The solution files produced by 3D ATLAS should be plotted using TONYPLOT3D. These files cannot be read directly into the 2D TONYPLOT program. TONYPLOT3D contains features that allows you to make slices of the 3D structure, which can be plotted in 2D TONYPLOT. For more information about TonyPlot3D, see the VWF INTERACTIVE TOOLS USER'S MANUAL.

### 6.4.5: More Information

Many examples using 3D ATLAS have been installed on your distribution tape or CD. You can find more information about 3D ATLAS by reading the text associated with each example. You can also find find some more information at [www.silvaco.com](http://www.silvaco.com).



## 7.1: Overview

GIGA extends ATLAS to account for lattice heat flow and general thermal environments. GIGA implements Wachutka's thermodynamically rigorous model of lattice heating [84], which accounts for Joule heating, heating, and cooling due to carrier generation and recombination, and the Peltier and Thomson effects. GIGA accounts for the dependence of material and transport parameters on the lattice temperature, and supports the specification of general thermal environments using a combination of realistic heat-sink structures, thermal impedances, and specified ambient temperatures. GIGA works with both S-PISCES and BLAZE, and with both the drift-diffusion and energy balance transport models. See Chapter 3: "Physics", the "Drift-Diffusion Transport Model" section on page 3-2 and the "Energy Balance Transport Model" section on page 3-4 for more information on these models.

Before continuing with this chapter, you should be familiar with ATLAS. If not, read Chapter 2: "Getting Started with ATLAS", along with Chapter 4: "S-Pisces: Silicon Based 2D Simulator" or Chapter 5: "Blaze: Compound Material 2D Simulator".

### 7.1.1: Applications

A major application of GIGA is the simulation of high-power structures including bipolar, MOS, IGBT, and thyristor devices. Another important application is the simulation of electrostatic discharge (ESD) protection devices. Thermal effects are also important in SOI device operation due to the low thermal conductivity of the buried oxide, and in devices fabricated in III-V material systems due to the relatively low thermal conductivity of these materials.

Recent studies have demonstrated that accounting self-consistently for lattice heating is necessary for accurate simulation of bipolar VLSI devices. This is due to the sensitive temperature dependence of the carrier injection process. Since bipolar devices are key components of CMOS technologies, and because many devices can be impacted by parasitic bipolar effects, the applications of GIGA are very general.

For other more information on GIGA's application, see Section 7.3: "Applications of GIGA".

### 7.1.2: Numerics

GIGA supplies numerical techniques that provide efficient and robust solution of the complicated systems of equations that result when lattice heating is accounted for. These numerical techniques include fully-coupled and block iteration methods. When GIGA is used in conjunction with the energy balance equations, the result is a "six equation solver", which defines the state-of-the-art for general purpose device simulation.

Also for more information on numerical techniques, see Chapter 15: "Numerical Techniques".

## 7.2: Physical Models

### 7.2.1: The Lattice Heat Flow Equation

GIGA adds the heat flow equation to the primary equations that are solved by ATLAS. The heat flow equation has the form:

$$C \frac{\partial T_L}{\partial t} = \nabla(\kappa \nabla T_L) + H \quad 7-1$$

where:

C is the heat capacitance per unit volume.

$\kappa$  is the thermal conductivity.

H is the heat generation

$T_L$  is the local lattice temperature.

The heat capacitance can be expressed as  $C = \rho C_p$ , where  $C_p$  is the specific heat and  $\rho$  is the density of the material.

Specifying the `LAT.TEMP` parameter in the `MODELS` statement includes the lattice heat flow equation in ATLAS simulations.

GIGA supports different combinations of models. For example, if the `HCTE` and `LAT.TEMP` parameters are specified in the `MODEL` statement, and both particle continuity equations are solved, all six equations are solved. If `HCTE.EL` is specified instead of `HCTE`, only five equations are solved and the hole temperature  $T_p$  is set equal to lattice temperature  $T_L$ .

### Specifying Heat Sink Layers For Thermal Solutions

Regions may be defined for inclusion only in thermal calculations. These regions will typically consist of layers associated with heat sinks. They are defined using the `REGION` statement. Even though in reality the heat sink materials are typically metal conductors, it is easier to specify these layers with the material type, `INSULATOR`. This is because as insulators the program will only solve heat flow and not attempt to solve current continuity in these layers. The region number is subsequently used as an identifier when thermal conductivities and heat capacities are assigned to these regions.

The following statements specify two layers of a heat sink for inclusion in the thermal calculation.

```
REGION NUM=5 Y.MIN=0.5 Y.MAX=2.0 INSULATOR
REGION NUM=6 Y.MIN=2.0 Y.MAX=3.0 INSULATOR
```

### Specifying Thermal Conductivity

The value of thermal conductivity,  $k$ , for each region should be specified in the `MATERIAL` statement. Because thermal conductivity is generally temperature dependent, the following four models are available:

$$k(T) = \text{TC.CONST} \quad (\text{W/cm} \cdot \text{K}). \quad 7-2$$

$$k(T) = (\text{TC.CONST}) / (T/300)^{\text{TC.NPOW}} \quad (\text{W/cm} \cdot \text{K}). \quad 7-3$$

$$k(T) = 1 / (\text{TC.A} + (\text{TC.B}) * T + (\text{TC.C}) * T^2) \quad (\text{W/cm} \cdot \text{K}). \quad 7-4$$

$$k(T) = (TC.E)/(T - TC.D) \quad (W/cm \cdot K). \quad 7-5$$

The TC.CONST, TC.NPOW, TC.A, TC.B, TC.C, TC.D and TC.E parameters are all user-specifiable in the MATERIAL statement. The choice of models is also user-specified in the MATERIAL statement. To choose the model in Equation 7-2, specify the TCON.CONST parameter. To choose the model in Equation 7-3, specify the TCON.POWER parameter. To choose the model in Equation 7-4, specify the TCON.POLYN parameter. To choose the model in Equation 7-5, specify the TCON.RECIP parameter. The default model is the polynomial model in Equation 7-4.

The following statements would be used to specify the temperature dependent thermal conductivity of the regions previously defined.

```
MATERIAL REGION=5 TC.A=<n> TC.B=<n> TC.C=<n>
```

```
MATERIAL REGION=6 TC.A=<n> TC.B=<n> TC.C=<n>
```

### C-Interpreter Defined Thermal Conductivity

You can use the C-INTERPRETER to define the thermal conductivity, TCOND, as a function of the lattice temperature, position, doping and fraction composition. This is defined using the syntax:

```
MATERIAL REGION=<n> F.TCOND=<filename>
```

where the <filename> parameter is an ASCII file containing the C-INTERPRETER function. For more information about the C-INTERPRETER, see Appendix A: "C-Interpreter Functions".

### Specifying Heat Capacity

For transient calculations, specify heat capacities for every region in the structure. These are also functions of the lattice temperature, and are modeled as:

$$C = HC.A + HC.BT + HC.CT^2 + \frac{HC.D}{T^2} \quad (J/cm^3/K) \quad 7-6$$

Default values of HC.A, HC.B, HC.C, and HC.D are provided for common materials. These values can be specified on the MATERIAL statement.

The following statements would be used to specify the temperature dependent heat capacities of the regions previously defined.

```
MATERIAL REGION=5 HC.A=<n> HC.B=<n> HC.C=<n> HC.D=<n>
```

```
MATERIAL REGION=6 HC.A=<>> HC.B=<n> HC.C=<n> HC.D=<n>
```

| Statement | Parameter | Units                             |
|-----------|-----------|-----------------------------------|
| MATERIAL  | HC.A      | J/cm <sup>3</sup> /K              |
| MATERIAL  | HC.B      | J/cm <sup>3</sup> ·K <sup>2</sup> |
| MATERIAL  | HC.C      | J/cm <sup>3</sup> ·K <sup>3</sup> |
| MATERIAL  | HC.D      | JK/cm <sup>3</sup>                |

### C-Interpreter Defined Thermal Capacity

You can use the C-INTERPRETER to define the thermal capacity, TCAP, as a function of the lattice temperature, position, doping and fraction composition. This is defined using the syntax:

```
MATERIAL REGION=<n.region> F.TCAP=<filename>
```

where the <filename> parameter is an ASCII file containing the C-INTERPRETER function. For more information about the C-INTERPRETER, see Appendix A: "C-Interpreter Functions".

## 7.2.2: Non-Isothermal Models

### Effective Density Of States

When lattice heating is specified with the drift-diffusion transport model, the effective density of states for electrons and holes are modeled as functions of the local lattice temperature as defined by Equations 3-31 and 3-32 in Chapter 3: "Physics".

When lattice heating is specified with the energy balance model, the effective densities of states are modeled as functions of the local carrier temperatures,  $T_n$  and  $T_p$ , as defined by Equations 3-110 and 3-111 in Chapter 3: "Physics".

### Non-isothermal Current Densities

When GIGA is used, the electron and hole current densities are modified to account for spatially varying lattice temperatures:

$$\vec{J}_n = -q\mu_n n(\nabla\phi_n + P_n \nabla T_L) \tag{7-7}$$

$$\vec{J}_p = -q\mu_p p(\nabla\phi_p + P_p \nabla T_L) \tag{7-8}$$

where:

$P_n$  and  $P_p$  are the absolute thermoelectric powers for electrons and holes.

$P_n$  and  $P_p$  are modeled as follows:

$$P_n = \frac{k}{q} \left( \ln \frac{n}{N_c} - \left( \frac{5}{2} + KSN \right) \right) \tag{7-9}$$

$$P_p = \frac{k}{q} \left( \ln \frac{p}{N_v} - \left( \frac{5}{2} + KSP \right) \right) \tag{7-10}$$

The default values for Equations 7-9 and 7-10 are given in Table 7-7.2.

| Table 7.2. User-Specifiable Parameters for Equations 7-9 and 7-10 |           |         |       |
|---|-----------|---------|-------|
| Statement   | Parameter | Default | Units |
| MODELS  | KSN       | -1      | None  |
| MODELS  | KSP       | -1      | None  |

### 7.2.3: Heat Generation

When carrier transport is handled in the drift-diffusion approximation the heat generation term,  $H$ , used in Equation 7-1 has the form [83]:

$$\begin{aligned}
 H = & q \frac{|\vec{J}_n|^2}{\mu_n n} + q \frac{|\vec{J}_p|^2}{\mu_p p} - q T_L (\vec{J}_n \nabla P_n) + q T_L (\vec{J}_p \nabla P_p) \\
 & + q(R - G) \left\{ \left[ T_L \left( \frac{\partial \phi_n}{\partial T} \right)_{n,p} - \phi_n \right] - \left[ T_L \left( \frac{\partial \phi_p}{\partial T} \right)_{n,p} - \phi_p \right] \right\} \\
 & - q T_L \left[ \left( \frac{\partial \phi_n}{\partial T} \right)_{n,p} + P_n \right] \text{div } J_n - q T_L \left[ \left( \frac{\partial \phi_p}{\partial T} \right)_{n,p} + P_p \right] \text{div } J_p
 \end{aligned} \tag{7-11}$$

In the steady-state case, the current divergence can be replaced by the net recombination and Equation 7-11 simplifies to:

$$H = \left[ q \frac{|\vec{J}_n|^2}{\mu_n n} + q \frac{|\vec{J}_p|^2}{\mu_p p} \right] + q(R - G)[\phi_p - \phi_n + T_L(P_p - P_n)] - q T_L (\vec{J}_n \nabla P_n + \vec{J}_p \nabla P_p) \tag{7-12}$$

where:

$\left[ q \frac{|\vec{J}_n|^2}{\mu_n n} + q \frac{|\vec{J}_p|^2}{\mu_p p} \right]$  is Joule heating term,

$q(R - G)[\phi_p - \phi_n + T_L(P_p - P_n)]$  is recombination and generation heating and cooling term,

$-q T_L (\vec{J}_n \nabla P_n + \vec{J}_p \nabla P_p)$  accounts for the Peltier and Thomson effects.

A simple and intuitive form of  $H$  that has been widely used in the past is:

$$H = (\vec{J}_n + \vec{J}_p) \cdot \vec{E} \tag{7-13}$$

GIGA can use either Equations 7-12 or 7-13 for steady-state calculations. By default, Equation 7-13 is used. Equation 7-12 is used if the `HEAT.FULL` parameter is specified in the `MODELS` statement. To enable/disable the individual terms of Equation 7-12, use the `JOULE.HEAT`, `GR.HEAT`, and `PT.HEAT` parameters of the `MODEL` statement.

If the general expression shown in Equation 7-11 is used for the non-stationary case, the derivatives

$\left( \frac{\partial \phi_n}{\partial T} \right)_{n,p}$  and  $\left( \frac{\partial \phi_p}{\partial T} \right)_{n,p}$  are evaluated for the case of an idealized non-degenerate semiconductor and complete ionization.

The heat generation term,  $H$ , is always set equal to 0 in insulators.

When carrier transport is modeled in the energy balance approximation the following expression is used for H:

$$H = W_n + W_p + E_g U, \quad 7-14$$

where U,  $W_n$  and  $W_p$  are defined by Equations 3-112 through 3-114 in Chapter 3: "Physics".

## 7.2.4: Thermal Boundary Conditions

At least one thermal boundary condition must be specified when the lattice heat flow equation is solved. The thermal boundary conditions used have the following general form:

$$\sigma \left( \vec{J}_{\text{tot}}^u \cdot \vec{s} \right) = \alpha (T_L - T_{\text{ext}}) \quad 7-15$$

where  $\sigma$  is either 0 or 1,  $\vec{J}_{\text{tot}}^u$  is the total energy flux and  $\vec{s}$  is the unit external normal of the boundary.

The projection of the energy flux onto  $\vec{s}$  is:

$$\left( \vec{J}_{\text{tot}}^u \cdot \vec{s} \right) = -\kappa \frac{\partial T_L}{\partial n} + (T_L P_n + \phi_n) \vec{J}_n \cdot \vec{s} + (T_L P_p + \phi_p) (\vec{J}_p \cdot \vec{s}) \quad 7-16$$

When  $\sigma = 0$ , Equation 7-15 specifies a Dirichlet (fixed temperature) boundary condition:

$$T_L = \text{TEMPER}. \quad 7-17$$

where TEMPER can be defined in the THERMCONTACT statement as shown in the next section. Dirichlet boundary conditions may be specified for an external boundary (which may coincide with an electrode), or for an electrode that is inside the device.

When  $\sigma = 1$ , Equation 7-15 takes the form:

$$\left( \vec{J}_{\text{tot}}^u \cdot \vec{s} \right) = \frac{1}{R_{\text{th}}} (T_L - \text{TEMPER}) \quad 7-18$$

where the thermal resistance,  $R_{\text{th}}$ , is given by:

$$R_{\text{th}} = \frac{1}{\text{ALPHA}}$$

and ALPHA is user-definable on the THERMCONTACT statement.

### Specifying Thermal Boundary Conditions

Setting thermal boundary conditions is similar to setting electrical boundary conditions. The THERMCONTACT statement is used to specify the position of the thermal contact and any optional properties of the contact. Thermal contacts can be placed at any position in the device (including sidewalls). Equation 7-18 is used if a value is specified for  $\alpha$ . Otherwise, Equation 7-17 is used.

The following command specifies that thermal contact number 1 is located between  $x=0 \mu\text{m}$  and  $x=2 \mu\text{m}$  at  $y=0 \mu\text{m}$ , and that the temperature at the contact is 300K.

```
THERMCONTACT NUM=1 X.MIN=0 X.MAX=2 Y.MIN=0 Y.MAX=0 TEMP=300
```

You can use simpler statement if the coordinates of a thermal contact coincide with the coordinates of an electrical contact. In this case, it is permissible to specify the location of the thermal contact by referring to the electrode number of the electrical contact. For example, the statement:

```
THERMCONTACT NUM=1 ELEC.NUM=3 TEMP=400
```

specifies that thermal contact number 1 is located in the same position as electrode number 3 and that the contact temperature is 400K.

Specifying the BOUNDARY parameter gives you flexibility in applying thermal boundary conditions. This parameter is set by default and means that the thermal boundary condition will only be set on the outside surface of the thermal contact, where it forms the exterior of the device. If the parameter is cleared by specifying ^BOUNDARY in the THERMCONTACT statement, the boundary conditions will be applied to the interior of the thermal contact and to the part of the surface of the thermal contact that forms an interface with the interior of the device. In a 2D model, you may have a thermal contact that is internal to the device and in this case you would need to specify ^BOUNDARY. Otherwise, the contact will be ignored.

For example:

```
THERMCONTACT ELEC.NUM=1 ^BOUNDARY TEMPER=450 ALPHA=2.5
```

where the ELECTRODE extends into the device and will set the interior points of the thermalcontact to 450K and will apply the flux boundary condition on all faces of the thermal contact that interface with the interior of the device.

**Table 7.3. User Specifiable Parameters for Equations 7-17 and 7-18**

| Statement    | Parameter | Units                     | Default |
|--------------|-----------|---------------------------|---------|
| THERMCONTACT | ALPHA     | W / ( cm <sup>2</sup> K ) | ∞       |
| THERMCONTACT | BOUNDARY  | -                         | True    |
| THERMCONTACT | TEMPER    | K                         | 300     |

Representing a thermal environment, in terms of thermal impedances, leads to efficient solutions. But, thermal impedance representations are typically only approximations. Detailed thermal modeling (e.g., the effect of heat sink design changes) typically requires using detailed modeling of thermal regions with specified external ambient temperatures.

---

Note: You can't alter the value of a thermal resistor within a sequence of SOLVE statements. Rerun the input file whenever a thermal resistor is changed.

---

## 7.2.5: Temperature Dependent Material Parameters

GIGA automatically uses the built-in temperature dependence of the physical models that are specified. When lattice heating is specified, temperature dependent values are evaluated locally at each point in the device. When lattice heating is not solved, the models only provide global temperature dependence (i.e., all points in the device are assumed to be at the specified temperature).

The non-isothermal energy balance model uses the same carrier temperature dependencies of the mobility and impact ionization models as in the pure energy balance case, but with coefficients that depend on the local lattice temperature. Impact ionization coefficients depend on lattice temperature. Almost all other models and coefficients depend on lattice temperature.

When lattice heating is used there is no point in specifying models that do not include temperature dependence. For mobilities, don't specify CONMOB. Instead, specify ANALYTIC or ARORA. For impact ionization coefficients, specify the SELBERHERR model.

GIGA can account for the temperature dependence of the minority carrier lifetimes for electrons and/or holes. The LT.TAUN (electrons) and LT.TAUP (holes) parameters of the MATERIAL statement are used to select this model. This model is turned on whenever the value of LT.TAUN or LT.TAUP is greater than 0, which is the default.

The temperature dependence of electron and hole lifetimes in the SRH recombination model have the forms:

$$\tau_n = \text{TAUN0} \left( \frac{T}{300} \right)^{\text{LT} \cdot \text{TAUN}} \tag{7-19}$$

$$\tau_p = \text{TAUP0} \left( \frac{T}{300} \right)^{\text{LT} \cdot \text{TAUP}} \tag{7-20}$$

| Table 7.4. User-Specifiable Parameters for Equations 7-19 and 7-20 |           |                    |       |
|--|-----------|--------------------|-------|
| Statement  | Parameter | Default            | Units |
| MATERIAL   | TAUN0     | 1×10 <sup>-7</sup> | s     |
| MATERIAL   | TAUP0     | 1×10 <sup>-7</sup> | s     |
| MATERIAL   | LT.TAUN   | 0                  |       |
| MATERIAL   | LT.TAUP   | 0                  |       |

See Equations 3-244 and 3-245 in Chapter 3: “Physics” for information regarding concentration dependent lifetimes.

### 7.2.6: C-Interpreter Defined Peltier Coefficients

You can use the C-INTERPRETER to define the Peltier coefficients, KSN and KSP, as a function of the electron and hole carrier temperatures, T<sub>n</sub> and T<sub>p</sub>. This is defined using the syntax:

```
MODELS F.KSN=<filename> F.KSP=<filename>
```

where the <filename> parameter is an ascii file containing the C-INTERPRETER function. See Appendix A: “C-Interpreter Functions” for more information regarding the C-INTERPRETER and its functions.



## 7.3: Applications of GIGA

### 7.3.1: Power Device Simulation Techniques

This section contains a series of techniques, which you may find useful when simulating typical power device structures. Not all of the features described below are specific to GIGA and are common to the ATLAS framework.

#### Floating Guard Rings

No special syntax is needed for the simulation of uncontacted doping areas used in floating guard rings. The program is able to simulate guard ring breakdown with the standard impact ionization models. In some extreme cases, convergence may be slow due to poor initial guesses. If convergence is slow, both GUMMEL and NEWTON should be specified in the METHOD statement.

#### Floating Field Plates

You should use the ELECTRODE statement to specify the field plate regions as electrodes. If these plates do not contact any semiconductor, then these electrodes can be set to float in the same manner as EEPROM floating gates. The following statement line specifies that the field plate region PLATE1 is a floating field plate.

```
CONTACT NAME=PLATE1 FLOATING
```

If the plates do contact the semiconductor, this syntax must not be used. Instead current boundary conditions are used at the electrode with zero current. See Chapter 2: “Getting Started with ATLAS”, the “Floating Contacts” section on page 2-27 for more information about floating electrodes.

#### External Inductors

Inductors are commonly used in the external circuits of power devices. The CONTACT statement can be used to set an inductor on any electrode. The following statement sets an inductance on the drain electrode of 3  $\mu\text{H}/\mu\text{m}$ .

```
CONTACT NAME=DRAIN L=3E-3
```

The next statement is used to specify a non-ideal inductor with a resistance of 100  $\Omega/\mu\text{m}$ .

```
CONTACT NAME=DRAIN L=3E-3 R=100
```

### 7.3.2: More Information

Many examples using GIGA have been installed on your distribution tape or CD. These include power device examples but also SOI and III-V technologies. You can find more information about the use of GIGA by reading the text associated with each example.

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## 8.1: Overview

LASER performs coupled electrical and optical simulation of semiconductor lasers. LASER works in conjunction with BLAZE and allows you to:

- Solve the Helmholtz Equation (see Equation 8-1) to calculate the optical field and photon densities.
- Calculate the carrier recombination due to light emission (i.e., stimulated emission).
- Calculate optical gain, depending on the photon energy and the quasi-Fermi levels.
- Calculate laser light output power.
- Calculate the light intensity profile corresponding to the multiple transverse modes.
- Calculate light output and modal gain spectra for several longitudinal modes.

To perform a LASER simulation, you need to know ATLAS and BLAZE first. If you don't, read Chapter 2: "Getting Started with ATLAS," and Chapter 5: "Blaze: Compound Material 2D Simulator,".

## 8.2: Physical Models

To simulate semiconductor lasers, the basic semiconductor equations (See Equations 3-1 to 3-4 in Chapter 3: “Physics”) are solved self-consistently with an optical equation that determines the optical field intensity distribution. LASER uses the following coordinate system:

- The x axis is perpendicular to the laser cavity and goes along the surface (from left to right).
- The y axis is perpendicular to the laser cavity and goes down from the surface.
- The z axis goes along the laser cavity.

The x and y axes are the same as in other ATLAS products. The electrical and optical equations are solved in the x and y plane (i.e., perpendicular to the laser cavity).

### 8.2.1: Helmholtz Equation

LASER solves a two-dimensional Helmholtz equation to determine the transverse optical field profile  $E_k(x,y)$  [102]:

$$\nabla_{xy}^2 E_k(x,y) + \left( \frac{\omega_m^2}{c^2} \varepsilon(x,y) - \beta_k^2 \right) E_k(x,y) = 0 \tag{8-1}$$

where:

$\nabla_{xy}^2 = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)$  is the two-dimensional Laplace operator,  $\omega_m$  is the frequency corresponding to longitudinal mode  $m$  ( $\omega_m$  corresponds to OMEGA on the LASER statement for single frequency simulations),  $c$  is the velocity of light in vacuum, and  $\varepsilon(x,y)$  is the high frequency dielectric permittivity.

Equation 8-1 is a complex eigenvalue problem. LASER solves this equation to determine the set of complex eigenvalues ( $\beta_k$ ) and corresponding eigenfunctions  $E_k(x,y)$ . LASER takes into account only the fundamental transverse mode solution, so the index ( $k$ ) will be dropped from subsequent equations.

In principle, Equation 8-1 should be solved for each longitudinal mode that is taken into account. Since very few longitudinal modes are actually lasing, LASER solves Equation 8-1 only once for the longitudinal mode with the greatest power and subsequently assumes:

$$E_m(x,y) = E_o(x,y) \tag{8-2}$$

where  $E_o(x,y)$  is the optical field corresponding to the most powerful longitudinal mode. This assumption is reasonable, since the shape of the solution is almost independent of the frequency within the range of interest.

For dielectric permittivity, LASER uses the following model [103]:

$$\varepsilon(r,z) = \varepsilon_0 + (-\mathbf{ALPHAR} + j) \frac{\sqrt{\varepsilon_0} g(r,z)}{k_\omega} - j \frac{\sqrt{\varepsilon_0} (\mathbf{ALPHAA} + \mathbf{FCN} \cdot n + \mathbf{FCP} \cdot p)}{k_\omega} \tag{8-3}$$

where:

- $n_0$  is the bulk refractive index.
- ALPHAR is a line width broadening factor.
- $j = \sqrt{-1}$
- $k\omega = \omega/c$
- $g(x,y)$  is the local optical gain.
- ALPHAA is the bulk absorption loss and is specified in the MATERIAL statement.
- ABSORPTION must be specified in the LASER statement to include absorption loss.
- FCN and FCP are the coefficients of the free-carrier loss and are set through the MATERIAL statement. FCARRIER must be specified on the LASER to include this loss mechanism.

**Table 8-1: User-Specifiable Parameters for Equation 8-3**

| Statement | Parameter  | Default               | Units |
|-----------|------------|-----------------------|-------|
| MATERIAL  | ALPHAR     | 4.0                   |       |
| MATERIAL  | ALPHAA     | 0.0                   |       |
| MATERIAL  | EPSINF     |                       |       |
| MATERIAL  | FCN        | $3.0 \times 10^{-18}$ | cm    |
| MATERIAL  | FCP        | $7.0 \times 10^{-18}$ | cm    |
| LASER     | ABSORPTION | FALSE                 |       |
| LASER     | FCARRIER   | FALSE                 |       |

## Bulk Permittivity ( $\epsilon_0$ )

The following rules apply to the specification of the bulk permittivity.

- If located in an MQW and EPSILON is defined in the MQW statement, that value is used.
- If EPSINF is defined in the MATERIAL statement, that value is used.
- If F.INDEX defined in the MATERIAL statement, then the bulk permittivity is calculated from the square of the index returned from the C-Interpreter function defined in the file specified by F.INDEX.
- If INDEX.FILE is defined in the MATERIAL statement, the bulk permittivity is calculated as the square of the index interpolated from the table specified in the file pointed to by INDEX.FILE.
- If the material is listed in Appendix B: “Material Systems”, Table B-26, the permittivity is calculated as the square of index interpolated from the built-in tables for that material.
- If PERMITTI is defined in the MATERIAL statement, that value is used. If it’s not defined, the default material permittivity is used.

## 8.2.2: Local Optical Gain

For a discussion of gain models, see Chapter 3: “Physics”, Sections 3.9.3: “The Standard Gain Model” through 3.9.5: “Tayamaya's Gain Model”.

### 8.2.3: Stimulated Emission

Carrier recombination due to stimulated light emission is modeled as follows:

$$R_{st}(x, y) = \sum_m \frac{c}{NEFF} g_m(x, y) |E(x, y)|^2 \cdot S_m \tag{8-4}$$

where  $R_{st}$  is the recombination rate due to stimulated light emission,  $NEFF$  is the group effective refractive index, and  $S$  is the linear photon density. The  $m$  subscript in this equation and all subsequent equations refer to a modal quantity. For example,  $S_m$  in Equation 8-4 is the photon linear density for mode  $m$ . The  $NEFF$  parameter is user-specifiable but has a default value of 3.57 (See Table 8-2).

| Table 8-2: User-Specifiable Parameters for Equation 8-4 |           |         |       |
|---|-----------|---------|-------|
| Statement   | Parameter | Default | Units |
| LASER   | NEFF      | 3.57    |       |

### 8.2.4: Photon Rate Equations

Optical gain provides a link between optical and electrical models. The optical gain depends on the quasi-Fermi levels and in turn impacts dielectric permittivity (see Equation 8-3), and by the coupling between the stimulated carrier recombination rate ( $R_{st}$ ) and the density of photons ( $S$ ) as described by Equation 8-4.

To determine  $S_m$ , LASER solves the system of photon rate equations:

$$\frac{dS_m}{dt} = \left( \frac{c}{NEFF} G_m - \frac{1}{\tau_p h_m} - \frac{c \text{ LOSSES}}{NEFF} \right) S_m + R_{sp_m} \tag{8-5}$$

where the modal gain  $G_m$  is given by:

$$G_m = \iint g_m(x, y) \cdot |E(x, y)|^2 \cdot dx \cdot dy \tag{8-6}$$

and the modal spontaneous emission rate  $R_{sp_m}$  is given by:

$$R_{sp_m} = \iint (r_{sp}(x, y))_m \cdot dx \cdot dy \tag{8-7}$$

LOSSES is the internal losses and can be specified in the MODEL statement (See Table 8-3).  $E(x,y)$  is the normalized optical field.

| Table 8-3: User Specifiable Parameters for Equation 8-5 |           |         |                  |
|---|-----------|---------|------------------|
| Statement   | Parameter | Default | Units            |
| LASER   | LOSSES    | 0       | cm <sup>-1</sup> |

The modal photon lifetime,  $\tau_{ph,m}$ , in Equation 8-8 represents the losses in the laser. The losses per mode are given by [104,107]:

$$\frac{1}{\tau_{ph}} = \frac{c}{NEFF}(\alpha_a + \alpha_{fc} + \alpha_{mir}) \tag{8-8}$$

$\alpha_a$  is the bulk absorption loss,  $\alpha_{fc}$  is the free-carrier loss, and  $\alpha_{mir}$  is the mirror loss. The models for absorption and free carrier loss are switched on with the ABSORPTION and FCARRIER parameters on the LASER statement. The mirror loss is always on. These are defined as:

$$\alpha_a = \iint ALPHAA \cdot |E(x, y)|^2 dx dy \tag{8-9}$$

$$\alpha_{fc} = \iint (FCN n + FCP p) \cdot |E(x, y)|^2 \cdot dx dy \tag{8-10}$$

The mirror loss,  $\alpha_{mir}$ , can be defined in two ways. One way is to define the percentage reflectivity of both mirrors. The other way is to define the individual facet mirror reflectivities. If the former is chosen, then set the MIRROR.LOSS parameter on the LASER statement to the percentage reflectivity for the facet cavity mirrors. This assumes that both front and back mirrors are identical and gives a mirror loss calculated by:

$$\alpha_{mir} = \frac{1}{2 \cdot CAVITY.LENGTH} \ln \left( \frac{1}{MIRROR.LOSS^2} \right) \tag{8-11}$$

where CAVITY.LENGTH is set to the length of the laser cavity on the LASER statement.

If you choose the latter model for  $\alpha_{mir}$ , set the RR and RF parameters on the LASER statement instead. These parameters are the rear and front facet reflectivities respectively. The mirror loss is then calculated by:

$$\alpha_{mir} = \frac{1}{2 \cdot CAVITY.LENGTH} \ln \frac{1}{RF \cdot RR} \tag{8-12}$$

The user-specified parameters for the loss models in Equations 8-8 to 8-12 are given in Tables 8-1, 8-2, 8-3, and 8-4.

| Table 8-4: User-Specifiable Parameters for LASER Loss Models |               |         |       |
|--|---------------|---------|-------|
| Statement  | Parameter     | Default | Units |
| LASER  | MIRROR.LOSS   | 90.0    | %     |
| LASER  | CAVITY.LENGTH | 100.0   | μm    |

---

**Note:** Absorption loss and free carrier loss are switched off by default. These are switched on by specifying the ABSORPTION and FCARRIER parameters in the LASER statement. Mirror loss is switched on by default to 90%.

---

## 8.2.5: Spontaneous Recombination Model

For a discussion of spontaneous recombination models, see Chapter 3: “Physics,” Sections 3.9.1: “The General Radiative Recombination Model” and 3.9.2: “The Default Radiative Recombination Model”.

## 8.2.6: Optical Power

The optical power emitted from the front mirror is calculated by [104, 156]

$$P_f = \frac{h\omega S_m C}{2NEFF} \frac{\ln(1/(R_f R_r))}{1 + \sqrt{R_f/R_r(1-R_r)/(1-R_f)}} \quad 8-13$$

where  $S_m$  is the photon density of mode  $m$ ,  $\omega$  is the frequency of emitted light,  $R_f$  and  $R_r$  are the front and rear mirror reflectivities, and NEFF is a user-defined in the LASER statement.

## 8.2.7: Gain Saturation

To simulate non-linear gain saturation in LASER, use the simple model described in following equation [159].

$$g(x, y) = \frac{g(x, y)}{1 + I(x, y)/GAIN\_SAT} \quad 8-14$$

where GAIN.SAT is a user-specifiable parameter on the MATERIAL statement,  $g(x, y)$  is the local gain and  $I(x, y)$  is the local intensity given by

$$I(x, y) = \frac{\sum}{m} \zeta m |E_m(x, y)|^2 \quad 8-15$$

To enable this model, specify GAIN\_SAT on the LASER statement. Non-linear, absorption loss is similarly modeled using the following expression.

$$\alpha(x, y) = \frac{\alpha(x, y)}{1 + I(x, y)/ABSORPTION\_SAT} \quad 8-16$$

where  $\alpha(x, y)$  is the local absorption and ABSORPTION.SAT is a user-definable parameter on the MATERIAL statement. To enable this model, specify ABSOR\_SAT on the LASER statement.



### 8.3: Solution Techniques

LASER solves the electrical and optical equations self consistently. LASER solves the Helmholtz equation in a rectangular region, which is a subdomain of the general ATLAS simulation region. An eigenvalue solver provides a set of eigenfunctions and corresponding eigenvectors.

LASER uses boundary conditions in the form,  $E(x,y)=0$ , on the boundaries of the solution region. This region should be large enough to cover the entire active region of the laser diode with some inclusion of the passive regions. When the single frequency model is used, the lasing frequency used in Equation 8-1 is an external parameter that is fixed during the calculation and either model can be then used for optical gain.

The multiple longitudinal mode model requires you to use a physically-based optical gain model. Specify an initial estimate of the lasing frequency. This is adjusted during calculations. You can also specify a frequency range or photon energy range, which LASER will then calculate multiple longitudinal modes.

LASER may also simulate multiple transverse modes.

## 8.4: Specifying Laser Simulation Problems

The structure of the laser diode and the mesh used to simulate it are specified in the normal way using the capabilities provided by ATLAS and BLAZE. To enable LASER simulation, use the parameters and do the following:

1. Activate LASER by specifying a LASER statement.
2. Define a mesh for solution of the Helmholtz equation. The Helmholtz Equation is solved on a rectangular mesh. The rectangular mesh can be independent of the triangular mesh, which is used for device simulation. This rectangular mesh is specified by the LX.MESH and LY.MESH statements. The area specified by the laser mesh must be completely inside the ATLAS simulation domain and should completely cover the active lasing region.
3. For single-frequency calculations, you can select different gain models for different regions/materials using the REGION or MATERIAL parameters of the MODELS statement.

---

**Note:** If multiple longitudinal modes are to be accounted for, then specify GAINMOD=1 for the active lasing region.

---

### 8.4.1: LASER Statement Parameters

You can simulate multiple transverse modes by setting the NMODE parameter in the LASER statement. Set it to the desired number of modes you want to simulate.

There are several kinds of parameters that appear in the LASER statement. There are parameters that deal with the numerical solution to the photon rate equation, parameters that deal with loss mechanisms, and parameters that deal with specifying energies to look for longitudinal solutions.

Specify laser physical parameters and models and do the following:

1. Specify the CAVITY.LENGTH parameter, which is the length of the laser cavity in the z direction.
2. Specify the PHOTON.ENERGY or OMEGA parameters for (initial) photon energy or laser frequency.
3. Specify laser loss mechanisms (MIRROR, FCARRIER, ABSORPTION parameters in the LASER statement) and any associated constants (FCN, FCP, ALPHAA in the MATERIAL statement).
4. Specify any additional laser losses (LOSSES parameter).

If you to calculate the laser spectrum, specify the multiple longitudinal modes model and additional parameters. Do the following:

1. Specify the LMODES in the statement. This enables the Multiple Mode Model.
2. Specify the EINIT and EFINAL parameters. These parameters set the photon energy range within, which LASER will take into account multiple longitudinal modes. Make sure that initial photon energy is within this range and that is specified for the active lasing region.
3. Specify the photon energy separation (ESEP parameter). If this isn't specified, LASER will automatically calculate the number of longitudinal modes based on the cavity length and the energy range. We recommend that you allow LASER to choose the photon energy separation.
4. Specify the spectrum file name (SPEC.NAME). LASER will produce a structure file containing spectrum data after calculation of each bias point. LASER will automatically append *\_dcN.log* to the specified file name (where *N* is the number of the bias point) for steady-state solutions or *\_trN.log* for a transient simulation. The first bias point where LASER is active will have *N*=1. This is often not the first bias point during simulation. These files can be examined using TONYPLOT. If the SPECSAVE parameter is specified, the spectrum files will only be saved on every *las.specsave* solution.

**Note:** The index in the spectrum file name will still increase by one each time. The spectrum data can be stored in a single file for the transient simulation, only if `MULTISAVE - LASER` statement is set to `FALSE`.

---

You can save near and far field patterns by specifying a value for the `PATTERNS` parameter in the `SAVE` statement. The value of the `PATTERNS` parameter is a character string representing the root name of a file for saving the near and far field patterns. The near field pattern is saved to a file with the string `.nfp` appended to the root and the far field pattern is saved to a file with the string `.ffp` appended to the root name. These files can be examined using `TONYPLOT`.

You can also use the numeric parameters. These parameters are: `TOLER`, `ITMAX`, `SIN`, `TAUSS`, and `MAXCH`. The default values of these parameters have been selected to give a good exchange between accuracy, efficiency, and robustness for most applications. You can adjust the calculation by specifying different values. These parameters are discussed in the next section.

## 8.4.2: Numerical Parameters

The following numerical parameters control the performance of the `LASER` simulation. All of these parameters have reasonable default values, but you can specify them.

- `TOLER` sets the desired relative tolerance of the photon density calculation. The default value is 0.01. Setting this parameter to a lower value may slow down the calculation significantly. Using a larger value will result in a faster but less accurate calculations.
- `ITMAX` sets maximum number of external `LASER` iterations during photon density calculation. The default value is 30.
- `SIN` is the initial photon density used only with simple `LASER` models. `LASER` starts the iteration process for photon density calculation from this value. This parameter influences only the calculation time for the first bias point after the laser threshold is reached.
- `TAUSS` is an iteration parameter used in the calculation of photon densities. Using a larger value of this parameter can speed up the calculation but may cause convergence problems.
- `MAXCH` is the maximum allowed relative change of the photon density between `LASER` iterations. Using a larger value of this parameter can speed up the calculation but may cause convergence problems.

## 8.5: Semiconductor Laser Simulation Techniques

The most common technique for simulating laser diodes is to simulate forward characteristics with a gradually increasing bias. The forward voltage is usually specified, but current boundary conditions can be used, and external elements can be included.

To save computational time, we recommend that you don't enable LASER models at the start of the simulation. Ramp the device bias first, and then enable Laser simulation by using the LASER parameter in an additional MODELS statement.

Generally, the single frequency LASER model, which doesn't take into account the longitudinal mode spectrum, is faster. This model provides accurate results, and is recommended for use if the lasing spectrum isn't the subject of interest. If the multiple longitudinal mode model is used, computational time will be longer and strongly dependent on the number of longitudinal modes involved in the calculation.

Although ATLAS is a two-dimensional device simulator, the laser spectrum and all other laser results are strongly dependent on cavity length, which is effectively the device length of the z direction. For example, terminal currents can be scaled to apply a different length in the third dimension by using simple multiplication. This isn't the case for LASER, since the cavity length determines energy spacing between longitudinal modes and influences all other laser characteristics.

Be sure to specify the CAVITY.LENGTH parameter in the MODELS statement when the longitudinal mode spectrum is to be calculated.

For symmetric devices, you can improve computational efficiency by simulating half of the device. To do this, define the device so that the center of the device is located at  $X=0$  and only half of the device is defined at coordinate values at  $X \geq 0$ .

For device simulation, the default boundary condition is a mirror boundary, which means symmetry is implied.

For laser simulation, (Helmholtz Equation, see Section 8.2.1: "Helmholtz Equation") specify that the laser mesh starts at  $X=0$ . Also, specify the REFLECT parameter in the LASER statement. This tells the Helmholtz Equation that a mirror boundary condition is to be used at  $X=0$ .

### 8.5.1: Generation of Near-Field and Far-Field Patterns

The intensity profile of the laser at the cleaved surface can be examined in the standard structure file using TONYPLOT. To generate a structure file, use the OUTFILE parameter of either the SOLVE or SAVE statements. The intensity far from the laser surface, in the Fraunhofer region, is important for designing the optical coupling to the laser.

The far-field pattern can be generated by LASER by specifying the PATTERNS parameter of the SAVE statement. The PATTERNS parameter specifies the file name prefix of two output files. The first of these files, with the *.nfp* suffix, contains the near-field pattern. This is essentially a copy of the near field pattern contained in the structure file output. The second of these files, with the *.ffp* suffix, contains the far-field pattern.

The far-field pattern is essentially a 2D fast Fourier transform (FFT) of the near-field pattern. The sampling for this transform is set by the minimum spacing in the laser mesh and the overall size of the laser mesh. The output samplings for the near-field and far-field patterns are controlled by the NEAR.NX, NEAR.NY, FAR.NX, and FAR.NY parameters of the LASER statement. These specify the numbers of samples in the X and Y directions in the near and far field. By default the values are set to 100.

## 9.1: Overview

VCSEL (Vertical Cavity Surface Emitting Lasers) performs electrical, thermal, and optical simulation of vertical cavity surface emitting lasers using accurate, robust, and reliable fully numerical methods and non-uniform meshes. With VCSEL, you can simulate advanced structures containing multiple quantum wells and oxide apertures including the effects, such as gain guiding, lattice heating, current crowding, and spatial hole burning. VCSEL works with BLAZE and GIGA and allows you to do the following:

- Test whether the structure complies to general VCSEL device requirements by simulating cold cavity reflectivity experiments. Calculate the reflectivity of a VCSEL cavity as a function of the incident light wavelength in a user-specified range and determine the resonant frequency of the cold cavity.
- Solve the Helmholtz equation (see Equation 9-1) in cylindrical coordinates to calculate optical intensities of the multiple transverse modes for index guiding and gain guiding structures.
- Calculate the optical gain in multiple quantum well systems depending on the photon energies, quasi-Fermi levels, temperature, and optical intensity distribution. Calculate the carrier recombination due to the spontaneous and stimulated emission.
- Solve the photon rate equations (see Section 9.2.4: “Photon Rate Equations”) for multiple transverse modes to calculate the photon density in each mode and the total photon density.
- Calculate the light output power and the wavelength for each transverse mode.
- Speed up solution of the Helmholtz equation by using perturbational treatment.
- Simulate more general cavities that support multiple longitudinal modes. This obtains modal gain spectra and determines the dominant mode with maximum gain.

To perform a VCSEL simulation, you need be familiar with ATLAS and BLAZE first. Please see Chapter 2: “Getting Started” and Chapter 5: “BLAZE” for more information.

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**Note:** To avoid the confusion in terms, we refer to a VCSEL device as VCSEL and to a VCSEL simulator as VCSEL:ATLAS in this chapter.

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## 9.2: Physical Models

When modeling VCSELs, it is essential to take into account interaction of optical, electrical, and thermal phenomena that occur during the VCSEL operation. Modeling only optical properties is already an involved task. Different methods developed recently in order to improve the accuracy of optical solution produce results that vary considerably from method to method [146]. The variation is especially strong between vectorial models that tend to produce a spread in results much larger than simpler scalar models.

On the other hand, the complexity of the vectorial methods makes the self-consistent electro-thermo-optical simulation impractical from the point of view of the calculation time required. For VCSEL simulation in VCSEL:ATLAS, we adopted an approach that can account for mutual dependence of electrical, optical, and thermal phenomena.

Basic semiconductor equations (See Equations 3-1 to 3-4 in Chapter 3: "Physics") are solved self-consistently with the Helmholtz Equation, Lattice Heat Flow Equation (See Chapter 6, Equation 6-1), and the Photon Rate Equation (see Equation 9-12). Since we are using a scalar method, we neglect polarization effects and reduce Maxwell equations to scalar Helmholtz equation. The method used for the solution of Helmholtz equation is based on a well developed effective index model, which showed its validity for a much wider range of problems than originally expected [147]. This method fine tuned for simulation of various VCSEL structures is often referred to as Effective Frequency Method (EFM). EFM is a fast and flexible method that allows further development to include dispersion, diffraction losses, and graded interfaces.

VCSEL:ATLAS uses a cylindrical coordinate system to take advantage of the cylindrical symmetry of the VCSEL devices. Figure 9-1 shows the relationship between ATLAS's X-Y coordinate system and the r- $\theta$ -z cylindrical system used in VCSEL:ATLAS. Note that the X coordinate axis is equivalent to the radius r, and the Y coordinate axis is equivalent to the z axis in the cylindrical system.

### 9.2.1: Reflectivity Test Simulation

Reflectivity experiment is an important test conducted to evaluate the quality of a VCSEL device. In this experiment, the light is normally incident on a VCSEL device and its reflectivity is measured as a function of wavelength. Most manufactured VCSEL resonators are tested this way to ensure adequate optical performance. Numerical simulation of this experiment enables you to calibrate the material parameters used in the optical model and eliminate possible specification errors at the early stage of numerical analysis of a VCSEL device.

Another purpose of the numerical reflectivity test is to ensure that the analyzed device complies with general VCSEL requirements. These requirements include the following:

1. Presence of a high reflectivity band in the reflectivity spectrum of a VCSEL cavity.
2. The reflectivity over 99% in the high reflectivity band.
3. Presence of a drop in reflectivity within the high reflectivity band. The drop in reflectivity (increase in absorptance) occurs at the resonant wavelength of the cavity.

VCSEL:ATLAS calculates reflectivity and absorptance using transfer matrix approach (Chapter 10: "Luminous: Optoelectronic Simulator", Section 10.2.4: "Matrix Method"). In the simulation, the incident light propagates along the axis of symmetry of the device.

The `VCSEL.INCIDENCE` parameter specifies the position of the light origin with respect to the device (top of bottom). Specific output associated with the reflectivity test includes reflectivity and absorptance spectra plotted in the corresponding files, `reflectivity(absorption)_top.log` and `reflectivity(absorption)_bottom.log`.

To run the reflectivity test simulation, specify the `VCSEL.CHECK` parameter and other parameters in Table 9-1 on a `VCSEL` statement. Section 9.3.3: "Enabling VCSEL Solution" will discuss parameter specification in detail.

| Table 9-1: User-Specifiable Parameters for the Reflectivity Test |                 |         |                 |
|--|-----------------|---------|-----------------|
| Statement  | Parameter       | Default | Units           |
| VCSEL  | VCSEL.CHECK     | False   |                 |
| VCSEL  | VCSEL.INCIDENCE | 1       |                 |
| VCSEL  | OMEGA           |         | s <sup>-1</sup> |
| VCSEL  | EINIT           |         | eV              |
| VCSEL  | EFINAL          |         | eV              |
| VCSEL  | PHOTON.ENERGY   |         | eV              |
| VCSEL  | INDEX.TOP       | 1.0     |                 |
| VCSEL  | INDEX.BOTTOM    | 1.0     |                 |
| VCSEL  | NSPEC           | 100     |                 |

If the structure does not meet requirements 1-3, VCSEL:ATLAS will close with an error. Otherwise, VCSEL:ATLAS uses Brent's minimization procedure to find the resonant frequency of the cold cavity. VCSEL:ATLAS uses the obtained value as a reference frequency in the solution of the Helmholtz equation.

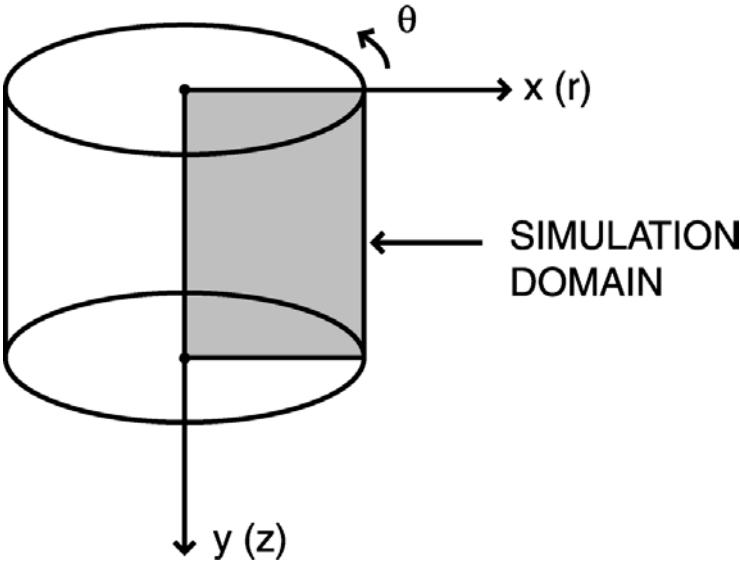


Figure 9-1: The relationship between rectangular and cylindrical coordinate systems used by VCSEL

## 9.2.2: Helmholtz Equation

VCSEL:ATLAS solves the Helmholtz Equation in cylindrical coordinates  $r$ ,  $z$ , and  $\phi$  using effective frequency method [147].

$$\nabla^2 E(r, z, \phi) + \frac{\omega^2}{c^2} \varepsilon(r, z, \phi, \omega) E(r, z, \phi) = 0 \quad 9-1$$

where  $\omega$  is frequency,  $\varepsilon(r, z, \phi, \omega)$  is the complex dielectric permittivity,  $E(r, z, \phi)$  is the optical electric field, and  $c$  is the speed of light in vacuum.

Using the expansion around a reference frequency  $\omega_0$ :

$$\frac{\omega^2}{c^2} \varepsilon(r, z, \phi, \omega) \approx \frac{\omega_0^2}{c^2} \varepsilon(r, z, \phi, \omega_0) + 2 \frac{\omega_0}{c^2} \varepsilon(r, z, \phi, \omega_0) (\omega - \omega_0) \quad 9-2$$

we transform the Helmholtz equation into:

$$\left[ \nabla^2 + k_0^2 \varepsilon(r, z, \phi) \right] E(r, z, \phi) = v k_0^2 \varepsilon(r, z, \phi) E(r, z, \phi) \quad 9-3$$

where  $k_0 = \omega_0/c$  and  $v$  is a dimensionless frequency parameter given by:

$$v = 2 \frac{\omega_0 - \omega}{\omega_0} = 2 \frac{\lambda - \lambda_0}{\lambda} - j 2 \frac{\text{Im}(\omega)}{\omega_0} \quad 9-4$$

We assume that the field is separable:

$$E(r, z, \phi) = f(r, z, \phi) \Phi(r, \phi) \quad 9-5$$

This assumption of separability is the main approximation of the method. The applicability of the method can be extended beyond this approximation by adding a non-separable component of the field on the right hand side of Equation 9-5. For dispersive materials, it is possible to make another modification of the effective frequency method by taking into account material dispersion in Equation 9-2. For separable fields, we obtain the longitudinal wave equation for function  $f$ :

$$\left[ \frac{\partial^2}{\partial z^2} + k_0^2 \varepsilon(r, z, \phi) \right] f(r, z, \phi) = v_{eff}(r, \phi) k_0^2 \varepsilon(r, z, \phi) f(r, z, \phi) \quad 9-6$$

at each lateral position  $(r, \phi)$ . Due to the cylindrical symmetry, we can ignore the azimuthal variations. In this case, we only need to solve Equation 9-6 for each cylindrically symmetric region characterized by a particular distribution of  $\varepsilon$  in the vertical direction  $z$ . Complex Newton method combined with the characteristic matrix approach (Chapter 10: "Luminous: Optoelectronic Simulator", Section 10.2.4: "Matrix Method") yields eigenvalues  $v_{eff}$  and eigenfunctions  $f(z)$  of the longitudinal wave equation.

The transverse wave equation takes the form:

$$\left[ \frac{1}{r} \frac{d}{dr} \left( r \frac{d}{dr} \right) - \frac{l^2}{r^2} + v_{eff}(r) k_0^2 \langle \varepsilon \rangle_r \right] \Phi_{lm}(r) = v_{lm} K_0^2 \langle \varepsilon \rangle_r \Phi_{lm}(r) \quad 9-7$$



where

$$\langle \varepsilon \rangle_r = \int_0^L \varepsilon(r, z) f^2(r, z) dz \tag{9-8}$$

VCSEL:ATLAS uses standard eigentechniques to solve an ordinary differential Equation 9-7. Solutions of this equation are  $LP_{lm}$  modes.

For each mode, the imaginary part of the eigenvalue determines the overall mode gain(loss) factor, which is negative below the lasing threshold. The lasing occurs when:

$$Im(v_{lm})|_{th} = 0 \tag{9-9}$$

The dielectric permittivity is given by:

$$\varepsilon(r, z) = \varepsilon_{inf} + (-\mathbf{ALPHAR} + j) \frac{\sqrt{\varepsilon_{inf}} g(r, z)}{k_0} - j \frac{\sqrt{\varepsilon_{inf}} (\mathbf{ALPHAA} + \mathbf{FCN} \cdot n + \mathbf{FCP} \cdot p)}{k_0} \tag{9-10}$$

where:

- $\varepsilon_{inf}$  is the bulk permittivity.
- ALPHAR is a line width broadening factor.
- $k_0 = \omega_0/c$
- $g(r, z)$  is the local optical gain.
- ALPHAA is the bulk absorption loss and is specified in the MATERIAL statement (specify ABSORPTION in the VCSEL statement to include absorption loss).
- FCN and FCP are the coefficients of the free-carrier loss and are set using the MATERIAL statement (specify FCARRIER in the VCSEL statement to include this loss mechanism).

**Table 9-2: User-Specifiable Parameters for Equation 9-10**

| Statement | Parameter  | Default               | Units            |
|-----------|------------|-----------------------|------------------|
| MATERIAL  | ALPHAR     | 4.0                   |                  |
| MATERIAL  | ALPHAA     | 0.0                   | cm <sup>-1</sup> |
| MATERIAL  | EPSINF     |                       |                  |
| MATERIAL  | FCN        | 3.0×10 <sup>-18</sup> | cm <sup>2</sup>  |
| MATERIAL  | FCP        | 7.0×10 <sup>-18</sup> | cm <sup>2</sup>  |
| VCSEL     | ABSORPTION | FALSE                 |                  |
| VCSEL     | FCARRIER   | FALSE                 |                  |

### Bulk Permittivity ( $\epsilon_0$ )

The following rules apply to the specification of the bulk permittivity.

- If located in an MQW and EPSILON is defined in the MQW statement, that value is used.
- If EPSINF is defined in the MATERIAL statement, that value is used.
- If F . INDEX defined in the MATERIAL statement, then the bulk permittivity is calculated from the square of the index returned from the C-Interpreter function defined in the file specified by F . INDEX.
- If INDEX . FILE is defined in the MATERIAL statement, the bulk permittivity is calculated as the square of the index interpolated from the table specified in the file pointed to by INDEX . FILE.
- If the material is listed in Appendix B: “Material Systems”, Table B-26, the permittivity is calculated as the square of index interpolated from the built-in tables for that material.
- If PERMITTI is defined in the MATERIAL statement, that value is used. If it’s not defined, the default material permittivity is used.

### 9.2.3: Local Optical Gain

For a discussion of gain models, see Chapter 3: “Physics”, Sections 3.9.3: “The Standard Gain Model” through 3.9.5: “Tayamaya's Gain Model”.

### Stimulated Emission

Carrier recombination due to stimulated light emission is modeled as follows:

$$R_{st}(r, z) = \sum_m \frac{c}{NEFF} g_m(r, z) |E_m(r, z)|^2 \cdot S_m \tag{9-11}$$

where  $R_{st}$  is the recombination rate due to stimulated light emission,  $NEFF$  is the group effective refractive index, and  $S_m$  is the photon number. The  $m$  subscript in this equation and all subsequent equations refers to a modal quantity. For example,  $S_m$  in Equation 9-11 is the photon number for mode  $m$ . The  $NEFF$  parameter is user-defined but has a default value of 3.57 (see Table 9-3).

| Table 9-3: User-Specifiable Parameters for Equation 9-11 |           |         |       |
|--|-----------|---------|-------|
| Statement  | Parameter | Default | Units |
| VCSEL  | NEFF      | 3.57    |       |

### 9.2.4: Photon Rate Equations

Optical gain provides the link between optical and electrical models. The optical gain depends on the quasi-Fermi levels and in turn impacts dielectric permittivity (see Equation 9-12), and by the coupling between the stimulated carrier recombination rate ( $R_{st}$ ) and the density of photons ( $S$ ) as described by Equation 9-11.

To determine  $S_m$ , VCSEL solves the system of photon rate equations:

$$\frac{dS_m}{dt} = \left( \frac{c}{NEFF} G_m - \frac{1}{\tau_{ph_m}} - \frac{c \text{ LOSSES}}{NEFF} \right) S_m + R_{sp_m} \tag{9-12}$$

where the modal gain  $G_m$  is given by

$$G_m = \iiint g_m(r, z) \cdot |E_m(r, z)|^2 r d\theta dr dz \quad 9-13$$

and the modal spontaneous emission rate  $R_{sp_m}$  is given by

$$R_{sp_m} = \iiint r_{sp}(r, z)_m r d\theta dr dz. \quad 9-14$$

$E_m(r, z)$  is the normalized optical field.

| Table 9-4: User Specifiable Parameters for Equation 9-12 |           |         |                  |
|--|-----------|---------|------------------|
| Statement  | Parameter | Default | Units            |
| VCSEL  | LOSSES    | 0       | cm <sup>-1</sup> |

The modal photon lifetime,  $\tau_{ph_m}$ , in Equation 9-11 represents the losses in the laser. The losses per mode are given by

$$\frac{1}{\tau_{ph_m}} = \frac{c}{NEFF} (\alpha_{a_m} + \alpha_{fc_m} + \alpha_{mir}) = \frac{c}{NEFF} G_m - \omega_0 \cdot v_{lm} \quad 9-15$$

$\alpha_a$  is the bulk absorption loss,  $\alpha_{fc}$  is the free-carrier loss, and  $\alpha_{mir}$  is the mirror loss. These are defined as:

$$\alpha_{a_m} = \iiint \mathbf{ALPHAA} \cdot |E_m(r, z)|^2 \times r d\theta dr dz \quad 9-16$$

$$\alpha_{fc_m} = \iiint (\mathbf{FCN} n + \mathbf{FCP} p) \cdot |E_m(r, z)|^2 r d\theta dr dz \quad 9-17$$

$$\alpha_{mir} = G_m - \alpha_{a_m} - \alpha_{fc_m} - \omega_0 \cdot v_{lm} \frac{c}{NEFF} \quad 9-18$$

## Spontaneous Recombination Model

For a discussion of spontaneous recombination models, see Chapter 3: “Physics”, Sections 3.9.1: “The General Radiative Recombination Model” and 3.9.2: “The Default Radiative Recombination Model”.

## Optical Power

The optical power emitted is given by Equation 9-19.

$$P_f = \frac{\hbar \omega S_m c}{NEFF} \frac{\alpha_{mir}}{1 + \sqrt{R_f/R_r(1-R_r)/(1-R_f)}} \quad 9-19$$

## 9.3: Simulating Vertical Cavity Surface Emitting Lasers

The key to simulating a Vertical Cavity Surface Emitting Laser is the input deck. The input deck describes the physical device structure, the physical models to be used, and the specific measurements to be performed. The deck itself can be roughly divided into three sections: structure specification, model definition, and obtaining solutions. The following sections will describe these concepts in detail.

### 9.3.1: Specifying the Device Structure

VCSEL devices are the most complicated devices to be addressed by device simulation. This is due to the many layers involved in making Distributed Bragg Reflectors (See “Specifying Distributed Bragg Reflectors” section on page 9-10) and the possible Multiple Quantum Well (See “Specifying Quantum Wells” section on page 9-11) active layers. This complexity is mitigated by the fact that these devices are mostly epitaxial. Also, many of the layers are periodic. Recognizing these simplifications, we’ve designed a custom syntax for defining VCSEL devices.

This syntax makes specification of periodic structures (e.g., super-lattices) simple, which completely avoids problems of aligning various layers to each other. This new syntax also simplifies meshing the structure.

Despite this simplification, specifying a VCSEL device can still be complex. We recommend that you look at the standard examples. See Chapter 2: “Getting Started with ATLAS”, Section 2.4: “Accessing The Examples” for more information about these examples.

The order of statements is important when specifying the device structure. The following order of statements should be strictly followed.

1. Specify the `MESH` statement. This initializes the structure definition and allows specification of cylindrical symmetry.
2. Set up the mesh in the X direction by using the `X.MESH` statements. The mesh in the Y direction is usually specified along with the device layers in the `REGION` statements. You can, however, introduce the Y mesh lines by using the `Y.MESH` statements after the `X.MESH` statements.
3. Specify the device regions using `REGION` and `DBR` statements. These statements specify the layer thickness, composition, doping, order of placement, and meshing information in the Y direction. The order of `REGION` and `DBR` statements is up to you and is usually defined by the order the layers appear through the structure.
4. You can use quantum well models for the gain and spontaneous recombination and then specify the locations of quantum wells within the device, using the `MQW` statement. These statements specify the location, doping and composition of the wells, and certain model information about the wells.

The wells are centered somewhere within the geometry of the previously specified (using `REGION` statements) regions, so that the well barrier layers take on the composition of the underlying region. The composition of the wells is specified in the `MQW` statement.

5. Specify the locations of the electrodes using `ELECTRODE` statements.
6. Use `DOPING` statements to specify additional doping or composition fraction information. This usually isn’t necessary since most, if not all doping and composition information can be specified during the specification of regions.

## Setting Up Cylindrical Symmetry

VCSELs use cylindrical symmetry to account for the 3D nature of VCSEL devices. To specify cylindrical symmetry in the MESH statement, use the CYLINDRICAL parameter. An example of specifying cylindrical symmetry is down below.

### Example

```
MESH CYLINDRICAL
```

The axis of symmetry for cylindrical is the Y axis at X=0. When using cylindrical symmetry, no X coordinates should be specified with negative values since X represents radius.

The usual abbreviation rules for parameter names can be used. See Section 2.5: “The ATLAS Syntax” section in Chapter 2 for more information.

## Specifying the Mesh

To specify the mesh in the X direction, use the X.MESH statement. Each X.MESH statement specifies the location of one mesh line in the X direction and the spacing between mesh lines at that location.

The location is specified by the LOCATION parameter in microns. The spacing is specified by the SPACING parameter, which is also in microns. The number of mesh lines specified is limited to built-in limits in the overall size of the mesh, but there should be at least two X.MESH statements. There shouldn't be X.MESH specifications with negative values in the LOCATION parameter. Such specification would be ill-defined due to the cylindrical symmetry.

You should also specify mesh lines at any defining edges of regions, electrodes, or other geometrical aspects in the X direction. Also for similar reasons, use the Y.MESH statements to specify mesh lines in the Y direction.

Mesh lines can be inserted automatically at defined region edges by using the REGION and DBR statements. To enable this feature, specify AUTO in the MESH statements. See Chapter 18: “Statements”, Section 18.26: “MESH” for information about the MESH statement.

## Specifying Regions

A region is a volume (in cylindrical coordinates a disk or annulus) that has a uniform material composition. The region is specified by a REGION statement. In the REGION statement, the material composition is specified by the MATERIAL parameter.

The MATERIAL parameter can take on values of any material name as described in Appendix B: “Material Systems”. For ternary and quaternary materials, you can also specify composition fractions X and/or Y, using the X.COMPOSE and/or Y.COMPOSE parameters. The DONORS and ACCEPTORS parameters can be used to specify uniform densities of ionized donors and/or acceptors.

The thickness of the region in the Y direction in microns is specified by the THICKNESS parameter. You can also use the X.MIN, X.MAX, Y.MIN, and Y.MAX parameters to specify the location and extent of the region. Except in special cases, we don't recommend this because of the difficulties aligning the numerous layers involved.

Unless it's specified, the region will encompass the entire range of mesh in the X direction as specified in the X.MESH statements. Mesh lines in the Y direction will then be added at the upper and lower edges of the region. The mesh spacing at the edges is specified in microns by the SY parameter.

The TOP/BOTTOM parameters specifies the relative ordering of regions in the Y direction. Specifying TOP indicates that the region starts at the top of all previously specified regions (i.e., at the minimum previously specified Y coordinate) and extends to the thickness in the negative Y direction. Remember for device simulation, the Y axis conventionally extends down into the wafer for increasing values of Y. If no previous regions are specified, TOP indicates the region starts at Y=0 and extends to the

thickness in the negative Y direction. `BOTTOM` indicates that the region starts at the bottom of all previously specified regions (i.e., at the maximum previously specified Y coordinate) and extends to the thickness in the positive Y direction. If no previous regions are specified, `BOTTOM` indicates the region starts at `Y=0` and extends to the thickness in the positive Y direction.

Conventionally, we have found it convenient to start the active layers at the `Y=0` location (as done in the standard examples). In ordering `REGION` statements:

1. Start with the upper DBR by using the `TOP` parameter.
2. Use the `TOP` parameter on the top side contact layers.
3. Use the `BOTTOM` parameter on the active layers.
4. Use the `BOTTOM` parameter on the lower DBR.
5. Use the `BOTTOM` parameter on the substrate/lower contact regions.

## Specifying Distributed Bragg Reflectors

A Distributed Bragg Reflector (DBR) is a periodic structure composed of regions of two alternating material compositions. A DBR can be specified by a series of `REGION` statements alternating between two different material composition. But DBRs typically consist of many of such layers and specifying them with `REGION` statements can be tedious, which could be prone to errors. The DBR statement can be used to simplify the specification instead. Generally, the DBR statement (alias `SUPERLATTICE`) can be used to specify any superlattice composed of layers of two alternating material compositions. For more information about this statement, see Chapter 18: "Statements", Section 18.6: "DBR".

The `MAT1` and `MAT2` parameters specify the material names of the two materials, which is used the same way the `MATERIAL` parameter of the `REGION` statement is used to specify a single material.

The `X1.COMP`, `Y1.COMP`, `X2.COMP`, and `Y2.COMP` parameters are used to specify the X and Y composition fractions of the two materials for ternary and quaternary materials.

The thicknesses of the two layers are specified by the `THICK1` and `THICK2` parameters of the DBR statement. The doping for the layers are specified by the `NA1` and `NA2` parameters for acceptors. The `ND1` and `ND2` parameters for donors.

The mesh spacing for the DBR can be specified using the `SPA1` and `SPA2` parameters, just like the `SY` parameter of the `REGION` statement. You can also use the `N1` and `N2` parameters to specify the integer number of the mesh divisions in the introduction of Y direction for each of the layers.

The total number of layers is specified by the integer `HALF.CYCLE` parameter. The `HALF.CYCLE` parameter specifies the total number of layers. Thus, an odd values specifies that one more layer of the material 1 is to be used than of material 2.

The `TOP` and `BOTTOM` parameters of the DBR statement are used just like the `REGION` statement, except the first material to be added to the top/bottom of the device is always of material 1.

DBR and `REGION` statements can be intermingled indiscriminately.

## Specifying Oxide Apertures

Once all the epitaxial layers of the VCSEL have been specified, you can then specify an oxide aperture by using a `REGION` statement with the `MATERIAL` parameter assigned to an insulator, and the geometry specified by the `X.MIN`, `X.MAX`, `Y.MIN`, and `Y.MAX` parameters.

## Specifying Quantum Wells

The Multiple Quantum Well (MQW) models enable special models for gain and spontaneous recombination that account for quantum carrier confinement inside of the wells. These models are described in detail in Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.6: “Multiple Quantum Well Model”.

The wells themselves are specified by using the MQW statement. The MQW statement should follow all the REGION and DBR statements and precede the ELECTRODE statements. For more information about this statement, see Chapter 18: “Statements”, Section 18.30: “MQW”.

The locations of the wells are specified by the XMIN, XMAX, YMIN, and YMAX parameters of the MQW statement. These parameters specify a bounding box in units of microns. XMIN and XMAX specify the extent of the wells in the X direction (i.e., the wells are horizontal and extend across the entire bounding box in the X direction). The YMIN and YMAX parameters act to define the center of the wells in the Y direction (i.e., the set of defined wells will be centered in the Y direction at the average coordinate of YMIN and YMAX. For example, if a single well is defined with YMIN=0 and YMAX=1.0, it will be centered at Y=0.5. If three wells were defined the middle one would be centered at Y=0.5.

The WW parameter specifies the width of the wells in microns. The WB specifies the width of the barrier between wells in microns. The number of wells is specified by the N WELL parameter.

The material composition of the wells is specified by the MATERIAL, XCOMP, and YCOMP parameters. The MATERIAL parameter is assigned one of the valid material names described in Appendix B: “Material Systems”. The XCOMP and YCOMP parameters are assigned to the X and Y composition fractions as necessary. The material composition of the barriers between wells is taken from whatever material regions that may have been defined coincident to the bounding box. This means, define the barrier material(s) the MQW with the REGION statements.

When MQW is specified mesh lines will be added to the device mesh to resolve the locations of the edges of the wells and the bounding box. The SY parameter can also be specified to limit the maximum spacing between mesh lines within the bounding box.

When using MQW, a secondary mesh must be set up for the solution of the Schrodinger’s Equation (See Chapter 13: “Quantum: Quantum Effect Simulator”, Equation 13-1) in the wells to determine the bound state energies. This mesh is specified by the NX and NY parameters in the MQW statement. Typically, NY should be set to some large number so that there will be several samples per well. NX should be comparable to the number of grid lines in the device mesh over the same extent in the X direction.

Finally, there are several parameters that describe the details of the physical models. These parameters are described in detail in Chapter 13: “Quantum: Quantum Effect Simulator”.

## Specifying Electrodes

Device electrodes are specified using the ELECTRODE statement. Note that electrodes in device simulation are treated as boundary conditions. Therefore, there’s no advantage to resolve the full outline of the electrode. It is usually easiest to simply place electrodes at the top and bottom of the structure.

This is done by specifying the TOP or BOTTOM parameters of the ELECTRODE statement. The extent along the top or bottom of the device can be described by the X.MIN and/or X.MAX parameters. If these parameters are omitted, the electrode will extend all the way along the corresponding surface of the device.

Use the NUMBER parameter to assign electrodes to a number. Electrodes should be assigned consecutive numbers starting at 1. They can also be given a name by using the NAME parameter. They can also be addressed later by their name or number when modifying the electrode characteristics, using the CONTACT statement or assigning biasing information in the SOLVE statements.

### 9.3.2: Specifying VCSEL Physical Models and Material Parameters

Much of the simulation results depend on how the physical models are described. For more information about physical models, see Chapter 3: “Physics”, Section 3.6: “Physical Models”.

#### Selecting Device Models

For most laser devices including VCSELs, we advise that you at least enable predominant recombination mechanisms, since these usually define the threshold characteristics and compete with stimulated emission for carrier recombination. Thus, directly impact the efficiency of the device.

Typically three bulk recombination mechanisms should be addressed: Shockley-Read-Hall (SRH), Auger, and Radiative Recombination. You can enable these mechanisms by specifying SRH, AUGER, and OPTR parameters on a MODEL statement.

The parameters of these models are specified on MATERIAL statements. These include TAUN and TAUP, which specify the SRH lifetimes. AUGN and AUGP, which specify the Auger coefficients. And COPT, which specifies the radiative recombination rate coefficient.

These models and associated parameters are discussed in more detail in Chapter 3: “Physics”, Section 3.6.3: “Carrier Generation-Recombination Models”.

#### Specifying Material Parameters

For LASER or VCSEL simulation there are several other material parameters that should be considered. First and foremost, specify the high frequency dielectric relative permittivity of each material region. This is specified by the EPSINF parameter in the MATERIAL statement.

The high frequency dielectric enters in the Helmholtz Equation and directly affects which laser mode may be present. In particular, try to consider the design of the DBRs carefully. Typically, the objective of the design of the DBRs is to choose the layer thicknesses so that they are one quarter wavelength thick relative to the local dielectric. During this design process, you need to also carefully consider the band-gap of the active region, since this affects the energy and wavelength of the maximal gain. A good design will try to operate near the peak gain, while satisfying the conditions for oscillation between the DBR mirrors.

Another important consideration for choosing material parameters is the selection of band edge parameters such as band gap and electron affinity. Although defaults do exist for many material systems it is almost always better for you to specify the best estimate. Also, consider the mobilities since they directly affect series resistance.

Chapter 3: “Physics”, Section 3.6.1: “Mobility Modeling” has more information about these parameters. For more about MATERIAL statements, see Chapter 18: “Statements”, Section 18.24: “MATERIAL”.

### 9.3.3: Enabling VCSEL Solution

#### VCSEL Solution Mesh

The solution to Helmholtz equation is performed on a spatially discrete domain or mesh. Use of matrix method for the solution of the longitudinal wave equation allows the reduction in the number of mesh points in  $y$  ( $z$  in VCSEL) to the number of material boundaries. This significantly improves calculation time while maintaining the accuracy. The mesh points in the transverse direction  $x$  ( $r$  in VCSEL) coincide with the device mesh.



## Specifying VCSEL Parameters

Specify the `VCSEL` statement to enable the VCSEL simulator. Once you enable it, the semiconductor device equations are solved self-consistently with the photon rate equations and the Helmholtz equation.

To enable reflectivity test simulation do the following:

1. Specify the `VCSEL.CHECK` parameter in a `VCSEL` statement.
2. Specify the `VCSEL.INCIDENTCE` parameter to monitor cold cavity reflectivity for light incident on a structure from either top or bottom of the structure.
  - `VCSEL.INCIDENTCE = 1` - The light incident from the top.
  - `VCSEL.INCIDENTCE = 0` - The light incident from the bottom.
  - `VCSEL.INCIDENTCE = 2` or `>2` - Both directions of light incidence are considered. The program compares cavity resonant frequencies obtained for each direction of incidence. If results do not agree within a certain tolerance, `VCSEL:ATLAS` will close with an error.

By default, light is incident from the top of the structure.

3. Specify `INDEX.TOP` for the refractive index of the medium above the structure.
4. Specify `INDEX.BOTTOM` for the refractive index of the medium below the structure. Default medium above and below the structure is air.
5. Specify the `PHOTON.ENERGY` or `OMEGA` parameters for (initial) photon energy or frequency.
6. Specify the `EINIT` and `EFINAL` parameters. These parameters set the photon energy range in reflectivity test. If not specified, they take the following default values: `EINIT=0.8` `PHOTON.ENERGY` and `EFINAL=1.2` `PHOTON.ENERGY`.
7. Specify `NSPEC` for the number of sampling points between `EINIT` and `EFINAL`. The default value is `NSPEC=100`.

You can specify the following optional parameters in the `VCSEL` simulation:

- `NMODE` specifies the number of transverse modes of interest. Default value is `NMODE=1`.
- `PROJ` enables faster solution of the photon rate equations below threshold. You should disable this solution scheme when the bias reaches lasing threshold. Specify `^PROJ` in a `VCSEL` statement to do that.
- `PERTURB` enables faster solution of the Helmholtz equation. When specified, the program solves the longitudinal wave equation only once. Perturbational approach is used to account for the refractive index changes [147].
- `LOSSES` specifies any additional laser losses.

### 9.3.4: Numerical Parameters

The following numerical parameters control the performance of the VCSEL simulation.

- `TOLER` sets the desired relative tolerance of the photon density calculation. The default value is 0.01. Setting this parameter to a lower value may slow down the calculation significantly. Using a larger value will result in a faster but less accurate calculations.
- `ITMAX` sets maximum number of external VCSEL iterations during photon density calculation. The default value is 30.
- `TAUSS` is an iteration parameter used in the calculation of photon densities. Using a larger value of this parameter can speed up the calculation but may cause convergence problems.
- `MAXCH` is the maximum allowed relative change of the photon density between VCSEL iterations. Using a larger value of this parameter can speed up the calculation but may cause convergence problems.

### 9.3.5: Alternative VCSEL Simulator

If you need to model a vertical cavity laser that supports multiple longitudinal modes, use the `LASER` statement to enable VCSEL solution.

Specify the `LASER` statement to enable the laser simulator. Once you enable it, the semiconductor device equations are solved self-consistently with the laser rate equations. The major difference between this simulator and the one discussed above is in the approach to the solution of the Helmholtz equation.

The solver used in this case allows multiple longitudinal modes, but it is not as efficient in dealing with structural variations in the transverse direction.

There are several kinds of parameters that appear in the `LASER` statement. Most of the parameters available are discussed above with respect to `VCSEL` statement.

Specify laser physical parameters and models, and specify the `DBR1.START`, `DBR1.FINAL`, `DBR2.START`, and `DBR2.FINAL` parameters in the `LASER` statement.

The mirror loss is defined as:

$$\alpha_{mir} = \frac{1}{2L} \ln\left(\frac{1}{R_f R_r}\right) \quad 9-20$$

where  $L$  is the cavity length given as:

$$L = \text{DBR2.START} - \text{DBR1.FINAL}$$

$R_f$  and  $R_r$  are the front and rear mirror reflectivities and are calculated from the solution of Helmholtz Equation in the range specified by `DBR1.START`, `DBR2.START`, and `DBR2.FINAL`.

`LASER` simulates single or multiple longitudinal modes as well as single or multiple transverse modes. Also with `LASER`, you can simulate index guiding only or gain guiding. Simulation of gain guiding takes more computation time but should be considered when spatially varying gain effects are anticipated.

If you to calculate the laser spectrum, specify the multiple longitudinal modes model and additional parameters. Do the following:

1. Specify the `LMODES` parameter in the statement. This enables the Multiple Mode Model.
2. Specify the `EINIT` and `EFINAL` parameters. These parameters set the photon energy range within, which `LASER` will take into account multiple longitudinal modes. Make sure initial photon energy is within this range and is specified for the active lasing region.
3. Specify the photon energy separation (`ESEP` parameter). If this isn't specified, `LASER` will automatically calculate the number of longitudinal modes based on the cavity length and the energy range. We recommend that you allow `LASER` to choose the photon energy separation.
4. Specify the spectrum file name (`SPEC.SAVE`). `LASER` will produce a structure file containing spectrum data after calculation of each bias point. `LASER` will automatically append `_dcN.log` to the specified file name (where `N` is the number of the bias point) for steady-state solutions or `_trN.log` for a transient simulation. The first bias point where `LASER` is active will have `N=1`. This is rarely the first bias point during simulation. Use `TONYPLOT` to examine these files. If you specify the `SPECSAVE` parameter, it will only save the spectrum files on every `las.SPECSAVE` solution.

The index in the spectrum file name will still increase by one each time. The spectrum data can be stored in a single file for the transient simulation, only if the `MULTISAVE-LASER` statement is set to `FALSE`. To enable multiple transverse mode solutions, specify the number of transverse modes by using the `NMODE` parameter from the `LASER` statement.

By default, VCSELs simulate using the Index Guiding Model. To simulate using the gain guiding, specify `INDEX.MODEL=1`.

You can save near and far field patterns by specifying a value for the `PATTERNS` parameter in the `SAVE` statement. The value of the `PATTERNS` parameter is a character string representing the root name of a file for saving the near and far field patterns. The near field pattern is saved to a file with the string `.ffp` appended to the root name. Use `TONYPLOT` to examine these files.

## 9.4: Semiconductor Laser Simulation Techniques

The most common technique for simulating laser diodes is to simulate forward characteristics with a gradually increasing bias. The forward voltage is usually specified. You can use, however, current boundary conditions and include external elements.

To save computational time, we recommend that you use the `VCSEL` statement. The effective frequency method employed for the solution of the Helmholtz equation in this case allows you to consider structures with oxide apertures or other structural variations in transverse direction. We also recommend that you test the structure using reflectivity experiment simulation prior to applying the bias.

If you use the multiple longitudinal mode model, computational time will be longer and strongly dependent on the number of longitudinal modes involved in the calculation.

Simulating multiple transverse modes takes more computation time and should only be preformed when the higher order modes are of interest.

## 10.1: Overview

LUMINOUS is a general purpose ray trace and light absorption program integrated into the ATLAS framework, which is used to run with device simulation products. When used with S-PISCES or BLAZE, or device simulators, LUMINOUS will calculate optical intensity profiles within the semiconductor device, and converts these profiles into photogeneration rates. This unique coupling of tools allows you to simulate electronic responses to optical signals for a broad range of optical detectors. These devices include but are not limited to pn and pin photodiodes, avalanche photodiodes, Schottky photodetectors, MSMs, photoconductors, optical FETs, optical transistors, solar cells, and CCDs.

The following sections address various types of optoelectronic devices. Go to the sections that are most relevant to your application, but we strongly recommend you that read the other sections as well.

---

**Note:** You should be familiar with ATLAS and either S-PISCES or BLAZE before you can use LUMINOUS. If not, read Chapter 2: “Getting Started with ATLAS” and either Chapter 4: “S-Piscses: Silicon Based 2D Simulator” or Chapter 5: “Blaze: Compound Material 2D Simulator” first.

---

## 10.2: Simulation Method

Optoelectronic device simulation is split into two distinct models that are calculated simultaneously at each DC bias point or transient timestep:

1. Optical ray trace using real component of refractive index to calculate the optical intensity at each grid point
2. Absorption or photogeneration model using the imaginary component of refractive index to calculate a new carrier concentration at each grid point.

This is followed by an electrical simulation using S-PISCES or BLAZE to calculate terminal currents.

---

**Note:** LUMINOUS assumes that the refractive indices, both real and imaginary, are constant within a particular region.

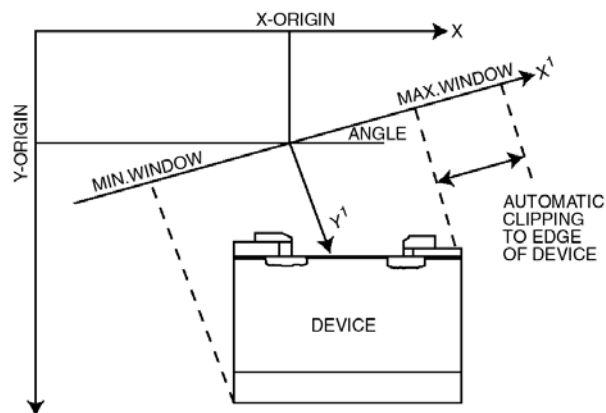
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### 10.2.1: Ray Tracing in 2D

#### Defining The Incident Beam

An optical beam is modeled as a collimated source using the BEAM statement. The origin of the beam is defined by parameters X.ORIGIN and Y.ORIGIN (see Figure 10-1). The ANGLE parameter specifies the direction of propagation of the beam relative to the x-axis. ANGLE=90 is vertical illumination from the top. MIN.WINDOW/MAX.WINDOW parameters specify the illumination window. As shown in Figure 10-1, the Illumination Window is “clipped” against the device domain so that none of the beam bypasses the device).

The beam is automatically split into a series of rays such that the sum of the rays covers the entire width of the illumination window. When the beam is split, ATLAS automatically resolves discontinuities along the region boundaries of the device.

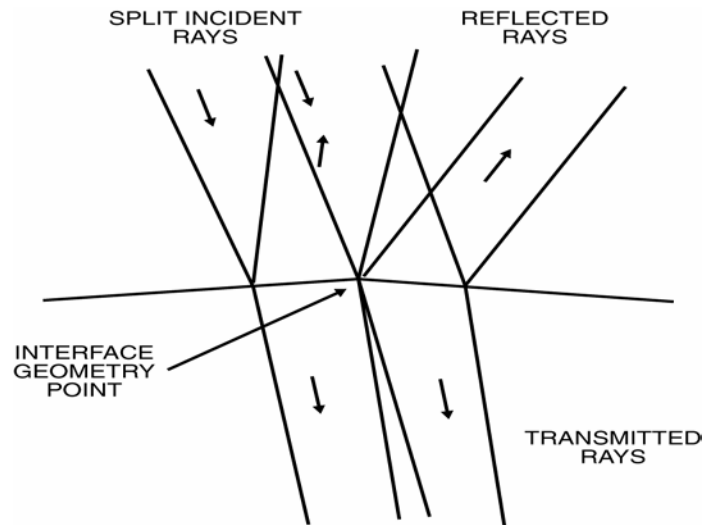


**Figure 10-1: Optical Beam Geometry**

Although the automatic algorithm is usually sufficient, you can also split the beam up into a number of rays using the RAYS parameter. Each ray will then have the same width at the beam origin and the sum of the rays will cover the illumination window. Even when the RAYS parameter is specified, ATLAS will automatically split the rays in order to resolve the device geometry.

## Ray Splitting At Interfaces

Rays are also split at interfaces between regions into a transmitted ray and a reflected ray. Figure 10-2 illustrates the difference between rays that are split to resolve the geometry and transmitted/reflected rays split at a region interfaces.



**Figure 10-2: Reflected and Transmitted Rays**

In Figure 10-2, the incident rays come in from the top left. They intersect a interface between two material regions with differing refractive indices. Within this interface lies a geometric point where the normal to the interface changes. This implies that the angles of reflection and transmission will be different for light incident to the left of the point from light incident on the right. Thus, the incident rays are split to resolve the interface point. The second level of splitting occurs at the interface itself. Here, the incident rays are split into reflected and transmitted rays.

### 10.2.2: Ray Tracing in 3D

In 3D, a simpler algorithm is used for ray tracing because the 2D algorithm takes up more computational time. Therefore in 3D, the algorithm doesn't automatically split rays to resolve topological features of the device.

---

**Note:** You must specify enough rays to resolve such features to the desired accuracy. But there's a trade off between the computation time and accuracy in specifying the number of rays.

---

The 3D source geometry is very similar to the geometry shown in Figure 10-1. In 3D, the source origin is specified by three coordinates: `X.ORIGIN`, `Y.ORIGIN`, and `Z.ORIGIN`. Unlike Figure 10-1, there are two angles that describe the direction of propagation. These are: `THETA`, which describes the rotation of the X axis (`THETA` is an alias of `ANGLE`), and `PHI`, which describes the angle of rotation of Z axis.

In 3D, the clipping of the window of propagation is done in two directions. In the X direction, this is described by `XMIN` and `XMAX` (`XMIN` and `XMAX` are aliases of `MIN.WINDOW` and `MAX.WINDOW`). In the Z direction, the window is described by `ZMIN` and `ZMAX`.

The numbers of rays in the X and Z directions are described by `NX` and `NZ`. Ray samples are taken at regular intervals over the source window.

Figure 10-3 shows an example of a 3D ray trace, where TonyPlot3D is used to visualize the rays.

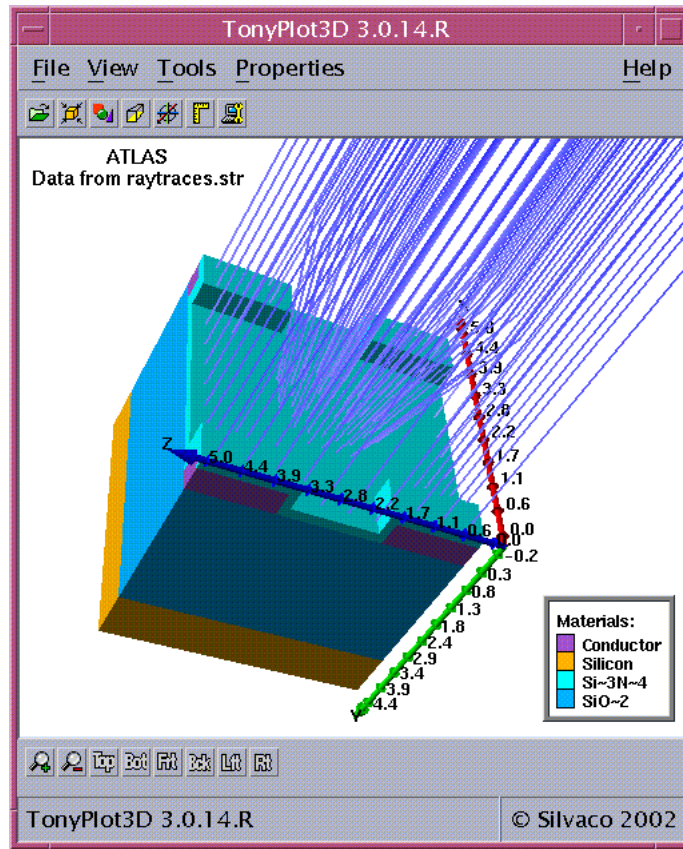
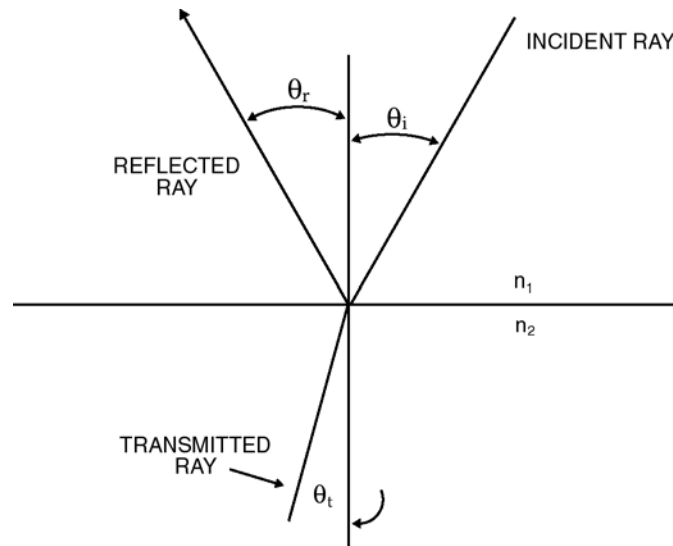


Figure 10-3: 3D Ray Trace

### 10.2.3: Reflection and Transmission

Figure 10-4 shows the relationship between the angles of incidence ( $\theta_i$ ), reflection ( $\theta_r$ ), and transmission ( $\theta_t$ ) at the interface between two media. These coefficients are calculated as a function of the refractive indices in the two media.





**Figure 10-4: Angles of incidence, reflection and transmission**

The reflection and transmission coefficients of the light for parallel and perpendicular polarization are calculated as shown in Equations 10-1 to 10-6.

$$E_r = \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_1 \cos \theta_t + n_2 \cos \theta_i} E_i \quad (\text{parallel polarization}) \quad 10-1$$

$$E_t = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} E_i \quad (\text{parallel polarization}) \quad 10-2$$

$$E_r = \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} E_i \quad (\text{perpendicular polarization}) \quad 10-3$$

$$E_t = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} E_i \quad (\text{perpendicular polarization}) \quad 10-4$$

$$R = \left( \frac{E_r}{E_i} \right)^2 \quad 10-5$$

$$T = \left( \frac{E_t}{E_i} \right)^2 \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \quad 10-6$$

where  $E_i$  is electric field of the incident wave,  $E_r$  is the field of the reflected wave,  $E_t$  is the field of the transmitted wave.  $R$  is the reflection coefficient,  $T$  is the transmission coefficient,  $n_1$  is the refractive index on the incident side and  $n_2$  is the refractive index on the transmission side.

The angles of reflection and transmission are given in Equations 10-7 and 10-8.

$$\theta_r = \theta_i \quad 10-7$$

$$n_1 \sin \theta_i = n_2 \sin \theta_t$$

where  $\theta_i$  is the angle of incidence,  $\theta_t$  is the angle of transmission and  $\theta_r$  is the angle of reflection.

## Specifying Reflections

By default no reflections are considered during the ray trace. The `REFLECTS=<i>` parameter is used to set an integer number of reflections to consider. Note that setting a very large number of reflections can lead to extremely long simulation times for the ray trace.

One very convenient way to overcome the long CPU times is to use the `MIN.POWER` parameter. This terminates each ray when the optical power falls to the fraction of the original power defined by this parameter.

## Front Reflection

By default, reflection and refraction at the first interface (the initial interface with the device) are ignored. The first reflection coefficient is zero and the transmission coefficient is one. The polarization and angle of the transmitted ray at the first interface is identical to the polarization and angle of the incident beam.

If the `FRONT.REFL` parameter of the `BEAM` statement is specified, the transmission coefficient is calculated using Equations 10-1 to 10-6. When the transmission coefficient is calculated, it's assumed that the material outside the device domain is a vacuum. The transmitted rays are attenuated by the transmission coefficient but the reflected ray is not traced.

## Back Reflection

By default, the reflection at the back of the device are ignored. No reflected ray is traced once the back of the device is reached. If the `BACK.REFL` parameter is specified, the backside reflection coefficient is calculated (again assuming a vacuum outside the device) and the back-side reflected ray is traced.

## Sidewall Reflection

By default, the reflection from the sides of the device are ignored. No reflected ray is traced back into the structure. As above, `BACK.REFL` is used to enable the sidewall reflections assuming a vacuum outside the device.

## Discontinuous Regions

You can simulate devices electrically where a single region is defined as two or more separated areas. The ray tracing algorithm, however, doesn't support such structures. If a structure has two separate areas with the same region number, we recommend you using `DEVEDIT` to renumber the regions, perhaps even creating a new region number for each area.

---

**Note:** This limitation is only for two separated areas with the same region number and not for two regions with different region numbers of the same material. This latter case can be simulated.

---

## Anti-Reflective Coatings

It's a popular strategy to place anti-reflective (AR) coatings on light detecting devices to improve device quantum efficiency. Such coatings rely on destructive interference of reflected waves to reduce overall reflection coefficient of light incident on the detecting device.

Simple AR coatings are typically composed of one layer of a transparent insulating material that is one quarter optical wavelength thick. Such coatings significantly reduce reflectivity of light at the design wavelength. Far from the wavelength in question, however, their performance is poor. Currently, more sophisticated multi-layer AR coatings are used for improved detection of broad-band light.

LUMINOUS enables you to model and design complicated AR coatings optimized for your specific application. AR coatings are simulated in LUMINOUS using an efficient transfer matrix method. This method enables you to deal with multi-layer AR coatings with virtually no overhead in computation time. Section 10.2.4: "Matrix Method" discusses matrix method and its application to wave propagation in a stratified medium.

Typically, AC coatings affect only optical properties of the device. Therefore, specifying the coating as a part of the device structure will unnecessarily increase the complexity of the electrical simulation. In ATLAS coatings are associated with the interfaces of the device instead. This allows you to specify certain optical properties of any material boundary while not affecting electrical properties of the structure.

To define optical properties of a coating associated with that interface, use the `INTERFACE` statement. Using this statement, you can define an AR coating, a dielectric mirror, or an ideally reflecting surface. Note that the coating is absent in the structure defined for ATLAS.

The `AR.THICK` parameter defines the thickness of the coating layer. The `AR.INDEX` parameter defines the refractive index of the layer. For a single-layer coating or for the first layer of a multi-layer coating, specify the coordinates of the points defining the coated surface `P1.X`, `P1.Y`, `P2.X`, and `P2.Y`.

---

**Note:** These coordinates should define a line, not a rectangular box of thickness (`AR.THICK`).

---

Figure 10-5 shows an example of a single-layer coating. The following shows the syntax used for a single-layer coating.

```
INTERFACE AR.INDEX=2.05 AR.THICK=0.0634 P1.X=0.0 P1.Y=0.0 P2.X=10.0 P2.Y=0.0
```

This defines a 63.4nm layer of real refractive index 2.05 at  $Y=0.0 \mu\text{m}$  in a structure.

You can specify any number of coatings for each device. The `COATING` parameter in the `INTERFACE` statement refers to the number of the coating. If `COATING` parameter is not set, the first coating will be used. Coatings should be specified in order (i.e., `COATING=3` can not be set before `COATING=2` is defined).

Different coatings should not overlap. If this occurs, the later coating will be used in the overlapping part.

Typically, the purpose of a single-layer AR coating is to minimize reflectivity of normally incident monochromatic light at the design wavelength  $\lambda$ .

Equations 10-9 and 10-10 define the parameters of choice for a single-layer AR coating between materials with refractive indexes  $n_1$  and  $n_2$ :

$$AR.INDEX = \sqrt{n_1 n_2} \quad 10-9$$

$$AR.THICK = \frac{\lambda}{4 \cdot AR.INDEX}$$

10-10

According to Equations 10-9 and 10-10, the coating in the example considered above has optimal properties for light at 520nm normally incident from air on a silicon detector.

You need several INTERFACE statements to specify a coating composed of multiple layers. Each statement defines only one layer of a coating. The syntax of the first INTERFACE statement for a multi-layer coating is identical to the specification of a single-layer coating. Each subsequent layer must have the number of the coating and the number of the layer specified by COATING and LAYER parameters. Specify the same COATING parameter for all INTERFACE statements that refer to the layers of the same AR coating. For example, the following statements specify a two-layer coating:

```
INTERFACE AR.INDEX=1.5 AR.THICK=0.06 P1.X=0.0 P1.Y=0.0 P2.X=10.0 P2.Y=0.0
INTERFACE AR.INDEX=2.05 AR.THICK=0.06 COATING=1 LAYER=2
```

Here, COATING=1 and LAYER=2 show the second INTERFACE statement describing a second layer of a two-layer coating number one. Use the LAYER parameter to describe the order of layers in a coating. If LAYER is not specified, the first (top) layer will be used. Again, you cannot specify LAYER=3 before LAYER=2. Note that you only need to specify the coordinates of the interface for the first layer of each coating.

If a coating is made out of an absorbing material, you can use AR.ABSORB parameter to take into account absorption. You can also use totally reflective coatings. The coating will behave as an ideal reflector if you set the AR.INDEX parameter to a value > 1000.

An alternative way to set the properties of the top interface is to use C-INTERPRETER function with F.REFLECT specified in the BEAM statement. Using this function, you can specify the reflection coefficient, angle of transmission, and transmitted polarization as a function of position, wavelength, angle of incidence, and incident polarization.

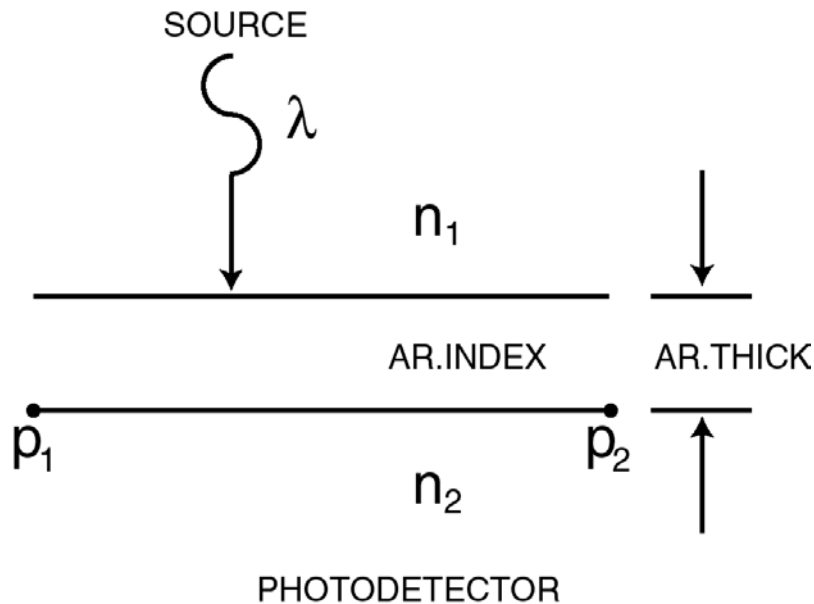


Figure 10-5: Single Layer AR Coating Under Normal Incidence

## Anti-Reflective Coatings in LUMINOUS3D

LUMINOUS3D enables you to model and design multi-layer AR coatings optimized for your specific 3D application.

As in LUMINOUS, you can define properties of an AR coating using `INTERFACE` statement in LUMINOUS3D. The `AR.THICK`, `AR.INDEX`, `AR.ABSORB`, `LAYER`, and `COATING` parameters retain their meaning and functionality in 3D. The only difference in description of an AR coating in 3D pertains to specification of the coating location. For a single-layer 3D coating or for the first layer of a multi-layer 3D coating, you need to specify coordinates of the bounding box `XMIN`, `XMAX`, `YMIN`, `YMAX`, `ZMIN`, and `ZMAX`. All interfaces within the bounding box obtain optical properties of the coating. If you don't set the bounding box coordinates, the default bounding box containing the whole device will be used.

The `REGION` parameter gives you additional flexibility in the description of an AR coating in 3D. `REGION` specifies the number of a region adjacent to the coating. `REGION=0` is the default value, corresponding to the ambient region outside the device boundaries.

When you define a bounding box for an interface, it could contain other interfaces, which you do not intend to be AR coated. When you use `REGION`, you can select only those interfaces adjacent to that region to have AR coating properties.

The following example

```
INTERFACE AR.INDEX=2.05 AR.THICK=0.0634 REGION=0
```

specifies that a 63.4nm layer of real refractive index 2.05 covers the entire outside boundary of a 3D device. All possible internal boundaries (heterojunctions) are not coated.

In a multi-layer coating, the first layer is assumed to be adjacent to the region specified by `REGION`.

```
INTERFACE AR.INDEX=1.5 AR.THICK=0.06 XMIN=0.0 XMAX=2.0 YMIN=0.0 YMAX=1.0 \
      ZMIN=0.0 ZMAX=6.0 REGION=2
INTERFACE AR.INDEX=2.05 AR.THICK=0.06 COATING=1 LAYER=2
```

In this example, the first coating layer with refractive index 1.5 is adjacent to the region number 2 on all boundaries within the specified bounding box. The second layer is next to the first layer at the same boundaries. Note that you only need to specify the bounding box and `REGION` only for the first layer of each coating.

### 10.2.4: Matrix Method

Matrix method presents a fast and accurate way to simulate electromagnetic wave propagation through a layered medium. Among a variety of approaches to matrix theory, the most commonly used are the characteristic matrix and the transfer matrix descriptions.

Using the matrix method is not limited to LUMINOUS only. It also finds its application in VCSEL and LED modules. ATLAS uses the characteristic matrix approach that relates total tangential components of the electric and magnetic fields at the multilayer boundaries. More often used transfer matrix, which relates tangential components of the electric field of left-travelling and right-travelling waves, has several disadvantages that limit its applicability.

The structure of a multilayer completely determines the characteristic matrix of this multilayer, the transfer matrix also contains the information about media on both sides of the multilayer. The characteristic matrix approach is more general and can be expanded to deal with graded interfaces, in which case, the transfer matrix method is inappropriate to use.

## Characteristic Matrix

First, we describe the characteristic matrix of a single layer. As mentioned earlier, the matrix relates tangential components of the electric  $E(z)$  and magnetic  $H(z)$  fields at the layer boundaries  $z=0$  and  $z=d$ .

$$\begin{bmatrix} E(0) \\ H(0) \end{bmatrix} = M \begin{bmatrix} E(d) \\ H(d) \end{bmatrix} \quad 10-11$$

The matrix itself is

$$M = \begin{bmatrix} \cos \varphi & j \sin \varphi / Y \\ j Y \sin \varphi & \cos \varphi \end{bmatrix} \quad 10-12$$

where

$$\varphi = \frac{2\pi}{\lambda} n d \cos \Theta \quad 10-13$$

is the phase shift for the wave propagating through the layer,  $n$  is the complex refractive index, and  $\Theta$  is the angle of wave propagation in the layer (Figure 10-6).  $Y$  is the optical admittance of the layer, which is for parallel ( $p$ ) and perpendicular ( $s$ ) polarizations, is given by:

$$Y^{(s)} = \sqrt{\frac{\varepsilon_0}{\mu_0}} n \cos \Theta \quad 10-14$$

$$Y^{(p)} = \sqrt{\frac{\varepsilon_0}{\mu_0}} n / \cos \Theta \quad 10-15$$

where  $\varepsilon_0$  and  $\mu_0$  are permittivity and permeability of free space.

The characteristic matrix of a multilayer is a product of corresponding single layer matrices. If  $m$  is the number of layers, then the field at the first ( $z=z_0$ ) and the last ( $z=z_m$ ) boundaries are related as follows:

$$\begin{bmatrix} E(Z_0) \\ H(Z_0) \end{bmatrix} = M_1, M_2 \dots M_m \begin{bmatrix} E(Z_m) \\ H(Z_m) \end{bmatrix}, M_i = \begin{bmatrix} \cos \varphi_i & j \sin \varphi_i / Y_i \\ j Y_i \sin \varphi_i & \cos \varphi_i \end{bmatrix} \quad 10-16$$

## Reflectivity, Transmissivity, and Absorptance

The detailed derivation of amplitude reflection ( $r$ ) and transmission ( $t$ ) coefficients is given in [145]. The resulting expressions are shown in Equations 10-17 and 10-18:

$$r = \frac{Y_0 M_{11} + Y_0 Y_s M_{12} + M_{21} - Y_s M_{22}}{Y_0 M_{11} + Y_0 Y_s M_{12} + M_{21} + Y_s M_{22}} \quad 10-17$$

$$t = \frac{2Y_0}{Y_0 M_{11} + Y_0 Y_s M_{12} + M_{21} + Y_s M_{22}} \quad 10-18$$

where  $Y_0$  and  $Y_s$  are the characteristic admittances of the media on both sides of the multilayer.  $M_{ij}$  are the elements of the characteristic matrix of the multilayer. Light is incident from the medium with admittance  $Y_0$ . The energy coefficients (reflectivity, transmissivity, and absorptance) are given by:

$$R = |r|^2 \quad 10-19$$

$$T = \frac{\text{Re}(Y_s)}{\text{Re}(Y_0)} |t|^2 \quad 10-20$$

$$A = (1-R) \left[ 1 - \frac{\text{Re}(Y_s)}{\text{Re}[(M_{11} + Y_s M_{12})(M_{21} + Y_s M_{22})^*]} \right] \quad 10-21$$

These expressions take into account imaginary part of refractive index and are, therefore, more general than Fresnel formulae (Equations 10-1 through 10-6). LUMINOUS automatically uses these expressions when appropriate.

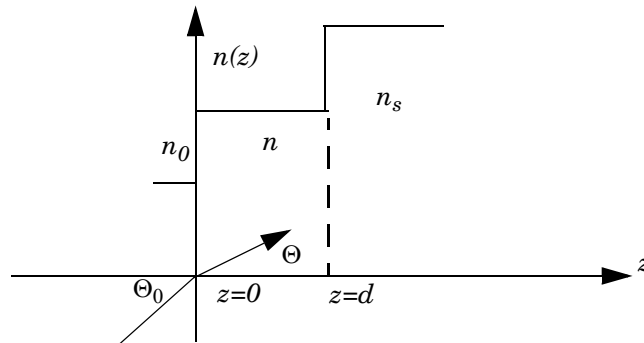


Figure 10-6: Refractive index profile of a single-layer coating

## 10.3: Generation of Photocurrent

### 10.3.1: Light Absorption and Photogeneration

The cumulative effects of the reflection coefficients, transmission coefficients, and the integrated loss due to absorption over the ray path are saved for each ray. The generation associated with each grid point can be calculated by integration of the Generation Rate Formula (Equation 10-22) over the area of intersection between the ray and the polygon associated with the grid point.

$$G = \eta_0 \frac{P^* \lambda}{hc} \alpha e^{-\alpha y} \quad 10-22$$

where:

$P^*$  contains the cumulative effects of reflections, transmissions, and loss due to absorption over the ray path.

$\eta_0$  is the internal quantum efficiency which represents the number of carrier pairs generated per photon observed.

$y$  is a relative distance for the ray in question.

$h$  is Planck's constant

$\lambda$  is the wavelength.

$c$  is the speed of light.

$\alpha$  is given by Equation 10-23.

$$\alpha = \frac{4\pi}{\lambda} k \quad 10-23$$

where:

$\alpha$  is the absorption coefficient.

$\lambda$  is the wavelength.

$k$  is the imaginary part of the optical index of refraction.

### Photogeneration on a Non-uniform Mesh

The photogeneration algorithm used integrates the optical intensity around each node point. This is done to ensure that the total photogeneration rate isn't grid sensitive. A uniform photogeneration rate is defined as a constant value of (photogeneration rate at any node)\*(element area around the node). In TONYPLOT a uniform photogeneration rate may appear to vary across a non-uniform mesh density.

### Photogeneration at Contacts

The photogeneration associated with nodes that are also defined as electrodes is a special case. The electrical boundary conditions require that the carrier concentration at electrode nodes equals the doping level. This means that photogeneration at nodes that are electrodes must be zero. But just setting these nodes to zero photogeneration will typically cause an apparent drop in quantum efficiency.

The photogeneration rate at the contact nodes is calculated as usual. However this photogeneration rate is applied to the neighboring node inside the semiconductor. This means for a uniform mesh and photogeneration rate, if the photogeneration rate is  $1.0 \times 10^{17}$  pairs/cm<sup>3</sup>s, then the nodes at the



contacts will have zero photogeneration and the next node into the semiconductor will have  $2.0 \times 10^{17}$  pairs/cm<sup>3</sup>s.

### User-Defined Arbitrary Photogeneration

An option exists for you to define the photogeneration rate. A C-INTERPRETER function written into a text file can be supplied to the program using the F.RADIATE parameter of the BEAM statement. For example, if a file, myoptics.c, was developed using the template C-INTERPRETER functions supplied it can be referenced by using:

```
BEAM NUM=1 F.RADIATE=myoptics.c
.
.
SOLVE B1=1.0
SOLVE B1=2.0
```

The file, myoptics.c, returns a time and position dependent photogeneration rate to the program. This returned value is multiplied at every node point by the value of B1.

With this option all other parameters of the BEAM statement and all the material refractive indices are overridden.

### 10.3.2: Photocurrent and Quantum Efficiency

One of the important figures of merit of a photodetector is quantum efficiency. Here, quantum efficiency is defined as the ratio of the number of carriers detected at a given photodetector electrode divided by the number of incident photons on the detector. Ideally, this ratio should be 1.0 in detectors without any positive feedback mechanisms, such as avalanche gain. LUMINOUS doesn't directly calculate quantum efficiency, but does calculate two useful quantities printed to the run-time output and saved to the log file. These quantities are source photocurrent and available photocurrent, which can be viewed in TONYPLOT from log files produced by LUMINOUS.

#### Definition of Source Photocurrent

The source photocurrent for a monochromatic source is given in Equation 10-24. Here,  $B_n$  is the intensity in beam number  $n$ , which is user-definable in the SOLVE statement.  $\lambda$  is the source wavelength specified by the WAVELENGTH parameter in the BEAM statement,  $h$  is Planck's constant,  $c$  is the speed of light, and  $W_t$  is the width of the beam including the effects of clipping (see Section 10.2.1: "Ray Tracing in 2D"). This can be considered as a measure of the rate of photons incident on the device expressed as a current density.

$$I_s = q \frac{B_n \lambda}{hc} W_t \quad 10-24$$

#### Definition of Available Photocurrent

The available photocurrent for a monochromatic source is given by Equation 10-25. Here, all the terms in front of the summation have the same definitions as for the source photocurrent. The sum is taken over the number of rays traced, NR.  $W_R$  is the width associated with the ray. The integral is taken over the length,  $Y_i$ , associated with the ray.  $P_i$  accounts for the attenuation before the start of the ray due to non-unity transmission coefficients and absorption prior to the ray start.  $\alpha_i$  is the absorption coefficient in the material that the ray is traversing.

The available photocurrent can be thought of as a measure of the rate of photo absorption in the device expressed as a current density. This should be similar but somewhat less than the source photocurrent. The losses are due to reflection and transmission of light out of the device structure.

$$I_A = q \frac{B_n \lambda}{hc} \sum_{i=1}^{N_R} W_R \int_0^{x_i} P_i \alpha_i e^{-\alpha_i y} dy \quad 10-25$$

Depending how you define it, quantum efficiency can be readily calculated by dividing the current from one of the device electrodes by either the source photocurrent or the available photocurrent.

## 10.4: Simulating Photodetectors

This section describes techniques simulate photodetectors. This section applies to the simulation of any of the following devices: p-n and p-i-n photodiodes, avalanche photodiodes, Schottky photodetectors, CCDs, MSMs, photoconductors, optical FETs and optically triggered power devices.

### 10.4.1: Defining Optical Sources

#### Identifying an Optical Beam

You can define up to ten optical sources. Optical sources are described by using the `BEAM` statement. All `BEAM` statements must appear somewhere after the `MESH`, `REGION`, `DOPING`, and `ELECTRODE` statements and before any `SOLVE` statement. The parameters in the `BEAM` statement describe a single optical source.

The `NUM` parameter is used to uniquely identify one optical source. Values between 1 and 10 are valid for the `NUM` parameter. Optical sources are subsequently referred to by the value of their `NUM` parameter. The power of the optical beam is set by using the `B<n>` parameter of the `SOLVE` statement, where `n` is the beam number defined by `NUM`.

#### Origin Plane of the Beam for 2D Optical Sources

To specify the origin of the optical source, use the `X.ORIGIN` and `Y.ORIGIN` parameters. These parameters describe the origin of the optical beam relative to the device coordinate system. Currently, it is required that the origin lie outside any device region. The `ANGLE` parameter specifies the angle of the direction of propagation of the beam with respect to the device coordinate system. `ANGLE=90` specifies vertical (normal) illumination from above.

The width of the optical beam is specified using the `MIN.WINDOW` and `MAX.WINDOW` parameters. These parameters specify the limits of the source beam relative to the beam origin. If either of the limits are omitted, that limit will be clipped to the edge of the device domain.

---

**Note:** It's extremely important that no section of the origin plane of the beam intersects or is inside the simulation grid. Otherwise, you'll get incorrect results. This is important to check in cases where the `ANGLE` isn't  $90^\circ$  or  $270^\circ$ .

---

#### Origin Plane of the Beam for 3D Optical Sources

To specify the origin of a 3D source, use the `X.ORIGIN`, `Y.ORIGIN`, and `Z.ORIGIN` parameters. These parameters describe the location of the origin relative to the device coordinate system. The `THETA` and `PHI` parameters describe the direction of propagation relative to the beam origin. The `THETA` parameter describes rotation of the X axis about the Z axis. The `PHI` parameter describes rotation of the Z axis about the Y axis. As with the 2D for normal illumination, specify a negative `Y.ORIGIN` and `THETA=90`.

Specify the window of illumination using the `XMIN`, `XMAX`, `ZMIN`, and `ZMAX` parameters, and specify the numbers of samples in the X and Z directions using the `NX` and `NZ` parameters. These values should be set to numbers large enough to resolve any salient features of the topology.

To save the rays into a file for visualization, specify the `RAYTRACE=<filename>` parameter.

## Reflections

You can also specify whether to ignore the first reflection using the `FRONT.REFL`, and the backside and sidewall reflection using the `BACK.REFL`. You should activate the backside reflections for devices, which use a back side reflector to improve collection efficiency. The number of reflections solved is set by the `REFLECTS` parameter.

Typically, `BACK.REFL` should be used if the structure simulated is equivalent to the complete photodetector geometry as in a discrete device. If the simulation structure is a section of a larger substrate as in CCD simulation then `BACK.REFL` shouldn't be used.

Since reflection and transmission coefficients are used in the ray trace, for arbitrary angles of incidence, specify the polarization by using the `POLARIZATION` parameter.

In complex structures, you should limit the ray tracing to trace only those rays with significant optical power. The `MIN.POWER` parameter is used to terminate ray traces that drop below `MIN.POWER*` (optical source power).

## Specifying Lenslets in 3D

In 3D, you can specify one of three lenslets to focus the light into the device. The lenslet has no direct effect on the device simulation mesh. It is only used in the ray trace. Lenslets are described by user defined parameters on the `BEAM` statement.

### Spherical Lenslets

The spherical lenslet is described by the intersection of a plane (perpendicular to the Y axis and a sphere. The Y coordinate of the plane is given by `LENS.PLANE`. The origin of the sphere is described by `LENS.X`, `LENS.Y`, and `LENS.Z`. The sphere radius is described by `LENS.RADIUS`.

For ray tracing purposes, the space between the plane and the device surface is uniformly of a single index of refraction specified by `LENS.INDEX`. The spherical section projecting above the plane in the negative Y direction is also considered to consist of the same index of refraction. The plane and the spherical section form the lenslet.

### Ellipsoidal Lenslets

To specify an ellipsoidal lenslet, define the axial half lengths using the `X.SEMIAxis`, `Y.SEMIAxis` and `Z.SEMIAxis` parameters of the `BEAM` statement. The ellipsoidal lenslet center is specified by the `LENS.X`, `LENS.Y` and `LENS.Z` parameters. The `LENS.PLANE` parameter defines the location of the lens plane. The `LENS.INDEX` parameter gives the lens real index of refraction. Equation 10-26 gives the equation for the lenslet surface above the lens plane.

$$\frac{(x - \text{LENS.X})^2}{\text{X.SEMIAxis}^2} + \frac{(y - \text{LENS.Y})^2}{\text{Y.SEMIAxis}^2} + \frac{(z - \text{LENS.Z})^2}{\text{Z.SEMIAxis}^2} \quad 10-26$$

### Composite Lenslets

You can also specify a composite lenslet. The composite lenslet is composed of a central planar section, quarter cylinder sections and eighth sphere sections, which is shown in Figure 10-7. The composite lenslet is defined by the `LENS.XMIN`, `LENS.XMAX`, `LENS.ZMIN`, `LENS.ZMAX`, `LENS.WIDTH`, `LENS.HEIGHT`, `LENS.PLANE` and `LENS.INDEX` parameters. Figure 10-7 shows the meanings of these parameters.

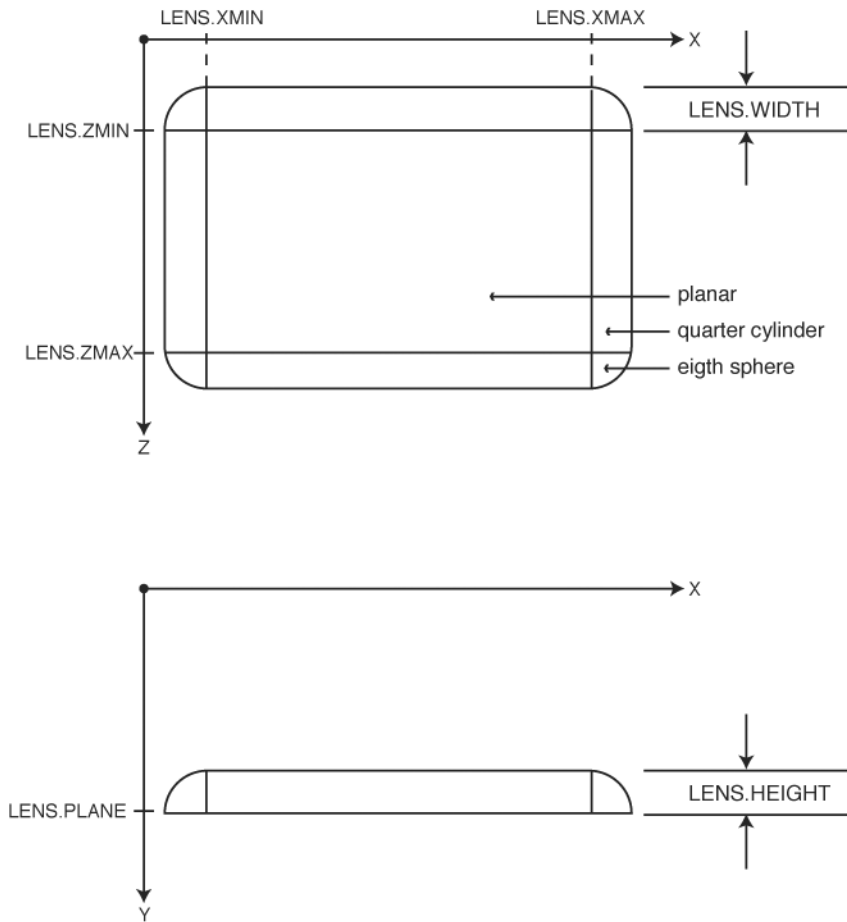


Figure 10-7: Composite Lenslet

### Specifying Periodicity in the Ray Trace

By default the unspecified boundary conditions for device simulation are mirror or periodic boundary conditions. For ray tracing, by default, the edges of the device are considered interfaces with a vacuum. Thus, at the edges of the device by default reflections are calculated. In some cases, it is convenient to consider the edges of the device to be periodic with respect to ray tracing. This is particularly true when the beam is not normal to the plane. You should specify `PERIODIC` in the `BEAM` statement to obtain such boundaries for ray tracing.

### Defining Luminous beam intensity in 2D

When a beam is defined in `LUMINOUS`, it is, by default, assumed to have a uniform light intensity across the width of the beam. The intensity is defined in the `SOLVE` statement with the `B<n>` parameter and is in the units of  $\text{W}/\text{cm}^2$ .

The beam intensity distribution can also be defined with a Gaussian profile.

$$f(x) = \frac{1}{x\text{sigma}\sqrt{2\pi}} \exp\left(-\frac{(x - \text{mean})^2}{2(x\text{sigma})^2}\right) \quad 10-27$$

The location of the peak of the Gaussian distribution with respect to the beam coordinates is specified by the MEAN parameter of the BEAM statement. The standard deviation of the distribution is specified with the SIGMA parameter.

$x$  is the cumulative distance over the beam width where the distribution will be formed. Define the RAYS parameter to get smooth distribution of intensity profile. This determines the increment of  $x$ . Therefore, the RAYS parameter should be set to a large number as the spacing between rays is always a constant (width of the beam / RAYS).

The resultant distribution has a unity peak value, which is then scaled by the B<n> value specified on the SOLVE statement. For example, the following BEAM statement will define a beam window 2  $\mu\text{m}$  wide centered at X.ORIGIN and Y.ORIGIN, which has a Gaussian peak of 0.01  $\text{W}/\text{cm}^2$  and a standard deviation of 0.05  $\mu\text{m}$ .

```
beam  num=1 x.origin=5.0 y.origin=-1.0 angle=90.0 wavelength=0.6 \  
xmin=-1 xmax=1 GAUSSIAN MEAN=0 SIGMA=0.05 RAYS=200 \  
SOLVE B1=1E-2
```

## Defining Luminous3D Beam Intensity

A beam defined in LUMINOUS3D is assumed by default to have a uniform light intensity across the width of the beam. The intensity is defined in the SOLVE statement with the B,n. parameter and is in the units of  $\text{W}/\text{cm}^2$ .

In LUMINOUS3D, you can also specify a circular or elliptical source. To specify an elliptical source you should specify the appropriate origin location using X.ORIGIN, Y.ORIGIN, and Z.ORIGIN. This will specify the center of the elliptical source. The major and minor axes of the ellipse are specified by the XRADIUS and ZRADIUS parameters. Remember you must also specify the NX and NZ parameters. These will sample uniformly across the diameters of the ellipse.

You may also specify Gaussian profiles in LUMINOUS3D. To do this, specify the location of the beam origin. You can specify the Gaussian(s) in the X and Z direction. These can be done independently or together. These Gaussians are specified by the XMEAN, XSIGMA, ZMEAN, and ZSIGMA parameters of the BEAM statement.

## Monochromatic or Multispectral Sources

The optical source can be either monochromatic or multispectral. For monochromatic sources, you can use the WAVELENGTH parameter to assign the optical wavelength. WAVELENGTH uses the units microns to be more consistent with the rest of ATLAS. Note this if you're accustomed to the optoelectronic engineering preference for nanometers.

For multispectral sources, spectral intensity is described in an external ASCII file indicated by the POWER.FILE parameter. This is a text file that contains a list of pairs defining wavelength and spectral intensity. The first line of the file gives the integer number of wavelength-intensity pairs in the file. An example of such a file is shown below.

```
4  
0.4 0.5  
0.5 1.0  
0.6 1.2  
0.7 1.1
```

This example specifies that there are four samples, and that at a wavelength of 0.4  $\mu\text{m}$ , the intensity is 0.5 Watts per square cm per  $\mu\text{m}$  of wavelength, and so on. With multispectral sources, specify a discretization of the interpolated information. Values must be specified for the WAVEL.START, WAVEL.END, and WAVEL.NUM parameters. These values specify the starting and ending wavelengths and the number of wavelengths to sample. LUMINOUS uses wavelengths at equal intervals over a specified range of wavelengths.

LUMINOUS performs an independent ray trace at each of the sample wavelengths. For example:

```
WAVEL.START=0.4 WAVEL.END=0.6 WAVEL.NUM=2
```

causes ray traces at wavelengths of 0.45 and 0.55. LUMINOUS obtains the intensity associated with each sample by integrating the values of the spectral intensity file using a piece wise linear approximation. Each integral is performed over the range between successive midpoints. In the preceding example, the integration for the sample at 0.45 would be performed over the range of 0.4 to 0.5.

For a multispectral source, the generation rate (like Equation 10-22) is given by:

$$G = \eta_0 \int_{\mathbf{WAVEL.START}}^{\mathbf{WAVEL.END}} \frac{P(\lambda)L\lambda}{hc} \alpha e^{-xy} d\lambda \quad 10-28$$

where:

$\eta_0$  is the internal quantum efficiency.

$P(\lambda)$  is the power spectral density of the source.

$L$  is a factor representing the cumulative loss due to reflections, transmissions, and absorption over the ray path.

$\lambda$  is the wavelength.

$h$  is Planck's constant.

$c$  is the speed of light.

$\alpha$  is the absorption coefficient given by Equation 10-23.

$y$  is the depth of the device, where  $x,y$  forms the two-dimensional mesh.

$\mathbf{WAVEL.START}$  and  $\mathbf{WAVEL.END}$  are the spectral limits specified on the **BEAM** statement.

---

**Note:** The integral in Equation 10-28 may be inexact due to the discrete sampling in conjunction with wavelength dependence of the absorption coefficient. For constant absorption coefficient, the integral is exact of the number of discrete wavelength samples specified by  $\mathbf{WAVEL.NUM}$  on the **BEAM** statement.

---

The source photocurrent (like Equation 10-24) is given by:

$$I_s = q \frac{Bn}{hc} w_t \int_{\mathbf{WAVEL.START}}^{\mathbf{WAVEL.END}} P(\lambda)_\lambda d\lambda \quad 10-29$$

where  $P(\lambda)$  is the power spectral density of the source, and the other parameters have the same definition as in Equation 10-24.

The available photo current (like Equation 10-25) is given by:

$$I_s = q \frac{Bn}{hc} \sum_{i=i}^{N_a} w_R \int_0^{X_i} \int_{WAVEL.START}^{WAVEL.END} P(\lambda) de^{-xy} P\lambda_\lambda dy \quad 10-30$$

where  $P(\lambda)$  is the power spectral density of the source, and the other parameters have the same definition as in Equation 10-25.

For either the monochromatic or multispectral sources, you can uniformly scale the wavelength(s) and intensities by using the `WAVEL.SCALE` parameter and the `POWER.SCALE` parameter respectively. These parameters are useful if the intensities or wavelengths are specified in units other than the default units.

---

**Note:** The units of spectral intensity in the `POWER.FILE` are  $W/cm^2$  per  $\mu m$  of wavelength. The per micron of wavelength is important to remember when integrating the total power across the spectrum.

---

## 10.4.2: Defining Optical Properties of Materials

For ray tracing, the complex index of refraction of the various material regions in the structure must be specified. For many of the more common semiconductors and insulators, there are built-in tables of index versus wavelength. You can specify the index for the materials lacking reasonable default complex index of refraction.

---

**Note:** You can add the `INDEX.CHECK` parameter to any `SOLVE` statement to print out the refractive indices being used for that bias step.

---

### Setting Single Values For The Refractive Index

The `REAL.INDEX` and `IMAG.INDEX` parameters of the `MATERIAL` statement can be used to set the real and imaginary indices of a specified material, region or regions.

For example, the statement:

```
MATERIAL MATERIAL=Air REAL.INDEX=1.0 IMAG.INDEX=0.0
```

would set the index for all material regions composed of "Air"

The statement:

```
MATERIAL REGION=1 REAL.INDEX=1.0 IMAG.INDEX=0.0
```

would set the index for region number 1.

The statement:

```
MATERIAL REAL.INDEX=1.0 IMAG.INDEX=0.0
```

would set the index for all regions.



## Setting A Wavelength Dependent Refractive Index

The preceding examples set the complex index of refraction for a material regardless of wavelength. This is probably adequate for monochromatic sources. For multispectral simulations, the index of refraction should be modeled as having a dependence on wavelength. There are two ways to do this.

### ASCII File Input

The first way is to specify index versus wavelength in a file. This is a text file that contains ordered triplets of wavelength, real index, and imaginary index. The first entry in the table is the number of samples. If you set the `INDEX.FILE` parameter of the `MATERIAL` statement to the name of the index file, the linear interpolation from this table will complete to obtain the index of refraction as a function of wavelength.

A valid index file is shown below.

```
2
0.5 2.0 0.0
0.6 3.0 0.02
```

In this example, a real index of 2.5, and an imaginary index of 0.015 would be used for a wavelength of 0.55 microns.

### C-Interpreter Function

The second way to specify index versus wavelength is by using the `C-INTERPRETER` function. The syntax is:

```
MATERIAL NAME=Silicon F.INDEX=myindex.c
```

The file `myindex.c` is an external file conforming to the template supplied with the program. It returns wavelength dependent real and imaginary indices. Instructions for using the `C-INTERPRETER` and finding the template functions are described in Appendix A: “C-Interpreter Functions”.

## 10.4.3: Extracting Dark Characteristics

One of the first tasks in analyzing a new detector design is to examine dark current, device capacitance, and possibly other unilluminated characteristics. This can normally be done without using `LUMINOUS`. Extraction of the characteristics is adequately covered in the chapters on `S-PISCES` or `BLAZE`.

The extraction of reverse bias leakage currents for diodes presents some difficult numerical problems for device simulators. These problems are associated with limitations on numerical precision. `ATLAS`, as well as most other available device simulators, use double precision arithmetic to evaluate terminal currents. Double precision arithmetic provides roughly 16 decimal digits of precision. Internal scaling allows the measurement of currents down to a level of between about  $10^{-12}$  A/micron to  $10^{-16}$  A/micron. Unfortunately, photodiode leakage currents are often around or below this level. This means that the currents printed are subject to significant numerical noise, and don't provide an accurate estimate of the device leakage currents. There are two ways to estimate reverse leakage current.

### Integrated Recombination

From a theoretical standpoint, the reverse behavior of diodes can be dominated by one of two effects: diffusion currents in the neutral regions or recombination currents inside the depletion region [9]. `ATLAS` can provide insight into both of these contributing mechanisms. To estimate recombination current, use the `MEASURE` statement to calculate the integrated recombination rate. The following statement can be used:

```
MEASURE U.TOTAL
```

When this statement is executed, it prints out the total integrated recombination rate. Multiply this value by the electron charge ( $1.6023 \times 10^{-19}$  coulombs) to obtain an estimate of the recombination current contribution to the reverse diode leakage current.

### Extrapolation from High Temperatures

The diffusion current contribution can be estimated by taking advantage of the non-linear relationship between the diffusion current and temperature. Referring to the expression for the “Ideal Diode” current given by Equation 10-31, the dominant temperature dependency arises from the variation of the intrinsic concentration.

$$J = \left( \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right) \left( \exp\left(\frac{qV}{kT_L}\right) - 1 \right) \quad 10-31$$

where  $n_{p0}$  and  $p_{n0}$  are thermal-equilibrium minority carrier densities on either side of the junction. This gives an exponential variation of the diffusion current with temperature as given in the following equation:

$$J \approx \exp\left(\frac{-E_g}{kT_L}\right) \cdot \left( \exp\left(\frac{qV}{kT_L}\right) - 1 \right) \quad 10-32$$

This relation can be used to estimate the diffusion current contribution at the operating temperature. The basic idea is to calculate the current at a high temperature where the problem of numerical precision does not arise, and then scale the current to the operating temperature using Equation 10-32. For example, if the device is to operate at 300K, the temperature may be set to 450K using the TEMPERATURE parameter of the MODEL statement. Any temperature dependence of the energy gap should be disabled by explicitly specifying the band gap using the EG300 parameter and setting EGALPHA and EGBETA parameters to zero, all on the MATERIAL statement. The following statement illustrates this approach as it might apply to a silicon diode:

```
MODEL TEMPERATURE=450
MATERIAL EG300=1.12 EGALPHA=0.0 EGBETA=0.0
```

ATLAS can then be used to obtain the reverse bias current at the elevated temperature. The following equation can be applied to obtain the depletion current contribution at the operating temperature:

$$J = J_e \cdot \exp\left(\frac{E_g}{kT_e} - \frac{E_g}{kT_L}\right) \cdot \left( \frac{\exp\left(\frac{qV}{kT_L}\right) - 1}{\exp\left(\frac{qV}{kT_e}\right) - 1} \right) \quad 10-33$$

where  $J_e$  is the current measured at the elevated temperature,  $E_g$  is the bandgap,  $T_e$  is the elevated temperature,  $T_L$  is the operating temperature,  $V$  is the operating bias voltage, and  $J$  is the current estimate at the operating temperature. Once you've obtained estimates of the recombination and diffusion contributions, you can obtain the total leakage current by summing the two contributions.

### Numerical Solution Parameters

ATLAS uses a cut-off value of carrier concentration below, which solutions are not required to converge. This limit is set by the CLIM.DD. parameter. See Chapter 17: “Numerical Techniques” for more details on CLIM.DD. For photodetectors, you often need to reduce CLIM.DD to  $10^5$  in order to resolve carrier concentrations in depleted regions before illumination.

### 10.4.4: Extracting Detection Efficiency

One of the simpler tasks in characterizing a photodetector design is to measure DC detection efficiency. This will be done typically as a function of bias voltage, optical intensity, or wavelength. Each of these analyses can be performed using the SOLVE statement. The Bn parameter can be used to set the optical intensity of the optical sources described in the previous section. The following example illustrates obtaining a solution with a specified optical intensity:

```
SOLVE B1=1.0
```

This specifies that a solution is to be obtained for an optical intensity in the beam numbered “1” of 1.0 Watt/cm<sup>2</sup>. If this were the first SOLVE statement specified, the ray trace in LUMINOUS would be initiated. At the start of the solution the optical intensities of each optical source with a positive intensity is printed. In addition, the available photocurrent and source photocurrent are printed. See the prior section on Photocurrent for a definition of these two quantities.

### Internal and External Quantum Efficiency

The available photocurrent divided by the source photocurrent is a measure of the external quantum efficiency of the detector. The calculated terminal current can be divided by the source or available photocurrents is used to evaluate the internal quantum efficiency of the device.

### 10.4.5: Obtaining Quantum Efficiency versus Bias

The intensities specified in the SOLVE statement apply until another SOLVE statement changes the intensity of the beam. Sequences of SOLVE statements can be used to vary the optical intensity at arbitrary intervals. The simple linear ramps of optical intensity can be abbreviated using the LIT.STEP and NSTEP parameters of the SOLVE statement. The LIT.STEP parameter specifies the size of the DC step and NSTEP specifies how many steps are desired.

Another option for analyzing DC quantum efficiency is to fix the optical intensity and vary bias voltages. The bias voltages can be varied in arbitrary discrete steps using several SOLVE statements, or in a linear ramp using individual SOLVE statements. This is useful for determining the optimum operating bias of devices such as avalanche detectors and photo transistors.

### 10.4.6: Obtaining Transient Response to Optical Sources

It is sometimes desirable to examine the time domain response of a detector to time-dependent (e.g., ramped or pulsed) optical sources. LUMINOUS provides this capability with the RAMP.LIT parameter. When the RAMP.LIT parameter is specified in a SOLVE statement, the optical intensity is changed linearly from the most recently set intensity to the intensity set in the B parameter. If a particular source intensity is not set using the corresponding B parameter, its intensity is not varied during the transient.

The period of the linear ramp is specified by the RAMPTIME parameter. The transient simulation stops after the time specified by the TSTOP parameter. If the time given by TSTOP is greater than that given by RAMPTIME, the source intensities remain constant until the time given by TSTOP. For transient ramps the TSTEP parameter should also be set. TSTEP is typically set to allow several samples within the RAMPTIME. After the first time step, subsequent time step sizes will be chosen automatically based on estimates of truncation error. The following is an example of the specification of an optical impulse transient:

```
SOLVE B1=1.0 RAMPTIME=1E-9 TSTOP=1E-9 TSTEP=1E-11
SOLVE B1=0.0 RAMPTIME=1E-9 TSTOP=20E-9 TSTEP=1E-11
```

In this example, a triangular impulse in the intensity of the optical source is simulated. The peak intensity is 1.0 and the impulse width is 2 ns. The response of the device is simulated for an additional 18 ns. An initial time step of 10 ps is chosen for both parts of the impulse.

### 10.4.7: Obtaining Frequency Response to Optical Sources

You can also simulate small signal response to optical sources. To obtain a solution for small signal response, set the `SS.PHOT` parameter in the `SOLVE` statement. The `BEAM` parameter must also be assigned to the specific optical source index for small signal response of that source. A single source small signal frequency can be specified using the `FREQUENCY` parameter. You can vary the frequency within a single `SOLVE` statement by using the `NFSTEP` and `FSTEP` parameters. The `NFSTEP` indicates how many frequency steps are to be simulated, while the `FSTEP` indicates the step size. If the `MULT.F` parameter is specified, the start frequency is multiplied by the step size for the specified number of steps. If not, the step size will be added to the start frequency for the specified number of steps. For example:

```
SOLVE SS.PHOT BEAM=1 FREQUENCY=1e6 NFSTEP=5 FSTEP=10 MULT.F
```

will invoke solutions as optical frequencies at every decade from 1MHz to 100 GHz.

If the small signal parameters are specified in the same `SOLVE` statement as a DC bias ramp the small signal response is extracted for each bias voltage for each small signal frequency. This is a useful strategy for analyzing the frequency response of the device as a function of bias voltage.

### 10.4.8: Obtaining Spatial Response

To obtain spatial response, move an optical spot along a line segment perpendicular to the direction of propagation of the source. Each incremental step is equal to the width of the spot. The total distance over which the source is scanned is defined by the `MIN.WINDOW` and `MAX.WINDOW` parameters of the `BEAM` statement. The number of steps is defined by the `RAYS` parameter of the `BEAM` statement. The spot width is defined by the ratio:

$$(\text{MAX.WINDOW} - \text{MIN.WINDOW}) / \text{RAYS}$$

The spot scan is started by the `SCAN.SPOT` parameter of the `SOLVE` statement. This parameter is set to the beam index of the optical source to be scanned (i.e., the beam defined by the `BEAM` statement whose `NUMBER` parameter is set to the beam index). During the spot scan, ATLAS obtains solutions and outputs terminal currents, and so on, as well as the relative beam location at each incremental spot location. This information can be used by `TONYPLOT` to produce plots of photoresponse as a function of position.

### 10.4.9: Obtaining Spectral Response

The spectral response, defined as device current as a function of the wavelength of the optical source wavelength, can be obtained. The `LAMBDA` parameter of the `SOLVE` statement sets the source wavelength of the beam in microns. Since the wavelength can be set in each `SOLVE` statement, successive solutions can be obtained as a function of wavelength. Each time the `LAMBDA` parameter is specified, a new ray trace is run for that new wavelength and the electrical solution recalculated.

The following statements could be used to extract terminal currents at a series of discrete wavelengths:

```
SOLVE B1=1 LAMBDA=0.2
SOLVE B1=1 LAMBDA=0.3
SOLVE B1=1 LAMBDA=0.4
SOLVE B1=1 LAMBDA=0.5
SOLVE B1=1 LAMBDA=0.6
SOLVE B1=1 LAMBDA=0.7
SOLVE B1=1 LAMBDA=0.8
```

In this example, the spectral response is obtained for wavelengths from 0.2 microns to 0.8 microns.

When using `LAMBDA`, the `WAVELENGTH` parameter of the `BEAM` statement will be overridden, however be sure to use a monochromatic beam and not a multi-spectral beam for this simulation.

---

**Note:** The units of LAMBDA and WAVELENGTH in the BEAM statement are in  $\mu\text{m}$ .

---

## 10.5: Simulating Solar Cells

### 10.5.1: Obtaining Open Circuit Voltage and Short Circuit Current

To obtain  $V_{OC}$  and  $I_{SS}$  for a solar cell, first define the illumination conditions. This should be done as discussed above in describing multi-spectral sources. The short circuit current is obtained by defining the contacts as voltage dependent contacts (default) and obtaining a solution with the device under zero bias with illumination. This can typically be done as a first step by the following input statement, for example:

```
SOLVE B1=1
```

In this statement, it's assumed the source, B1, has been already defined and the intensity is expected in the actual device. When you obtain a solution, the terminal currents represent the short circuit current.

The open circuit voltage is obtained by defining one or more of the contacts as current controlled. This is done using the CONTACT statement. For example:

```
CONTACT NAME=anode CURRENT
```

defines that electrode number 1 is a current controlled electrode. The open circuit voltage is then obtained by setting the current at this contact to zero, and obtaining a solution. The following statement illustrates:

```
SOLVE I1=0.0 B1=1
```

Once the solution is obtained, the bias associated with I1 is the open circuit voltage.

## 10.6: Beam Propagation Method in 2D

You can simulate most optoelectronic devices using ray tracing based on geometrical optic principles. But when diffraction or coherent effects are important, ray tracing methods are no longer sufficient. In this case, you need a method that takes into account the wave nature of light.

The method that does this is called the Beam Propagation Method (BPM). BPMs such as [131] rely on paraxial approximation. The BPM in LUMINOUS, however, has been extended to solve a more general Helmholtz Wave Equation (Equation 10-34).

$$\nabla^2 E(\hat{r}, t) - \frac{n^2}{c^2} \frac{\partial^2 E(\hat{r}, t)}{\partial t^2} = 0 \quad 10-34$$

Here,  $E$  is the electric field of an optical wave,  $n$  is the complex refractive index of the material, and  $c$  is the speed of light in vacuum.

The Helmholtz Wave Equation is consistent with the Rayleigh-Sommerfeld formulation of scalar diffraction theory [132]. It can also be derived from Maxwell's equations assuming homogeneous and isotropic media and neglecting non-linear effects.

These assumptions put certain restrictions on the applicability of BPM. For example, material regions with gradual change in refractive index or photodetector saturation modeling aren't supported. But the framework of the BPM library allows the non-linear effects (e.g., saturation) and treatment of inhomogeneous media (e.g., graded index regions) to be included in the future.

### 10.6.1: Using BPM

The BPM in LUMINOUS isn't designed to completely replace the fast and robust ray tracing algorithm. In fact, we recommend you start the analysis of your particular application using the ray tracing method (see Sections 10.2.1: "Ray Tracing in 2D" to 10.2.3: "Reflection and Transmission").

Only use BPM when you think light diffraction or coherent effects are important. Here are the following guidelines when to use it:

- The source is monochromatic (no coherent effects are observed for multispectral sources).
- The application is 2D (currently, a 3D BPM isn't implemented due to calculation time considerations).
- Spatial distribution of irradiance or photogenerated carrier density is important.
- The structure isn't periodic in x.

BPM should be useful for:

- Multilayer structures with layer thicknesses comparable to wavelength.
- Narrow incident beams (when transverse beam size is comparable to wavelength).

Currently, BPM doesn't support either user-specified reflection coefficient models (`F.REFLECT`) or photogeneration rate vs. position or time. The `SCAN.SPOT` parameter of `SOLVE` statement (see Chapter 18: "Statements", Section 18.40: "SOLVE") and anti-reflection coatings (see "Anti-Reflective Coatings" on page 10-7) are also not included.

If you need to use BPM, include the BPM parameter in the `BEAM` statement (see Chapter 18: "Statements", Section 18.2: "BEAM"). `BEAM` parameters related specifically to ray tracing (such as `RAYTRACE`, `RAYS`, `THINEST`, `MAX.WINDOW`, and `MIN.WINDOW`) are ignored when BPM is specified.

Unlike ray tracing, the incident beam is specified on the top of the device. The origin of the beam is then assumed to be at the `X.ORIGIN` in the `BEAM` statement, where `Y.ORIGIN` parameter is ignored. This is done to avoid unnecessary beam propagation in the material surrounding the device.

You can specify additional parameters (`LONGIT.STEP` and `TRANSV.STEP`) in the `BEAM` statement to set respective step sizes for the internal BPM grid. If you don't define these step sizes, the default values are used. The default step size in both directions is equal to  $\lambda/16.0$ , where  $\lambda$  is the wavelength of light in vacuum. Don't use step sizes larger than  $\lambda/2.0$ , especially if coherent effects are of interest. Also, we don't recommend extremely small step sizes because it can result in unnecessarily long computation times. The default values are adequate for most cases.

### 10.6.2: Light Propagation In A Multiple Region Device

Since Equation 10-34 doesn't describe light propagation through the region's boundary, each region has to be considered separately. Each region's boundary is composed of straight line segments (edges) that form a polygon. Light propagating from one of the segments could be reflected back into the region from other segments of the boundary, while transmitted light enters other regions. Reflected and transmitted optical fields are calculated using Fresnel formulae described in Equations 10-1 to 10-6 in Section 10.2.3: "Reflection and Transmission".

Once the field reflected from a certain boundary is known, it then propagates back into the region. The light then reaches all edges of the polygon. At this point, the field incident upon each boundary is saved (i.e., added to the total field incident on each boundary). Once all polygon edges are addressed like this, the algorithm then proceeds to the next region.

When the pass through the device is complete, one reflection of light on each boundary has been accounted. The `REFLECTS` parameter specifies the number of passes to be done.

Like in ray tracing, if the `REFLECTS` parameter is large (e.g., 10), the optical part of the simulation might take considerable amount of time. To limit the number of propagation routines, use the `MIN.POWER` parameter. But unlike in ray tracing, where the default value of this parameter is zero, the default is `MIN.POWER=1e-6`. This limit helps avoid unnecessary computations.

Since only propagation through convex polygons can be properly addressed, concave polygons are automatically split to form two convex regions. If necessary, air polygons are added at the top of the device structure to fill the empty regions, where the propagation of light also needs to be considered.

### 10.6.3: Fast Fourier Transform (FFT) Based Beam Propagation Algorithm

Field propagation from a boundary segment through a region is considered in the coordinate system of that segment. The `X` axis is along the boundary and `Z` axis is along the normal (Figure 10-8).

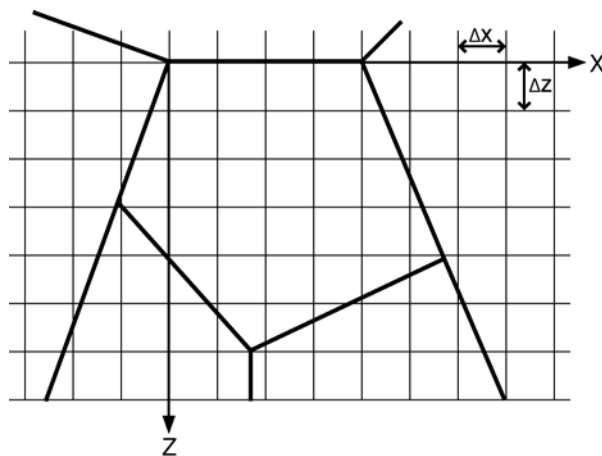


Figure 10-8: Internal Coordinate System



We assume the optical field and the device structure are uniform in the Y direction (perpendicular to the plane of the Figure 10-8). The rectangular grid covering the whole region is chosen according to the step sizes defined by `LONGIT.STEP` ( $\Delta Z$ ) and `TRANSV.STEP` ( $\Delta X$ ) parameters. The Helmholtz Equation in a 2D cartesian coordinate system (see Equation 10-35) describes field propagation through the region.

$$\frac{\partial^2 E(x, z)}{\partial z^2} + \frac{\partial^2 E(x, z)}{\partial x^2} + K^2 E(x, z) = 0 \quad 10-35$$

Provided that the field on the input plane  $Z=0$  is known, Equation 10-35 allows you to find the field on any subsequent plane  $Z=\Delta Z$ . The numerical solution of Equation 10-35 is based on the transformation of input complex field into superposition of plane waves. This superposition represents the direction cosine spectrum of plane waves, which is obtained by the FFT of the original field (see Equation 10-36).

$$F(K_x, z=0) = \int_{-\infty}^{\infty} E(x, z=0) \exp(-iK_x X) dx \quad 10-36$$

Each plane wave propagates at a certain angle to the Z axis. The phase accumulated by each plane wave component before reaching the plane  $Z=\Delta Z$  is given by:

$$F(K_x, z=\Delta Z) = F(K_x, z=0) \exp\left(i\sqrt{K^2 - K_x^2} \Delta Z\right) \quad 10-37$$

where  $K=2\pi n/\lambda$ ,  $n$  is the complex refractive index. We then can include diffraction and absorption upon propagation simultaneously. The direction cosine spectrum given by Equation 10-37 at  $Z=\Delta Z$  is transformed back into the spatial domain by applying an inverse FFT.

$$E(x, z=\Delta Z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(K_x, Z=\Delta Z) \exp(iK_x X) dK_x \quad 10-38$$

The field distribution at  $Z=\Delta Z$  is then found.

These steps are repeated until the field in the whole region is found. The field incident on each boundary segment and the field at each node within the region are obtained using bi-linear interpolation.

When the propagation through the same region is considered, the resulting field values at each node are added to the values saved upon the previous propagation. Since the phase information is retained in our propagation scheme, adding the field ensures the coherent effects are taken into account.

In ray tracing, the phase information is lost and irradiance values are added upon consecutive runs through the same region. This approach is only valid for incoherent sources.

The numerical scheme to solve Equation 10-35 requires the rectangular grid in the transverse direction (X) to cover an area significantly larger than the region of interest.

Zero-padding of the input field distribution is done automatically to specify the input field on the grid. Super-gaussian filters are used in the spatial domain to suppress possible reflections from numerical boundary.

Evanescient waves are included in the propagation scheme to avoid discontinuities in the spectral domain [132].

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## 11.1: Overview

LED is a simulator within the ATLAS framework that provides general capabilities for simulation of light emitting diode (LED) devices. When used with the BLAZE simulator, LED supports the simulation of DC and transient electrical and light emitting characteristics of LEDs. When used with the GIGA simulator, LED permits the self-consistent analysis of thermal effects on both electrical and optical emission characteristics. You can also use the LED simulator with the MIXEDMODE simulator to analyze the circuit level performance of LED devices.

The LED simulator supports simulation of both zincblende (e.g., AlGaAs/GaAs, InGaAsP/InP) as well as wurtzite (e.g., GaN/AlGaN/InGaN) material systems. It can also account polarization effects and the effects of strain on both emission spectra and piezoelectric polarization.

Extraction of electrical characteristics, such as DC, transient and small signal response, is augmented by the capability to extract light emitting characteristics, such as emission power versus current, emission spectra, emission wavelength, efficiency and output coupling (a function of emission angle).

The following sections describe how to specify LED devices, how to select and specify physical models including most importantly the optical models and how to extract the most pertinent device characteristics for device performance optimization.

## 11.2: Defining Light Emitting Devices (LEDs)

There are several ways to define an LED device structures in ATLAS/LED. A structure may be defined using the ATHENA process simulator. ATHENA simulates the "construction" of devices by simulating the process flow and the physical process steps. Second, you can define the device structure using the DEVEDIT device builder tool. The DEVEDIT tool allows you to specify the device structure in a simple visual point and click environment. Finally, you can define device structures using ATLAS framework commands (statements). For LED devices, the ATLAS command language approach is probably the most convenient since the device structures are somewhat simple due to their epitaxial nature.

In the following sections, we will concentrate on definition of the device structure using the ATLAS command syntax. We recommend that you read Chapter 2: "Getting Started with ATLAS" where we describe general features of the ATLAS simulator, commands and structure definition before you proceed. Chapter 3: "Physics" also provides insight into the details of the electrical and optical physical models used by ATLAS/LED. Chapter 5: "Blaze: Compound Material 2D Simulator" describes some general physics of simulation of compound semiconductors and heterojunctions.

Within the ATLAS command syntax, there are two approaches for defining device structures. The general purpose structure definition approach (see Chapter 2: "Getting Started with ATLAS", Section 2.6.3: "Using The Command Language To Define A Structure") requires more user-specification and requires that you describe the entire mesh. The auto-mesh approach (see Chapter 2: "Getting Started with ATLAS", Section 2.6.4: "Automatic Meshing (Auto-meshing) Using The Command Language") is simpler to use, requires less user-specification and is particularly well-suited to specification of epitaxial (especially multiple-quantum well or super-lattice) devices. It is for these reasons that we recommend the auto-mesh approach when defining LED devices .

In the following sections, we will focus mainly on this approach. We will point out important differences with the other methods: ATHENA, DEVEDIT or manual-mesh as these differences may arise.

The first command in any ATLAS input deck is the MESH command. When loading a structure from ATHENA, DEVEDIT or a previous ATLAS simulation, you should assign the INFILE parameter of the MESH statement to the name of the file containing the device structure. For example:

```
MESH INFILE=led.in
```

would cause the simulator to load a device structure from the file named led.in in the current working directory. When defining the device structure in the ATLAS auto-meshing syntax, the first statement should contain the AUTO parameter as shown in the following statement:

```
MESH AUTO
```

This will invoke the auto meshing capability.

---

**Note:** The INFILE parameter is not specified since this would indicate that the device was both being loaded as well as constructed in the ATLAS syntax and would therefore produce an ambiguity or conflict.

---

When using auto-meshing, you must only specify the mesh in the X direction using X.MESH statements. The mesh spacing in the Y direction is specified in the REGION statements as described later. The following example shows how you would specify an X mesh 1  $\mu\text{m}$  long with a uniform mesh spacing of 0.1  $\mu\text{m}$ .

```
X.MESH LOCATION=0      SPACING=100
X.MESH LOCATION=1000  SPACING=100
```

Using auto-meshing, you should next specify the device regions using REGION statements. The REGION statement can be used to specify the material types of individual "regions", as characterized by a spatial extent in the X and Y directions, and their composition, doping, strain and certain other characteristics describing how the region is to be modeled.

In the following example, we will describe a simple GaN/InGaN diode structure suitable for LED device simulation.

```
REGION MATERIAL=GaN THICKNESS=0.25 ACCEPTOR=1e19 BOTTOM NY=20
REGION MATERIAL=InGaN THICKNESS=0.003 DONOR=2e14 X.COMP=0.2 BOTTOM NY=20 LED
REGION MATERIAL=GaN THICKNESS=0.25 DONOR=1e18 BOTTOM NY=20
```

In this example, we describe a three layer LED. The top layer is composed of GaN (MATERIAL=GaN), it has a thickness of 0.25 microns (THICKNESS=0.25), and has an acceptor concentration of  $1e19$  (ACCEPTOR=1e19). The middle layer is composed of InGaN (MATERIAL=InGaN), it has a thickness of 0.003 microns (THICKNESS=0.003)  $\text{cm}^{-3}$ , and has an In composition fraction of 0.2 (X.COMP=0.2), and has a donor concentration of  $2e14$  (DONOR=2e14)  $\text{cm}^{-3}$ . The bottom layer is also composed of GaN (MATERIAL=GaN), it has a thickness of 0.25 microns (THICKNESS=0.25), and has a donor concentration of  $1e18$  (DONOR=1e18)  $\text{cm}^{-3}$ .

The BOTTOM parameter in each of the REGION statements specifies that each region resides directly below the preceding region. NY specifies the minimum number of Y grid lines used to resolve the region. The LED parameter in the second REGION statement specifies that region will be treated as a light emitting region during the post-processing stages of the simulation, and certain light emitting characteristics of that region will be extracted.

The final step in defining the LED using auto-meshing is to specify the electrodes. To specify electrodes, use the ELECTRODE statement. The following example specifies two electrodes extending all the way across the top and the bottom of the device.

```
ELECTRODE NUMBER=1 NAME=anode TOP
ELECTRODE NUMBER=2 NAME=cathode BOTTOM
```

Here, the NUMBER parameter is used to give the electrodes numerical tags they can be referred to in subsequent operations. Similarly, the NAME parameter is used for future references (see Chapter 18: "Statements", Section 18.40: "SOLVE").

## 11.3: Specifying Light Emitting Diode Models

### 11.3.1: Specifying Polarization and Piezoelectric Effects

In some material systems (such as the GaN/InGaN system), the built-in fields due to polarization and strain (piezoelectric effect) can play significant roles in the LED emission characteristics. ATLAS introduces these polarization fields as sheet charges at the top and bottom edges of regions. To include the effects of polarization on a region, you should specify the `POLARIZATION` parameter on the corresponding `REGION` statement.

This will only include spontaneous polarization. If you want to also include piezoelectric polarization, you can also specify the `CALC.STRAIN` parameter. If you specify `CALC.STRAIN`, the simulator will automatically calculate strain from the lattice mismatch and will calculate the piezoelectric polarization and apply it to the region. You can also specify the value of the `STRAIN` parameter, which specifies the axial strain in the region.

With `STRAIN` and `POLARIZATION` set, the simulator will apply a piezoelectric polarization calculated using the strain value assigned by the `STRAIN` parameter.

### 11.3.2: Choosing Radiative Models

The next step in simulating LED devices is the selection of appropriate radiative models. For LED devices, the most relevant radiative model is the model for spontaneous (radiative) recombination. For radiative recombination, ATLAS/LED offers several options. Chapter 3: "Physics", Section 3.9, "Optoelectronic Models" discusses these options in more detail.

First, is the general radiative model (see Chapter 3: "Physics", Equation 3-238). To enable this equation, specify `OPTR` in a `MODELS` statement associated with the active region(s) of the LED device (i.e., those regions with the `LED` parameter specified in the `REGION` statement). For our example, the LED discussed is shown in the following statement:

```
MODELS MATERIAL=InGaN OPTR
```

will enable the standard radiative recombination model. The disadvantage of using the standard model is that it provides no information about the spectral content of the LED light emission. In fact to properly specify emission intensity, you must specify the emission wavelength in the `SOLVE` statement for extraction of LED luminous intensity. To specify the emission wavelength for the general radiative recombination model given by Equation 3-238 in Chapter 3: "Physics", assign the value of the wavelength to the `L.WAVE` parameter as shown in the following `SOLVE` statement, where `L.WAVE` is in units of microns.

```
SOLVE L.WAVE=0.51
```

The `COPT` parameter of the `MATERIAL` statement assigns the rate constant for the general radiative recombination model. For example:

```
MATERIAL COPT=1.25e-10
```

`COPT` assigned a value of  $1.25 \times 10^{-10} \text{ cm}^3/\text{s}$  to the radiative rate constant. You can calibrate the value of this constant using the more physical radiative models discussed next. This calibration will be discussed at the end of this section.

Beyond the basic model just described, ATLAS/LED provides three more physical models for radiative rates. For zincblende materials, ATLAS provides a one band model [137] and a two band [136] model. For wurtzite materials, ATLAS/LED provides a three band model [149].

The one band zincblende model by Yan *et al.* [137] accounts for optical transitions between a single valence band and the conduction band. To activate this model, specify `YAN` in the `MODELS` statement. See Chapter 3: "Physics", Section 3.9.7: "Yan's and Li's Models for Gain and Radiative Recombination in Zincblende Materials" for a discussion of the Yan model.

The two band zincblende model by *Li et.al.* [136] accounts for optical transitions between light and heavy hole valence bands and the conduction band. To activate this model, specify `LI` in the `MODELS` statement. See Chapter 3: “Physics”, Section 3.9.7: “Yan's and Li's Models for Gain and Radiative Recombination in Zincblende Materials” for a discussion of the `LI` model.

The three band wurtzite model by Chuang and Chang [149], is based on k.p modeling and accounts for optical transitions between the conduction band and heavy and light hole and the crystal field split-off valence bands. See Chapter 3: “Physics”, Section 3.9.8: “Chuang's Three Band Model for Gain and Radiative Recombination in Wurtzite Materials” for a discussion of the Chuang model. To activate this model, specify `CHUANG` in the `MODELS` statement. For the on-going example, we chose the following `CHUANG` model (since `InGaN` is a wurtzite material).

```
MODEL MATERIAL=InGaN CHUANG
```

You should note that any of the `YAN`, `LI` or `CHUANG` model can be used to analyze spectral characteristics, such as emission wavelength and emission spectra.

You can also choose to analyze LED efficiency degradation due to competing recombination mechanisms by enabling these other non-radiative mechanisms. Particularly, you can enable Shockley-Read-Hall or Auger mechanisms. To activate these models, specify `SRH` and `AUGER` in the `MODELS` statement as follows:

```
MODELS SRH AUGER
```

Make sure you do not enable two radiative mechanisms for the same region, such as `OPTR` and one or more of the `YAN`, `LI` or `CHUANG` models. If you do, you may over account for the same radiative recombination. For more information about recombination models, see Chapter 3: “Physics” Section 3.6.3: “Carrier Generation-Recombination Models”.

As mentioned before, you can calibrate the radiative rate constant (using `COPT` of the `MATERIAL` statement) of the basic radiative recombination model (enabled by the `OPTR` parameter of the `MODELS` statement) to the more physical models (`YAN`, `LI` or `CHUANG`). To do this, first prepare a simulation with the activated physical model. In this simulation, save a structure file around the device operating conditions. You can then extract the proper value of `COPT` to use with the `OPTR` model by dividing the radiative recombination rate at any point by the product of the electron and hole concentrations.

### 11.3.3: Using k.p Band Parameter Models in Drift Diffusion

For the Chuang model, the band calculations performed in Equations 3-371, 3-372, 3-373 and 3-374 can be used in the drift diffusion part of the simulation. To use this capability, you should specify the `K.P` parameter on the `MODELS` statement as follows:

```
MODELS CHUANG K.P
```

## 11.4: Data Extraction

### 11.4.1: Extracting Luminous Intensity

When the LED parameter is specified on any REGION statement, the LUMINOUS intensity emitted by the LED device is automatically calculated and written to the log file. The file that this information is output to is specified by the OUTFILE parameter of the LOG statement. The following example outputs the log file to the file led.log.

```
LOG OUTFILE=led.log
```

You can then load led.log into TONYPLOT for post-processing visualization, where you can plot characteristics, such as luminous intensity versus current (see Figure 11-1).

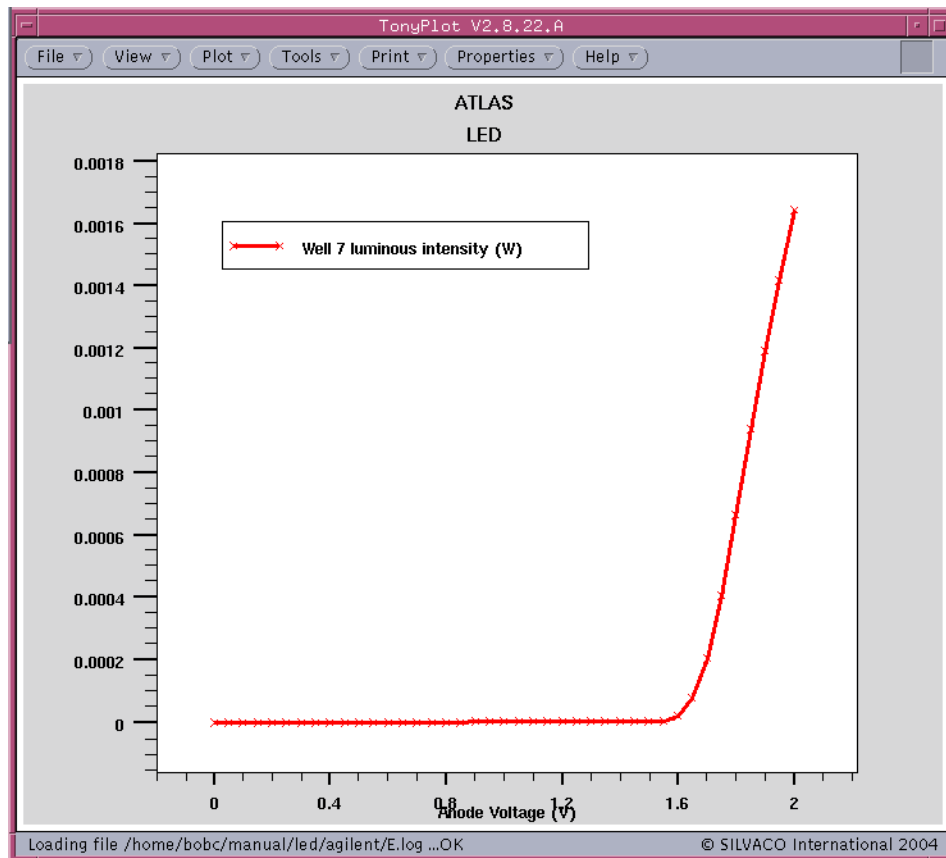


Figure 11-1: Example Luminous Intensity Plot

### 11.4.2: Extracting Emission Spectra

The LED simulator can save multiple spectrum files from the SOLVE statement. To save a spectrum file, specify the SPECTRUM parameter after each solution. SPECTRUM is assigned to the file name prefix. Each subsequent file will be written to a file named by SPECTRUM and appended with a version number starting at 0.

The LED simulator can output spectral intensity as a function of energy and wavelength integrated over all wells specified as LEDs. To output spectral intensity, specify the SPECTRUM parameter of the SAVE statement. SPECTRUM is assigned to the name of a file that the LED spectrum is written.



You must also specify either LMIN and LMAX or EMIN and EMAX. LMIN and LMAX specify the minimum and maximum values of wavelength in microns to be captured. EMIN and EMAX specify the minimum and maximum values of energy in eV to be captured. Specify either energy range or wavelength range but not both. To capture the number of discrete samples, specify the NSAMP parameter of the SAVE statement.

Figure 11-2 shows an example spectrum file plotted in TONYPLOT.

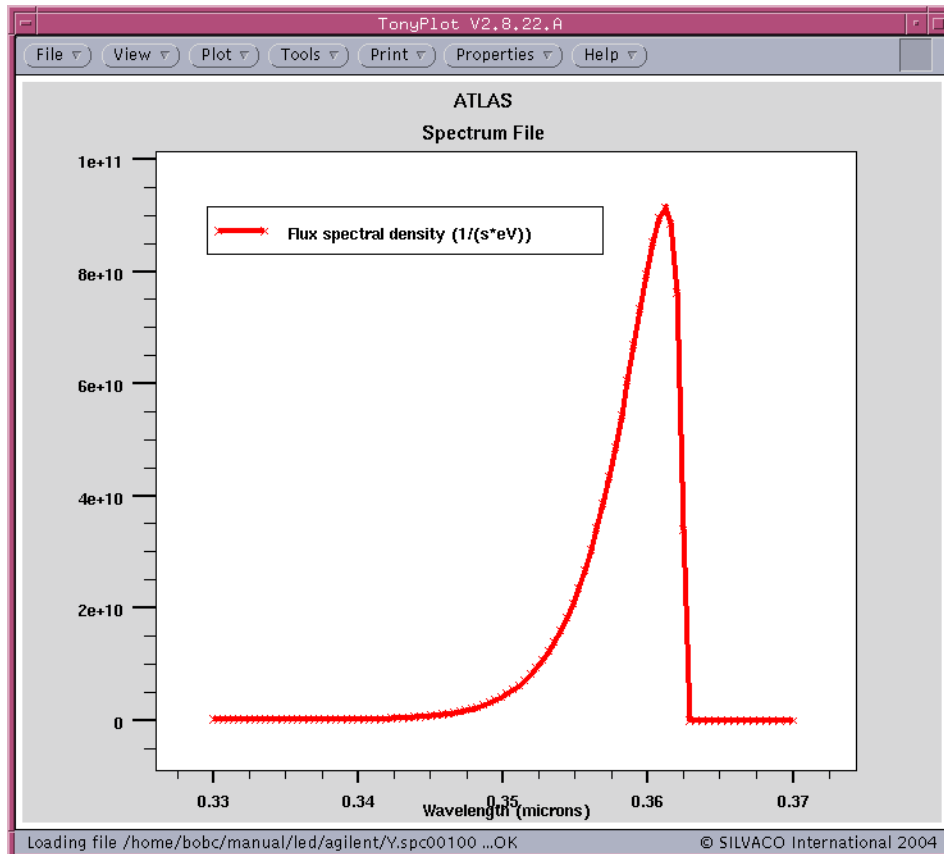


Figure 11-2: Plot of Spectrum File for LED

### 11.4.3: Extracting Emission Wavelength

In the LED simulator, you can use the probe to measure wavelength for LED devices. This will extract the wavelength from the peak of the spectral response over a specified range. To use this capability, specify WAVELENGTH in the PROBE statement. Use either EMIN and EMAX or LMIN and LMAX in the PROBE statement to specify the search range. EMIN and EMAX specify the range in terms of energy in eV, while LMIN and LMAX specify the range in terms of wavelength in microns.

## 11.5: Reverse Ray-Tracing

Reverse ray-tracing is a technique that allows you to obtain optical output characteristics of an active optoelectronic device based on material properties and device geometry. Ray-tracing is commonly used for modeling of passive optoelectronic components, such as photo-detectors.

Rays originating at the external light source are traced into the device and are absorbed to form electron/hole pairs, which are subsequently detected (using the ray-tracing method in LUMINOUS is described in Chapter 10: “Luminous: Optoelectronic Simulator”, Sections 10.2.1: “Ray Tracing in 2D” and 10.2.2: “Ray Tracing in 3D”). Unlike direct ray-tracing, the rays in the reverse method originate inside the active region and are traced until they exit the device. One or multiple origin points (user specified) for rays are considered, and interference effects for rays originating at the common source point can be taken into account. When you enable interference, you can analyze the spectral selectivity of the device structure by performing ray-tracing at multiple wavelengths.

You can assess light extraction from the device by using the `SAVE` statements (after biasing). Five different sets of parameters for reverse ray-tracing are used in the examples throughout the section to demonstrate the features available for modeling LEDs. The parameter sets are given in the order of increasing complexity of simulation. Computation times also vary. It takes approximately 200 times longer to run the last `SAVE` line compared to the first one.

Set the `ANGPOWER` parameter in the `SAVE` statement to start the reverse ray-tracing algorithm. The name of the output file containing the angular power density vs. output angle dependence is specified as a value for `ANGPOWER`. The information in the `angpower` file includes the angular power density for `TE-` and `TM-` polarized light, and total angular power density and total flux angular density vs. output angle.

---

**Note:** In TonyPlot, polar charts show the y-axis directed upward (in the opposite direction to the internal coordinate system used in ATLAS). Therefore, the plots will appear to be flipped around x-axis (top of the structure is at the bottom of the chart).

---

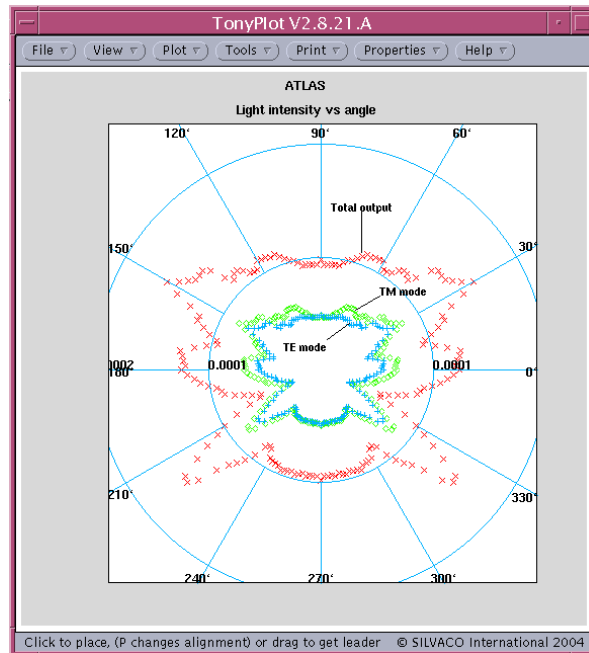
The `RAYPLOT` parameter specifies the name of the output file containing the information on each ray exiting the device. This file is only created when single origin for all rays is assumed. The information includes ray output angle, relative ray power (`TE-`, `TM-` polarization, and total), and initial internal angle at the origin (only if `INTERFERE` parameter is not specified).  $0^\circ$  angle corresponds to the rays in the X axis direction.  $90^\circ$  angle corresponds to the rays in the Y axis direction.

To start ray-tracing from one point of origin, specify the origin's coordinates for rays X and Y and the wavelength `L.WAVE`. It is important to choose the origin in the active region of the device. Rays are not traced if the radiative recombination is zero at the ray origin. All remaining parameters outlined below are optional and their default values are assumed if the parameters are not specified.

`REFLECTS` specifies a number of reflections to be traced for each ray originating at the point (X,Y) (similar to `REFLECTS` parameter in the `BEAM` statement). The default value (`REFLECTS=0`) provides for a quick estimate of the coupling efficiency. To obtain a more accurate result, use `REFLECTS>0`, especially if you specify `MIR.TOP` or `MIR.BOTTOM`. The choice of this parameter is based on a compromise between calculation time and accuracy. The maximum allowed value is `REFLECTS=10`. Number of reflections set to 3 or 4 is often a good choice. Example 1 produces a simple ray-tracing analysis of an LED. Figure 11-3 shows the resulting angular distribution of the emitted light intensity.

### Example 1

```
SAVE ANGPOWER=OPTOEX18ANG_1.LOG RAYPLOT=OPTOEX18RAY_1.LOG X=2.0 Y=1.01
L.WAVE=0.9 REFLECTS=4
```



**Figure 11-3: Emitted Light Intensity vs Angle for Example 1**

Specify the `DIPOLE` parameter to turn on a particular angular distribution of the internal radiating field that corresponds to a preferred in-plane orientation of dipoles. This orientation is often found in polymer based OLEDs and results in higher optical output coupling. The default setting (`DIPOLE=false`) corresponds to isotropic distribution of emitting dipoles and spherically symmetric radiation pattern.

`MIR.TOP` specifies that the top surface of the device be treated as an ideal mirror.

`MIR.BOTTOM` specifies that the bottom surface of the device be treated as an ideal mirror.

`SIDE` specifies that the rays reaching the sides of the device terminate there and do not contribute to the total light output. This is often a good assumption for realistic LEDs as these rays tend to be either absorbed internally or blocked by the casing of the device.

`TEMPER` is the temperature (needed for using appropriate refractive indexes of the materials). The default setting of 300 K will be used if `TEMPER` is not specified.

`POLAR` specifies polarization of the emitted photons in degrees (linearly polarized light is assumed). Parallel (TM-mode, `POLAR=0.0`) and perpendicular (TE-mode, `POLAR=90.0`) polarizations result in significantly different output coupling values.

You should use the default value (`POLAR=45.0`) if there is no preferred direction of polarization of emitted photons (unpolarized light emission).

`MIN.POWER` specifies the minimum relative power of a ray (similar to `MIN.POWER` parameter in the `BEAM` statement). The ray is not traced after its power falls below `MIN.POWER` value. This is useful for limiting the number of rays traced. The default value is `MIN.POWER=1e-4`.

`NUMRAYS` specifies the number of rays starting from the origin. The default is 180. The acceptable range 36-3600.

Example 2 shows how some of the parameters described above are used for modeling of a realistic LED. The angular distribution of light power in Figure 11-4 exhibits almost a Lambertian pattern for this simple planar LED geometry. Note that optical coupling coefficient produced in this calculation reflects a 2D nature of the example (the light origin is not a point but rather an infinite line in  $z$ -direction).

Simultaneously, you can calculate the optical coupling efficiency for an axially symmetric 3D device (Normally, this is the value to be compared with experimental results). To do this, specify the COUPLING3D parameter (while SIDE is set). For this calculation, the light source is assumed to be a point located on the axis of symmetry.

## Example 2

```
SAVE ANGPOWER=OPTOEX18ANG_2.LOG RAYPLOT=OPTOEX18RAY_2.LOG X=2.0 Y=1.01
L.WAVE=0.9 SIDE MIR.BOTTOM NUMRAYS=360 REFLECTS=4
```

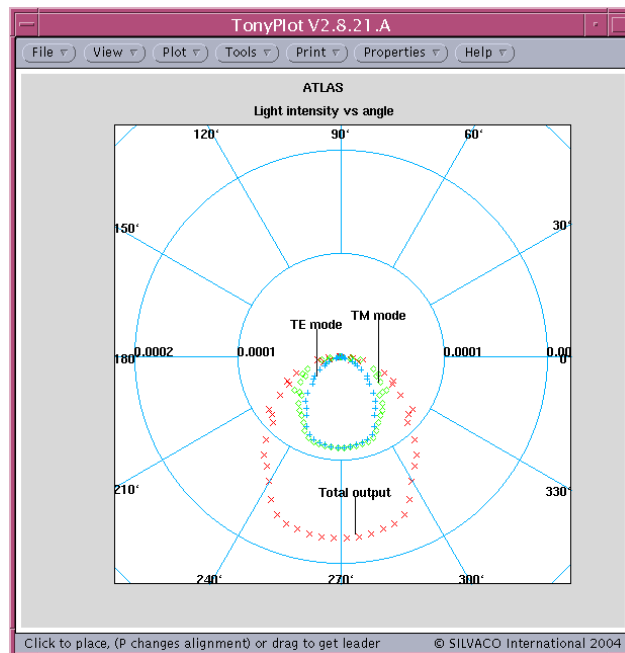


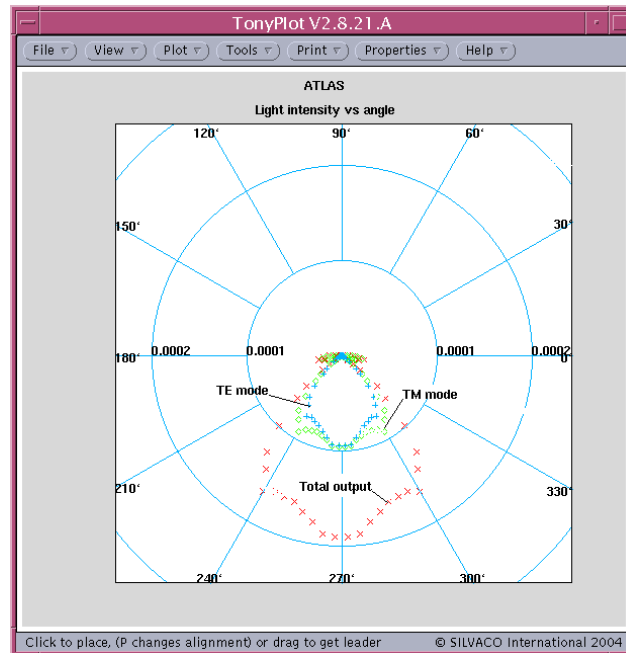
Figure 11-4: Emitted Light Intensity vs Angle for Example 2

The rays are assumed to be incoherent by default. This is a good approximation if the thickness of the active layer of the device is on the order of a wavelength/index. For layer thicknesses, smaller than the wavelength coherent effects might be important. When INTERFERE is set, the rays originating at the common source point are taken to be 100% coherent. In this case, the phase information upon propagation is preserved. Phase change upon reflection is also considered. Thus, interference of rays exiting the device at the same angle is taken into account. In this case, the internal angle information is not written to the output rayfile.

Example 3 takes into account interference. Figure 11-5 shows the result. You can take absorption of rays into account by setting the ABSORB parameter. The absorption is assumed to be specified for each material by the imaginary part of the refractive index. Carrier density dependent absorption and photon-recycling are not considered at this point.

### Example 3

```
SAVE ANGPOWER=OPTOEX18ANG_3.LOG RAYPLOT=OPTOEX18RAY_3.LOG X=2.0 Y=1.01
L.WAVE=0.9 INTERFERE SIDE MIR.BOTTOM REFLECTS=4
```



**Figure 11-5: Emitted Light Intensity vs Angle for Example 3**

Although ray-tracing from one point of origin can give a reasonable estimate of optical output coupling and angular distribution of light power, it is often desirable to consider multiple points within the active layer of the device to obtain more accurate results. To set multiple origin points, use the following parameters.

- XMIN, XMAX, YMIN, and YMAX define a rectangular area containing all origin points.
- XNUM and YNUM specify the number of points along x and y axes within the rectangular area. If XNUM=1, the x-coordinate of all origin points will be set to XMIN so that the points are chosen along the line X=XMIN. Similarly, you can choose points along the specific y-line.

Ray-tracing from multiple origins is realized by repeating single origin algorithm for each point and by adding up the normalized angular power density values thus obtained. The luminous power assigned to each source (origin) is proportional to the radiative recombination at that point. The luminous power of all sources adds up to the value obtained by integration of radiative recombination over the entire device. Rays originating at different source points are completely incoherent (even when INTERFERE is set), which is consistent with the spontaneous character of the radiation produced by an LED. The rayplot file is not written for multiple origins (even if RAYPLOT parameter is set). Example 4 shows how multiple origin simulation can be done. Figure 11-6 shows angular distribution of light obtained in this case.

### Example 4

```
SAVE ANGPOWER=OPTOEX18ANG_4.LOG XMIN=1.0 XMAX=3.0 XNUM=3 YMIN=1.01 YMAX=1.09
YNUM=9 INTERFERE SIDE L.WAVE=0.9 MIR.BOTTOM REFLECTS=4
```

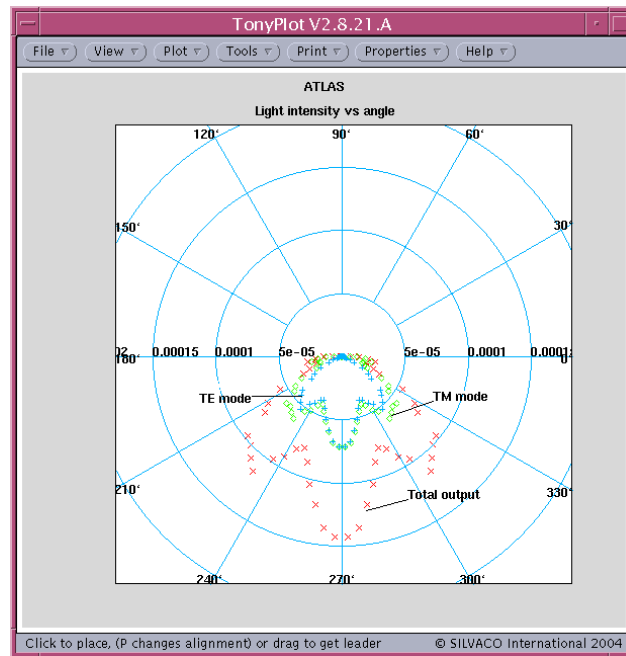


Figure 11-6: Emitted Light Intensity vs Angle for Example 4

You can also take spectral selectivity of optical output coupling for LEDs into account. Reverse ray-tracing at multiple wavelengths is considered if the SPECTRUM parameter specifies a filename for spectral selectivity output while the ANGPOWER parameter is set.

EMIN and EMAX, or LMIN and LMAX specify the energy or wavelength range respectively.

NSAMP specifies the number of spectral components to be considered. We suggest that you specify the SPECTRUM file only when INTERFERE is set. Otherwise, a warning will be issued during ray-tracing. When ANGPOWER and SPECTRUM are set in the SAVE statement, the resulting optical output coupling is averaged over the entire energy (wavelength) range from EMIN to EMAX (from LMIN to LMAX). The same applies to the quantities in the output angular distribution file. The spectrum file only shows how output coupling changes with wavelength. Currently, the shape of the gain curve is not taken into account (flat gain).

Example 5 shows how to use multiple spectral components. Figure 11-7 shows that the results obtained after averaging over spectral components and multiple origin points while taking interference into account are similar to the single point source model, where interference and multiple spectral content are ignored (Example 2). This demonstrates the applicability of a simpler model in this case.

### Example 5

```
SAVE ANGPOWER=OPTOEX18ANG_5.LOG SPECTRUM=OPTOEX18SP_5.LOG XMIN=1.0 XMAX=3.0
XNUM=3 YMIN=1.01 YMAX=1.09 YNUM=5 INTERFERE SIDE LMIN=0.86 LMAX=0.94 NSAMP=15
MIR.BOTTOM REFLECTS=4
```

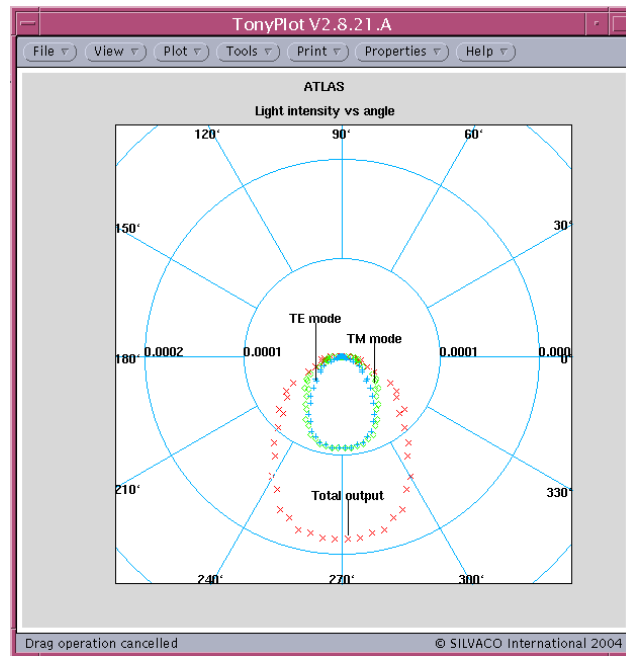


Figure 11-7: Emitted Light Intensity vs Angle for Parameter Set 5

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## 12.1: Overview

MIXEDMODE is a circuit simulator that can include elements simulated using device simulation, as well as compact circuit models. It combines different levels of abstraction to simulate relatively small circuits where compact models for single devices are not available or sufficiently accurate. MIXEDMODE also allows you to also do multi-device simulations. MIXEDMODE uses advanced numerical algorithms that are efficient and robust for DC, transient, small signal AC and small signal network analysis.

MIXEDMODE is typically used to simulate circuits that contain semiconductor devices for accurate compact models don't exist or circuits, where devices that play a critical role must be modeled very accurately. Applications of MIXEDMODE include: power circuits which may include diodes, power transistors, IGBTs, and GTOs, optoelectronic circuits, circuits subject to single event upset, thin film transistor circuits, high-frequency circuits, precision analog circuits, and high performance digital circuits.

MIXEDMODE circuits can include up to 100 nodes, 300 elements, and up to ten numerical simulated ATLAS devices. These limits are reasonable for most applications, but they can be increased in custom versions on request to Silvaco. The circuit elements that are supported include dependent and independent voltage and current sources, as well as resistors, capacitors, inductors, coupled inductors, MOSFETs, BJTs, diodes, and switches. Commonly used SPICE compact models are available, and the SPICE input language is used for circuit specification.

This chapter describes circuit simulation capabilities rather than device simulation capabilities. The first part of the chapter contains introductory and background information. Then, it describes presents and explains MIXEDMODE syntax. This is followed by some sample input decks. The final sections contain a statement reference and a detailed description of the provided electrical compact models for diodes, BJTs, and MOSFETs.

### 12.1.1: Background

Circuit simulators such as SPICE [97] solve systems of equations that describe the behavior of electrical circuits. The devices that are of interest to circuit designers are normally well characterized. Compact or circuit models are analytic formulae that approximate measured terminal characteristics. Advanced compact models provide high accuracy with minimum computational complexity. Device modeling, device characterization and parameter extraction are concerned with the development and use of accurate and efficient compact models.

Physically based device simulation solves systems of equations that describe the physics of device operation. This approach provides predictive capabilities, and information about the conditions inside a device, but it can require significant amounts of CPU time. Information is usually transferred from device simulation to circuit simulation as follows: Electrical characteristics are calculated using a physically-based device simulator. These calculated electrical characteristics are then used as input by a device modeling and parameter extraction package such as UTMOST [98]. The extracted parameters are used to characterize a compact model used by the circuit simulator.

This approach is adequate for many purposes, but has limitations. It requires that satisfactory compact models already exist. The use of compact models always introduces some error, and models that are adequate for digital circuit simulation may be inadequate for other applications. Applications and devices for which compact modeling is not always satisfactory includes: Precision low power, high power, high frequency circuit simulation, SOI, IGBT, GTO, TFT, and optoelectronic devices.

## 12.1.2: Advantages of MixedMode Simulation

The limitations of compact models can be overcome by using physically-based device simulation to predict the behavior of some of the devices contained in a circuit. The rest of the circuit is modeled using conventional circuit simulation techniques. This approach is referred to as mixed-mode simulation, since some circuit elements are described by compact models, and some by physically-based numerical models.

MIXEDMODE simulation provides several worthwhile advantages. No compact model need be specified for a numerical physically-based device. The approximation errors introduced by compact models can be avoided particularly for large signal transient performance. You can also examine the internal device conditions within a numerical physically-based device at any point during the circuit simulation. But the cost is increased CPU time over SPICE as CPU time is comparable to a device simulation excluding the external circuit nodes. MIXEDMODE simulation normally uses numerical simulated devices typically only for critical devices. Non-critical devices are modeled using compact models.

## 12.2: Using MixedMode

Input file specification for MIXEDMODE is different in many respects to the rest of ATLAS. But if you're familiar with SPICE and ATLAS syntax, you should have little difficulty understanding how these two syntax styles are joined in MIXEDMODE.

Each input file is split in two parts. The first part is SPICE-like and describes the circuit netlist and analysis. The second part is ATLAS-like and describes the device simulation model parameters. These two sections of an input file are separated as described in the next section.

The circuit description includes the circuit topology (called the netlist) and the electrical models and parameters of the circuit components. The simulation conditions specify the types of analysis to be performed. These items are described using syntax based on SPICE.

The ATLAS device descriptions provide information about device geometry, doping distribution, meshes. Device descriptions can be prepared using the built-in ATLAS syntax, the ATHENA process simulator, or the DEVEDIT structure specification and meshing tool. You can also read-in previously calculated device solutions. The device data is read-in from standard structure format files.

When a simulation has finished, the following information is available:

- I-V data (voltages in all circuit nodes and currents in all circuit branches).
- Internal distributions of solution variables (such as electron, hole, and potential distributions) within the numerical devices.

The results of previous runs of MIXEDMODE can be used as initial guesses for future simulations. This is particularly helpful when multiple simulations must be performed from the same starting point.

The accessing and running of examples for ATLAS are documented in the DECKBUILD chapter of the VWF INTERACTIVE TOOLS USER'S MANUAL. We recommend that you run at least one MIXEDMODE example provided on the distribution tape before trying their own simulations.

### 12.2.1: General Syntax Rules

The SPICE-like part of any MIXEDMODE input file starts with the `.BEGIN` parameter. The SPICE-like part of the input file ends with `.END`. All parameters related to the device simulation models appear after the `.END` statement.

The first non-comment statement after initializing ATLAS (`go atlas`) has to be `.BEGIN`. The order of the following netlist and control statements is arbitrary, but the last SPICE-like statement has to be `.END`.

Unlike the rest of ATLAS, for SPICE-like statements the exact command has to be used, unique abbreviations are not accepted. Statements are not case sensitive.

There has to be at least one numerical ATLAS device ("A" device) within the netlist.

Comment characters are `#` and `$`, but not `*`.

All ATLAS statements specifying the parameters for the numerical device simulation have to be specified after `.END`

After all ATLAS statements the simulation has to be explicitly terminated (`quit`, `go <simulator>`)

These rules do not apply to the `SET` statement for parameterization of the input file, since it is interpreted by DECKBUILD only.

EXTRACT statements are also an exception similar to SET. Since MIXEDMODE input files are parsed completely before execution (see Section 12.2.4: "Recommendations" for more information), extractions can only be done after completion of the simulation. To extract results from a MIXEDMODE simulation, EXTRACT should be specified after re-initialization of ATLAS (`go atlas`).

## 12.2.2: Circuit and Analysis Specification

The SPICE-like MIXEDMODE statements can be divided into three categories:

- **Element Statements:** These statements define the circuit netlist.
- **Simulation Control Statements:** These statements specify the analysis to be performed.
- **Special Statements:** These statements typically related to numerics and output (first character being a dot “.”).

The specification of the circuit and analysis part has to be bracketed by a .BEGIN and an .END statements (i.e., all MIXEDMODE statements before .BEGIN or after .END will be ignored or regarded as an error). The order is between .BEGIN and .END is arbitrary.

### Netlist Statements

Each device in the circuit is described by an element statement. The element statement contains the element name, the circuit nodes to which the element is connected and the values of the element parameters. The first letter of an element name specifies the type of element to be simulated. For example, a resistor name must begin with the letter, R, and can contain one or more characters. This means that R1, RSE, ROUT, and R3AC2ZY are all valid resistor names. Some elements, such as diodes and transistors, must always refer to a model. A set of elements can refer to the same model. For some elements, such as resistors and capacitors, model referencing is optional. Each element type has its own set of parameters. For example, a resistor statement can specify a resistance value after the optional model name. The bipolar transistor statement (Q) can specify an area parameter. All parameters have corresponding default values. Independent voltage and current sources have different specifications for transient, DC, and AC phases of simulation. Transient specifications use the keywords: EXP, PULSE, GAUSS, SFFM, SIN, and TABLE. AC parameters start with the keyword, AC.

Elements to be simulated numerically are defined as “A” devices (ATLAS devices). At least one ATLAS device in a circuit is mandatory.

MIXEDMODE supports the use of the following circuit elements:

- Numerically simulated ATLAS devices (“A” devices)
- User-defined two-terminal elements (“B” devices)
- Capacitors (“C” devices)
- Diodes (“D” devices)
- Voltage controlled voltage source (“E” devices)
- Current controlled current source (“F” devices)
- Voltage controlled current source (“G” devices)
- Current controlled voltage source (“H” devices)
- Independent current sources (“I” devices, may be time dependent)
- JFETs (“J” devices)
- Coupled (mutual) inductors (“K” devices)
- Inductors (“L” devices)
- MOSFETs (“M” devices)
- Optical sources (“O” devices)
- Bipolar junction transistors (“Q” devices)
- Resistors (“R” devices, may be time dependent)
- Lossless transmission lines (“T” devices)
- Independent voltage sources (“V” devices, may be time dependent)

- MESFETs (“Z” devices)

The physical models for linear elements (resistors, capacitors, sources, and so on) are described Section 12.4.1: “Circuit Element Statements”. The models for diodes: BJTs, JFETs, MESFETs and MOSFETs are described in Section 12.4.2: “Control and Analysis Statements”, but more extensive documentation can be found in the SMARTSPICE/UTMOST MODELING MANUALS Volumes 1, 2, and 3.

A node is a point in the circuit where two or more elements are connected. A node can be described either in terms of a node name or as a node number. The node names and numbers are arbitrary with the exception of the ground node. The ground node is set either by specifying “0” as the node number or using the name GND. All voltages at the nodes are calculated with respect to the voltage at the ground node.

**Example**

The netlist for the circuit shown in Figure 12-1 is represented by the following MIXEDMODE input deck fragment.

```
# independent voltage source, 0.1V, connected to node 0 (GND) and 1:
V0    1          0          0.1
# 1kOhm resistor, connected to node 1 and 2
R1    1          2          1K
# ATLAS device, connected to node 2 (anode) and 0 (cathode),
# current scaled by 5e7, mesh from file dio.str
ADIO  2=anode   0=cathode  WIDTH=5e7  INFILE=dio.str
```

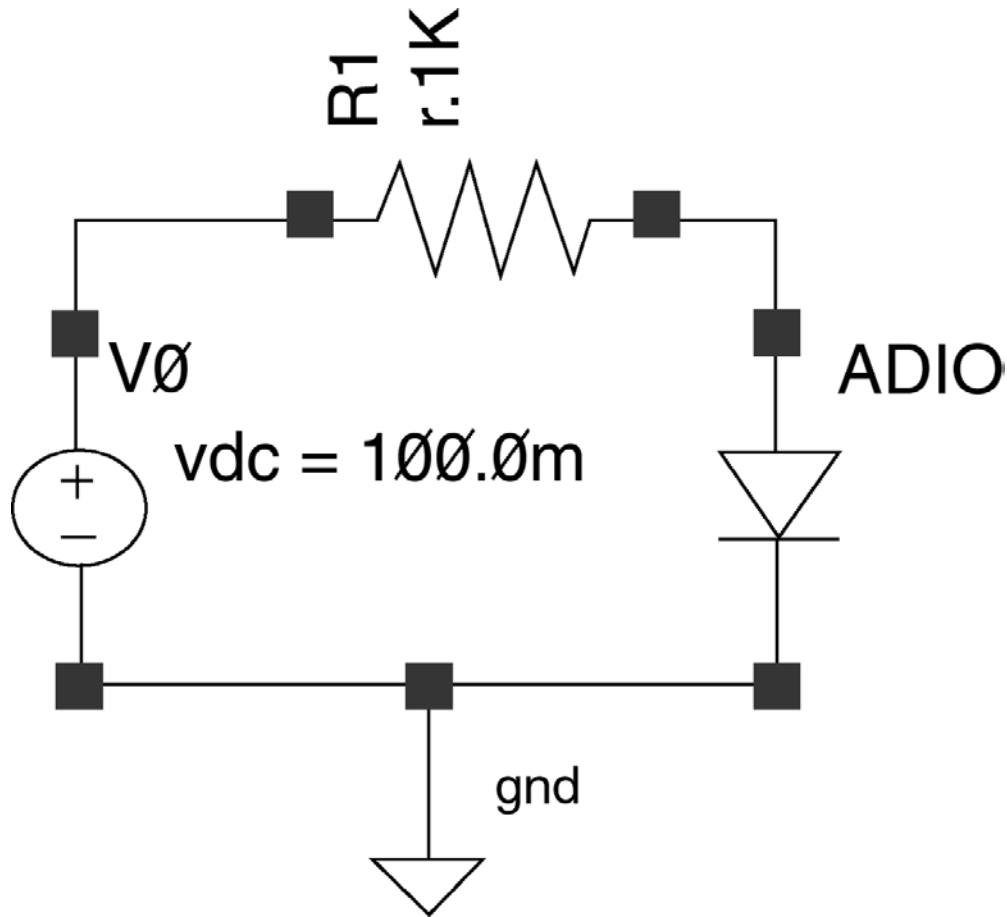


Figure 12-1: Schematic of Primitive Example Circuit

### Control Statements

Control statements are used to specify the analysis to be performed in MIXEDMODE. These take the place of the SOLVE statements in a regular ATLAS input file. At least one of these statements must appear in each MIXEDMODE input file. These statements are:

- **.DC:** steady state analysis including loops
- **.TRAN:** transient analysis
- **.AC:** small signal AC analysis
- **.NET:** small signal parameter extraction (e.g., s-parameters)

For more information about these statements, see Section 12.4.2: “Control and Analysis Statements”.

## Special statements

Other statements beginning with a dot “.” specify special parameters for the circuit simulation. These include numerical options, file input and output, and device parameter output. These statements are listed below.

- compact device models (.MODEL)
- the output files (.LOG, .SAVE)
- initial conditions settings (.NODESET, .IC)
- initial conditions from a file (.LOAD)
- numerics (.NUMERIC, .OPTIONS)
- device parameter output (.PRINT)
- miscellaneous (.OPTIONS)

Full descriptions of each statement and associated parameters are found in Section 12.4.2: “Control and Analysis Statements”.

### 12.2.3: Device Simulation Syntax

The second part of a MIXEDMODE command file (after .END) is used to define physical models, material parameters, and numerical methods for ATLAS devices referenced in the “A”-element statements. The following statements may appear in this part of the command file: BEAM, CONTACT, DEFECT, IMPACT, INTERFACE, INTTRAP, MATERIAL, MOBILITY, METHOD, MODELS, OUTPUT, PROBE, TRAP, and THERMCONTACT.

You always need to include an indicator to the circuit element name in each device simulation statement even if there is only one A-device in the circuit. All statements specifying the device properties and models are just supplemented by the DEVICE=name parameter, where name is the circuit element in the netlist, and name will always begin with the letter “A”. This makes it possible to define different material properties and model settings for different devices within the circuit.

We recommended that you specify the REGION parameter referring to only one region in IMPACT, MATERIAL, and MODELS statements. If the device consists of more than one region, several statements with the same device parameters and different region parameters are recommended.

For example to specify the bipolar set of models to a device the syntax used might be:

```
MODEL DEVICE=AGTO REGION=2 BIPOLAR PRINT
```

### 12.2.4: Recommendations

#### Input Parsing

In regular ATLAS (non-MIXEDMODE) simulations, the input is interpreted line by line and each statement is executed immediately. This is very useful and nicely supported by DECKBUILD for the interactive development of the input. Circuit simulations, however, require the complete input before any simulation can be performed. Consequently, the following occur:

- The complete input is read and parsed before any simulation is initiated.
- An explicit termination of a simulation is required (quit).
- All post processing (extraction and plotting) has to be done after re-initializing ATLAS again.

No simulation is started until either a QUIT statement or a GO statement is seen in the input file. Post-processing can be done by restarting ATLAS.

## Scale and Suffixes

In the MIXEDMODE part of the input, numerical values of parameters are represented in standard floating-point notation. The scale suffix may be followed by a unit suffix (e.g., A for Ampere, V for Volt, and so on). Using a unit suffix can increase the clarity of a command file. The unit suffix is ignored by the program. The scale suffixes are shown in Table 12-1.

| Factor     | Name   | Suffix |
|------------|--------|--------|
| $10^{-15}$ | femto- | F      |
| $10^{-12}$ | pico-  | P      |
| $10^{-9}$  | nano-  | N      |
| $10^{-6}$  | micro- | U      |
| $10^{-3}$  | milli- | M      |
| $10^3$     | kilo-  | K      |
| $10^6$     | mega-  | MG     |
| $10^9$     | giga-  | G      |
| $10^{12}$  | tera-  | T      |

## Numerics

MIXEDMODE solves circuit and device equations simultaneously using fully coupled algorithms. This provides better convergence and requires less CPU time than alternative approaches. The number of circuit variables is often small in comparison with the number of device variables. In this case the CPU time required for simulation performed using MIXEDMODE does not increase drastically compared to the sum of the simulation times required for the individual numerical physically based devices.

MIXEDMODE uses the Newton algorithm for each bias point during steady-state analysis and for each time step during transient analysis. Different variants of the Newton algorithm are used depending on the circumstances [95, 96]. The full Newton method [.OPTIONS FULLN] and a modified two-level Newton method [.OPTIONS M2LN] are available for steady-state simulation. The full Newton method provides rapid convergence when a good initial guess is available. The modified two-level Newton algorithm is less sensitive to the initial guess. For transient simulation a good initial guess always exists. The full Newton method therefore works very well, and is therefore always used for transient simulation.

When using MIXEDMODE3D, it is recommended that you specify the DIRECT or GMRES solver in the ATLAS part of the MIXEDMODE input deck on the METHOD statement. Also, use the NOPROJ parameter in the .OPTIONS statement in the MIXEDMODE of the input deck.

## Multi-Device Structure Representation

If more than one ATLAS device is defined in a MIXEDMODE simulation, the structures are merged together internally. The output solution file is a single file which contains both structures. The first structure referenced will be on top, all other structures will be attached below.

### Example

A diode and a bipolar transistor are specified as numerical devices with the following element statements:

```
ABJT 1=BASE 2=EMITTER 4=COLLECTOR WIDTH=1E4 INFILE=bjt.str
```



```
ADIO 3=ANODE 4=CATHODE WIDTH=1.5E5 INFILE=dio.str
```

After outputting the solution with:

```
.SAVE MASTER=mas
```

The solution file for the first DC-point, `mas_dc_1`, contains both structures with the second ATLAS device (diode) shifted downwards (see Figure 12-2).

This coordinate shift has to be accounted for eventually when extracting position dependent solution quantities or when defining spatially dependent properties with the C-INTERPRETER (See Appendix A: “C-Interpreter Functions” for more information).

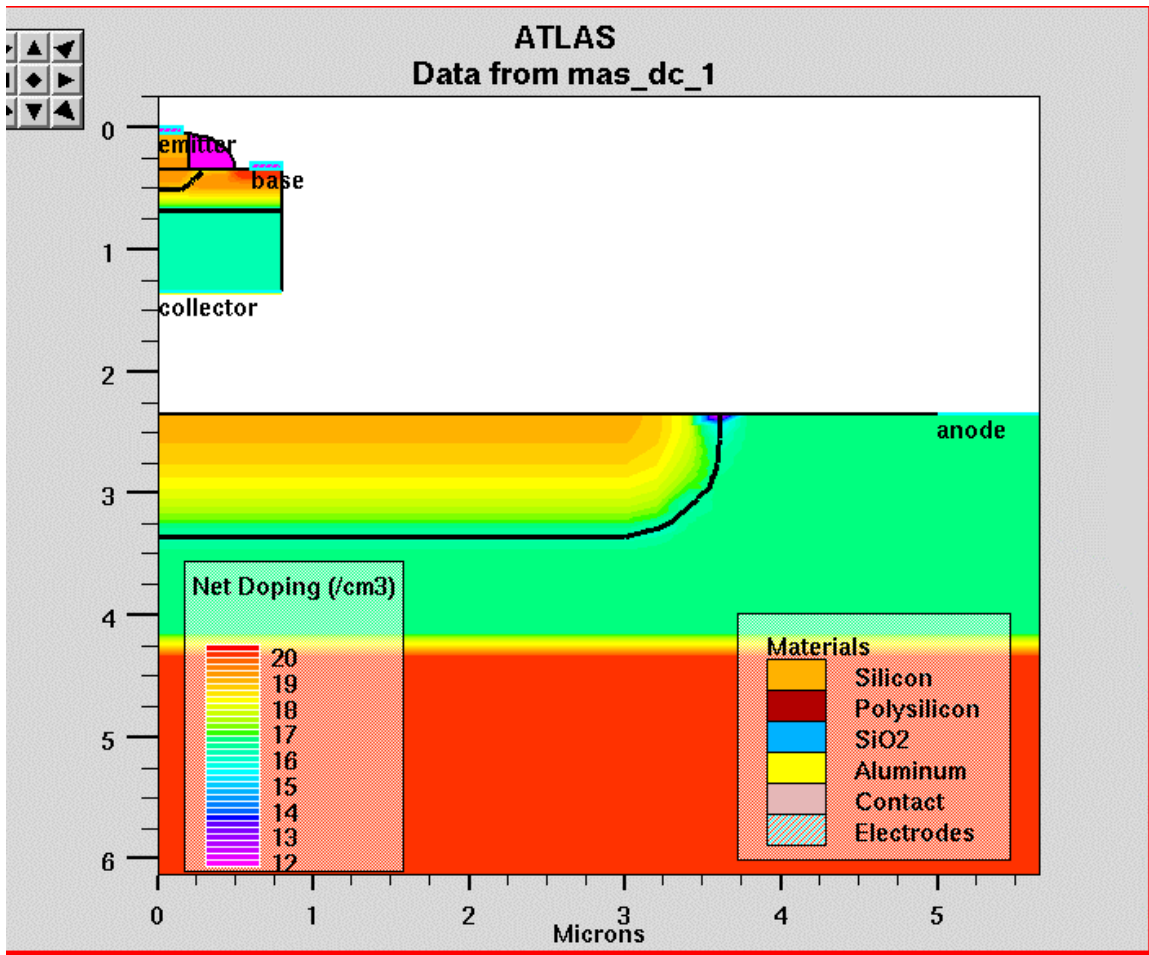


Figure 12-2: Display of a MixedMode solution with two Numerical Devices

## Extraction of Results

By default, `EXTRACT` reads its data from the currently opened log-file when executed along with `ATLAS`. Since the extraction of `MIXEDMODE` log-files require a re-initialization of `ATLAS` (see “Input Parsing” section on page 11-7), `EXTRACT` has to be initialized explicitly with the correct name of the `MIXEDMODE` log file. To extract voltages at specific nodes, use the syntax `vcct.node."circuit node"`. To extract circuit elements, use `icct.node."circuit element"`.

### Example

Specify the log file:

```
.LOG OUTFILE=hallo
```

Subsequent extraction from the transient log-file is done with:

```
go atlas
extract init inf="hallo_tr.log"
extract name="t0" x.val from curve(time,icct.node."Adio_anode") \
    where y.val=0
```

It extracts the time, `t0`, when the transient of the current from the anode electrode of the `adio` device in the circuit crosses zero. For more details for the `EXTRACT` syntax refer to the `VWF INTERACTIVE TOOLS USER'S MANUAL`.

## Using MixedMode inside the VWF Automation Tools

Like all other Silvaco products, `MIXEDMODE` is fully integrated into the `VWF` framework and can be used for automated experiments. There are, however, some factors to take into account.

One factor is that the **auto-interface** feature doesn't work with `MIXEDMODE`. All structures have to be explicitly saved in unique files previous to the `MIXEDMODE` runs and referred to in the `A-` element statements. Another factor is that splits within `MIXEDMODE` runs are not possible. To overcome this problem, use the `SET` statement to define a variable in a process simulator or in the “dummy” internal run. This variable is used to parameterize the input file.

### Example

Capacitance as an independent split variable in a `VWF` experiment.

```
go internal
# define the independent split variable in a re-entrant simulator:
set cap=5e-9

go atlas

.BEGIN
# use the variable as parameter in MixedMode:
C1    2    3    $cap
```

Another factor is that the automation tools only store files opened by the normal `ATLAS LOG` statement in the `VWF` database, but ignore those defined by `.LOG`. To overcome this, re-initialize `ATLAS` and open the relevant log file of the previous `MIXEDMODE` run with `.log` as the append option (so that the file is not reset).

**Example**

MIXEDMODE log-file definition.

```
.LOG OUTFILE=hallo
```

Re-opening the second DC-log file and the transient log file to get them stored in the VWF database.

```
go atlas
```

```
log outfile=hallo_dc_2.log append
```

```
log outfile=hallo_tr.log append
```

**Initial Settings**

Initial convergence is critically dependent on the initial settings of the node voltages (i.e., .IC and .NODESET). There should not be any problem starting from the zero bias case. Just like starting from a preceding MIXEDMODE solution is simple, since the complete solution of the circuit and the ATLAS devices is directly available (i.e., .LOAD and .SAVE). But when loading solutions for the numerical devices from ATLAS, using .OPTIONS LOADSOLUTIONS, sometimes precise matching of the initial circuit condition is required. In this case it is practical to extract the relevant properties in the preceding ATLAS run and use them to parameterize the MIXEDMODE input.

In the following example, the voltages and current of an ATLAS solution is extracted, and the results are used for the initial definition of the circuit.

The end of the first part is the stand-alone ATLAS simulation:

```
# extract the final voltage drop on the anode:
extract name="Von" max(vint."anode")

# extract the gate current:
extract name="I_gate" y.val from curve(vint."anode",i."gate") \
where x.val = $"Von"
extract name="V_gate" y.val from curve(vint."anode",vint."gate") \
where x.val = $"Von"

# now the MIXEDMODE part

go atlas

.BEGIN

# define the gate current source, use extracted value as parameter
I1 0 7 $"I_gate"

#

# use extracted gate bias and other expressions to calculate
# the node settings:
set Rg1 = 10.5
set v7= $V_gate + $I_gate * $Rg1

.NODESET V(1)=2000 V(2)=$"Von" V(3)=$"V_gate" V(4)=$"V_gate" V(5)=-25 \
V(6)=-15 V(7)=$"v7"
```

## 12.3: A Sample Command File

A sample MIXEDMODE command file is shown below. This file is used to simulate the reverse recovery of a power diode. Several MIXEDMODE examples are provided with the product which can be accessed using DECKBUILD.

```
1. go atlas
2. .BEGIN
3. V1 1 0 1000.
4. R1 1 2 1m
5. L1 2 3 2nH
6. R2 4 0 1MG EXP 1MG 1E-3 0. 20NS 10 200
7. IL 0 4 300
8. ADIODE 3=cathode 4=anode WIDTH=5.E7 INFILE=pd.str
9. .NUMERIC LTE=0.3 TOLTR=1.E-5 VCHANGE=10.
10. .OPTIONS PRINT RELPOT WRITE=10
11. $
12. .LOAD INFILE=pdsave
13. .LOG OUTFILE=pd
14. .SAVE MASTER=pd
15. $
16. .TRAN 0.1NS 2US
17. $
18. .END
19. $
20. MODELS    DEVICE=ADIODE REG=1 CONMOB FLDMOB CONSRH AUGER BGN
21. MATERIAL DEVICE=ADIODE REG=1 TAUN0=5E-6 TAUP=2E-6
22. IMPACT    DEVICE=ADIODE REG=1 SELB
23. $
24. METHOD     CLIM.DD=1.E8 DVMAX=1.E6
25. $
26. go atlas
27. tonyplot pd_tr.log
```

### Description

**Line 1:** All ATLAS input files should begin with `go atlas`

**Line 2:** The `.BEGIN` and `.END` statements indicate the beginning and end of the circuit simulation syntax. These commands are similar to those used in SPICE.

**Lines 3-7:** Circuit components, topology, and analysis are defined within. Generally, the circuit component definition consists of three parts: the type of component, the lead or terminal mode assignments, and the component value or model name. For example, if the first component definition in this simulation is a DC voltage source, then `V1` defines the component as voltage source number one, `1` and `0` are the two circuit modes for this component, and `1000` indicates that the voltage source value is 1000 volts. The remaining circuit components are resistors (`R1`, `R2`) inductor (`L1`) and independent current source (`IL`).

The reverse recovery of the diode is simulated by dropping the value of output resistor `R2` over a small increment of time. The `R2` statement contains additional syntax to perform this task. Here, the resistor is treated as a source whose resistance decreases exponentially from 1 mOhm to 1 mOhm over the specified time step. This action essentially shorts out the parallel current source `IL` which is also connected to the base of the diode.

**Line 8:** The `ADIODE` statement specifies a device to be analyzed by `ATLAS`. The `A` part of the `ADIODE` command specifies that this is a device statement. The `DIODE` portion simply defines the device name. The option `INFILE=` indicates which device structure file is to be used.

**Lines 9-10:** These set numerical options for the circuit simulation. `WRITE=10` specifies that every tenth timestep will be saved into the solution file specified on the `.SAVE` statement.

**Line 12:** Specifies a file generated by a previous `MIXEDMODE` simulation to be used as an initial guess to the voltage.

**Line 13-14:** Specifies the output log and solution filenames. These names are root names and extensions will be added automatically by the program.

**Line 16:** Indicates the type of analysis required. In this case it is a transient simulation lasting 2 microseconds with an initial timestep of 0.1 nanoseconds.

**Line 18:** Indicates the end of the circuit description. All following statements will be related to the `ATLAS` device.

**Lines 20-22:** To completely specify the simulation, the physical models used by `ATLAS` must be identified. Note that `DEVICE=ADIODE` must be specified for each line. The `MODEL` statement is used to turn on the appropriate transport models. This set includes:

- `conmob`: the concentration dependent mobility mode,
- `fldmob`: the lateral electric field-dependent mobility model,
- `consrh`: Shockley-Read-Hall recombination using concentration dependent lifetimes,
- `auger`: recombination accounting for high level injection effects,
- `bgn`: band gap narrowing.

The `MATERIAL` statement is used to override default material parameters. In this case, the carrier recombination fixed lifetimes are set. Finally, the Selberherr impact ionization model is enabled using the `IMPACT` statement with the `SELB` option.

**Line 24:** The `METHOD` statement specifies numerical options for the device simulation. The `METHOD` statement must come after all other device simulation statements.

**Line 26:** The command `GO ATLAS` or a `QUIT` statement is needed to initiate simulation. Since a plot of the final log file is desired, the `GO ATLAS` option is used to restart `ATLAS` after the end of the `MIXEDMODE` simulation.

**Line 27:** The `TONYPLOT` command is used to plot the resulting log file.

## 12.4: MixedMode Syntax

This section is split into two parts. The first part describes circuit element statements, which describe the netlist. The second part describe the control and analysis statements.

### 12.4.1: Circuit Element Statements

#### A – ATLAS device to be simulated using device simulation

##### Syntax

```
Axxx n1=name1 n2=name2 [n3=name3 ...] infile=filename [width=val]
```

##### Description

This statement defines a device to be represented by a numerical ATLAS model. The device description with all necessary information (geometry, mesh, doping, models, electrode names, and so on) must be available in a standard structure file prior to starting a MIXEDMODE simulation.

**Axxx:** Name of the element. It must begin with A.

**n1:** Circuit node to which the ATLAS device electrode with the name, name1, is connected. The ATLAS device must have at least two electrodes. The maximum number of electrodes allowed in ATLAS is 55. This means that up to 25 ATLAS devices can be specified (For example, 25 devices with 2 electrodes each, or 10 devices with 5 electrodes each can be specified). The ATLAS device models should be used sparingly, because it can be very time consuming. Use circuit models for less important circuit components to conserve CPU time.

**infile:** Name of standard structure format file with device geometry, mesh, doping, electrodes names, and so on. The number of electrodes and their names should match those mentioned in this statement. Optionally, this file can contain a solution, which MIXEDMODE will use as an initial guess (see the .OPTIONS statement for more details).

**width:** Device width. This is an optional parameter (default=1). All currents through ATLAS device terminals calculated using the 2-D ATLAS model will be multiplied by this parameter to account for the third dimension of the device. width can still be used as a multiplier to the ATLAS current if a 3D ATLAS structure is used in MIXEDMODE3D.

##### Example

```
ABJT1 3=EMITTER 4=BASE 6=COLLECTOR INFILE=BJT1.STR WIDTH=10
```

---

**Note:** Optional parameters for a statement are shown with square brackets (e.g., [n3=name3]).

---

## B – User-defined two-terminal element

### Syntax

```
Bxxx n+ n- INFILE=file_name FUNCTION=function_name
```

### Description

**Bxxx:** User-defined two terminal element name. It must begin with B.

**n+, n-:** Positive and negative terminal nodes.

**INFILE:** Name of the text file (*file\_name*) that contains C source code for a user-defined function that describes element behavior. This file can contain more than one function description.

**function\_name:** Name of the function (“*function\_name*”) from the file.

### Example

```
B1 2 3 infile=ud.c function=rc
```

---

**Note:** For more information on User-defined Two-Terminal Elements, see the “User-Defined Model” section on page 11-36.

---

## C – Capacitor

### Syntax

```
Cxxx n+ n- value
```

### Description

**Cxxx:** Name of a capacitor element. It must begin with “C”.

**n+, n-:** Positive and negative terminal nodes.

**value:** Capacitance in farads.

### Example

```
Cload 3 0 1pF
```

## D – Diode

### Syntax

```
Dxxx n+ n- mname [area] [L=val] [W=val] [PJ=val] [WP=val] [LP=val]
[WM=val]
[LM=val] [OFF] [IC=val] [M=val] [TEMP=val] [DTEMP=val]
```

### Description

**Dxxx:** Name of the diode element. It must begin with D.

**n+, n-:** Positive (anode) and negative (cathode) terminal nodes.

**mname:** Diode model name. It must refer to a diode model.

**area:** Area factor. The default is 1.0.

**L:** Length of the diode in meters. Used for LEVEL 3 diode model only.

**W:** Width of the diode in meters. Used for LEVEL 3 diode model only.

**PJ:** Periphery of the diode junction. Calculated from W and L if they are specified (in the LEVEL 3 diode model). The ISW and CJSW model parameters are affected by the value of PJ.

**WP:** Width of the polysilicon capacitor in meters. Used for LEVEL 3 diode model only. Default is 0m.

**LP:** Length of the polysilicon capacitor in meters. Used for LEVEL 3 diode model only. Default is 0m.

**WM:** Width of the metal capacitor in meters. Used for LEVEL 3 diode model only. Default is 0m.

**LM:** Length of the metal capacitor in meters. Used for LEVEL 3 diode model only. Default is 0m.

**OFF:** Sets ON/OFF startup condition for DC analysis. Default is ON.

**IC:** Initial voltage across the diode.

**M:** Multiplier used to describe multiple parallel diodes.

**TEMP:** Device operating temperature (°C).

**DTEMP:** Difference (in °C) between the device operating temperature and the circuit temperature. Default value is 0.

#### Example

```
D1 2 3 dmodel1
Dclmp 3 7 Diol 3.0 IC=0.3
```

---

**Note:** See the SMARTSPICE/UTMOST MODELING MANUAL VOLUME 2 for a complete description of the diode models.

---

## E – Linear voltage controlled source

### Syntax

```
Exxx n+ n- nc+ nc- gain
```

### Description

**Exxx:** Name of the linear voltage controlled voltage source. It must begin with E.

**n+, n-:** Positive and negative terminal nodes. A positive current flows from the node, n+, through the source to the node, n-.

**nc+, nc-:** Positive and negative controlling node numbers.

**gain:** Voltage gain.

The linear voltage-controlled voltage source is characterized by Equation 12-1.

$$v(v+, n) = gain * v(nc+, nc) \quad 12-1$$

### Example

```
ER 4 5 6 7 55
```

## F – Linear current controlled current source

### Syntax

```
Fxxx n+ n- vcontrolname gain
```

### Description

**Fxxx:** Name of the linear current controlled current source. It must begin with F.

**n+, n-:** Positive and negative terminal nodes. A positive current flows from the node, n+, through the source to the node, n-.



**vcontrolname:** Name of the voltage source through which the controlling current flows. The direction of positive controlling current flow is from the positive node, through the source, to the negative node of **vcontrolname**.

**gain:** Current gain.

The linear current-controlled current source is characterized by Equation 12-2.

$$i(n+, n-) = \text{gain} * i(\text{vcontrolname}) \quad 12-2$$

**Example**

```
F12 4 5 VIN 0.1
```

## G – Linear voltage controlled current source

**Syntax**

```
Gxxx n+ n- nc+ nc- transconductance
```

**Description**

**Gxxx:** Name of the linear voltage controlled current source. It must begin with G.

**n+, n-:** Positive and negative terminal nodes. A positive current flows from the node, n+, through the source to the node, n-.

**nc+, nc-:** Positive and negative controlling node numbers.

**transconductance:** Transconductance (in 1/Ohms).

The linear voltage controlled current source is characterized by Equation 12-3.

$$i(n+, n-) = \text{transconductance} * v(\text{nc+}, \text{nc-}) \quad 12-3$$

**Example**

```
G2 4 5 6 7 5.5
```

## H – Linear current controlled voltage source

**Syntax**

```
Hxxx n+ n- vcontrolname transresistance
```

**Description**

**Hxxx:** Name of the linear current controlled voltage source. Must begin from H.

**n+, n-:** Positive and negative terminal nodes. A positive current flows from the node, n+, through the source to the node, n-.

**vcontrolname:** Name of voltage source through which the controlling current flows. The direction of positive controlling current flow is from the positive node, through the source, to the negative node of **vcontrolname**.

**transresistance:** transresistance (in Ohms).

The linear current controlled voltage source is characterized by Equation 12-4.

$$v(n+, n-) = \text{transresistance} * i(\text{vcontrolname}) \quad 12-4$$

**Example**

```
H12 4 5 V1 0.1K
```

## I – Independent current source

### Syntax

```
Ixxx n+ n- value [AC acmag] [transient_parameters]
```

### Description

**Ixxx:** Name of the independent current source. It must begin with I.

**n+, n-:** Positive and negative terminal nodes.

**value:** DC value of the source (amperes).

**AC:** Keyword for the AC source value.

**acmag:** AC magnitude.

**transient\_parameters:** The transient parameters are described in Section 12.4.3: “Transient Parameters”.

### Example

```
I1 2 8 0. PULSE 0 200 0 20ns 20ns 100ns 10 100
I2 1 5 1u AC 2u
```

## J – Junction Field-Effect Transistor (JFET)

### Syntax

```
Jxxx nd ng ns [nb] mname [area] [M=val] [L=val] [W=val] [OFF]
[IC=vds,vgs]
[TEMP=val] [DTEMP=val]
```

### Description

**Jxxx:** Name of the JFET element. It must begin with J.

**nd, ng, ns, nb:** Drain, gate, source and bulk terminal nodes. The bulk node doesn't need to be specified. If the bulk node is not specified, then the bulk is connected to the source node

**mname:** Model name. It must refer to a JFET model.

**area:** Area factor. The default is 1.0.

**M:** Multiplier used to describe multiple parallel JFETs.

**L:** Length of the gate in meters.

**W:** Width of the gate in meters.

**OFF:** Sets ON/OFF startup condition for DC analysis. Default is ON.

**IC:** Initial condition specification for *vds* and *vgs*.

**TEMP:** Device operating temperature (°C).

**DTEMP:** Difference (in °C) between the device operating temperature and the circuit temperature. Default value is 0.

### Example

```
J44 1 4 6 jmodel
```

---

**Note:** See SMARTSPICE/UTMOST MODELING MANUAL, VOLUME 2 for a complete description of the JFET models.

---

## K – Coupling between two inductors

### Syntax

```
Kxxx Lyyy Lzzz kval
```

### Description

This is not a real circuit element. This statement defines only the coupling between two inductors.

**Kxxx:** Name. This parameter is not important and is used only to distinguish the statement. It must begin with K.

**Lyyy:** First inductor element name. It must begin with an L and match one of the inductor names from the circuit.

**Lzzz:** Second inductor element name. It must begin with an L and match one of the inductor names from the circuit.

**kval:** Coefficient of mutual coupling, which must be in the range  $0 < kval < 1$ . The mutual inductance M will be determined from Equation 12-5.

$$M = kval * L1 * L2 \quad 12-5$$

### Example

```
K1 L22 LLOAD 0.99
```

## L – Inductor

### Syntax

```
Lxxx n+ n- value
```

### Description

**Lxxx:** Name of the inductor. It must begin with L.

**n+, n-:** Positive and negative terminal nodes.

**value:** Inductance in henries.

### Example

```
L2 2 3 2.5nH
```

## M – MOSFET

### Syntax

```
Mxxx nd ng ns [nb] mname [L=val] [W=val] [AD=val] [AS=val]
[PD=val] [PS=val] [NRD=val] [NRS=val] [OFF] [IC=vds,vgs,vbs] [M=val]
[TEMP=val] [DTEMP=val] [GEO=val] [DELVTO=val]
```

### Description

**Mxxx:** MOSFET element name. It must begin with *M*.

**nd, ng, ns, nb:** Drain, gate, source, and bulk terminal nodes. The bulk terminal node name is optional. If it is unspecified, ground is used.

**mname:** Model name. It must refer to a MOSFET model.

**L=val:** Channel length in meters.

**W=val:** Channel width in meters.

**AD:** Drain diffusion junction area (meters<sup>2</sup>). This default is 0.

**AS:** Source diffusion junction area (meters<sup>2</sup>). This default is 0.

**PD:** Drain diffusion junction perimeter (meters). This default is 0.

**PS:** Source diffusion junction perimeter (meters). This default is 0.

**NRD:** The Number of squares of drain diffusion for resistance calculations. The default is 0.

**NRS:** The Number of squares of source diffusion for resistance calculations. The default is 0.

**OFF:** Sets ON/OFF startup condition for DC analysis. Default is ON.

**IC:** Initial voltage condition specification for *vds*, *vgs*, and *vbs*.

**M:** Multiplier used to describe multiple parallel MOSFETs. The default is 1.

**TEMP:** Device operating temperature (°C).

**DTEMP:** Difference (in °C) between the device operating temperature and the circuit temperature. Default value is 0.

**DELVTO:** Threshold-voltage shift. When specified on the device line, the value overrides the value of the model parameter, *DELVTO*. If not specified, the value of the model parameter is used.

### Example

```
M1 2 4 8 9 mod1
Mout2 19 20 21 0 nmos L=5u W=2u TEMP=50
M22 3 5 7 8 mosmod1 L=10u W=5u AD=150p AS=150p PD=50u
PS=50u NRD=10 NRS=20
```

---

**Note:** See SMARTSPICE/UTMOST MODELING MANUAL, VOLUME 1 for a complete description of the MOSFET models.

---

## O – Optical source

### Syntax

```
Oxxx beam value [transient_parameters]
```

### Description

**Oxxx:** Name of an independent optical source. It must begin with O.

**beam:** Beam number. The beam with this number should be described in the ATLAS section of the command file. See Chapter 10: “Luminous: Optoelectronic Simulator” for a complete description of optoelectronic simulation.

**value:** DC optical intensity value (W/cm<sup>2</sup>).

**transient\_parameters:** The transient parameters are described in Section 12.4.3: “Transient Parameters”.

---

**Note:** The treatment of optical sources is fully similar to the treatment of independent voltage/current sources (i.e., DC statements can be used to simulated DC light responses of the circuit and transient parameters can be used to describe the transient behavior of the optical sources).

---

### Example

```
O1 1 0.001 pulse 0.001 0.002 0 2ns 2ns 100ns 10 100
```

## Q – Bipolar junction transistor

### Syntax

```
Qxxx nc nb ne [ns] mname [area] [OFF] [IC=vbe,vce] [M=val] [TEMP=val]
[DTEMP=val]
```

or

```
Qxxx nc nb ne [ns] mname [area=val] [areab=val] [areac=val] [OFF]
[IC=vbe,vce] [M=val] [TEMP=val] [DTEMP=val]
```

### Description

**Qxxx:** Name of a bipolar junction transistor. It must begin with Q.

**nc, nb, ne, ns:** Collector, base, emitter, and substrate nodes. The substrate terminal node name is optional. If it is unspecified, ground is used.

**mname:** Model name. It must refer to a BJT model.

**area:** Emitter area factor. The default value is 1.0.

**areab:** Base area factor. The default is area.

**areac:** Collector area factor. The default is area.

**OFF:** Sets ON/OFF startup condition for DC analysis. Default is ON.

**IC:** Initial voltage condition specification for *vbe*, *vce*.

**M:** Multiplier used to describe multiple parallel BJTs. The default is 1.

**TEMP:** Device operating temperature (°C).

**DTEMP:** Difference (in °C) between the device operating temperature and the circuit temperature. Default value is 0.

**Example**

```
Q1 2 3 9 npnmod 1.5 IC=0.6,5.0
Q9 10 11 12 20 mod22 OFF TEMP=50
```

---

**Note:** See SMARTSPICE MODELING MANUAL, VOLUME 2 for a complete description of the BJT models.

---

**R – Resistor****Syntax**

```
Rxxx n+ n- value [transient_parameters]
```

**Description**

**Rxxx:** Name of the resistor element. It must begin with “R”.

**n+, n-:** Positive and negative terminal nodes.

**value:** Resistance in ohms.

**transient\_parameters:** The transient parameters are described in Section 12.4.3: “Transient Parameters”.

---

**Note:** Unlike the traditional SPICE program, transient parameters are acceptable for resistor elements. This allows simulation of different kinds of time-dependent resistors and switches in a simple way.

---

**Example**

```
R12 4 5 100k
```

**T – Lossless transmission line****Syntax**

```
Txxx n1 n2 n3 n4 Z0= val TD=val
```

**Description**

**Txxx:** Name of the transmission line element. It must begin with T.

**n1, n2:** Nodes at port 1.

**n3, n4:** Nodes at port 2.

**Z0:** Characteristic impedance.

**TD:** Transmission delay.

**Example**

```
T1 1 0 2 0 Z0=50 TD=10ns
```

---

## V – Independent voltage source

### Syntax

```
Vxxx n+ n- value [AC acmag] [transient_parameters]
```

### Description

**Vxxx:** Name of the independent voltage source. It must begin with v.

**n+, n-:** Positive and negative terminal nodes.

**value:** DC value of the source in units of volts.

**AC:** Keyword for the AC source value.

**acmag:** AC magnitude.

**transient\_parameters:** The transient parameters are described in Section 12.4.3: “Transient Parameters”.

### Example

```
VCC 5 0 10.5
VIN 2 4 5.5 AC 1
```

## Z – MESFET

### Syntax

```
Zxxx nd ng ns [nb] mname [area] [M=val] [L=val] [W=val] [OFF]
[IC=vds,vgs]
[TEMP=val] [DTEMP=val]
```

### Description

**Zxxx:** Name of the MESFET element. It must begin with z.

**nd, ng, ns, nb:** Drain, gate, source and bulk terminal nodes. The bulk node doesn’t need to be specified. If the bulk node is not specified, then the bulk is connected to the source node

**mname:** Model name. It must refer to a MESFET model.

**area:** Area factor. The default is 1.0.

**M:** Multiplier used to describe multiple parallel MESFETs.

**L:** Length of the gate in meters.

**W:** Width of the gate in meters.

**OFF:** Sets ON/OFF startup condition for DC analysis. Default is ON.

**IC:** Initial condition specification for *vds* and *vgs*.

**TEMP:** Device operating temperature (°C).

**DTEMP:** Difference (in °C) between the device operating temperature and the circuit temperature. Default value is 0.

### Example

```
Z44 1 4 6 jmodel
```

---

**Note:** See SMARTSPICE MODELING MANUAL, VOLUME 2 for a complete description of the MESFET models.

---

## 12.4.2: Control and Analysis Statements

### .AC

.AC performs an AC linear small-signal analysis on the circuit. MIXEDMODE first creates a linearized small-signal model at the operating point of the circuit and then computes the frequency response over a user-specified range of frequencies.

#### Syntax

```
.AC DEC|OCT|LIN nump fstart fstop.
```

#### Description

**DEC:** Sweep frequency by decades.

**OCT:** Sweep frequency by octaves.

**LIN:** Linear frequency sweep. This is default.

**nump:** Total number of points per decade or per octave, or the total number of points of the linear sweep.

**fstart:** Starting frequency (Hz).

**fstop:** Final frequency (Hz).

Several .AC statements can be specified in the same command file. In this case, they will be executed sequentially. Before executing the first .AC statement, the program will execute all .DC statements (if any), regardless of the order of the .AC and .DC statements in the command file.

#### Example

```
.AC DEC 3 1.e3 1.e12  
.AC LIN 20 1.e5 2.e6
```

### .BEGIN

.BEGIN indicates the start of the circuit part of a MIXEDMODE command file.

### .DC

.DC causes a DC transfer curve to be computed for the circuit with all capacitors opened and all inductors shorted.

#### Syntax

```
.DC DEC|OCT|LIN source_name start stop numbers_steps  
source_name2 DEC|OCT|LIN start2 stop2 number_steps2
```

#### Description

**DEC:** Sweep DC bias (voltage or current) by decades.

**OCT:** Sweep DC bias by octaves.

**LIN:** Linear DC bias sweep. This is the default.

**source\_name:** Name of the independent voltage or current source to be swept.

**start:** Starting value of the sweep argument.



**stop:** Final value of the sweep argument.

**number\_steps:** Number of steps of the inner sweep

**source\_name2:** Name of the secondary sweep source.

**start2:** start value of the secondary sweep source

**stop2:** Final value of the secondary sweep source

**number\_steps2:** Number of steps of the secondary sweep.

Several `.DC` statements can be specified in a command file. In this case, they will be executed sequentially. Before executing the first `.DC` statement, the program will simulate the circuit with the independent source values given in the description of those sources.

The `.DC` statement is also often used to increment the values of independent voltage and current sources in a circuit to avoid convergence problems.

### Examples

```
.DC VIN 0. 5. 0.25
.DC IE 50 500 50
```

### .END

`.END` indicates the end of the circuit part of a `MIXEDMODE` command file.

### .IC

`.IC` sets specified node voltages during the steady-state simulation.

### Syntax

```
.IC [V(I)=val_I...]
```

### Description

This statement forces the specified node voltages to be set to specified values during the steady-state simulation. These voltages are release when the transient simulation begins.

### Example

```
.IC V(1)=10
.IC V(node1)=-0.5
```

### .LOAD

`.LOAD` loads a solution file.

### Syntax

```
.LOAD INFILE=filename
```

### Description

**INFILE:** Name of a file (*filename*) to be loaded as an initial guess for further simulation. This file must have been saved during a previous run of `MIXEDMODE` using the `.SAVE` statement.

### Example

```
.LOAD INFILE=pdsave
```

---

**Note:** This statement is not used to load SSF format solution files from `ATLAS` (see `OPTIONS LOADSOLUTIONS`)

---

## .LOG

.LOG specifies the filename for the circuit voltages and currents that will be saved.

### Syntax

```
.LOG OUTFILE=filename
```

### Description

**OUTFILE:** Name of a file (*filename*) for the circuit voltages and currents to be saved in standard structure format files.

These files will have the following names:

For steady-state analysis:

```
"filename"_dc_1.log
```

```
"filename"_dc_2.log
```

```
"filename"_dc_3.log
```

```
..
```

(new file will be created for each .DC statement).

For AC analysis:

```
"filename"_ac_1.log
```

```
..
```

For network parameter extraction:

```
"filename"_net_1.log
```

```
..
```

For transient analysis:

```
"filename"_tr.log
```

```
..
```

To plot results of an entire steady-state analysis simultaneously, load all files related to steady-state analysis into TONYPLOT.

### Example

```
.LOG OUTFILE=pd
```

## .MODEL

.MODEL specifies the circuit element model to be used for diodes, BJTs, or MOSFETs, and the numerical values of parameters associated with the model.

### Syntax

```
.MODEL name type <parameters>
```

### Description

**name:** This is the model name. Circuit element definition statements refer to this name to link elements to models.

**type:** This is the model type. This type must be consistent with the type of the circuit elements that uses the model. The type can be one of the following:

- **D** - Diode model

- **NMOS** - n-channel MOSFET model.
- **PMOS** - p-channel MOSFET model.
- **NPN** - npn BJT model
- **PNP** - pnp BJT model
- **NJF** - n-channel JFET/MESFET model
- **PJF** - p-channel JFET/MESFET model

**parameters:** Model parameters. The parameters are described in the SMARTSPICE/UTMOST MODELING MANUALS VOLUMES 1,2 and 3.

#### Example

```
.MODEL MODBJT NPN IS=1.E-17 BF=100 CJE=1F TF=5PS \
CJC=0.3F RB=100 RBM=20
```

## .NET

.NET specifies that a network parameter extraction is to be performed.

#### Syntax

```
.NET INPORT OUTPORT DEC|OCT|LIN nump fstart fstop [Z0] [INDIN] [RSIN]
[INDOUT]] [RSOUT] [CIN] [COUT]
```

#### Description

**INPORT:** Input port description. It should be in one of the following formats:

- **V(n+,n-):** two nodes (positive (n+) and negative (n-)).
- **Vxxxx:** where Vxxxx is the name of an existing voltage source. The positive terminal of the source becomes the positive input port node and the negative terminal becomes the negative input node.
- **Ixxxx:** where Ixxxx is the name of an existing current source. The positive terminal of the source becomes the positive input port node and the negative terminal becomes the negative input node.

---

**Note:** If the nodes specified as the input port are the same nodes as an existing current or voltage source, then the name of the source must be specified as `inport`. Also, remove all AC parameters from voltage or current sources before using the .NET statement.

---

**OUTPORT:** Output port description. It should be in one of the following formats.

- **V(n+,n-):** two nodes (positive (n+) and negative (n-)).
- **Vxxxx:** where Vxxxx is the name of an existing voltage source. The positive terminal of the source becomes the positive output port node and the negative terminal becomes the negative output node.
- **Ixxxx:** where Ixxxx is the name of an existing current source. The positive terminal of the source becomes the positive output port node and the negative terminal becomes the negative output node.

---

**Note:** If the nodes specified as the output port are the same nodes as an existing current or voltage source, then the name of the source must be specified as `outport`.

---

**DEC:** Sweep frequency by decades.

**OCT:** Sweep frequency by octaves.

**LIN:** Linear frequency sweep. This is default.

**nump:** Total number of points per decade or per octave, or the total number of points of the linear sweep.

**fstart:** Starting frequency (Hz).

**fstop:** Final frequency (Hz).

Additional optional parameters may also be specified on the .NET statement.

**Z0:** Matching Impedance (default = 50 Ohms).

**INDIN:** Inductance through which the DC voltage source is connected to the input source (only if INPORT is given as Vxxxx).

**RSIN:** Series resistance of INDIN.

**INDOUT:** Inductance through which the DC voltage source is connected to the output source (only if OUTPORT is given as Vxxxx).

**RSOUT:** Series resistance of INDOUT.

**CIN:** Capacitance through which the S-parameter test circuit is connected to the input port.

**COUT:** Capacitance through which the S-parameter test circuit is connected to the output port.

---

**Note:** The S-parameters will be automatically saved to the log file. The Z, Y, H, ABCD, and gain small-signal parameters can also be written to the log file. These are selected through the .OPTIONS statement. You can also view the default values if PRINT is specified in the .OPTIONS statement

---

## Examples

```
.NET V1 V2 DEC 10 1e6 1e10
.NET I1 V2 DEC 10 1e6 1e10 Z0=75 RSOUT=100
.NET V(1,0) V(2,3) DEC 10 1e6 1e10
```

## .NODESET

.NODESET sets initial values for circuit node voltages.

### Syntax

```
.NODESET [V(I)=VAL_I ...]
```

### Description

This statement specifies the initial values for circuit node voltages. If a node voltage is not specified, the program will try to find a solution using zero as an initial guess for this node. This statement can significantly reduce the CPU time needed to calculate the initial condition.

### Example

```
.NODESET V(1)=50 V(2)=49.4 V(3)=10 V(5)=-1.5
.NODESET V(in1)=0 V(2)=2 V(out1)=-1
```

## .NUMERIC

.NUMERIC specifies special numeric parameters for the circuit analysis.

### Syntax

```
.NUMERIC [parameters]
```

| Parameter | Type    | Default             | Units |
|-----------|---------|---------------------|-------|
| IMAXDC    | Integer | 25                  |       |
| IMAXTR    | Integer | 15                  |       |
| DTMIN     | Real    | $1 \times 10^{-12}$ | s     |
| LTE       | Real    | 0.1                 |       |
| TOLDC     | Real    | $1 \times 10^{-4}$  |       |
| TOLTR     | Real    | $1 \times 10^{-4}$  |       |
| VCHANGE   | Real    | $5 \times 10^7$     | V     |
| VMAX      | Real    | $5 \times 10^7$     | V     |
| VMIN      | Real    | $-5 \times 10^7$    | V     |

### Description

**IMAXDC:** Maximum number of mixed circuit-device iterations to be performed during steady-state analysis.

**IMAXTR:** Maximum number of mixed circuit-device iterations to be performed during transient analysis.

**DTMIN:** Minimum time step value for transient analysis.

**LTE:** Local truncation error for transient analysis.

**TOLDC:** Relative accuracy to be achieved during steady-state analysis for the calculation of voltages in circuit nodes.

**TOLTR:** Relative accuracy to be achieved during transient analysis for the calculation of voltages in circuit nodes.

**VCHANGE:** Maximum allowable change in circuit node voltages between two mixed circuit-device iterations. (This parameter can be useful for reaching steady-state convergence with a bad initial guess.)

**VMAX:** Maximum value for circuit node voltages.

**VMIN:** Minimum value for circuit node voltages.

### Example

```
.NUMERIC LTE=0.05 TOLDC=1.*10-8 DTMIN=1ns
```

## .OPTIONS

.OPTIONS specifies various circuit simulation options.

### Syntax

.OPTIONS [parameters]

| Parameter     | Type    | Default             | Units |
|---------------|---------|---------------------|-------|
| ABCD.PARAM    | Logical | False               |       |
| CNODE         | Real    | $1 \times 10^{-16}$ | F     |
| CYLINDER      | Logical | False               |       |
| FULLN         | Logical | True                |       |
| GAINS         | Logical | False               |       |
| H.PARAM       | Logical | False               |       |
| LOADSOLUTIONS | Logical | False               |       |
| M2LN          | Logical | False               |       |
| M2LN.TR       | Logical | False               |       |
| NOPROJ        | Logical | False               |       |
| NOSHIFT       | Logical | False               |       |
| PRINT         | Logical | False               |       |
| RELPOT        | Logical | False               |       |
| RV            | Real    | $1 \times 10^{-4}$  | W     |
| TEMP          | Real    | 300                 | K     |
| TNOM          | Real    | 300                 | K     |
| WRITE         | Integer | 1                   |       |
| Y.PARAM       | Logical | False               |       |
| Z.PARAM       | Logical | False               |       |

### Description

**ABCD.PARAM:** ABCD parameters will be written to the log file. This is used in conjunction with the .NET statement.

**CNODE:** A very small capacitance, which for algorithmic reasons automatically connected from each circuit node to ground. This value can be set to 0.

**CYLINDR:** Cylindrical coordinate system for all ATLAS devices.

**FULLN:** Full Newton solution method is used during steady-state simulation.

**GAIN:** Stability factor (K), unilateral power gain (GU), maximum unilateral transducer power gain (GTUmax) and  $|H21|^2$  are written to the LOG file. This is used in conjunction with the .NET statement.

**H.PARAM:** H-parameters will be written to the LOG file. This is used in conjunction with the .NET statement.

**LOADSOLUTIONS:** Solutions, structures, doping distributions, and meshes, are to be loaded from standard structure files. The solutions are used as the initial guess or initial conditions for subsequent MIXEDMODE simulation. To use this feature, you must:

- Calculate a solution for each ATLAS device and save each solution in a separate standard structure format file using SAVE or SOLVE . . . MASTER.
- For each ATLAS device, use the A statement in the MIXEDMODE command file to specify the associated standard structure format file
- Set node voltages to appropriate values with the .NODESET statement
- Specify LOADSOLUTIONS in the .OPTIONS statement

---

**Note:** If using this feature, specify solutions for all ATLAS devices.

---

The .NODESET statement must always be used when LOADSOLUTIONS is used. The .NODESET statement is used to make the initial circuit voltages match those device solutions that were obtained. You may also need to specify the NOSHIFT parameter of the OPTIONS statement. By default, MIXEDMODE shifts device terminal voltages with respect to the voltage on the first terminal that is specified in the A statement. You must either prepare initial solutions with this terminal grounded, or specify NOSHIFT in the OPTIONS statement.

**M2LN:** Uses the modified two-level Newton solution method during steady-state simulation. The full NEWTON method provides faster solution than the modified two-level Newton method when a good initial guess is available. The modified two-level method is more reliable when the initial guess is far from the solution. The default is the full NEWTON method.

**M2LN.TR:** Uses the modified two-level Newton solution method during transient simulations.

**NOPROJ:** Disables the initial guess project method for the ATLAS iterations. MIXEDMODE attempts to extrapolate the values of the ATLAS device variables (such as potential and carrier concentration) for the each iteration. Specifying NOPROJ disables the extrapolation and the previous values of potential and carrier concentration are used instead.

**NOSHIFT:** Disables the shift of voltages for ATLAS device models. MIXEDMODE normally shifts the voltages on ATLAS device terminals to be referenced to the voltage on the first terminal. From the physical point of view, the state of the p-n diode is the same for voltages of 0V and 0.5V on the diode terminals with 1000V and 1000.5V, but the first situation is better for numerical simulation.

**PRINT:** Enables printing of circuit nodes voltages after the calculation for each bias point (DC analysis) or time step (transient the analysis).

**RELPO:** Enables the use of relative convergence criteria for potential for ATLAS models. By default, ALTAS models use absolute convergence criteria for potential. When bias voltages are large (a common situation for power devices), then absolute convergence criteria are not appropriate and this parameter should be specified.

**RV:** Defines the ohmic resistance that MIXEDMODE associates with all voltage sources and all inductances. This value should never be set to 0. The default value is small enough to avoid errors due to the influence of the internal resistance. Usually, extremely small values of this parameters can cause convergence problems. It is usually acceptable to decrease this parameter to the range of  $1 \cdot 10^{-6}$ - $1 \cdot 10^{-7}$ . This parameter should not be varied unless there is a compelling reason to do so.

**TEMP:** Device temperature to be use during the simulation.

**TNOM:** Circuit temperature to be use during the simulation.

**WRITE:** How often the solution is to be saved in standard structure files during the simulation. For example, `write=3` specifies that the solution will be saved at every third timestep. Specifying this parameter can help avoid disk overflow.

**Y.PARAM:** Y-parameters should be written to the log file. This is used in conjunction with the `.NET` statement.

**Z.PARAM:** Z-parameters should be written to the log file. This is used in conjunction with the `.NET` statement.

#### Example

```
.OPTIONS TNOM=293 FULLN
```

#### **.PRINT**

`.PRINT` specifies which device output parameters will be printed to the log files.

#### Syntax

```
.PRINT [antype] parameter(device_name) [parameter2(device_name) ...]
```

#### Description

**antype:** Type of analysis for which the outputs are desired. If `antype` is unspecified, the outputs of all simulation types will be printed. `antype` must be one of the following keywords:

- **AC:** AC analysis outputs
- **DC:** DC analysis outputs
- **NET:** Network analysis outputs
- **TRAN:** Transient analysis outputs

**parameter:** Output variables or expressions to be printed.

**device\_name:** The device name.

#### Example

```
.PRINT ic(q1) ib(q1) is(q1)
.PRINT AC ic(q1) ib(q2)
.PRINT DC ic(q1) ib(q2) i(d1)
.PRINT TRAN cd(m1) cg(m1) cs(m1) cb(m1)
```

#### **.SAVE**

`.SAVE` saves simulation results into files for visualization or for future use as an initial guess.

#### Syntax

```
.SAVE OUTFILE=name [MASTER=mname]
```

#### Description

**OUTFILE:** Specifies that after the simulation is finished the solution is to be written to a file called *name*. The ATLAS model solutions will be written to the file (*name*) and the circuit solution will be written to the file, *name.cir*. These files can be used later for loading solutions to be used as an initial guess (see `.LOAD` statement).

**MASTER:** Internal states of all ATLAS models should be written during the simulation in standard structure format for future visualization using `TONYPLOT`. These files, with the base name, *mname*, will be written after the calculation of each bias point during DC simulation, and after of each time step during transient simulation.



The program will automatically add the following suffixes to *mname*:

- During DC simulation: *\_dc\_number*, where *number* is the number of the DC point.
- During transient simulation: *\_tr\_number*, where *number* is the number of the time step.

#### Example

```
.SAVE OUTFILE=pdsave MASTER=pd
```

#### .TRAN

.TRAN specifies that a transient analysis is to be performed.

#### Syntax

```
.TRAN tstep tstop
```

#### Description

**tstep**: Time interval in seconds.

**tstop**: Final time value for which the simulation is to be performed.

Transient analysis is performed only after the execution of all .DC statements. If no DC statements are used the transient starts after the calculation of the initial circuit state with the values of the independent sources given in the descriptions of those sources.

Multiple .TRAN statements are supported. The TSTOP parameter is not reset between each .TRAN statement.

#### Example

```
.TRAN 1ns 100ns
```

### 12.4.3: Transient Parameters

MIXEDMODE allows you to specify transient parameters for voltage sources (Vxxx), current sources (Ixxx), and resistors (Rxxx). These parameters describe the time development behavior of the source.

#### EXP

**EXP** is used to define an exponential waveform. The waveform is specified as follows:

```
EXP i1 i2 td1 tau1 td2 tau2
```

where:

**i1** is the initial value.

**i2** is the pulsed value.

**td1** is the rise delay time.

**td2** is the fall delay time.

**tau1** is the rise time constant.

**tau2** is the fall time constant.

The transient behavior is shown in Table 12-2.

| Table 12-2. Transient behavior for EXP |  |
|--|--|
| Time                                   | Value  |
| $0 < t < td1$                          | $i1$   |
| $td1 \leq t < td2$                     | $i1+(i2-i1) \cdot (1-\exp[-(t-td1)/\tau1])$  |
| $td2 \leq t$                           | $i1+(i2-i1) \cdot (1-\exp[-(t-td1)/\tau1]) + (i1-i2) \cdot (1-\exp[-(t-td2)/\tau2])$ |

**GAUSS**

**GAUSS** is used to define a Gaussian waveform. The waveform is specified as follows:

```
GAUSS i1 i2 td1 tau1 td2 tau2
```

where:

**i1** is the initial value.

**i2** is the pulsed value.

**td1** is the rise delay time.

**td2** is the fall delay time.

**tau1** is the rise time constant.

**tau2** is the fall time constant.

The transient behavior is shown in Table 12-3.

| Table 12-3. The transient behavior for GAUSS |  |
|--|--|
| Time   | Value  |
| $0 < t < td1$                                | $i1$   |
| $td1 \leq t < td2$                           | $i1+(i2-i1) \cdot (1-\exp[-((t-td1)/\tau1)^2])$  |
| $td2 \leq t$                                 | $i1+(i2-i1) \cdot (1-\exp[-((t-td1)/\tau1)^2]) + (i1-i2) \cdot (1-\exp[-((t-td2)/\tau2)^2])$ |

**PULSE**

**PULSE** is used to define a pulse waveform. The waveform is specified as follows:

```
PULSE i1 i2 td tr tf pw per
```

where:

**i1** is the initial value.

**i2** is the pulsed value.

**td** is the delay time before the pulse is started.

**tr** is the rise time of the pulse.

**tf** is the fall time of the pulse.

**pw** is the pulse length per period

**per** is the period.

The transient behavior is described in Table 12-4. Intermediate points are found by linear interpolation.

| Time              | Value              |
|-------------------|--------------------|
| 0                 | i1                 |
| td                | i1                 |
| td + tr           | i2                 |
| td + tr + pw      | i2                 |
| td + tr + pw + tf | i1                 |
| td + per          | i1                 |
| td + per + tr     | i2 (second period) |

## SFFM

**SFFM** is used to define a modulated sinusoidal waveform. The waveform is specified as follows:

```
SFFM io ia fc mdi fs
```

where:

**io** is the DC offset.

**ia** is the amplitude.

**fc** is the carrier frequency.

**mdi** is the modulation index.

**fs** is the signal frequency.

The transient behavior will be:

$$\text{value}(t) = io + ia \cdot \sin[\pi \cdot fc \cdot t + mdi \cdot \sin(2\pi \cdot fs \cdot t)]$$

## SIN

**SIN** is used to define a sinusoidal waveform. The waveform is specified as follows:

```
SIN io ia freq td theta
```

where:

**io** is the offset.

**ia** is the amplitude.

**freq** is the frequency.

**td** is the delay.

**theta** is the damping factor.

The transient behavior is shown in Table 12-5.

| Table 12-5. Transient Behavior for SIN |  |
|--|--|
| Time                                   | Value  |
| $t < t_d$                              | $value(t) = i_o$   |
| $t \geq t_d$                           | $value(t) = i_o + i_a \cdot \exp[(-t - t_d)/\text{THETA}] \cdot \sin[2\pi \cdot \text{freq.} \cdot (t - t_d)]$ |

**TABLE**

**TABLE** is used to define a waveform using a table of values. This parameter is used as follows:

```
TABLE infile=<table_file_name>
```

where `table_file_name` is an ASCII text file that contains the tabulated time-dependence of a variable in the following format:

```
t1 v1
t2 v2
t3 v3
...
tN vN
end
```

Each line contains two numbers. The first number is the time in seconds. The second number is the time-dependent variable) voltage in volts, the current in amps, or the resistance in ohms). Up to 1000 lines can be used. Input is terminated by the word `end`.

If during the simulation the transient time becomes larger than the last value in the table, then the last value will be used for the remainder of the simulation

**12.4.4: User-Defined Two-Terminal Elements**

MIXEDMODE users who are familiar with C-INTERPRETER can define their own two-terminal elements using the B statement and a function written in C that defines the behavior of the element.

**User-Defined Model**

A user-defined model is specified by defining the following:

- The dependencies of the device terminal current on the terminal voltages
- The derivatives of the terminal current with respect to the terminal voltages
- The device current (I) is described by Equation 12-6.

$$I = F1(U, t) + F2(U, t) \cdot \left(\frac{dU}{dt}\right) \tag{12-6}$$

where:

U is the device voltage, t is time, and F1 and F2 are functions that determine the behavior of the device. The first term on the right hand side describes the “DC” current and the second term describes “capacitive” current.

The following four functions are user-specified:

- **F1(U,t)**: the DC current.
- **F2(U,t)**: the capacitance.
- **dF1(U,t)/dU**: the DC differential conductance.
- **Q**: the charge associated with F2(U,t).

To define the element, prepare a text file that contains an appropriate function written in C. A template for this user-defined function is shown below:

```
int udef(double v, double temp, double ktq, double time, double *curr,
double *didv, double *cap, double *charge)
{
/* user-supplied code here */
return(0);
}
```

### Input Parameters

Four input parameters are supplied to the function and can be used in the user-defined code. The input parameters are:

- **v**: the voltage across the element (V)
- **temp**: the temperature (K)
- **ktq**: the thermal voltage  $kT/q$  (V)
- **time**: transient time (sec); a value of 0 is supplied during DC calculations

### Output Parameters

The four output parameters that must be returned by the function are:

- **curr**: the value of F1 (Amps)
- **didv**: the value of  $dF1(v, \text{time})/dU$  (A/V)
- **cap**: the value of F2(v, time)
- **charge**: the value of the charge (Q)

### Example

Consider an element that consists of a resistor R and a capacitor C connected in parallel. The equation for the total current through this combination is:

$$I(U, t) = \frac{U}{R} + C \cdot \left(\frac{dU}{dt}\right) \quad 12-7$$

The quantities that must be user-defined are:

$$F1(U, t) = \frac{U}{R} \quad 12-8$$

$$F2(U, t) = C \quad 12-9$$

$$\frac{dF(U, t)}{dU} = \frac{1}{R} \quad 12-10$$

$$Q = C \cdot U$$

12-11

When  $R=2k\Omega$  and  $C=100pF$ , a user-defined function could have the following form:

```
intrc(double v, double temp, double ktq, double time, double *curr, double
*didv, double *cap, double *charge)
{
    *curr = v/2000.0;
    *didv = 1.0/2000.0
    *cap = 1.0e-10;
    *charge=1.0e-10*v;
    return(0);          /* 0 - ok */
}
```

### 13.1: Self-Consistent Coupled Schrodinger Poisson Model

To model the effects of quantum confinement, ATLAS also allows the solution of Schrodinger's Equation along with the fundamental device equations. The solution of Schrodinger's Equation gives a quantized description of the density of states in the presence of quantum mechanical confining potential variations.

The calculation of the quantized density of states relies upon a solution of Schrodinger's Equation.

$$-\frac{\hbar}{2} \frac{\partial}{\partial x} \left( \frac{1}{m_l} \frac{\partial \Psi_{il}}{\partial x} \right) + E_C(x) \Psi_{il} = E_{il} \Psi_{il} \quad 13-1$$

$$-\frac{\hbar}{2} \frac{\partial}{\partial x} \left( \frac{1}{m_t} \frac{\partial \Psi_{it}}{\partial x} \right) + E_C(x) \Psi_{it} = E_{it} \Psi_{it} \quad 13-2$$

where  $E_{it}$  is the  $i$ th bound state energy for transverse mass,  $E_{il}$  is longitudinal,  $\Psi_{it}$  is the transverse wavefunction,  $\Psi_{il}$  is the longitudinal wavefunction, and  $E_C$  is the band edge energy. This expression is for electrons but an equivalent expression exists for holes.

In the case that the mass is isotropic, only one solution to Schrodinger's equation is obtained with the appropriate mass. To choose the number of directions in  $k$  space, specify the `NUM.DIRECT` parameter. If you set `NUM.DIRECT` to 1, you will obtain the solution for isotropic effective mass. If you set `NUM.DIRECT` is set to 3, you will obtain a solution for a single lateral effective mass and 2 equivalent transverse masses.

To specify how many valence bands to consider, specify the `NUM.BAND` parameter. If you set `NUM.BAND` to 1, you will obtain a Schrodinger solution for only one valence band. If you set `NUM.BAND` to 3, you will cause solutions for heavy holes, light holes and holes in the split off band.

Using Fermi-Dirac statistics, the discrete nature of the quantized density of states reduces the integral over energy to a sum over bound state energies.

$$n_x = 2 \frac{k_B T}{\pi \hbar^2} m_t \sum_{i=0}^{\infty} \left| \Psi_{il}(x) \right|^2 \ln \left[ 1 + \exp \left( -\frac{E_{il} - E_F}{k_B T} \right) \right] + 4 \frac{k_B T}{\pi \hbar^2} \sqrt{m_l m_t} \sum_{i=0}^{\infty} \left| \Psi_{it}(x) \right|^2 \ln \left[ 1 + \exp \left( -\frac{E_{it} - E_F}{k_B T} \right) \right] \quad 13-3$$

The self-consistent coupled Schrodinger-Poisson model is enabled for electrons by setting the `SCHRO` parameter of the `MODEL` statement. With this parameter set, ATLAS solves the one-dimensional Schrodinger's Equation along a series of slices in the  $y$  direction relative to the device.

The locations of the slices in the  $y$  direction is developed in two ways. For rectangular ATLAS-defined meshes, the slices will automatically be taken along the existing mesh lines in the ATLAS mesh. If the mesh is non-rectangular and/or not an ATLAS defined mesh, specify a rectangular mesh. To do this, specify the locations of individual mesh lines and their local spacings using the `SX.MESH` and `SY.MESH` statements like that to the specification of a device mesh using the `X.MESH` and `Y.MESH` or a laser mesh using the `LX.MESH` and `LY.MESH` statements.

If you want, specify a mesh for Schrodinger's Equation to solve on an ATLAS rectangular mesh using the `SX.MESH` and `SY.MESH` statements. But since, by default, the solver uses the ATLAS mesh, you must specify `NEW.SCHRODINGER` in the `MODEL` statement to use the separate mesh.

For holes, the Schrodinger-Poisson model is enabled by setting the `P.SCHRO` parameter in the `MODEL` statement.

Once the solution of Schrodinger's Equation is taken, carrier concentrations calculated from Equation 13-3 are substituted into the charge part of Poisson's Equation. The potential derived from solution of Poisson's Equation is substituted back into Schrodinger's Equation. This solution process (alternating between Schrodinger's and Poisson's equations) continues until convergence and a self-consistent solution of Schrodinger's and Poisson's equations is reached.

Since the wavefunctions diminish rapidly from the confining potential barriers in the Schrodinger solutions, the carrier concentrations become small and noisy. You can refine these carrier concentrations by setting a minimum carrier concentration using the `QMINCONC` parameter from the `MODELS` statement. This parameter sets the minimum carrier concentration passed along to the Poisson solver and the output to the structure files. The transition between the Schrodinger solution and the minimum concentration is refined between  $10 \times QMINCONC$  and `QMINCONC` so that it is continuous in the first derivative.

Use the `SAVE` statement or the `OUTFILE` parameter from the `SOLVE` statement to write the solutions of the self-consistent system into a structure file. These structure files will then contain the self-consistent potential and electron or hole concentrations.

The Eigen energies and functions can also be written to the structure file by specifying the `EIGENS` parameter from the `OUTPUT` statement. This parameter specifies the number of Eigen energies/wave functions to be written.

The number of Eigen values solved is limited to a number of 2 less than the total number of grid points in the Y direction. Note that the self-consistent solution of Schrodinger's Equation with the Poisson's Equation doesn't allow solutions for the electron and hole continuity equations in the current ATLAS version. Non-self-consistent solutions, however, can be obtained by setting the `POST.SCHRO` parameter in the `MODELS` statement. These non-self-consistent solutions are obtained by solving Schrodinger's Equation only after convergence is obtained. That way, you can obtain Schrodinger solutions with the electron and hole continuity equations.

Similar results are saved to the structure file and the meaning of the `EIGENS` parameter in the `OUTPUT` statement are the same. In obtaining post-processed (`POST.SCHRO`) solutions for the Schrodinger's Equation, an assumption is made about the location of the electron or hole quasi-fermi level. You can set two flags in the `MODELS` statement to vary the interpretation of these results. These flags are the `FIXED.FERMI` and `CALC.FERMI` parameters, which have interpretations in Table 13-1.

| Table 13-1. Interpretations of optional parameters during post-processed Schrodinger solution |            |  |
|---|------------|--|
| FIXED.FERMI   | CALC.FERMI | Quasi-Fermi Level Calculation Method   |
| FALSE   | FALSE      | Quasi-Fermi level is calculated from the local electron density using Equation 3-9.  |
| FALSE   | TRUE       | Quasi-Fermi level varies with Y position and is calculated to match the local classical and quantum-mechanical charge concentration. |
| TRUE  | FALSE      | Quasi-Fermi level is uniformly zero.   |
| TRUE  | TRUE       | Quasi-Fermi level is uniform across Y slice and is calculated to match the classical and quantum-mechanical sheet charge.            |



## 13.2: Density Gradient (Quantum Moments Model)

The quantum models apply to several different types of problems. These problems are HEMT channel confinement simulation, thin gate oxide MOS capacitors and transistors, and other problems such as small geometry MESFETs and heterojunction diodes.

The effects due to confinement of carriers associated with variations of local potential on the scale of the electron wave functions (i.e., quantum effects) can be modeled in ATLAS using a density gradient. This model is based on the moments of the Wigner Function Equations-of-Motion [34, 119, 120, 142], which consists of quantum correction to the carrier temperatures in the carrier current and energy flux equations (see Chapter 3: “Physics”, Equations 3-20 to 3-23).

In the density gradient model, the expression for electron current given in Chapter 3: “Physics”, Equation 3-11 is replaced by the expression given in Equation 13-4.

$$\vec{J}_n = qD_n \nabla n - qn\mu_n \nabla(\psi - \Lambda) - \mu_n n (kT_L \nabla(\ln n_{ie})) \quad 13-4$$

Here,  $\Lambda$  is a quantum correction potential.

Equation 13-5 is the density gradient model for holes.

$$\vec{J}_p = qD_p \nabla p - qp\mu_p \nabla(\psi - \Lambda) - \mu_p p (kT_L \nabla(\ln n_{ie})) \quad 13-5$$

The quantum potential can be calculated using either of the two expressions given in Equations 13-6 and 13-7.

$$\Lambda = -\frac{\gamma\hbar^2}{12m} \left[ \nabla^2 \log n + \frac{1}{2} (\nabla \log n)^2 \right] \quad 13-6$$

$$\Lambda = -\frac{\gamma\hbar^2}{6m} \frac{\nabla^2 \sqrt{n}}{\sqrt{n}} \quad 13-7$$

where  $\gamma$  is a fit factor,  $m$  is the carrier effective mass, and  $n$  represents electron or hole concentration as appropriate. To choose between these expressions, specify DGLOG for Equation 13-6 or DGROOT for Equation 13-7 in the MODELS statement. By default, DGLOG is used. The fit factors for electrons and holes can be specified independently using the DGN.GAMMA or the DGP.GAMMA parameters of the MODELS statement respectively.

These expressions and particularly their derivatives can be seen to be sensitive to low carrier concentrations. You can specify a minimum concentration to use in these calculations using the QMINCONC parameter in the MODELS statement. This parameter specifies the minimum concentration used in the calculations of Equations 13-6 and 13-7 in  $\text{cm}^{-3}$ .

You can activate the model for electrons and holes independently. To activate the quantum model with the Quantum Moments Equation for electrons, use the quantum switch, MODELS QUANTUM, in the MODELS statement. To activate the Quantum Moments Equation for holes, use the quantum switch, MODELS P.QUANTUM.

Specify T.QUANTUM in the OUTPUT statement to write the quantum temperatures in the standard structure file. Once written you can examine the quantum temperature distribution using TONYPLOT.

Since the distributions of carriers given by the density gradient can vary greatly from the distributions predicted by the standard drift-diffusion or energy-balance models, the standard initial guess strategies (e.g., INIT) aren't usually suitable for obtaining solutions for quantum moments. Until more

suitable initial guess strategies can be devised, we've included a damping factor to gradually apply to the density gradient.

This damping factor is specified by the QFACTOR parameter in the SOLVE statement. The QFACTOR is implemented as a pre-factor to the expression for the quantum temperature in Equations 13-6 and 13-7. As such, a value of QFACTOR of 0.0 implies that the density gradient is either turned off or not applied. A value of QFACTOR of 1.0 implies that the Quantum Moment Model is turned on and applied.

You can vary the value of QFACTOR between 0.0 and 1.0 to overcome the problems of initial guess. During this ramping of QFACTOR, PREVIOUS should be used as an initial guess. Also, while varying the QFACTOR, trapping is available if a given solution doesn't converge. In such cases, the QFACTOR is reduced and solutions proceed until convergence is obtained or the maximum number of trap steps is exceeded.

The following is a typical fragment from an input file that ramps the QFACTOR parameter from 0 to 1:

```
MODEL NUMCARR=1 QUANTUM FLDMOB CONMOB SRH PRINT
OUTPUT CON.BAND VAL.BAND BAND.PARAM T.QUANTUM
SOLVE INIT
SOLVE QFACTOR=0.0
SOLVE QFACTOR=0.0001
SOLVE QFACTOR=0.001
SOLVE QFACTOR=0.01
SOLVE QFACTOR=0.1
SOLVE QFACTOR=1.0
LOG OUTF=test.log
SOLVE VDRAIN=0.01
```

### 13.3: Bohm Quantum Potential (BQP)

This model was developed for SILVACO by the University of Pisa and has been implemented into ATLAS with the collaboration of the University of Pisa. This is an alternative to the Density Gradient method and can be applied to a similar range of problems. There are two advantages to using Bohm Quantum Potential (BQP) over the density gradient method. First, it has better convergence properties in many situations. Second, you can calibrate it against results from the Schrodinger-Poisson equation under conditions of negligible current flow.

The model introduces a position dependent Quantum Potential,  $Q$ , which is added to the Potential Energy of a given carrier type. This quantum potential is derived using the Bohm interpretation of quantum mechanics [122] and takes the following form

$$Q = \frac{-\hbar^2 \gamma \nabla(M^{-1} \nabla(n^\alpha))}{2 n^\alpha} \quad 13-8$$

where  $\gamma$  and  $\alpha$  are two adjustable parameters,  $M^{-1}$  is the inverse effective mass tensor and  $n$  is the electron (or hole) density. This result is similar to the expression for the quantum potential in the density gradient model with  $\alpha = 0.5$ , but there are some differences about how they are implemented.  $Q$  is added to the continuity equations the same way  $\Lambda$  is for the density gradient method as shown in Equations 13-4 and 13-5.

The Bohm Quantum Potential (BQP) method can also be used for the Energy balance and hydrodynamic models, where the semi-classical potential is modified by the quantum potential the same way as for the continuity equations.

The iterative scheme used to solve the non-linear BQP equation along with a set of semi-classical equations is as follows. After an initial semi-classical solution has been obtained, the BQP equation is solved on its own Gummel iteration to give  $Q$  at every node in the device. The semi-classical potential is modified by the value of  $Q$  at every node and the set of semi-classical equations is then solved to convergence as usual (using a Newton or Block iterative scheme). Then, the BQP equation is solved to convergence again and the process is repeated until self-consistency is achieved between the solution of the BQP equation and the set of semi-classical equations. The set of semi-classical equations solved can be any of the combinations usually permitted by ATLAS.

#### 13.3.1: Calibration against Schrodinger-Poisson Model

You can obtain close agreement between BQP and the results of Schrodinger-Poisson (S-P) calculations for any given class of device. ATLAS has a Schrodinger-Poisson model that can model spatial confinement in only one direction. Therefore, calibration is currently restricted to this case. To obtain comparisons with S-P results, we recommend to use either the new quasistatic capacitance-voltage profile feature or compare charge-voltage curves. This will ensure similar charge control properties between the two models.

To use the BQP model for electrons (or holes), specify `BQP.N` (`BQP.P`) in the `MODELS` statement. You can also set the parameter values ( $\alpha$  and  $\gamma$ ) and the direction of the quantization (confinement). Tables 13-2 and 13-3 show the parameters to use for the `MODEL` statement.

Table 13-2. MODEL Statement Parameters for Electrons

| Parameter          | Type    | Default | Units |
|--------------------|---------|---------|-------|
| <code>BQP.N</code> | Logical | false   |       |

| Table 13-2. MODEL Statement Parameters for Electrons |         |     |    |
|--|---------|-----|----|
| BQP.NGAMMA   | Real    | 1.2 | -- |
| BQP.NALPHA   | Real    | 0.5 | -- |
| BQP.QDIR   | Integer | 2   | -- |

| Table 13-3. MODEL Statement Parameters for Holes |         |         |       |
|--|---------|---------|-------|
| Parameter  | Type    | Default | Units |
| BQP.P  | Logical | false   |       |
| BQP.PGAMMA                                       | Real    | 1.0     | --    |
| BQP.PALPHA                                       | Real    | 0.5     | --    |
| BQP.QDIR   | Integer | 2       | --    |

BQP.N switches on the model for electrons. BQP.P switches it on for holes. The BQP.NGAMMA and BQP.PGAMMA allow you to set the  $\gamma$  parameter for electrons and holes respectively. BQP.NALPHA and BQP.PALPHA allow you to set the  $\alpha$  parameter for electrons and holes respectively.

You can specify BQP.N and BQP.P separately. But if quantum effects for electrons and holes occur in the same device, then you can specify them together in the same MODELS statement.

The BQP.QDIR parameter specifies the principal quantization direction.

BQP.QDIR = 1 means the x-direction

BQP.QDIR = 2 means the y-direction

BQP.QDIR = 3 means the z-direction

For example, if a MOSFET channel is in the x-y plane, the direction of quantization (quantum confinement) is the z-direction you would set BQP.QDIR=3. For semiconductors with spherical bands, BQP.QDIR will have no effect.

The first part of the calibration is to choose a suitable biasing for the device. There should be negligible current flow and quantum confinement effects that manifest at the chosen biases. The second part of the calibration is to set the appropriate BQP parameters in the MATERIAL or MODELS statements, and to set CARRIERS=0 in the METHOD statement.

This will cause the BQP equation to be coupled with Poisson's equation using the charge density terms.

$$n = N_c \exp\left(-\frac{(E_c + qQ)}{kT}\right) \tag{13-9}$$

$$p = N_v \exp\left(-\frac{(qQ - E_v)}{kT}\right) \tag{13-10}$$

This gives the same results as solving the current continuity equations with the constraint of zero current density.

The third part of calibration is to choose the quantity to compare with S-P results.

For example, for a MOSFET holding the drain and source voltages at the same bias and ramping the gate bias will give us a bias dependent capacitance with negligible current flow. So for an NMOS, you may have the statement

```
SOLVE VGATE=0.0 NAME=GATE VSTEP=0.01 VFINAL=2.0 QSCV
```

to give us the quasi-static C-V curve as it is biased into inversion. It is best to use a fine voltage step with QSCV to give good resolution. The process can be repeated by setting the S-P model in the MODELS statement instead of BQP to obtain the same set of curves for the S-P model.

The BQP model is then rerun with different sets of parameters until an acceptable agreement with the curves produced by the S-P model is achieved.

### 13.3.2: Post Calibration runs

After obtaining the parameters for BQP, either the Drift-Diffusion or energy balance (hydrodynamic) equations can be solved as usual. For cases where Lattice Heating is important then LAT . TEMP can be enabled at the same time.

The iteration scheme uses a modified version of BLOCK. Set BLOCK in the METHOD statement (although NEWTON and GUMMEL are ignored, BLOCK is always used if the BQP model is set). If an Energy Balance model is chosen (HCTE . EL or HCTE . HO on the MODELS statement), then an alternative iteration scheme will become available by specifying BQP . ALTEB in the METHOD statement. This method is slower and is only available in ATLAS2D but may have better convergence properties.

By using BQP . NOFERMI, the BQP equation will only use its Boltzmann statistics form. Without this parameter, the statistics used are those specified for the other equations. With fermi statistics, the convergence can be poor for very high carrier densities, and this parameter can circumvent some convergence properties.

Re-calibrate the BQP parameters if you set BQP . NOFERMI.

| Parameter     | Type    | Default | Units |
|---------------|---------|---------|-------|
| BQP . ALTEB   | Logical | false   |       |
| BQP . NOFERMI | Logical | false   |       |

To speed up convergence, specify the NOCURRENT parameter on the first SOLVE statement after SOLVE INIT. It should prevent the need to use the QFACTOR parameter as was necessary for the Density Gradient method. QSCV enables the quasistatic capacitance calculation and output.

| Parameter | Type    | Default | Units |
|-----------|---------|---------|-------|
| NOCURRENT | Logical | false   |       |
| QSCV      | Logical | false   |       |
| QFACTOR   | Real    | 1.0     |       |

Use the parameters in Table 13-6 to control solution convergence behavior.

| Table 13-6. METHOD Statement Parameters |         |                          |
|---|---------|--------------------------|
| Parameter                               | Type    | Default                  |
| BQPX.TOL                                | Real    | 2.5e-7                   |
| BQPR.TOL                                | Real    | 1.0E-26 (2d)1.0E-18 (3d) |
| NBLOCKIT                                | Integer | 15                       |
| ITLIMIT                                 | Integer | 25                       |
| GUMITS                                  | Integer | 100                      |

The solution comprises of OUTER iterations (which end when self-consistency occurs) and within these are solutions of groups of equations or single equations. The BQP equation is implemented so that both LHS and RHS convergence are required. You cannot override this default behavior. Tests carried out have shown it gives the best performance. ITLIMIT controls how many iterations can occur for the BQP equation in SOLVE INIT. This is 10 \* ITLIMIT. For CARRIERS=0 solutions, the maximum number of iterations for the individual equation solvers is GUMITS. The maximum number of OUTER iterations is ITLIMIT. NBLOCKIT controls the number of OUTER cycles in the Drift-Diffusion and Energy-Balance cases. The maximum number of Drift-Diffusion solution and Carrier-Energy solution iterations is ITLIMIT, and the maximum number of BQP solutions is GUMITS.

**Note:** The Bohm Quantum potential is stored in ATLAS as an energy and so the convergence criteria are actually of order KT less than those for scaled electrostatic potential. In ATLAS 3D, the BQP equation had an extra scaling factor applied and so the RHS norms are larger than in 2D. LHS norms, however, are the same.

The Bohm Quantum Potential is automatically calculated in insulators. If you specify the SEMICONDUCTOR parameter in the MATERIAL statement for the insulator, the drift-diffusion equations will be solved in the insulator and will include the BQP corrections. It is also recommended to set the densities of states of the insulator to be the same as the semiconductor to which they interface. For example for Silicon/SiO2 system, set

```
MATERIAL REGION=N NC300=2.8E19 NV300=1.04E19
```

where N is region number of SiO2.

You can also set the BQP parameters on a material by material basis, which may be necessary for heterojunction based devices. The BQP model is applied globally and cannot be set on a region by region basis.

Table 13-7 shows the material parameters that have a direct impact on the BQP equation.

| Table 13-7. MATERIAL Statement |         |         |
|--------------------------------|---------|---------|
| Parameter                      | Type    | Default |
| SEMICONDUCTOR                  | Logical | false   |
| EG300                          | Real    |         |
| AFFINITY                       | Real    |         |

|            |      |     |
|------------|------|-----|
| NC300      | Real |     |
| NV300      | Real |     |
| BQP.NALPHA | Real | 0.5 |
| BQP.NGAMMA | Real | 1.2 |
| BQP.PALPHA | Real | 0.5 |
| BQP.PGAMMA | Real | 1.0 |

There is one more pertinent parameter, BQP.NEUMANN, which can be set on the MODELS statement.

BQP.NEUMANN sets the normal gradient of classical+quantum potential explicitly to zero on non-contact boundaries. If cleared using MODELS ^BQP.NEUMANN, the Neumann conditions will then be applied implicitly. Clearing this flag may give a slight speed increase and slight differences in solution.

| Table 13-8. OUTPUT Statement Parameters |         |         |
|---|---------|---------|
| Parameter                               | Type    | Default |
| P.QUANTUM                               | Logical | False   |

Setting the P.Quantum parameter in the OUTPUT statement will cause the Bohm Quantum Potential to output to a structure file. The Electron Quantum Potential and Hole Quantum Potential will both output.

## 13.4: Quantum Correction Models

In deep submicron MOS devices, quantum effects in the channel can have significant effects on the device characteristics. These effects are directly due to the increased doping levels and thinner gate oxide. In the channel of such devices, the potential well formed during inversion where the effects of quantum confinement must be considered. The direct effect of such quantum confinement is that the peak of the carrier concentration is shifted away from the interface and the thinner gate oxide can cause a marked difference in gate capacitance. Consideration of the effects may be essential for accurate prediction of the device turn-on voltage.

To fully treat quantum effects, solving the Schrodinger's Equation, isn't always desirable or necessary.

### 13.4.1: Hansch's Model

The quantum mechanical correction given by Hansch [123] is suitable for accurate simulation of the effects of quantum mechanical confinement near the gate oxide interface in MOSFETs. To enable the model, specify the HANSCHQM parameter of the MODEL statement. This correction model is a modification of the density of states as a function of depth below the Si/SiO<sub>2</sub> interface, which is given by Equation 13-11.

$$N_C^* = N_C \left[ 1 - \exp\left(-\left(\frac{z}{\text{LAMBDA}}\right)^2\right) \right]. \tag{13-11}$$

Here,  $N_C$  is the standard density of states,  $z$  is the depth below the interface. LAMBDA is a user-definable parameter in the MODEL statement.

| Table 13-9. User-definable parameter for Equation 13-11 |           |                      |       |
|---|-----------|----------------------|-------|
| Statement   | Parameter | Default              | Units |
| MODELS  | LAMBDA    | 1.0x10 <sup>-3</sup> | µm    |

### 13.4.2: Van Dort's Model

In the Van Dort's Model [121], the effects of the quantum confinement are modeled by broadening the bandgap near the surface, which makes a function of a perpendicular electric field and distance from the surface. In Van Dort's Model, the change in bandgap is given by the expression in Equation 13-12.

$$\Delta E_g = B \cdot \text{DORT} \beta \frac{13}{9} \left( \frac{\epsilon_{si}}{4 q k_B T_L} \right)^{1/3} (E_{\perp})^{2/3} g(y). \tag{13-12}$$

Here, B.DORT is a user-definable parameter in the MODEL statement,  $\beta$  is equal to 6.1x10<sup>-8</sup> eV cm,  $E_{\perp}$  is the perpendicular electric field, and  $g(y)$  is a function to restrict the application of the model to the channel region, given by Equation 13-13.

$$g(y) = \frac{2e^{-(Y/D \cdot \text{DORT})^2}}{1 + e^{-2(Y/D \cdot \text{DORT})^2}}. \tag{13-13}$$

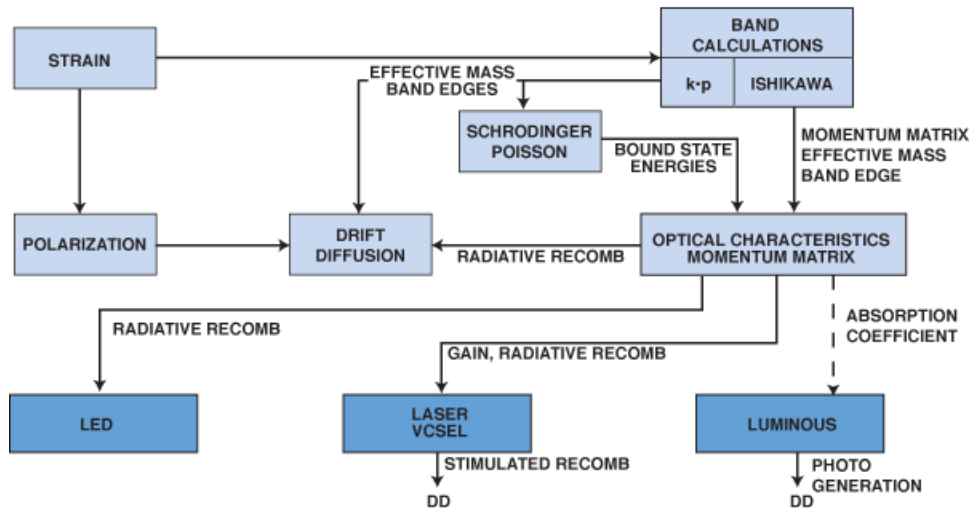
The Van Dort's Model for N channel devices is enabled by specifying N.DORT in the MODELS statement. For P channel devices, the Van Dort's Model is enabled by specifying P.DORT in the MODELS statement.



| <b>Table 13-10. User-definable parameters for Equation 13-13</b> |                  |                      |              |
|--|------------------|----------------------|--------------|
| <b>Statement</b>   | <b>Parameter</b> | <b>Default</b>       | <b>Units</b> |
| MODELS   | D.DORT           | $2.5 \times 10^{-6}$ | cm           |
| MODELS   | B.DORT           | 1.0                  | cm           |

## 13.5: General Quantum Well Model

The general quantum well model is used to predict bound state energies in a region for subsequent use in modelling optoelectronic gain, radiative recombination and absorption. Figure 13-1 shows the simulation flow for such modelling.



**Figure 13-1: Simulation Flow For Physically Based Optoelectronic Models**

The extraction of bound state energies is done by solving the Schrodinger equation (see Equation 13-1) along discrete slices in the Y direction using the interpolated values of the local potential and effective masses.

You can enable the quantum well model by specifying `QWELL` in the `REGION` statement. You should also specify `WELL.NX` and `WELL.NY` in the `REGION` statement. The `WELL.NX` parameter specifies the integer number of slices along which Schrodinger solutions are taken. The `WELL.NY` parameter describes the number of samples along each slice. The sampling along both X and Y is uniform and bound state energy values are interpolated back onto the device mesh for the optical modelling. Generally, you should select `WELL.NX` and `WELL.NY` to adequately resolve the geometry but there is a tradeoff between computational accuracy and speed.

The `WELL.CNBS` and `WELL.VNBS` parameters of the `REGION` statement specify the maximum number of bound state energies to resolve in the conduction and valence band. When calculating the bound state energies, the actual number of bound states may be less than or equal to the value specified by these parameters. The actual number of bound states calculated also must be less than the number of samples specified by the `WELL.NY` parameter minus 2.

You can also ignore the effects of electric field by specifying the `WELL.FIELD` parameter of the `REGION` statement. This parameter enables calculation bound state dependencies on bias conditions. By default, `WELL.FIELD` is true. If disabled by specifying `^WELL.FIELD`, the bound states are only calculated once at zero bias and used for all subsequent solutions regardless of bias conditions.

You can also specify regions for quantum well simulation in the `SUPERLATTICE (DBR)` statement. To enable the model, specify the `QWELL1` and `QWELL2` parameters. These enable quantum modelling for the first and second superlattice cycles respectively. The sampling of the quantum wells are controlled by the `WELL1.NX`, `WELL2.NX`, `WELL1.NY` and `WELL2.NY` parameters.

The numbers of bound states are controlled by the `WELL1.CNBS`, `WELL2.CNBS`, `WELL1.VNBS` and `WELL2.VNBS` parameters. The field effects are controlled by the `WELL1.FIELD` and `WELL2.FIELD` parameters.

## 13.6: Multiple Quantum Well Model

Optical gain and spontaneous recombination models implemented in ATLAS are used to account for the effects of quantum mechanical confinement of carriers and strain effects in Multiple Quantum Wells (MQW). To enable these models, use the MQW statement (see Chapter 18: “Statements”, Section 18.30: “MQW”).

The MQW statement has parameters describing the locations and compositions of the wells, the effects of strain on the band edges, parameters relating to the gain and recombination models, and parameters relating to how the models interact with other electrical and optical simulation models.

---

**Note:** The method for defining quantum wells using the MQW statement described in this section has been superseded by the method described in Section 13.6: “Multiple Quantum Well Model”. Therefore, we highly recommended that you use to the newer syntax.

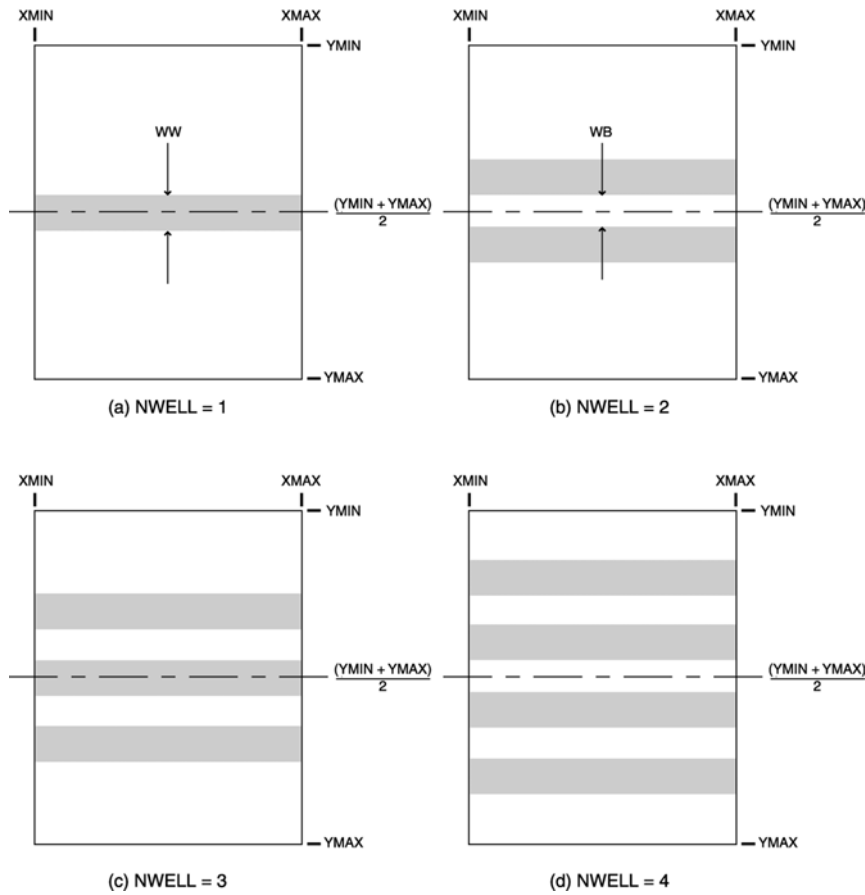
---

### 13.6.1: Specifying MQW Location and Composition

In order to model the MQWs, specify the locations of the wells. The location of the wells is specified by the XMIN, XMAX, YMIN, and YMAX parameters. These parameters specify the location of a bounding box in units of microns (See Figure 13-2). XMIN and XMAX specify the extent of the wells in the X direction (i.e., the wells are horizontal and extend across the entire bounding box in the X direction). The YMIN and YMAX parameters define the center of the wells in the Y direction (i.e., the set of defined wells will be centered in the Y direction at the average coordinate of YMIN and YMAX).

The WW parameter specifies the width of each well in microns. The WB parameter specifies the width of the barrier between the wells in microns. The NWEELL parameter specifies the number of wells.

Figure 13-2 gives illustrations of the how quantum wells are located for 1, 2, 3, and 4 quantum wells.



**Figure 13-2: Examples of Specifying MQW Locations**

The MATERIAL, XCOMP, YCOMP, DONORS, and ACCEPTORS parameters in the MQW statement define the composition of the wells. The MATERIAL parameter is assigned to the name of one of the allowed ATLAS materials discussed in Appendix B: “Material Systems”, Section B.3: “ATLAS Materials”. For ternary and quaternary materials, the XCOMP and YCOMP parameters can be used to specify the X and Y composition fractions. The DONORS and ACCEPTORS parameters specify uniform densities of ionized donors and acceptors in the wells.

The STRAIN, ASTR, BSTR, CSTR, DSTR, ESTR, FSTR, and STABLE parameters specify the strain effects. See Chapter 18: “Statements”, Section 18.30: “MQW” for more information on these effects.

### 14.1: Polycrystalline and Amorphous Semiconductor Models

TFT is an ATLAS module that simulates disordered material systems. TFT doesn't contain material models so you need to combine either S-PISCES or BLAZE with TFT to simulate these material systems.

TFT enables you to define an energy distribution of defect states in the bandgap of semiconductor materials. This is necessary for the accurate treatment of the electrical properties of such materials as polysilicon and amorphous silicon.

The syntax used by TFT is a part of the ATLAS syntax so there's no need for you to learn how to use a new simulator to run TFT simulations.

Before continuing with this chapter, you should be familiar with ATLAS physics. If not, read Chapters 2: "Getting Started with ATLAS" and 3: "Physics" before proceeding further. For more information on S-PISCES and BLAZE, see Chapters 4: "S-Piscses: Silicon Based 2D Simulator" and 5: "Blaze: Compound Material 2D Simulator".

## 14.2: Simulating TFT Devices

This section is intended to illustrate the basic building blocks for a thin-film transistor simulation.

To use TFT, specify the addition of defect states into the bandgap of a previously defined crystalline material. Throughout this section the example of polysilicon is used. Amorphous silicon and other disordered materials are handled in a similar manner.

### 14.2.1: Defining The Materials

Use the ATLAS command syntax to define a simple polysilicon thin-film transistor structure. The MESH, X.MESH, and Y.MESH statements can be used to construct a mesh as described in Chapter 2: "Getting Started with ATLAS", Section 2.6: "Defining A Structure". For more informations on mesh statements, Chapter 18: "Statements,", Sections 18.26: "MESH" and 18.51: "X.MESH, Y.MESH, Z.MESH".

When defining the material regions, use the following syntax.

```
REGION Y.MIN=-0.05 Y.MAX=0    OXIDE
REGION Y.MIN=0      Y.MAX=0.2 SILICON
REGION Y.MIN=0.2   Y.MAX=2    OXIDE
```

Note that the region is defined as silicon. You can also define the material as polysilicon. But note that it is the defect distribution rather than this initial material definition that will determine the electrical characteristics.

### 14.2.2: Defining The Defect States

Disordered materials contain a large number of defect states within the band gap of the material. To accurately model devices made of polycrystalline or amorphous materials, use a continuous density of states. The DEFECT statement is used to specify the density of defect states (DOS) as a combination of exponentially decaying band tail states and Gaussian distributions of mid-gap states [81, 82]. In addition, you may need to model the grain-grain boundary interface as a thermionic field emission boundary [143].

---

**Note:** The INTDEFECTS, INTERFACE S.S and TRAP.COULOMBIC models are available for grain-grain boundary interface modeling. These models have been developed in collaboration with Epsom and Cambridge University. For more information, see Chapter 18: "Statements,", Sections 18.17: "INTDEFECTS", 18.18: "INTERFACE", and 18.29: "MODELS".

---

### 14.2.3: Density of States Model

It is assumed that the total density of states (DOS) and  $g(E)$ , is composed of four bands: two tail bands (a donor-like valence band and an acceptor-like conduction band) and two deep level bands (one acceptor-like and the other donor-like) which are modeled using a Gaussian distribution.

$$g(E) = g_{TA}(E) + g_{TD}(E) + g_{GA}(E) + g_{GD}(E) \quad 14-1$$

Here,  $E$  is the trap energy,  $E_C$  is the conduction band energy,  $E_V$  is the valence band energy and the subscripts (T, G,A, D) stand for tail, Gaussian (deep level), acceptor and donor states respectively.

$$g_{TA}(E) = NTA \exp\left[\frac{E - E_C}{WTA}\right] \quad 14-2$$

$$g_{TD}(E) = \mathbf{NTD} \exp\left[\frac{E_v - E}{\mathbf{WTD}}\right] \quad 14-3$$

$$g_{GA}(E) = \mathbf{NGA} \exp\left[-\left[\frac{\mathbf{EGA} - E}{\mathbf{WGA}}\right]^2\right] \quad 14-4$$

$$g_{GD}(E) = \mathbf{NGD} \exp\left[-\left[\frac{E - \mathbf{EGD}}{\mathbf{WGD}}\right]^2\right] \quad 14-5$$

For an exponential tail distribution, the DOS is described by its conduction and valence band edge intercept densities (NTA and NTD), and by its characteristic decay energy (WTA and WTD).

For Gaussian distributions, the DOS is described by its total density of states (NGA and NGD), its characteristic decay energy (WGA and WGD), and its peak energy/peak distribution (EGA and EGD). Table 14-1 shows the user-specifiable parameters for the density of defect states.

| Table 14-1. User-Specifiable Parameters for Equations 14-2 to 14-5 |           |                       |                  |
|--|-----------|-----------------------|------------------|
| Statement  | Parameter | Default               | Units            |
| DEFECT   | NTA       | 1.12x10 <sup>21</sup> | cm <sup>-3</sup> |
| DEFECT   | NTD       | 4.0x10 <sup>20</sup>  | cm <sup>-3</sup> |
| DEFECT   | NGA       | 5.0x10 <sup>17</sup>  | cm <sup>-3</sup> |
| DEFECT   | NGD       | 1.5x10 <sup>18</sup>  | cm <sup>-3</sup> |
| DEFECT   | EGA       | 0.4                   | eV               |
| DEFECT   | EGD       | 0.4                   | eV               |
| DEFECT   | WTA       | 0.025                 | eV               |
| DEFECT   | WTD       | 0.05                  | eV               |
| DEFECT   | WGA       | 0.1                   | eV               |
| DEFECT   | WGD       | 0.1                   | eV               |

#### 14.2.4: Trapped Carrier Density

The electron and hole concentrations due to trapped states ( $n_T$  and  $p_T$  respectively) are given by:

$$n_T = n_{TA} + n_{GA} \quad 14-6$$

$$p_T = p_{TD} + p_{GD} \quad 14-7$$

where  $n_{TA}$ ,  $n_{GA}$ ,  $p_{TD}$  and  $p_{GD}$  are given below.

$$n_{TA} = \int_{E_C}^{E_V} g_{TA}(E) \cdot f_{t_{TA}}(E, n, p) dE \quad 14-8$$

$$n_{GA} = \int_{E_V}^{E_C} g_{GA}(E) \cdot f_{t_{GA}}(E, n, p) dE \quad 14-9$$

$$p_{TD} = \int_{E_V}^{E_C} g_{TD}(E) \cdot f_{t_{TD}}(E, n, p) dE . \quad 14-10$$

$$p_{GD} = \int_{E_V}^{E_C} g_{GD}(E) \cdot f_{t_{GD}}(E, n, p) dE \quad 14-11$$

$f_{t_{TA}}(E, n, p)$  and  $f_{t_{GA}}(E, n, p)$  are probabilities of occupation for the tail and Gaussian acceptor DOS, while  $f_{t_{TD}}(E, n, p)$  and  $f_{t_{GD}}(E, n, p)$  are the equivalent for the donors.

In the steady-state case, the probability of occupation of a trap level at energy E for the tail and Gaussian acceptor and donor states are given by Equations 14-12 through 14-15.

$$f_{t_{TA}}(E, n, p) = \frac{v_n \text{SIGTAE } n + v_p \text{SIGTAH } n_i \exp\left[\frac{E_i - E}{kT}\right]}{v_n \text{SIGTAE} \left(n + n_i \exp\left[\frac{E - E_i}{kT}\right]\right) + v_p \text{SIGTAH} \left(p + n_i \exp\left[\frac{E_i - E}{kT}\right]\right)} \quad 14-12$$

$$f_{t_{GA}}(E, n, p) = \frac{v_n \text{SIGGAE } n + v_p \text{SIGGAH } n_i \exp\left[\frac{E_i - E}{kT}\right]}{v_n \text{SIGGAE} \left(n + n_i \exp\left[\frac{E - E_i}{kT}\right]\right) + v_p \text{SIGGAH} \left(p + n_i \exp\left[\frac{E_i - E}{kT}\right]\right)} \quad 14-13$$

$$f_{t_{TD}}(E, n, p) = \frac{v_n \text{SIGTDE } n + v_p \text{SIGTDH } n_i \exp\left[\frac{E_i - E}{kT}\right]}{v_n \text{SIGTDE} \left(n + n_i \exp\left[\frac{E - E_i}{kT}\right]\right) + v_p \text{SIGTDH} \left(p + n_i \exp\left[\frac{E_i - E}{kT}\right]\right)} \quad 14-14$$

$$f_{t_{GD}}(E, n, p) = \frac{v_n \text{SIGGDE } n + v_p \text{SIGGDH } n_i \exp\left[\frac{E_i - E}{kT}\right]}{v_n \text{SIGGDE} \left(n + n_i \exp\left[\frac{E - E_i}{kT}\right]\right) + v_p \text{SIGGDH} \left(p + n_i \exp\left[\frac{E_i - E}{kT}\right]\right)} \quad 14-15$$



where  $v_n$  is the electron thermal velocity and  $v_p$  is the hole thermal velocity,  $n_i$  is the intrinsic carrier concentration. SIGTAE and SIGGAE are the electron capture cross-section for the acceptor tail and Gaussian states respectively. SIGTAH and SIGGAH are the hole capture cross-sections for the acceptor tail and Gaussian states respectively and SIGTDE, SIGGDE, SIGGDH, and SIGGDH are the equivalents for donors states.

| Table 14-2. User-Specifiable Parameters for Equations 14-12 to 14-15 |           |                       |               |
|--|-----------|-----------------------|---------------|
| Statement  | Parameter | Default               | Units         |
| DEFECT   | SIGTAE    | $1.0 \times 10^{-16}$ | $\text{cm}^2$ |
| DEFECT   | SIGTDE    | $1.0 \times 10^{-14}$ | $\text{cm}^2$ |
| DEFECT   | SIGGAE    | $1.0 \times 10^{-16}$ | $\text{cm}^2$ |
| DEFECT   | SIGGDE    | $1.0 \times 10^{-14}$ | $\text{cm}^2$ |
| DEFECT   | SIGTAH    | $1.0 \times 10^{-14}$ | $\text{cm}^2$ |
| DEFECT   | SIGTDH    | $1.0 \times 10^{-16}$ | $\text{cm}^2$ |
| DEFECT   | SIGGAH    | $1.0 \times 10^{-14}$ | $\text{cm}^2$ |
| DEFECT   | SIGGDH    | $1.0 \times 10^{-16}$ | $\text{cm}^2$ |

### 14.2.5: Steady-state Trap Recombination

For steady-state conditions, the net recombination/generation rate is identical for electrons ( $R_n$ ) and holes ( $R_p$ ) (i.e., instantaneous equilibrium). Using Equations 14-12 through 14-15 to give the values of  $f_t$  and following the derivation by Shockley and Read [21] and Hall [124], the Shockley-Read-Hall recombination/generation rate due to the defect states is given by:

$$\begin{aligned}
 R_{n,p} = & \int_{E_V}^{E_C} \left( \frac{v_n v_p \text{SIGTAE SIGTAH} (n p - n_i^2) g_{TA}(E)}{v_n \text{SIGTAE} (n + n_i \exp[\frac{E-E_i}{kT}]) + v_p \text{SIGTAH} (p + n_i \exp[\frac{E_i-E}{kT}])} \right. \\
 & + \frac{v_n v_p \text{SIGTGAE SIGGAH} (n p - n_i^2) g_{GA}(E)}{v_n \text{SIGGAE} (n + n_i \exp[\frac{E-E_i}{kT}]) + v_p \text{SIGGAH} (p + n_i \exp[\frac{E_i-E}{kT}])} \\
 & + \frac{v_n v_p \text{SIGTDE SIGTDH} (n p - n_i^2) g_{TD}(E)}{v_n \text{SIGTDE} (n + n_i \exp[\frac{E-E_i}{kT}]) + v_p \text{SIGTDH} (p + n_i \exp[\frac{E_i-E}{kT}])} \\
 & \left. + \frac{v_n v_p \text{SIGGDE SIGGDH} (n p - n_i^2) g_{GD}(E)}{v_n \text{SIGGDE} (n + n_i \exp[\frac{E-E_i}{kT}]) + v_p \text{SIGGDH} (p + n_i \exp[\frac{E_i-E}{kT}])} \right) dE = \quad = \quad 14-16
 \end{aligned}$$

## 14.2.6: Transient Traps

For the transient case, time is required for carriers to be emitted or captured and therefore instantaneous equilibrium cannot be assumed. This means that Equation 14-16 is no longer valid for transient simulations. Instead, the total recombination/generation rate for electrons (which is equal to electron recombination rate minus the generation rate for electrons) is calculated using the transient probabilities of occupation for acceptors ( $f_{tTA}$  and  $f_{tGA}$ ). These are calculated by solving additional rate equations (Equations 14-17 and 14-18).

$$\begin{aligned} \frac{d}{dt}(n_{TA}) = & \int_{E_V}^{E_C} g_{TA}(E) \left[ v_n \text{SIGTAE} \left( n \left( 1 - f_{tTA}(E) \right) - f_{tTA}(E) n_i \exp \left[ \frac{E - E_i}{k T} \right] \right) \right. \\ & \left. - v_p \text{SIGTAH} \left( p f_{tTA}(E) - \left( 1 - f_{tTA}(E) \right) n_i \exp \left[ \frac{E_i - E}{k T} \right] \right) \right] dE \end{aligned} \quad 14-17$$

$$\begin{aligned} \frac{d}{dt}(n_{GA}) = & \int_{E_V}^{E_C} g_{GA}(E) \left[ v_n \text{SIGGAE} \left( n \left( 1 - f_{tGA}(E) \right) - f_{tGA}(E) n_i \exp \left[ \frac{E - E_i}{k T} \right] \right) \right. \\ & \left. - v_p \text{SIGGAH} \left( p f_{tGA}(E) - \left( 1 - f_{tGA}(E) \right) n_i \exp \left[ \frac{E_i - E}{k T} \right] \right) \right] dE \end{aligned} \quad 14-18$$

The total hole recombination/generation rate can also be determined from the transient values of  $f_{tTD}$  and  $f_{tGD}$  (see Equations 14-19 and 14-20).

$$\begin{aligned} \frac{d}{dt}(p_{TD}) = & \int_{E_V}^{E_C} g_{TD}(E) \left[ v_n \text{SIGTDE} \left( n \left( 1 - f_{tTD}(E) \right) - f_{tTD}(E, n, p) n_i \exp \left[ \frac{E - E_i}{k T} \right] \right) \right. \\ & \left. - v_p \text{SIGTDH} \left( p f_{tTD}(E) - \left( 1 - f_{tTD}(E) \right) n_i \exp \left[ \frac{E_i - E}{k T} \right] \right) \right] dE \end{aligned} \quad 14-19$$

$$\begin{aligned} \frac{d}{dt}(p_{GD}) = & \int_{E_V}^{E_C} g_{GD}(E) \left[ v_n \text{SIGGDE} \left( n \left( 1 - f_{tGD}(E) \right) - f_{tGD}(E) n_i \exp \left[ \frac{E - E_i}{k T} \right] \right) \right. \\ & \left. - v_p \text{SIGGDH} \left( p f_{tGD}(E) - \left( 1 - f_{tGD}(E) \right) n_i \exp \left[ \frac{E_i - E}{k T} \right] \right) \right] dE \end{aligned} \quad 14-20$$

A transient trap simulation using this model is more time consuming than using the static model but gives a much more accurate description of the device physics. It may sometimes be acceptable to perform transient calculations using the static trap distribution and assume that traps reach equilibrium instantaneously. Specifying `FAST` on the `DEFECTS` statement will neglect the trap rate equation from the simulation.

### Trap-Assisted Tunneling

Trap-Assisted Tunneling models the trap-to-band phonon-assisted tunneling effects for Dirac wells. At high electric fields, tunneling of electrons from the valence band to the conduction band through trap or defect states can have an important effect on the current.

Trap-assisted tunneling is modeled by including field-effect enhancement terms [113] ( $\Gamma_n^{DIRAC}$  and  $\Gamma_p^{DIRAC}$ ) in the trap lifetimes in capture cross-sections. This model is enabled by specifying `TRAP.TUNNEL` in the `MODELS` statement.

The electron capture cross-section (`SIGTAE`, `SIGGAE`, and `SIGTDE`, and `SIGGDE`) are modified by including the electron field-effect term ( $\Gamma_n^{DIRAC}$ ). For example, the electron capture cross-section for acceptor tail states (`SIGTAE`) becomes:

The field-effect enhancement term for electrons is given by:

$$SIGTAE \times 1 + \Gamma_n^{DIRAC} \quad 14-21$$

`SIGGAE`, `SIGTDE`, and `SIGGDE` are also modified this way.

$$\Gamma_n^{DIRAC} = \frac{1}{kT_L} \int_0^{\Delta E_n} \exp\left(\frac{\Delta E_n}{KT_L} u - k_n u^{3/2}\right) du \quad 14-22$$

While the field-effect enhancement term for hole is:

$$\Gamma_p^{DIRAC} = \frac{1}{kT_L} \int_0^{\Delta E_p} \exp\left(\frac{\Delta E_p}{KT_L} u - k_p u^{3/2}\right) du \quad 14-23$$

The hole capture cross-sections (`SIGTAH`, `SIGGAM`, `SIGTDM`, and `SIGGDM`) are modified by including the hole field effect term ( $\Gamma_n^{DIRAC}$ ). For example, `SIGTAM` now becomes:

$$SIGTAH \times 1 + \Gamma_n^{DIRAC} \quad 14-24$$

`SIGGAM`, `SIGTDM`, and `SIGGDM` are also modified this way.

where  $u$  is the integration variable,  $\Delta E_n$  is the energy range where tunneling can occur for electrons,  $\Delta E_p$  is the tunneling energy range for holes, and  $K_n$  and  $K_p$  are defined as:

$$k_n = \frac{4}{3} \sqrt{\frac{2m_0 \text{MASS.TUNNEL} \Delta E_n^3}{3q \hbar |E|}} \quad 14-25$$

$$k_p = \frac{4\sqrt{2m_0 \text{MASS.TUNNEL} \Delta E_p^3}}{3q \hbar |E|} \quad 14-26$$

$\hbar$  is the reduced Planck's constant,  $m_0$  is the rest mass of an electron, and `MASS.TUNNEL` is the effective mass (You can specify `MASS.TUNNEL` by setting the `MASS.TUNNEL` parameter in the `MODELS` statement).

### Poole-Frenkel Barrier Lowering

The Poole Frenkel barrier lowering effect enhances the emission rate for trap-to-band phonon-assisted tunneling and pure thermal emissions at low electric fields. The Poole Frenkel effect occurs when the Coulombic potential barrier is lowered due to the electric field and only occurs in traps with a Coulombic potential (such as traps that are neutral when filled).

The Poole-Frenkel effect is modeled by including field-effect enhancement terms for Coulombic wells ( $\Gamma_n^{COUL}$  and  $\Gamma_p^{COUL}$ ) and thermal emission ( $\chi_F$ ) [135] in the capture cross-sections. The model also includes the trap-assisted tunneling effects in the Dirac well. To enable this model, specify `TRAP.COULOMBIC` in the `MODELS` statement.

In the electron recombination/generation term ( $R_N$ ), the Coulombic barrier lowering term ( $\chi_F$ ), and the electron Coulombic field-effect enhancement term ( $\Gamma_n^{COUL}$ ) are applied to the electron capture cross-sections.

For example, `SIGTAE` now becomes:

$$\text{SIGTAE} \times (\chi_F + \Gamma_n^{COUL}) \quad 14-27$$

`SIGGAE`, `SIGTDE`, and `SIGGDE` are modified in the same manner.

The hole capture cross-section are modified by including the Dirac field-effect enhancement term for holes ( $\Gamma_n^{DIRAC}$ ).

For example, `SIGTAH` now becomes:

$$\text{SIGTAE} \times (\chi_F + \Gamma_n^{COUL}) \quad 14-28$$

`SIGGAH`, `SIGTDH`, and `SIGGDM` are modified in the same manner.

In the hole recombination/generation term ( $R_p$ ), the Coulombic terms are applied to the hole capture cross-sections and the Dirac terms applied to the electron capture cross-sections.

The Poole-Frenkel thermal emission enhancement factor,  $\chi_F$ , is defined as:

$$\chi_F = \exp\left(\frac{\Delta E_{fp}}{kT_L}\right) \quad 14-29$$

$\Delta E_{fp}$  is the barrier lowering term for a Coulombic well (see Equation 14-30).

$$\Delta E_{fp} = \sqrt{\frac{q|E|}{\pi\epsilon}} \quad 14-30$$

The Coulombic field-enhancement terms,  $\Gamma_n^{COUL}$  and  $\Gamma_p^{COUL}$ , are defined as:

$$\Gamma_n^{COUL} = \frac{\Delta E_n}{kT_L} \int_{\frac{\Delta E_{fp}}{\Delta E_n}}^1 \exp\left(\frac{\Delta E_n}{KT_L} u - k_p u^{3/2} \left[1 - \left(\frac{\Delta E_{fp}}{u \Delta E_n}\right)^{5/3}\right]\right) du \quad 14-31$$

$$\Gamma_p^{COUL} = \frac{\Delta E_p}{kT_L} \int_{\frac{\Delta E_{fp}}{\Delta E_n}}^1 \exp\left(\frac{\Delta E_p}{KT_L} u - k_p u^{3/2} \left[1 - \left(\frac{\Delta E_{fp}}{u \Delta E_p}\right)^{5/3}\right]\right) du \quad 14-32$$

### 14.2.7: Continuous Defects

If CONTINUOUS is specified in the DEFECTS statement, then the integral equations for the charge and recombination are evaluated using a numerical integral scheme [83]. In this case, the NUMA and NUMD (DEFECTS statement) parameters correspond to the number of acceptor and donor energy level intervals used in the integral.

### 14.2.8: Discrete Defects

If CONTINUOUS is not specified on the DEFECTS statement, the equation is modeled with discrete energy levels. The integrals terms in Equations 14-8 to 14-11 are replaced by summations, which run over the number of discrete energy levels (NUMA and NUMD). The acceptor and donor density of states terms are integrated separately. For example, the equation for the electron trap concentration (Equation 14-6) is replaced by:

$$n_T = \sum_{i=0}^{NUMA} \left( f_{t_{TA}}(E_i, n, p) \cdot \int_{-\infty}^{+\infty} g_{TA}(E) dE + f_{t_{GA}}(E_i, n, p) \cdot \int_{-\infty}^{+\infty} g_{GA}(E) dE \right) \quad 14-33$$

**Table 14-3. Additional Parameters for the DEFECTS Statement**

| Statement | Parameter  | Default | Units |
|-----------|------------|---------|-------|
| DEFECT    | FAST       | FALSE   |       |
| DEFECT    | CONTINUOUS | FALSE   |       |
| DEFECT    | NUMA       | 12      |       |
| DEFECT    | NUMD       | 12      |       |

Syntax for a typical defect states definition is given below.

```
DEFECTS NTA=1.12E21 NTD=4.E20 WTA=0.025 WTD=0.05 \  
        NGA=5.E17 NGD=1.5E18 EGA=0.4 EGD=0.4 \  
        GA=0.1 WGD=0.1 SIGTAE=1.E-16 \  
        SIGTAH=1.E-14 SIGTDE=1.E-14 \  
        SIGTDH=1.E-16 SIGGAE=1.E-16 SIGGAH=1.E-14 \  
        SIGGDE=1.E-14 SIGGDH=1.E-16
```

Figure 14-1 shows how the syntax is used to define the peak density of states and distribution widths for the two tail states and two Gaussian distributions.

### 14.2.9: Plotting The Density Of States Versus Energy

The `DFILE` and `AFILE` parameters were used to allow you to specify output file names for capture of defect densities as a function of energy for donor states and acceptor states, respectively. For example, if you want to look at the donor and acceptor defect distributions, specify the following line:

```
DEFECTS DFILE=donors AFILE=acceptors
```

The files, *donors* and *acceptors*, could then be loaded into `TONYPLOT` to look at the distributions of donor and acceptor defects as a function of energy.

### 14.2.10: Using the C-Interpreter to define DEFECTS

The `C-INTERPRETER` can be used to define the defect states in the bandgap. The `F.TFTDON` and `F.TFTACC` parameters of the `DEFECT` statement indicate the filenames containing the C functions. For more information on using the `C-INTERPRETER`, See Appendix A: “C-Interpreter Functions”.

```
DEFECTS F.TFTDON=mydefects.c F.TFTACC=mydefects.c
```

The file, *mydefects.c*, will contain C functions for donor and acceptor defect densities as a function of energy. These user defined defects are added to the existing defect distribution. If you want to use only your own function, set the gaussian and tail functions to zero. The following example defect states are defined in the file, *tft.lib*. These are added to a zero background set using the tail and gaussian state syntax. The resultant distribution of defects versus energy can be plotted in the files, *don.dat* and *acc.dat*.

```
DEFECTS F.TFTDON=tft.lib F.TFTACC=tft.lib DFILE=don.dat AFILE=acc.dat \  
        NTA=0 NTD=0 WTA=1.0 WTD=1.0 \  
        NGA=0 NGD=0 EGA=0.6 EGD=0.6 WGA=1 WGD=1 \  
        SIGTAE=1.E-16 SIGTAH=1.E-14 SIGTDE=1.E-14 SIGTDH=1.E-16  
        SIGGAE=1.E-16 SIGGAH=1.E-14 SIGGDE=1.E-14 SIGGDH=1.E-16
```

### 14.2.11: Setting Mobility and Other Models

`TFT` uses adaptations of the standard models of `S-PISCES` or `BLAZE`. The example below shows how to select the models and material parameters for polysilicon.

```
MATERIAL MUN=300 MUP=30  
MODELS SRH
```

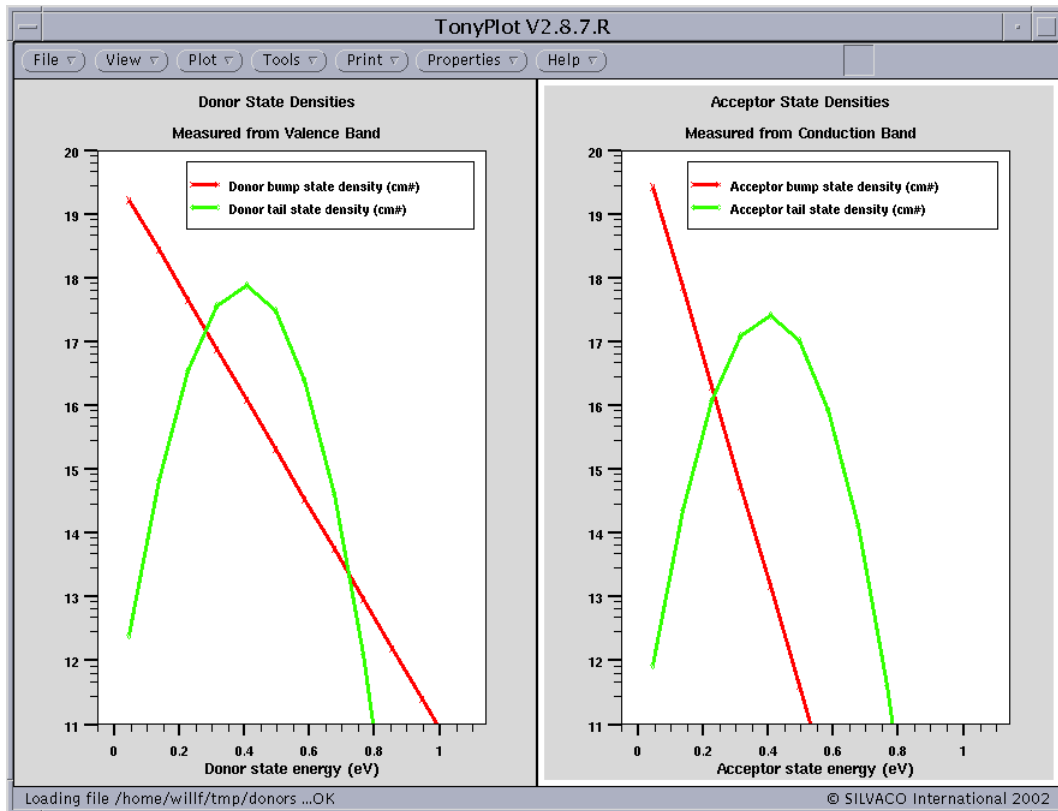
Typical mobility values for amorphous silicon can be set by:

```
MATERIAL MUN=20 MUP=1.5
```

Other models are also available in TFT. These include impact ionization and tunneling. Set them by using:

```
MODELS BBT .STD IMPACT
```

**Note:** Don't use concentration dependent mobility models (CONMOB, ANALYTIC, ARORA, KLA) because they overwrite the low field mobilities set in the MATERIAL statement.



**Figure 14-1: Syntax Guide to Define Two Tail States and Two Gaussian Distributions. NGA and NDG are the integrated values of the Gaussian distributions. Gaussians are entered on energies EGA and EGD respectively.**

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## 15.1: Introduction

NOISE is an ATLAS based product that simulates the small-signal noise generated by devices. Electronic noise results in an unavoidable degradation of a circuit's performance. It is important to understand the properties of noise to minimize its effect.

You should already be familiar with ATLAS before using NOISE. If not, see Chapter 2: "Getting Started with ATLAS".

## 15.2: Simulating Noise in ATLAS

ATLAS models the noise of a device by calculating the statistical behavior of equivalent random voltage sources at its ports. You can use the results of this calculation in a circuit simulator (e.g., SMARTSPICE) to minimize the disruption caused by the (inevitable) presence of noise. The following shows the minimum needed to simulate noise in ATLAS.

1. Add the noise parameter to a `log` command. For example:

```
log outfile=noise.log inport=gate outport=drain noise
```

2. Use the noise parameter on the subsequent `solve` command. For example:

```
solve noise frequency=100.0
```

**NOISE** is an extension of the AC analysis of a device (see Chapter 2: “Getting Started with ATLAS”, Section 2.9.3: “Small-Signal AC Solutions” for more information on AC analysis). You can perform a noise simulation on any device (one-port or two-port) where small-signal AC analysis can be performed.

A direct AC analysis is automatically performed on the device before the noise simulation (i.e., you don't need to perform the analysis).

For more information about the `LOG` and `SOLVE` commands, see Chapter 18: “Statements”, Sections 18.22: “LOG” and 18.40: “SOLVE”.

### 15.3: Circuit Level Description of Noise

Noise is the name given to the random fluctuations in the currents and voltages of real devices.

The simple Drude model of an n-type resistor gives

$$\langle J \rangle = \langle \sigma \rangle \cdot E = q \cdot \langle n \rangle \cdot \langle v \rangle \quad 15-1$$

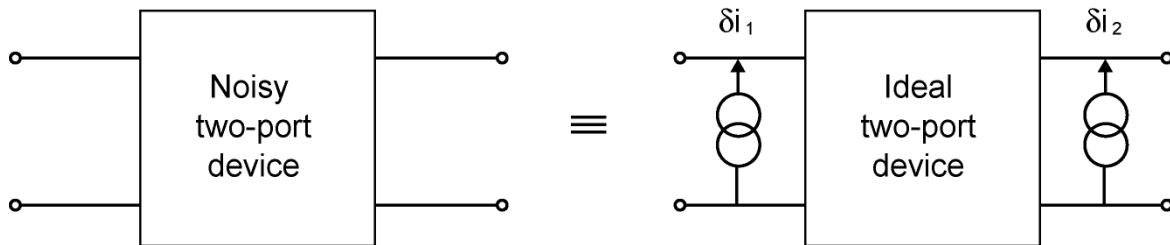
where  $\langle J \rangle$  is the mean current density,  $q$  is the electronic charge,  $\langle n \rangle$  is the mean electron density, and  $\langle v \rangle$  is the mean electron drift velocity. Time dependent fluctuations in the instantaneous electron density and drift velocity will cause fluctuations in the resultant current density.

The current at a contact of the resistor would be

$$i(t) = \langle i \rangle + \delta i(t) \quad 15-2$$

where the  $\delta i(t)$  term is the noise generated by the resistor.

A noisy device can be represented by external current sources added to the terminals of an ideal (noiseless) device (see Figure 15-1).



**Figure 15-1: A real (noisy) device is modelled as an ideal (noiseless) device with random current sources attached to the ports.**

These current sources are small and random. The description of noise is the statistical properties of these current sources. Normally, you describe the behavior of the frequency domain representation of the current sources.

The means of the current sources are zero. For example:

$$\langle \delta i_1(\omega) \rangle = 0 \text{ and } \langle \delta i_2(\omega) \rangle = 0 \quad 15-3$$

The noise is described by the auto-correlation:

$$\langle \delta i_1^2(\omega) \rangle \text{ and } \langle \delta i_2^2(\omega) \rangle \quad 15-4$$

and the cross-correlation:

$$\langle \delta i_1(\omega) \cdot \delta i_2(\omega)^* \rangle \text{ and } \langle \delta i_2(\omega) \cdot \delta i_1(\omega)^* \rangle \quad 15-5$$

It may be more convenient to describe the noise in terms of the behavior of voltage sources instead of current sources. The noise current can be easily translated into a noise voltage. For example:

$$\begin{pmatrix} \delta v_1(\omega) \\ \delta v_2(\omega) \end{pmatrix} = \begin{pmatrix} Z_{11}(\omega) & Z_{12}(\omega) \\ Z_{21}(\omega) & Z_{22}(\omega) \end{pmatrix} \cdot \begin{pmatrix} \delta i_1(\omega) \\ \delta i_2(\omega) \end{pmatrix} \tag{15-6}$$

Figure 15-2 shows that both representations are the same.

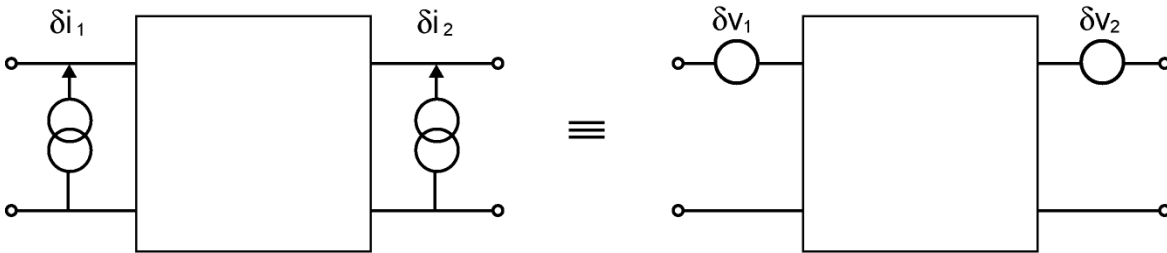


Figure 15-2: The noise can be modelled with random current sources or random voltage sources.

### 15.3.1: Noise “Figures of Merit” for a Two-Port Device

Figure 15-3 shows a simple two-port circuit.

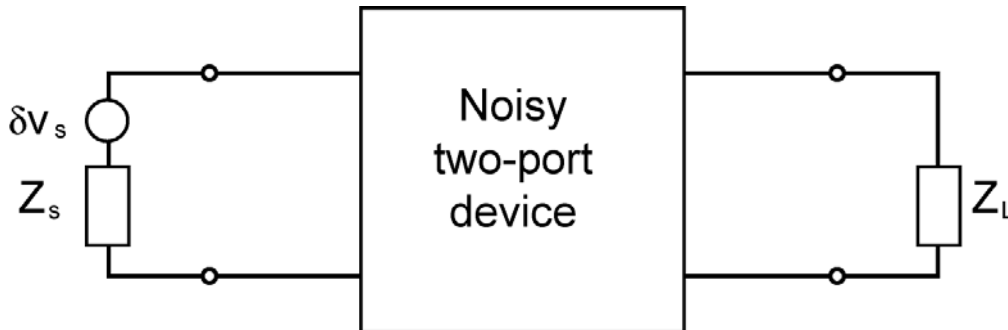


Figure 15-3: A block diagram of a simple circuit. We are interested in how much noise reaches the load.

The noise figure,  $F$ , is a measure of the increased amount of noise power delivered to the load because of the device’s noise.

$$F = \frac{P_{S,D}}{P_S} \tag{15-7}$$

Here:

- $P_S$  is the noise power that would be delivered to the load if the device was noiseless (i.e., only the noise from the source is transferred to the load).
- $P_{S,D}$  is the noise power that is delivered to the load from both the source and the device.

The standard definition of noise figure assumes the source is generating thermal noise at the temperature of the device:

$$\langle v_s^2 \rangle = 4kTR_s \tag{15-8}$$

Here, we have for the two-port circuit:

$$F = F_{min} + \frac{g_n}{R_s} [Z_S - Z_0]^2 \quad 15-9$$

where the traditional two-port figures of merit for noise are as follows:

- the minimum noise figure,  $F_{min}$  ;
- the best source impedance,  $Z_0$  ;
- the noise conductance,  $g_n$ .

The best source impedance gives is the minimum noise figure (i.e.,  $F=F_{min}$  when  $Z_S=Z_0$ ). The noise conductance is a measure of how much the noise figure increases as the source impedance moves away from  $Z_0$ .

## 15.4: Noise Calculation

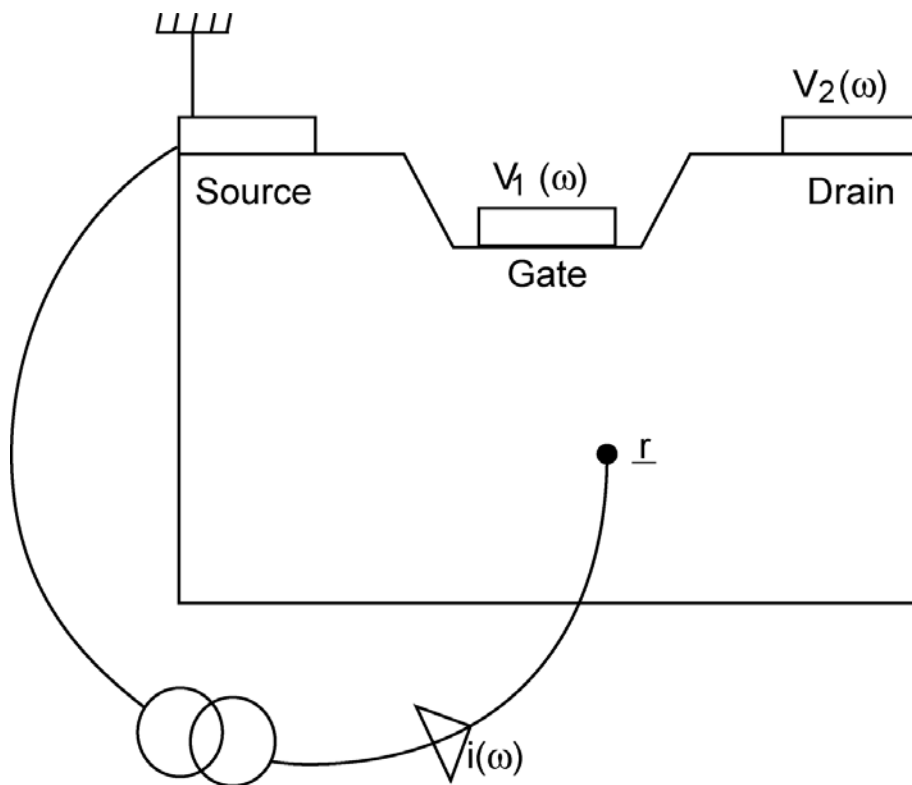
ATLAS does the following to calculate the noise of a device.

1. Takes a small volume of a device and calculates the random current fluctuations in that volume.
2. Uses the impedance field to calculate the resultant voltage on a contact.
3. Repeats the above steps until the noise from each part of the device has been calculated, which is then the total noise of a device.

### 15.4.1: The Impedance Field

The impedance field is a transfer function relating current (injected at some point in the device) to the resultant contact voltage.

Suppose a current is injected into a point  $r$  of a device (see Figure 15-4).



**Figure 15-4:** We calculate the impedance field at point  $r$  by injecting a unit current at the point getting the resultant voltages  $V_1$  and  $V_2$ . (This is impossible to do in practice but is easy for ATLAS to simulate.)

This will generate a voltage on the open circuit contacts. The device is assumed to be linear so that the voltage will be at the same frequency as the input current. Here, we get

$$v_1(\omega) = Z_1(r; \omega) \cdot i(\omega) \quad 15-10$$

and

$$v_2(\omega) = Z_2(r; \omega) \cdot i(\omega) \quad 15-11$$

The  $Z_i(r;\omega)$  parameters, when taken over the whole device, are called the impedance fields.

There are separate impedance fields for when the injected current is electrons or holes. In other words, a two-port device has four associated impedance fields:  $Z_1^n(r;\omega)$ ,  $Z_2^n(r;\omega)$ ,  $Z_1^p(r;\omega)$ , and  $Z_2^p(r;\omega)$ .

### 15.4.2: Microscopic Noise Source

We assume the statistical behavior of the noise from one point in the device is totally uncorrelated with the statistical behavior of the noise at all other points. So we describe the correlation of a parameter,  $x$ , as:

$$\langle \delta x \cdot \delta x' \rangle(\mathbf{r}, \mathbf{r}'; \omega) = k_{\delta_{x'} \delta_x}(\mathbf{r}; \omega) \cdot \delta(\mathbf{r} - \mathbf{r}') \quad 15-12$$

where the term  $k_{\delta_{x'} \delta_x}(\mathbf{r}; \omega)$  is called the microscopic noise source.

The theory of Generation-Recombination noise gives the auto-correlation of the current:

$$k_{\delta_i, \delta_i}(\mathbf{r}; \omega) \quad 15-13$$

The theory of Diffusion noise gives the auto-correlation of the current density:

$$k_{\delta_{\mathbf{J}} \delta_{\mathbf{J}}}(\mathbf{r}; \omega) \quad 15-14$$

### 15.4.3: Local Noise Source

The local noise source is the effect that a microscopic noise source has on the noise behavior of the device.

For  $k_{\delta_i, \delta_i}(\mathbf{r}; \omega)$  we have

$$\langle \delta v_i, \delta v_j^* \rangle(\omega) = \int_{\Omega} z_i(\mathbf{r}; \omega) k_{\delta_i, \delta_i}(\mathbf{r}; \omega) \cdot Z_j^*(\mathbf{r}; \omega) \cdot d\mathbf{r} \quad 15-15$$

where the integral is over the device volume. The integrand function is called the local noise source.

For  $k_{\delta_{\mathbf{J}} \delta_{\mathbf{J}}}(\mathbf{r}; \omega)$  we have

$$\langle \delta v_i, \delta v_j^* \rangle(\omega) = \int_{\Omega} \mathbf{Z}_i(\mathbf{r}; \omega) k_{\delta_{\mathbf{J}} \delta_{\mathbf{J}}}(\mathbf{r}; \omega) \cdot \mathbf{Z}_j^*(\mathbf{r}; \omega) \cdot d\mathbf{r} \quad 15-16$$

Again, the integral is over the device volume and the integrand function is called the local noise source.

The vector impedance field is defined as

$$\mathbf{Z}(\mathbf{r}; \omega) = \nabla Z(\mathbf{r}; \omega) \quad 15-17$$

## 15.5: ATLAS Models

ATLAS has models for three types of microscopic noise source: Diffusion Noise, Generation-Recombination Noise, and Flicker Noise.

If noise is being calculated then diffusion noise is on by default. Generation-recombination noise is on if any Generation-Recombination (GR) or Impact Ionization (II) models are defined. Flicker noise is off by default.

The default noise models for diffusion and GR/II have no user-definable parameters. They get all the needed information from the simulation.

### 15.5.1: Diffusion Noise

Diffusion noise is caused by variations in the velocity of the carriers.

#### Einstein Diffusion Equation

There are no independent user-definable parameters for this model (you can set the mobility model in a MATERIAL statement (See Chapter 18: "Statements", Section 18.24: "MATERIAL") but that will affect the whole simulation not just the noise calculation). It is on by default and can only be turned off by choosing a different model for diffusion noise.

The equation for the microscopic noise source is

$$k_{\delta \mathbf{J} \delta \mathbf{J}}(\mathbf{r}; \omega) = 4q^2 n(\mathbf{r}) D(\omega) \quad 15-18$$

where:

- $q$  is the fundamental electronic charge.
- $n(\mathbf{r})$  is the carrier concentration.
- $D(\omega)$  is the diffusion coefficient.

The diffusion coefficient is given by Einstein's relationship, which is:

$$D(\omega) = \frac{kT}{q} \mu \quad 15-19$$

where:

- $k$  is Boltzmann's constant.
- $T$  is the temperature.
- $\mu$  is the carrier mobility.

#### C-Interpreter

You can define a C-Interpreter function to calculate the microscopic noise source for diffusion noise. If a C-Interpreter function is defined, then the default model is turned off.

For a C-Interpreter function to calculate the electron microscopic noise source, use the MATERIAL statement:

```
material F.MNSNDIFF=<filename>
```

The header for this C-Interpreter function is

```
/*
 * Microscopic Noise Source for electron diffusion noise.
 * Statement: MATERIAL
 * Parameter: F.MNSNDIFF
```



```

* Arguments:
* xcomp      composition fraction x
* ycomp      composition fraction y
* temp       lattice temperature (K)
* n          electron concentration (cm-3)
* mun        electron mobility (cm2/V s)
* e          electric field (V/cm)
* *mns       microscopic noise source (s A2 / cm)
*/
int mnsndiff(double xcomp, double ycomp, double temp, double n,
double mun, double e, double *mns);

```

For a C-Interpreter function to calculate the hole microscopic noise source, use the MATERIAL statement:

```
material F.MNSPDIFF=<filename>
```

The header for this C-Interpreter function is

```

/*
* Microscopic Noise Source for hole diffusion noise.
* Statement: MATERIAL
* Parameter: F.MNSPDIFF
* Arguments:
* xcomp      composition fraction x
* ycomp      composition fraction y
* temp       lattice temperature (K)
* p          hole concentration (cm-3)
* mup        hole mobility (cm2 / V s)
* e          electric field (V / cm)
* *mns       microscopic noise source (s A2 / cm)
*/
int mnspdiff(double xcomp, double ycomp, double temp, double p,
double mup, double e, double *mns);

```

## 15.5.2: Generation-Recombination Noise

Generation-Recombination noise is caused by variations in the number of the carriers.

There are no user-definable parameters for GR noise. You can, however, set the parameters for the various GR models in the MATERIAL statement (see Chapter 18: “Statements”, Section 18.24: “MATERIAL”) and the various II models in the IMPACT statement (Chapter 18: “Statements”, Section 18.16: “IMPACT”). Setting these parameters will affect the whole simulation, not just the noise calculation.

There are two families of GR in ATLAS: direct and trap assisted. Direct GR is when the electron travels directly from the conduction band to the valence band (or vice versa). Trap assisted GR is when the electron travels from a band to a trap level. If more than one trap level is defined, then they are treated as independent trap assisted GR sites (i.e., electrons are not assumed to move between different trap levels).

Generation-Recombination is defined by four parameters:

- $G_n$
- $G_p$
- $R_n$
- $R_p$

G is the generation rate, R is the recombination rate, n is for electrons, and p is for holes. The generation rate of electrons is the number of electrons that appears (per unit time, per unit volume) in the conduction band. The recombination rate is the number of electrons that disappears from the conduction band.

### Direct GR

Since there are no trap levels all electrons leaving the conduction band end up in the valence band. All electrons leaving the valence band end up in the conduction band.

Therefore:

$$G_n = G_p \text{ and } R_n = R_p \quad 15-20$$

The GR parameters are calculated with

$$\begin{aligned} G &= C \cdot n_i^2 \\ R &= C \cdot np \end{aligned} \quad 15-21$$

For optical GR (OPTR in the MODELS statement) the C parameter is COPT in the MATERIALS statement. For Auger GR (AUGER in the MODELS statement), the C parameter is a function of the carrier density.

The microscopic noise sources are

$$k_{\delta n, \delta n} = k_{\delta p, \delta p} = k_{\delta n, \delta p} = 2(G + R) \quad 15-22$$

### Trap Assisted GR

There are assumed to be no direct transitions in trap assisted GR. Therefore, an electron leaving the conduction band ends up at the trap level. An electron entering the conduction band comes from the trap level. Unlike direct GR, the following four parameters are independent.

$$\begin{aligned} G_n &= \frac{n_1 n_t}{\tau_n N_t} \\ G_p &= \frac{p_1 \left(1 - \frac{n_t}{N_t}\right)}{\tau_p} \\ R_n &= \frac{n}{\tau_n} \left(1 - \frac{n_t}{N_t}\right) \\ R_p &= \frac{p}{\tau_p} \frac{n}{N_t} \end{aligned} \quad 15-23$$

The ratio  $n_t/N_t$  is the fraction of ionized traps. The concentration  $n_1$  is the electron concentration, if the Fermi level were at the trap level.  $p_1$  is the hole concentration if the Fermi level were at the trap level.

You can define the lifetimes  $\tau_n$  and  $\tau_p$  using the TAUN0 and TAUP0 parameters from the MATERIALS statement.

The microscopic noise sources are

$$\begin{aligned} k_{\delta n, \delta n} &= 2(G_n + R_p) \\ k_{\delta p, \delta p} &= 2(G_p + R_n) \end{aligned} \quad 15-24$$

There are no direct transitions between the conduction and valence band. Therefore:

$$k_{\delta n, \delta p} = 0 \quad 15-25$$

### Impact Ionization

Impact ionization is a pure generation term. For each electron created in the conduction band, a corresponding hole is also created in the valence band. This is similar to direct GR without a recombination term.

The microscopic noise sources are

$$k_{\delta n, \delta n} = k_{\delta p, \delta p} = k_{\delta p} = 2G \quad 15-26$$

### 15.5.3: Flicker Noise

Flicker noise is observed experimentally; however, a complete theory about what causes flicker noise isn't known [62].

#### Hooge

The Hooge model, which is shown below, is a phenomenological microscopic noise source.

$$K_{\delta J_n, \delta J_n}(\mathbf{r}; \omega) = \frac{\alpha_{Hn} |J_n(\mathbf{r})|^2}{f n(\mathbf{r})} \quad \text{and} \quad K_{\delta J_p, \delta J_p}(\mathbf{r}; \omega) = \frac{\alpha_{Hp} |J_p(\mathbf{r})|^2}{f p(\mathbf{r})} \quad 15-27$$

In this model:

- $\alpha_{Hn}$  is the electron Hooge constant.
- $\alpha_{Hp}$  is the hole Hooge constant.
- $f$  is the frequency.
- $J_n(\mathbf{r})$  is the electron current density.
- $J_p(\mathbf{r})$  is the hole current density.
- $n(\mathbf{r})$  is the electron concentration.
- $p(\mathbf{r})$  is the hole concentration.

The Hooge constants are defined in the MATERIAL statement:

```
material HOOGEN=<value> HOOGEP=<value>
```

The default values for these parameters is zero (which means the flicker noise is turned off).

#### C-Interpreter

You can define a C-Interpreter function to calculate the microscopic noise source for flicker noise. If a C-Interpreter function is defined, then the default model is turned off.

For a C-Interpreter function to calculate the electron microscopic noise source, use the MATERIAL statement:

```
material F.MNSNFLICKER=<filename>
```

The header for this C-Interpreter function is:

```
/*
 * Microscopic Noise Source for electron flicker (1/f) noise.
 * Statement: MATERIAL
 * Parameter: F.MNSNFLICKER
```

```
* Arguments:
* x          location x (microns)
* y          location y (microns)
* temp       lattice temperature (K)
* n          electron concentration (cm-3)
* jn         electron current density (A / cm2)
* f          frequency (Hz)
* e          electric field (V / cm)
* *mns      microscopic noise source (s A2 / cm)
*/
int mnsnflicker(double x, double y, double temp, double n,
double jn, double f, double e, double *mns);
```

For a C-Interpreter function to calculate the hole microscopic noise source, use the MATERIAL statement:

```
material F.MNSPFLICKER=<filename>
```

The header for this C-Interpreter function is

```
/*
* Microscopic Noise Source for hole flicker (1/f) noise.
* Statement: MATERIAL
* Parameter: F.MNSPFLICKER
* Arguments:
* x          location x (microns)
* y          location y (microns)
* temp       lattice temperature (K)
* p          hole concentration (cm-3)
* jp         hole current density (A / cm2)
* f          frequency (Hz)
* e          electric field (V/cm)
* *mns      microscopic noise source (s A2/cm)
*/
int mnspflicker(double x, double y, double temp, double p,
double jp, double f, double e, double *mns);
```

## 15.6: Output

The noise simulation results can output to the log file. The intermediate values in the calculation can output to the structure file.

### 15.6.1: Log Files

There are five groups of data that can output to a log file. They are as follows:

- The two-port figures of merit (FOM):  $F_{\min}$ ,  $Z_{\text{opt}}$ ,  $g_n$ .
- The correlation of the total noise voltage sources.
- The correlation of the total noise current sources.
- The correlation of the individual noise voltage sources (GR, II, electron and hole diffusion; electron and hole flicker).
- The correlation of the individual noise current sources (GR, II, electron and hole diffusion; electron and hole flicker).

Table 15-1 shows the logical parameters in the LOG command (see Chapter 18: “Statements”, Section 18.22: “LOG” for more information) that cause these groups to output. The columns in this table correspond to the groups above.

|             | two-port FOM <sup>(a)</sup> | Total V correlation | Total I correlation | Individual V correlation | Individual I correlation |
|-------------|-----------------------------|---------------------|---------------------|--------------------------|--------------------------|
| NOISE       | X                           | _ (b)               | -                   | -                        | -                        |
| NOISE.V     | X                           | X                   | -                   | -                        | -                        |
| NOISE.I     | X                           | -                   | X                   | -                        | -                        |
| NOISE.IV    | X                           | X                   | X                   | -                        | -                        |
| NOISE.VI    | X                           | X                   | X                   | -                        | -                        |
| NOISE.V.ALL | X                           | X                   | -                   | X                        | -                        |
| NOISE.I.ALL | X                           | -                   | X                   | -                        | X                        |
| NOISE.ALL   | X                           | X                   | X                   | X                        | X                        |

**Note a:** If the device is a one-port, then this data will not be output: the two-port figures of merit have no meaning for a one-port device.

**Note b:** If the device is a one-port and NOISE is the only noise output in the LOG command, then the total noise voltage sources will output.

## 15.6.2: Structure Files

There are five groups of data that can output to a structure file. They are as follows:

- Total Local Noise Source (LNS)
- Impedance fields
- Short-circuit Green's function
- Individual Microscopic Noise Sources (MNS)
- Individual local noise sources

Table 15-2 shows the logical parameters from the `OUTPUT` command (see Chapter 18: “Statements”, Section 18.32: “OUTPUT” for more information) that cause these groups to output. The columns in this table correspond to the groups above.

| <b>Table 15-2. Logical Parameters in the OUTPUT command</b> |                  |                         |                                       |                       |                       |
|---|------------------|-------------------------|---------------------------------------|-----------------------|-----------------------|
|   | <b>Total LNS</b> | <b>Impedance Fields</b> | <b>Short-circuit Green's function</b> | <b>Individual MNS</b> | <b>Individual LNS</b> |
| NOISE   | X                | -                       | -                                     | -                     | -                     |
| NOISE.IMP   | -                | X                       | -                                     | -                     | -                     |
| NOISE.ALL   | X                | X                       | X                                     | X                     | X                     |

### 16.1: Overview

THERMAL3D solves the steady-state heat equation to find the equilibrium temperature distribution in planar and non-planar three-dimensional structures. Specify the heat sinks and sources and choose from several temperature-dependent models for thermal conductivity within each region. A typical application for THERMAL3D is a package simulation for a power circuit or III-V ICs.

If you're unfamiliar with THERMAL3D, see also Chapter 6: "3D Device Simulator". If you're unfamiliar with ATLAS, see Chapter 2: "Getting Started with ATLAS".

#### 16.1.1: 3D Structure Generation

THERMAL3D supports structure defined on 3-D prismatic meshes. Structures may have arbitrary geometries in two dimensions and consist of multiple slices in the third dimension. There are two methods for creating a 3-D structure that can be used with THERMAL3D. One method is through the command syntax of ATLAS. The other method is through an interface to DEVEDIT. See Chapter 6: "3D Device Simulator", Section 6.2: "3D Structure Generation" for more information on both methods.

#### Defining Heat Sources

Heat sources are identified with regions in the 3-D structure. Regions are defined in the manner documented in Chapter 2: "Getting Started with ATLAS", the "Specifying Regions And Materials" section on page 2-12 and Chapter 6: "3D Device Simulator", the "ATLAS Syntax For 3D Structure Generation" section on page 6-3. A region has a unique number, which is used to identify the region on the MATERIAL statement. The POWER parameter of the MATERIAL statement is used to set the power of the heat source in watts.

```
MATERIAL REGION=2 POWER=0.35
```

Set the POWER parameter in the SOLVE statement if you want to step the power through a range of values. See Section 16.4: "Obtaining Solutions In THERMAL3D" for the proper syntax.

#### Defining Heat Sinks

Heat sinks are identified as electrodes in the 3-D structure. Heat sink areas should be defined as electrodes in the manner documented in Chapter 2: "Getting Started with ATLAS", the "Specifying Electrodes" section on page 2-13 and Chapter 6: "3D Device Simulator", the "ATLAS Syntax For 3D Structure Generation" section on page 6-3.

Each electrode (heat sink) has a unique number, which is used to set the temperature on the heat sink during simulation. For more information on setting the temperature of the heat sink, see Section 16.4: "Obtaining Solutions In THERMAL3D".

## 16.2: Model and Material Parameter Selection

### 16.2.1: Thermal Simulation Model

To obtain steady-state solutions for the temperature distribution, THERMAL3D solves Poisson's equation for temperature:

$$\nabla(k(T) \nabla T) = q \tag{16-1}$$

where T represents the steady state temperature, k the temperature-dependent thermal conductivity, and q the power generation per unit volume in the medium (heat sources).

The prescribed temperatures at the heat sinks form boundary conditions for Equation 16-1.

The solution of the heat equation by THERMAL3D is invoked by the following syntax:

```
MODELS THERMAL
```

### 16.2.2: Setting Thermal Conductivity

The value of thermal conductivity k in units of W/cm/K, for each region should be specified in the MATERIAL statement. Because thermal conductivity is generally temperature dependent. The following four models available for thermal conductivity are:

$$k(T) = TC.CONST \tag{16-2}$$

$$k(T) = \left( \frac{TC.NPOW}{T/300} \right) \tag{16-3}$$

$$k(T) = 1 / (TC.A + TC.B \times T + TC.C \times T^2) \tag{16-4}$$

$$k(T) = TC.E / (T - TC.D) \tag{16-5}$$

These models are specified on a material by material basis as follows.

To choose the model in Equation 16-2, specify the TCON.CONST (default) parameter in the MATERIAL statement. To choose the model in Equation 16-3, specify the TCON.POWER parameter in the MATERIAL statement. To choose the model in Equation 16-4, specify the TCON.POLY parameter in the MATERIAL statement. To choose the model in Equation 16-5, specify the TCON.RECIP parameter in the MATERIAL statement.

| Table 16-1. User-Specifiable Parameters For Equations 16-2 to 16-5 |           |        |
|--|-----------|--------|
| Parameter  | Statement | Units  |
| TC.CONST   | MATERIAL  | W/cm/K |
| TC.NPOW  | MATERIAL  | cmk/W  |
| TC.A   | MATERIAL  |        |
| TC.B   | MATERIAL  | cm/W   |



| Table 16-1. User-Specifiable Parameters For Equations 16-2 to 16-5 |           |        |
|--|-----------|--------|
| Parameter  | Statement | Units  |
| TC.C   | MATERIAL  | cm/W/k |
| TC.D   | MATERIAL  | K      |
| TC.E   | MATERIAL  | W/cm   |

### Example

```
MATERIAL REGION=2 TCON.POWER TC.CO=1.0 TC.NPOW=1.2
```

means that the temperature-dependent thermal conductivity for region #2 is expressed as:

$$K(T) = \frac{1}{(T/300)^{1.2}} \quad 16-6$$

### 16.2.3: Suggested Parameters For Thermal Conductivity

There are no preset material defaults in THERMAL3D. The following values are recommended for thermal conductivity of GaAs and Si.

For GaAs, use model B with:

```
MATERIAL TCON.POWER TC.CO=0.44 TC.POW=1.25
```

For Si, use model B, C, or D with:

```
(model B) MATERIAL TCON.POWER TC.CO=1.55 TC.POW=-1.33
```

```
(model C) MATERIAL TCON.POLYN TC.A=0.03 TC.B=1.56e-3 TC.C=1.65e-6
```

```
(model D) MATERIAL TCON.RECIP TC.E=320 TC.D=80
```

## 16.3: Numerical Methods

No special numerical methods are required for thermal simulation. A METHOD statement with no parameters is assumed by default.

## 16.4: Obtaining Solutions In THERMAL3D

The SOLVE statement is used in THERMAL3D for heat-flow solutions much the same as it is used in other ATLAS simulations involving electrical biases. The temperature in kelvin on each heat sink is used to prescribe the boundary condition temperatures. For example:

```
SOLVE T1=300 T2=500
```

sets the temperature at 300 K and 500 K on heat sink #1 and #2 respectively.

Multiple SOLVE statements are allowed in THERMAL3D. This is useful for obtaining solutions for several combinations of heat sinks and thermal power sources. A range of solutions can also be obtained by stepping the value of a heat sink or power source. For example:

```
SOLVE T1=300 POWER2=0.35 POWER3=0.4 NSTEPS=5 STEPREGION=3 \
POWERFINAL=0.8 OUTFILE=thermal_out0
```

increments the thermal power source in region #3 from 0.4 watts to 0.8 watts in 5 steps and:

```
SOLVE T1=300 POWER2=0.35 NSTEPS=3 ELECTRODE=1 \
TEMPFINAL=600 OUTFILE=thermal_out0
```

increments the temperature on electrode #1 from 300 K to 600 K in 3 steps. Thermal power and temperature can be simultaneously sweep.

If more than one region power is specified during a sweep, the region to be stepped must be specified by STEPREGION=# as shown in the first example above. If the STEPREGION parameter is not specified, the smallest numerical value of POWER# is stepped.

During temperature and power sweeps, the output filename is modified according to the following rule: The rightmost character is incremented using the sequence: 0-9, A-Z, a-z. When a character is incremented beyond z, the character is set to 0> and the character to the left (smaller than 'z') is incremented.

Complete syntax information for the SOLVE statement can be found in Chapter 18: "Statements", Section 18.40: "SOLVE".

The SOLVE statement is used in THERMAL3D for heat flow solutions much as it is used in other ATLAS simulations for electrical biases. The temperature in Kelvin on each heat sink in the device must be set in the SOLVE statement. The Tn parameter, where n is the number of the heat sink, is used to set the temperature. For example:

```
SOLVE T1=300 T2=500
```

This sets 300K on heat sink #1 and 500K on heat sink #2. Only one SOLVE statement is allowed in any THERMAL3D input file.

## 16.5: Interpreting The Results From THERMAL3D

The output of thermal simulation consists of the minimum and maximum calculated temperature of each region and its location. The three-dimensional temperature distribution can be saved in an output structure file by setting the `OUTFILE` parameter in the `SOLVE` statement and visualized using `TONYPLOT3D`.

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## 16.6: More Information

Many examples using THERMAL3D have been installed on your distribution tape or CDROM. More information about the use of THERMAL3D can be found by reading the text associated with each example.

You can also find some information at [www.silvaco.com](http://www.silvaco.com).

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## 17.1: Overview

This chapter describes the overall process of obtaining a numerical solution, the subtasks involved, and the options and defaults available in ATLAS.

You don't need to master this material in order to use ATLAS. Chapter 2: "Getting Started with ATLAS", Section 2.8: "Choosing Numerical Methods" presents the information about numerical techniques that is needed. This chapter provides additional information that will mainly be of interest to advanced users.

## 17.2: Numerical Solution Procedures

Semiconductor device operation is modeled in ATLAS by a set of anywhere from one to six coupled, non-linear, partial differential equations (PDEs). ATLAS produces numerical solutions of these equations by calculating the values of unknowns on a mesh of points within the device. An internal discretization procedure converts the original, continuous model to a discrete non-linear algebraic system that has approximately the same behavior. The set of PDEs, the mesh and the discretization procedure determine the non-linear algebraic problem that must be solved.

The non-linear algebraic system is solved using an iterative procedure that refines successive estimates of the solution. Iteration continues until the corrections are small enough to satisfy convergence criteria, or until it is clear that the procedure is not going to converge. The non-linear iteration procedure starts from an initial guess. The corrections are calculated by solving linearized versions of the problem. The linear subproblems are solved by using direct techniques or iteratively.

Different solution procedures exhibit different behavior with respect to convergence, accuracy, efficiency, and robustness. The two main aspects of convergence are whether a solution is obtained, and if so, how rapidly it is approached. Accuracy is how closely the computed solution approximates the true solution. Efficiency is the time required to produce a solution. Robustness is the ability to converge for a wide range of structures, using meshes and initial guess strategies that are not optimum.

When solving general systems of non-linear equations there are no guarantees that any particular method will always work. It is also the case that different methods can work better for different problems. Fortunately, there is now a lot of practical experience concerning the numerical techniques that are effective for device simulation. This practical experience has been captured in ATLAS in the form of default methods and parameters that work well in almost all circumstances. This chapter provides advanced information of interest to users who want to change the defaults.



## 17.3: Meshes

The specification of meshes involves a trade-off between the requirements of accuracy and numerical efficiency. Accuracy requires a fine mesh that can resolve all significant features of the solution. Numerical efficiency requires a coarse mesh that minimizes the total number of grid points. This trade-off between accuracy and numerical efficiency is frequently a source of problems for beginners. Fortunately, enough experience to define reasonable meshes is soon acquired.

ATLAS uses triangular meshes. Some triangulations yield much better results than others. Mesh generation is still an inexact science, but guidelines and heuristics for defining satisfactory meshes exist. Good triangulations have the following features:

- They contain enough points to provide the required accuracy.
- They do not contain too many unnecessary points that impair efficiency.
- They avoid, or at least minimize, the number of obtuse triangles. Obtuse triangles tend to impair accuracy, convergence, and robustness.
- They avoid, or at least minimize, the number of long, thin triangles. These triangles also tend to impair accuracy, convergence, and robustness.
- They allow the average size of triangles to change smoothly in transition from a region where very small triangles must be used to a region where the use of much larger triangles is acceptable.

The error associated with a mesh can be investigated systematically by repeating a calculation using a sequence of finer meshes. This is very time consuming and is hardly ever done. The typical approach is to adequately resolve structural features, including doping, with an initial or base mesh, and then add nodes as required to resolve significant features of the solution. The insertion of additional nodes (regridding) is normally done by the program, using user-specified criteria.

The initial mesh used by ATLAS can be specified in several ways: it can be inherited from ATHENA, it can be constructed using DEVEDIT, or it can be specified using the ATLAS command language. Meshes can be refined using ATLAS commands, or using DEVEDIT. The remainder of this section will focus on the capabilities available using ATLAS commands. The capabilities provided by DEVEDIT are documented in the VWF INTERACTIVE TOOLS manual.

There are limits on the maximum number of nodes that can be specified. Two-dimensional ATLAS simulations may have up to 20,000 nodes. Three-dimensional simulations may have up to 200,000 nodes, 400,000 elements, with no more than 20,000 in a single plane and a maximum of 200 planes in the z direction. Most devices can be adequately simulated in two dimensions using meshes that contain from several hundred to around 3000 nodes.

### 17.3.1: Mesh Regridding

The REGRID statement supports refinement of regions of the mesh according to specified criteria. Refinement can occur when a specified solution variable exceeds some value, or when the change in that variable across a triangle exceeds a value. The variable can be any of the key quantities in a problem, such as potential, carrier concentration, doping concentration, or electric field.

The regrid algorithm searches the initial grid for triangles that meet the criterion specified for refinement. Each triangle that is identified is divided into four congruent subtriangles. Grid quantities (doping, potential, carrier concentrations, and so forth) are interpolated onto the new nodes, using linear or logarithmic interpolation, as appropriate for that quantity. The initial grid is referred to as being "on level 0" and the new triangles are referred to as "on level 1". After all level 0 triangles have been examined, the same procedure is applied to level 1 triangles, and any subtriangles of level 1 become "level 2" triangles. The grid is checked for consistency at each level and is updated to avoid abrupt changes of size from one triangle to the next. The regrid process continues until no more triangles meet the refinement criteria, or until a specified maximum level of refinement is reached. Grids used in practice are often coarser than is required to meet desirable refinement criteria, and so the maximum level is the key factor in determining the size of the grid after refinement.

The `MAX.LEVEL` parameter of the `REGRID` statement is used to limit the amount of refinement at each step. By default, ATLAS sets the maximum level equal to one more than the highest level in the existing mesh. To update a coarse region without regriding the finer regions, after a mesh has already been refined several times, set the maximum level below the level of the finer regions in the existing grid.

If several levels of regrid are performed in immediate succession, interpolated data is used to make the refinement decisions at higher levels. Since semiconductor problems are non-linear, this interpolation may not produce satisfactory results. It is often a good idea to calculate a new solution between regrid operations, i.e. to regrid only one level at a time and obtain a new solution after each regrid operation.

Two popular choices of quantities to be used for mesh refinement are potential and doping. Ideally, variations of electrostatic and quasi-Fermi potentials across an element would be limited to no more than  $kT/q$ , and variations in doping would be no more than a factor of 5 or so. In practice the refinement criteria are often significantly coarser: around 10-20  $kT/q$  for potential, and two to three orders of magnitude for doping. In high level injection situations, it is a good idea to regrid when the value of minority carrier concentration exceeds the local doping concentration.

### 17.3.2: Mesh Smoothing

Although every step of grid generation can introduce obtuse triangles, two steps in particular can cause problems. The first is that distorting a rectangular mesh introduces a very large number of obtuse elements. The second is that when regriding a rectangular grid that contains triangles with an aspect ratio of 4:1 or greater, very obtuse triangles are created in the transition region between high and low grid density. The `REGRID` statement allows several procedures to be used when dealing with poorly shaped elements such as obtuse triangles.

The two techniques are node smoothing and triangle smoothing. With node smoothing, several iterative passes are carried out during which each node is moved to a position which improves the angles of the triangles surrounding it. Node smoothing should only be used for grids that are already irregular. If node smoothing is used for nearly rectangular grids, it may significantly degrade the quality of the mesh.

With triangle smoothing (which is also referred to as diagonal flipping), each adjoining pair of triangles is examined. If appropriate, the diagonal of the quadrilateral is flipped to stabilize the discretization. The diagonal is never flipped when two elements are composed of different materials. When elements are of the same material but have different region numbers, you can specify whether or not to flip the diagonals.

Triangle smoothing is desirable in almost all cases, and should be performed on both the initial grid and on subsequent regrids. The only exception to this rule arises from an undesirable interaction of three elements: regrid, high aspect ratio triangles, and smoothing. This situation frequently occurs in gate oxide regions that involve long, thin triangles. In these cases, smoothing may produce large triangles surrounded by many smaller triangles, giving the appearance of a hole in the mesh. To overcome this, use the smoothing command `SMOOTH=4` to limit the formation of the large triangles.

## 17.4: Discretization

### 17.4.1: The Discretization Process

The discretization process yields relationships between the variables defined at mesh points [66]. In order to be useful, a discretization must be consistent (i.e., it must limit to the underlying equation in the limit that the mesh size tends to zero). All of the discretizations used in ATLAS have this property. Different discretizations can have different properties with respect to accuracy. The most important measure of accuracy is the order of the scheme (i.e., how errors scaled as the difference between mesh points tends to zero). Discretization schemes used in device simulation are often second order, i.e. as the mesh becomes very fine the discretization error varies as the square of the separation between mesh points.

The discretizations implemented in ATLAS uses the Box Integration Method [64] to approximate differential operators on a general triangular grid. Each equation is integrated over a small polygon which encloses each node. The set of all polygons completely covers the solution domain. The integration procedure equates fluxes into a polygon with sources and sinks inside the polygon, which means that quantities that are conserved physically are also conserved by the numerical solution.

The fluxes must be discretized carefully for the carrier continuity and energy balance equations, otherwise nonphysical oscillations and negative carrier concentrations and temperatures may arise. Scharfetter and Gummel [65] introduced approximations for current densities that overcome this problem. Generalizations of this approach are used in ATLAS for the discretization of current densities and energy fluxes.

## 17.5: Non-Linear Iteration

The non-linear solution method, and associated parameters such as iteration and convergence criteria, are specified in the `METHOD` statement. Non-linear iteration solution methods are specified in the `METHOD` statement using the `NEWTON`, `GUMMEL`, or `BLOCK` parameters. Combinations of these parameters may also be specified. In order to understand the effect of these parameters, it is helpful to briefly review how numerical solutions are obtained.

The non-linear algebraic system that results from discretization on a mesh is solved iteratively starting from an initial guess [57,58,59,67,68]. Linearized subproblems are set up and solved. These provide corrections that are used to update the current estimate of the solution. Different sequences of linear subproblems correspond to different non-linear iteration strategies. Iteration continues until convergence criteria are met, in which case the solution is accepted; or until a preset maximum allowable number of iterations is reached, in which case a different technique is tried or the solution procedure is abandoned. When a solution fails to converge, a user normally tries a different grid, a different initial guess strategy, or a different non-linear iteration technique.

### 17.5.1: Newton Iteration

Each iteration of the Newton method solves a linearized version of the entire non-linear algebraic system. The size of the problem is relatively large, and each iteration takes a relatively long time. However, the iteration will normally converge quickly (in about three to eight iterations) so long as the initial guess is sufficiently close to the final solution. Strategies that use automatic bias step reduction in the event of non-convergence loosen the requirement of a good initial guess. Newton's method is the default for drift-diffusion calculations in ATLAS. There are several calculations for which ATLAS requires that Newton's method is used. These are: DC calculations that involve lumped elements; transient calculations; curve tracing; and when frequency-domain small-signal analysis is performed.

The Newton-Richardson Method is a variant of the Newton iteration that calculates a new version of the coefficient matrix only when slowing convergence demonstrates that this is necessary. An automated Newton-Richardson method is available in ATLAS, and improves performance significantly on most problems. The automated Newton-Richardson Method is enabled by specifying the `AUTONR` parameter of the `METHOD` statement.

If convergence is obtained only after many Newton iterations, the problem is almost certainly poorly defined. The grid may be very poor (i.e., it contains many obtuse or high aspect ratio triangles), or a depletion region may have extended into a region defined as an ohmic contact, or the initial guess may be very poor.

### 17.5.2: Gummel Iteration

Each iteration of Gummel's method solves a sequence of relatively small linear subproblems. The subproblems are obtained by linearizing one equation of the set with respect to its primary solution variable, while holding other variables at their most recently computed values. Solving this linear subsystem provides corrections for one solution variable. One step of Gummel iteration is completed when the procedure has been performed for each independent variable. Gummel iteration typically converges relatively slowly, but the method will often tolerate relatively poor initial guesses. The Gummel algorithm can not be used with lumped elements or current boundary conditions

Two variants of Gummel's method can improve its performance slightly. These both limit the size of the potential correction that is applied during each Gummel loop. The first method, called damping, truncates corrections that exceed a maximum allowable magnitude. It is used to overcome numerical ringing in the calculated potential when bias steps are large (greater than 1V for room temperature calculations). The maximum allowable magnitude of the potential correction must be carefully specified: too small a value slows convergence, while too large a value can lead to overflow. The `DVLLIMIT` parameter of the `METHOD` statement is used to specify the maximum allowable magnitude of the potential correction. By default the value of this parameter is 0.1 V. Thus, by default Gummel

iterations are damped. To specify undamped Gummel iterations, specify `DVLIMIT` to be negative or zero.

The second method limits the number of linearized Poisson solutions per Gummel iteration, usually to one. This leads to under-relaxation of the potential update. This “single-Poisson” solution mode extends the usefulness of Gummel’s method to higher currents. It can be useful for performing low current bipolar simulations, and simulating MOS transistors in the saturation region. It is invoked by specifying the `SINGLEPOISSON` parameter of the `METHOD` statement.

### 17.5.3: Block Iteration

ATLAS offers several block iteration schemes that are very useful when lattice heating or energy balance equations are included. Block iterations involve solving subgroups of equations in various sequences. The subgroups of equations used in ATLAS have been established as a result of numerical experiments that established which combinations are most effective in practice.

In non-isothermal drift-diffusion simulation, specifying the `BLOCK` method means that Newton’s method is used to update potential and carrier concentrations, after which the heat flow equation is solved in a decoupled step.

When the carrier temperature equations are solved for a constant lattice temperature, the `BLOCK` iteration algorithm uses Newton’s method to update potential and concentrations. The carrier temperature equation is solved simultaneously with the appropriate continuity equation to update the carrier temperature and again carrier concentration.

When both the heat flow equation and the carrier temperature equations are included, the `BLOCK` scheme proceeds as described previously for the carrier temperature case, and then performs one decoupled solution for lattice temperature as a third step of each iteration.

### 17.5.4: Combining The Iteration Methods

It is possible to start with the `GUMMEL` scheme and then switch to `BLOCK` or `NEWTON` if convergence is not achieved within a certain number of iterations. One circumstance where this can be very helpful is that Gummel iteration can refine initial guess to a point from which Newton iteration can converge. The number of initial `GUMMEL` iterations is limited by `GUM.INIT`.

It can also be desirable to use `BLOCK` iteration and then switch to `NEWTON` if convergence is not achieved. This is the recommended strategy for calculations that include lattice heating or energy balance. The number of initial `BLOCK` iterations is limited by `NBLOCKIT`

Any combination of the parameters: `GUMMEL`, `BLOCK`, and `NEWTON` can be specified on the `METHOD` statement. ATLAS will start with `GUMMEL` if it is specified. If convergence is not achieved within the specified number of iterations, it will then switch to `BLOCK` if `BLOCK` is specified; if convergence is still not achieved the program will then switch to `NEWTON`.

### 17.5.5: Solving Linear Subproblems

The linear subproblems generated by non-linear iteration can be solved by direct or iterative methods. Direct methods produce solutions in a predictable number of arithmetic operations. Solutions are affected by roundoff error, but are otherwise exact. Iterative methods obtain solutions by making a series of corrections to an initial guess. Iteration proceeds until the calculated corrections satisfy specified convergence criteria. The results are not exact to within roundoff error, and convergence is not guaranteed for general problems. Iterative methods, however, can be more efficient than direct methods for large linear systems, and generally require less memory.

There are mathematical proofs regarding the types of linear system for which iterative techniques converge. All common iterative schemes converge for linear systems that are symmetric positive definite (SPD). The linearized form of Poisson’s equation is of this type. The continuity equations are not SPD, but they can be reliably solved by modern, advanced iterative methods.

The size and structure of the coefficient matrix of the linear system plays an important role in the choice of direct or iterative methods. The overall problem size is determined by the number of variables per node ( $m$ ) and the number of nodes ( $n$ ). The number of unknowns is  $m \times n$ . The linear subproblems associated with Newton iteration have a coefficient matrix with  $(m \times n)^2$  elements. Each linearized subproblem which is used in Gummel iteration has a coefficient matrix with  $n^2$  elements.

For practical 2-D device simulation problems, the number of elements in the coefficient matrix is typically between  $10^5$  and  $10^8$ . Fortunately the matrices are sparse (i.e., most of the entries are zero, and need not be stored explicitly). The sparsity arises because the variables at each node are coupled to only a few neighboring nodes. Special direct techniques are available for solving sparse matrices.

Direct techniques are preferred for relatively small problems. They provide reliable solutions that are exact to within roundoff error in a time that is predictable. Iterative techniques are preferred for very large problems because they are faster and require less memory. Direct techniques for solving sparse matrices have a competitive performance for the problem sizes typically encountered in 2-D device simulation, and are used by ATLAS to solve most of the linear subproblems that arise.

### 17.5.6: Convergence Criteria for Non-linear Iterations

After a few non-linear iterations, the errors will generally decrease at a characteristic rate as the iteration proceeds. Non-linear iteration techniques typically converge at a rate that is either linear or quadratic. The error decreases linearly when Gummel iteration is used (i.e., it is reduced by about the same factor at each iteration). For Newton iteration the convergence is quadratic, i.e., small errors less than one are approximately squared at each iteration. The non-linear iteration is terminated when the errors are acceptably small. The conditions required for termination are called convergence criteria. Much effort has gone into developing reliable default convergence criteria for ATLAS. The default parameters work well for nearly all situations, and most will never need to change them.

The main technique in ATLAS is Gaussian Elimination (or LU Decomposition) with a minimum degree of reordering applied to the nodes [69].

### 17.5.7: Error Measures

A single positive number that characterizes error is obtained by taking a norm of the errors associated with each unknown. The quantity that ATLAS tries to reduce to zero is the difference between the left and right hand sides of the equation. It is natural to use this quantity as the measure of the error. The associated error norm is called the right hand side (RHS) norm. The units of the RHS norm are  $C/\mu\text{m}$  for the Poisson equation, and  $A/\mu\text{m}$  for the continuity equations.

### Carrier Concentrations and CLIM.DD (CLIMIT)

Another measure of error is provided by the size of the calculated corrections for each unknown. Since the updates are the unknown "xs" at each step, this is called the X norm. Potential updates are measured in units of  $kT/q$ . Updates to carrier concentrations are measured relative to the previous value at the point. This relative error ( $\epsilon_C$ ) is defined as:

$$\epsilon_C = \max_m \frac{C_m^{K+1} - C_m^K}{\max(C_0, C_m^K)} \quad 17-1$$

where  $C = n$  or  $p$ , for electrons and holes respectively.  $m$  is the node identifier.  $C_0$  is a characteristic concentration.  $K$  is the iteration number.  $C_0$  is specified as or as `CLIM.DD` or as `CLIM.c*` and

$$\text{CLIM.DD} = \text{CLIMT} \cdot c^* \quad 17-2$$

where:

$$c^* = 4\sqrt{N_c N_v} \quad 17-3$$

And CLIM.DD (or CLIMIT) is specified in the METHOD statement.

It is difficult to specify a reasonable default value for the CLIM.DD parameter in all situations. In many difficult cases, the round-off numerical errors do not allow for the resolution of very low concentrations. The default value of CLIMIT is set at  $10^4$  (the corresponding default value for CLIM.DD in Silicon is  $4.5 \cdot 10^{13} \text{cm}^{-3}$ ). In simulation of breakdown, a lower value of CLIM.DD ( $\sim 10^8 \text{cm}^{-3}$  for Silicon diodes) should be specified; otherwise, a “false” solution may be obtained.

### Discussion of CLIM.EB

To estimate errors in the lattice temperature equation and the energy balance equations, corresponding RHS norms and X norms are calculated in ATLAS. Updates to temperature are measured relative to some characteristic value of temperature. The CLIM.EB parameter can be viewed as a regularization parameter for the case of very small electron or hole densities in the energy balance equations. The CLIM.EB parameter specifies the minimum value of concentration for which the relaxation term in the energy balance equation will be properly resolved. The temperatures for points where the concentration is much less than CLIM.EB are equal to the lattice temperature. The units of CLIM.EB are  $\text{cm}^{-3}$  and the default is 0.0.

### 17.5.8: Terminal Current Criteria

Another qualification for convergence is derived from the relative changes in terminal currents and the satisfaction of total current conservation. This qualification can be expressed as the simultaneous satisfaction of the following conditions:

$$\left| I_i^{K+1} - I_i^K \right| \leq E_1 \left| I_i^{K+1} \right| + E_2 \quad 17-4$$

and

$$\left| \sum I_i^{K+1} \right| < 0.01 \max_i \left( \left| I_i^{K+1} \right|, E_2 \right) \quad 17-5$$

$I = 1, nc$

where

$I_i$  is the current through contact  $i$

$K$  is the iteration number

$E_1$  and  $E_2$  are specified tolerances

$nc$  is the number of contacts

### 17.5.9: Convergence Criteria

A summary of the termination criteria that is enough for most purposes will now be given. Detailed reference information is provided in the next section.

The non-linear iteration is terminated when one of the following four criteria is satisfied.

1. The X norm for every equation falls below a specified tolerance. The specified tolerances for X norms are:

$P_{tol}^x$  - for potential equation.

$C_{tol}^x$  - for concentration equations.

$TL_{tol}^x$  - for lattice temperature equation.

$TC_{tol}^x$  - for carrier temperature equation.

2. The RHS for all equations and X norms for energy balance falls below a specified tolerance. The specific tolerances are:

$P_{tol}^r$  - for potential equations.

$C_{tol}^r$  - for concentration equations.

$TL_{tol}^r$  - for lattice temperature equations.

$TC_{tol}^r$  -for carrier temperature equations.

3. For every equation either the X norm or the RHS norm falls below a specified tolerance. In this case, both the XNORM and RHSNORM parameters must be specified true.
4. If either 1. or 2. or 3. criterion is fulfilled for weaker values of tolerances (i.e., for specified tolerances multiplied by the W parameter and current criteria 14-4 and 14-5 are satisfied).

To exclude the X-norm criterion, ^XNORM should be specified in the METHOD statement; to exclude RHS-norm criterion, ^RHSNORM should be specified; to exclude the current criterion E1 and E2 should be made very small. All the above mentioned tolerances can be changed simultaneously by specifying the relaxation factor TOL.RELAX in the METHOD statement.

**Table 17.1. User-Specifiable Parameters for Convergence Criteria**

| Symbol       | Statement | Parameter | Default   |
|--------------|-----------|-----------|-----------|
| $P_{tol}^x$  | METHOD    | PX.TOL    | $10^{-5}$ |
| $C_{tol}^x$  | METHOD    | CX.TOL    | $10^{-5}$ |
| $TL_{tol}^x$ | METHOD    | TLX.TOL   | $10^{-5}$ |



| Table 17.1. User-Specifiable Parameters for Convergence Criteria |           |           |                       |
|--|-----------|-----------|-----------------------|
| Symbol   | Statement | Parameter | Default               |
| $TC_{tol}^x$   | METHOD    | TCX.TOL   | $10^{-5}$             |
| $P_{tol}^r$  | METHOD    | PR.TOL    | $5.0 \times 10^{-26}$ |
| $C_{tol}^r$  | METHOD    | CR.TOL    | $5.0 \times 10^{-18}$ |
| $TL_{tol}^r$   | METHOD    | TLR.TOL   | 100                   |
| $TC_{tol}^r$   | METHOD    | TCR.TOL   | 100                   |
| $E_1$  | METHOD    | IX.TOL    | $2.0 \times 10^{-5}$  |
| $E_2$  | METHOD    | IR.TOL    | $5.0 \times 10^{-15}$ |
| W  | METHOD    | WEAK      | 200                   |
| TOL.RELAX  | METHOD    | TOL.RELAX | 1                     |
| XNORM  | METHOD    | XNORM     | TRUE                  |
| RHSNORM  | METHOD    | RHSNORM   | TRUE                  |
| CLIMIT   | METHOD    | CLIMIT    | $10^4$                |
| CLIM.DD  | METHOD    | $C_0$     | $4.5 \times 10^{13}$  |
| CLIM.EB  | METHOD    | CLIM.EB   | 0                     |

### 17.5.10: Detailed Convergence Criteria

Only in very difficult situations is more detailed information concerning error estimation and the specification of convergence criteria needed. The material is organized by algorithm.

#### Convergence Criteria For Gummel's Algorithms

Relative update errors are defined as follows:

For potential:

$$\varepsilon_v = \frac{\max_m \left| \varphi_m^{K+1} - \varphi_m^K \right|}{\max(1, \varphi_{mmax}^{K+1})}, \quad 17-6$$

where  $mmax$  is the node where  $\left| \varphi_m^{K+1} - \varphi_m^K \right|$  has its maximum value;

For electrons:

$$\varepsilon_n = \frac{\max_m \left| \binom{K+1}{n} - \binom{K}{n} \right|}{\max(C_0, \binom{K}{n_m})} \quad 17-7$$

For holes:

$$\varepsilon_p = \frac{\max_m \left| \binom{K+1}{p} - \binom{K}{p} \right|}{\max(C_0, \binom{K}{p_m})} \quad 17-8$$

For lattice temperature:

$$\varepsilon_{T_L} = \frac{(T_L)_{nmax}^{K+1} - (T_L)_{nmax}^K}{(T_L)_{nmax}^{K+1}} \quad 17-9$$

where  $nmax$  is the node where  $(T_L)_i^{K+1}$  has its maximum value;

For carrier temperature:

$$\varepsilon_{T_c} = \max(\varepsilon_{T_n}, \varepsilon_{T_p}) \quad 17-10$$

where

$$\varepsilon_{T_n} = \frac{\max_m \left| (T_n)_m^{K+1} - (T_n)_m^K \right|}{\max_m (T_n)_m^{K+1}} \quad 17-11$$

$$\varepsilon_{T_p} = \frac{\max_m \left| (T_p)_m^{K+1} - (T_p)_m^K \right|}{\max_m (T_p)_m^{K+1}} \quad 17-12$$

For drift diffusion, iterations are terminated if the following criteria are satisfied:

$$\varepsilon_v \leq P_{tol}^x \quad 17-13$$

$$\varepsilon_n \leq c_{tol}^x \quad 17-14$$

$$\varepsilon_v \leq C_{tol}^x \quad 17-15$$

In non-isothermal drift diffusion, iterations are terminated if Equations 17-10 to 17-12 are satisfied, the current convergence criteria in Equations 17-4 and 17-5 are met and:

$$\varepsilon_{T_L} < TL_{tol}^x \quad 17-16$$

In Gummel's method with energy balance equations NITGUMM iterations in which only the non-linear Poisson equation is solved, will always be done. Gummel's method with energy balance equations is terminated if Equation 17-16 is fulfilled, the carrier temperature convergence criteria.

$$\varepsilon_{T_c} \leq TC_{tol}^x \quad 17-17$$

is achieved, and one of the following conditions is valid:

- a) NITGUMM < K+1 ≤ NITGUMM+NT1 and Equation 17-13 is fulfilled;
- b) NT1 + NITGUMM < K+1 ≤ NITGUMM + NT3 and:

$$\varepsilon_n \leq P_{tol}^x \cdot w \quad m \quad 17-18$$

where w = 10

- c) NT1 + NITGUMM < K + 1 ≤ NITGUMM + NT3, the current convergence criteria (Equations 17-4 and 17-5) are satisfied, and inequality (Equation 17-18) is valid for w = 100;
- d) NT1 + NITGUMM < K+1 and (Equation 17-18) is valid for w = 100;
- e) NT1 + NITGUMM < K+1 the current convergence criteria (Equations 17-4 and 17-5) are satisfied, and (Equation 17-18) is valid for w = 500.

The default values of the iteration parameters are NITGUMM = 5, NT0 = 4, NT1 = 10, NT3 = 100

## Convergence Criteria For Newton's Algorithm

Relative update errors are defined as follows:

For potential

$$\varepsilon_v = \frac{\max}{m} \left| \phi_m^{K+1} - \phi_m^K \right| \quad 17-19$$

For electron concentration:

$$\varepsilon_n = \frac{\max}{m} \left| n_m^{K+1} - n_m^K \right|}{\max(C_0, n_m^K)} \quad 17-20$$

For hole concentration:

$$\varepsilon_p = \frac{\max}{m} \left| p_m^{K+1} - p_m^K \right|}{\max(C_0, p_m^K)} \quad 17-21$$

For lattice temperature and carrier temperature:

$$\varepsilon_{T_L} = \frac{\max_m \left| (T_L)_m^{K+1} - (T_L)_m^K \right|}{T_{scale}}, \quad 17-22$$

$$\varepsilon_{T_n} = \frac{\max_m \left| (T_n)_m^{K+1} - (T_n)_m^K \right|}{T_{scale}}, \quad 17-23$$

$$\varepsilon_{T_p} = \frac{\max_m \left| (T_p)_m^{K+1} - (T_p)_m^K \right|}{T_{scale}}, \quad 17-24$$

where the scaling temperature,  $T_{scale}$ , is by default equal to 300K.

To define the RHS norms used in ATLAS, first represent the non-linear equations obtained after discretization at every node as

$$(\alpha) \vec{(\chi)} = 0 \quad 17-25$$

where  $\alpha$  can be  $\psi$ ,  $n$ ,  $p$ ,  $T_L$ ,  $T_n$  and  $T_p$  for the potential equation, electron continuity equation, hole continuity equation, lattice temperature equation, electron temperature equation and hole temperature equation, respectively.  $\vec{\chi}$  represents the vector of unknowns.

The RHS norms in ATLAS is then defined as follows:

For the potential equation:

$$\varepsilon_v^g = \max_m |F_\psi| \quad 17-26$$

For the electron and continuity equations:

$$\varepsilon_n^g = \max_m |F_n| \cdot C_T \quad 17-27$$

$$\varepsilon_p^g = \max_m |F_p| \cdot C_T \quad 17-28$$

where  $C_T = 10^{-4} \sqrt[4]{N_c N_v} \quad kT$

For the lattice temperature and carrier temperature equations:

$$\varepsilon_{T_L}^g = \max_m |F_{T_L}| \quad 17-29$$

$$\varepsilon_{T_n}^g = \max_m |F_{T_n}| \quad 17-30$$

$$\varepsilon_{T_p}^g = \max_m |F_{T_p}| \quad 17-31$$

Newton iterations are terminated if one of the following criteria is satisfied:

a) the XNORM parameter is true and:

$$\varepsilon_v \leq P_{tol}^x \cdot w, \quad 17-32$$

$$\varepsilon_n \leq C_{tol}^x \cdot w, \quad 17-33$$

$$\varepsilon_p \leq P_{tol}^x \cdot w, \quad 17-34$$

$$\varepsilon_{T_L} \leq TL_{tol}^x \cdot w, \quad 17-35$$

$$\varepsilon_{T_n} \leq TC_{tol}^x \cdot w, \quad 17-36$$

$$\varepsilon_{T_p} \leq TL_{tol}^x \cdot w, \quad 17-37$$

where  $w = 1$

b) the RHSNORM parameter is true, conditions for Equations 17-36 and 17-37 are satisfied for  $w = 1$  and:

$$\varepsilon_v^g \leq P_{tol}^r \cdot w_1, \quad 17-38$$

$$\varepsilon_n^g \leq C_{tol}^r \cdot w_1, \quad 17-39$$

$$\varepsilon_p^g \leq P_{tol}^r \cdot w_1, \quad 17-40$$

$$\varepsilon_{T_L}^g \leq TL_{tol}^r \cdot w_1, \quad 17-41$$

$$\varepsilon_{T_n}^g \leq TC_{tol}^r \cdot w_1, \quad 17-42$$

$$\varepsilon_{T_p}^g \leq TL_{tol}^r \cdot w_1, \quad 17-43$$

c) both the XNORM and RHSNORM parameters are true, the convergence criteria for Equations 17-36 and 17-37 for carrier temperature are fulfilled, and for the inequalities (Equations 17-32 and 17-38), (Equations 17-33 and 17-39), (Equations 17-34 and 17-40), (Equations 17-35 and 17-41) one of the conditions is fulfilled for every pair.

d) if the current convergence criteria are satisfied and condition a) or condition b) or condition c) is fulfilled for:  $w = w_1 = \text{WEAK}$

## Convergence Criteria For Block Iteration

For the potential equation and the continuity equations, the X norms and RHS norms are defined as for the Newton method by Equations 17-19 to 17-21 and Equations 17-26 to 17-28.

With s as an index that denotes the number of block iterations, update errors between successive pairs of block iterations for lattice and carrier temperature are defined by the following expression:

For lattice temperature:

$$\varepsilon_{T_L}^B = \frac{|(T_L)_{mmax}^{s+1} - (T_L)_{mmax}^s|}{(T_L)_{mmax}^{s+1}} \quad 17-44$$

where mmax is the number of the node where  $(T_L)_m$  has its maximum value.

For electron temperature:

$$\varepsilon_{T_n}^B = \frac{|(T_n)_{mmax}^{s+1} - (T_n)_{mmax}^s|}{(T_n)_{mmax}^{s+1}} \quad 17-45$$

For hole temperature:

$$\varepsilon_{T_p}^B = \frac{|(T_p)_{mmax}^{s+1} - (T_p)_{mmax}^s|}{(T_p)_{mmax}^{s+1}} \quad 17-46$$

Block iterations are terminated if:

$$\varepsilon_{T_L}^B \leq TL_{tol}^x \quad 17-47$$

$$\varepsilon_{T_n}^B \leq TC_{tol}^x \quad 17-48$$

$$\varepsilon_{T_p}^B \leq TL_{tol}^x \quad 17-49$$

and one of the following criteria is fulfilled:

- the XNORM parameter is true and Equations 17-32, 17-33, and 17-34 are valid for  $w = 1$ .
- the RHSNORM parameter is true and Equations 17-38, 17-39, and 17-40 are valid for  $w_1 = 1$ .
- both XNORM and RHSNORM are true and for the pairs of inequalities (Equations 17-32 and 17-38), (Equations 17-33 and 17-39), (Equations 17-34 and 17-40) one of the conditions is satisfied for each pair.
- the current convergence criteria are satisfied and condition 1, condition 2, or condition 3 is fulfilled for  $w = w_1 = \text{WEAK}$ .

## 17.6: Initial Guess Strategies

Non-linear iteration starts from an initial guess. The quality of the initial guess (i.e., how close it is to the final solution) affects how quickly the solution is obtained, and whether convergence is achieved. ATLAS users aren't required to specify an initial guess strategy. If no strategy is defined, ATLAS follows certain rules that implement a sensible, although not necessarily optimum, strategy.

There is some interaction between the choice of non-linear iteration scheme and the initial guess strategy. Decoupled iteration usually converges linearly, although perhaps slowly, even from a relatively poor initial guess. Newton iteration converges much faster for a good initial guess, but fails to converge if started from a poor initial guess.

One very simple initial guess strategy is to use the most recent solution as the initial guess. Of course, there is no previous solution for the first calculation in a series of bias points. In this case, an initial solution is obtained for equilibrium conditions. There is no need to solve the current continuity equations at equilibrium, and a solution of Poisson's equation is quickly obtained.

It is also possible to modify the initial guess in a way that makes some allowance for the new bias conditions. Typical strategies include:

- Using two previous solutions and interpolation to project a new solution at each mesh point.
- Solving a form of current continuity equation with carrier concentrations held constant. This strategy yields an improved estimate of new potential distribution.
- Modifying the majority carrier quasi-Fermi levels by the same amount as the bias changes.

Parameters on the SOLVE statement can be used to specify an initial guess strategy. Six initial guess strategies are available.

- INITIAL starts from space charge neutrality throughout the device. This choice is normally used to calculate a solution with zero applied bias.
- PREVIOUS uses the currently loaded solution as the initial guess at the next bias point. The solution is modified by setting a different applied bias at the contacts.
- PROJECTION takes two previous solutions whose bias conditions differ at one contact and extrapolates a solution for a new applied bias at that contact. This method is often used when performing a voltage ramp.
- LOCAL sets the applied bias to the specified values, and changes the majority carrier quasi-Fermi levels in heavily doped regions to be equal to the bias applied to that region. This choice is effective with Gummel iteration, particularly in reverse bias. It is less effective with Newton iteration.
- MLOCAL starts from the currently loaded solution and solves a form of the total current continuity equation that provides an improved estimate of the new potential distribution. All other quantities remain unchanged. MLOCAL is more effective than LOCAL because it provides a smooth potential distribution in the vicinity of p-n junctions. It is usually more effective than PREVIOUS because MLOCAL provides a better estimate of potential. This is especially true for highly doped contact regions and resistor-like structures.
- NOCURRENT assumes there is negligible current flow in the device and solves the non-linear Poisson equation to arrive at the initial guess. If the assumption of negligible current density is indeed correct, then the initial guess should be the solution to the current continuity equations too. You can use NOCURRENT to avoid ramping a bias to attain the solution at high bias.

When a regrid is performed, the solution is interpolated from the original grid onto a finer grid. This provides an initial guess that can be used to start the solution of the same bias point on the new grid. Although the initial guess is an interpolation of an exact solution, this type of guess does not provide particularly fast convergence.

## 17.6.1: Recommendations And Defaults

It is not normally required to specify any initial guess parameter.

The `INITIAL` parameter is normally used only to obtain a thermal equilibrium solution. The `PREVIOUS`, `PROJECT`, `LOCAL`, and `MLOCAL` parameters are used for other bias points. `PREVIOUS` and `PROJECTION` are the most frequently used. `PROJECTION` is normally preferred to `PREVIOUS` when it is available (i.e., when there are two previous solutions differing in the bias applied to the appropriate terminal). `PREVIOUS` is required for transient simulations, and for simulations that use current boundary conditions. `LOCAL` and `MLOCAL` tend to work well for reverse-biased devices, and are especially efficient when trying to increase very large voltage increments. By default, `PROJECTION` is used whenever two appropriate solutions are available. Otherwise, the `PREVIOUS` guess is used, unless there is no previous solution, in which case `INITIAL` is used.



## 17.7: The DC Curve-Tracer Algorithm

Tracing I-V curves for complicated device phenomena such as breakdown or latchup can be very difficult using conventional methods. ATLAS includes a special purpose DC curve-tracing algorithm that overcomes these problems. This algorithm is based on a dynamic load-line technique that adapts the boundary conditions for each step. The approach implemented in ATLAS for curve tracing is based on the work describe in [116].

The key idea is that bias conditions can evolve smoothly between the limits of pure voltage control and pure current control. This is achieved using external resistors that adapt dynamically to the shape of the I-V curves to ensure that at each point the load line is perpendicular to the local tangent of the trace. With this value for the external resistor, the solution is projected to the next operating point by stepping the external voltage. Once the solution has converged, a new external resistance is calculated based on the new tangent information, and the process repeats itself.

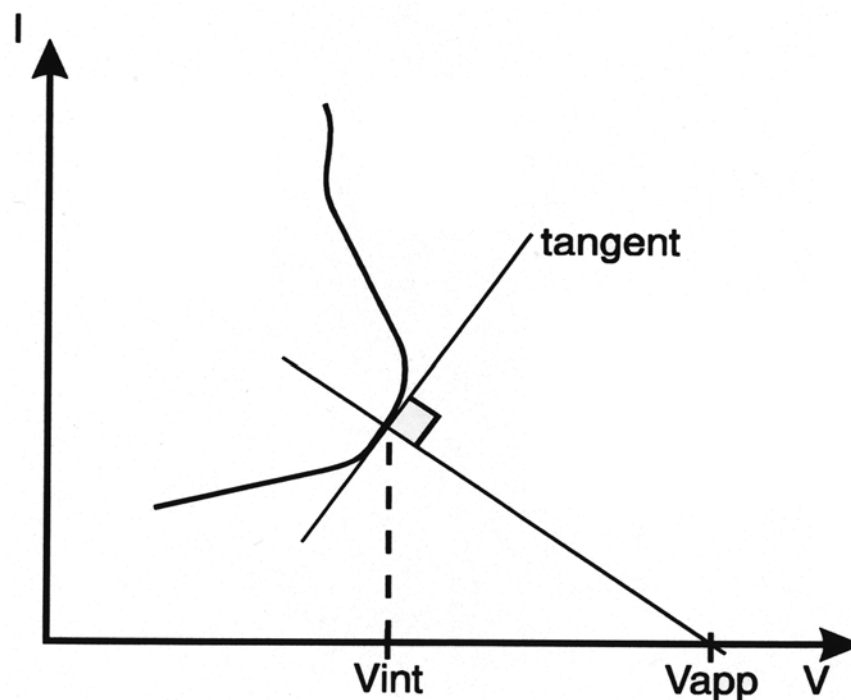


Figure 16-1: Load the algorithm used in the Curve Tracer

The curve tracing capability is activated by specifying the CURVETRACE parameter in the SOLVE statement. Prior to this, the CURVETRACE statement is used to set the parameters for the tracing algorithm. These parameters are the name CONTR.NAME of the ramped electrode (which will be referred to as a control electrode), the initial voltage increment STEP.INIT, the upper bound of the tracing curve, and additional parameters if they differ from the default values. The Upper bound parameter, END.VAL, is used to stop tracing. If the VOLT.CONT parameter is specified, END.VAL is a voltage. If the CURR.CONT parameter is specified, END.VAL is a current.

The applied voltage at each step is altered in accordance with the slope of the I-V curve. The resistor between the applied voltage and the semiconductor is also changed dynamically to ensure the voltage at the semiconductor (VINT) is smoothly varied along the I-V curve. If STEP.CONT is specified, the number of operational points on a trace will not exceed specified parameter STEPS.

## 17.8: Transient Simulation

When transient simulation is performed, the carrier continuity equations are integrated in the time domain. Time integration schemes differ in their accuracy, in the number of previous time levels they employ, and in their stability properties.

Accuracy is usually referred to as being “nth order”, where n is usually an integer between 1 and 4. In the limit of a small timestep, the magnitude of the local truncation error (LTE) introduced by the time integration scheme is proportional to the nth power of the timestep. Schemes that require the storage of solutions at timesteps previous to the most recent one are unattractive due to storage requirements. Single step integration schemes that use the solution at only one previous time level have a maximum order of 2.

The continuity equations are “stiff” (i.e., they are impacted by phenomena with very short timescales). Stiffness imposes stringent requirements on the stability of time integration schemes. Two forms of stability, A-stability and L-stability, are important. A-stability guarantees that errors introduced at one time step will not increase at the next timestep. L-stability guarantees that errors will decay even for large time step values. A-stability is a requirement for any practical scheme. L-stability is extremely desirable to avoid non-physical “ringing”.

Most device simulation codes use a simple first-order (implicit) backward difference formula for time integration [71,72,73]. This scheme, which is known as BDF1, is both A-stable and L-stable. Unfortunately, the scheme is inaccurate for typical timesteps of interest. Second order accuracy is obtained using the trapezoidal rule (TR) for time integration. This scheme is A-stable, but it is not L-stable. This means that solutions exhibit non-physical “ringing”, unless very small timesteps (much smaller than those dictated by LTE considerations) are used. The BDF2 scheme is second order, and both A-stable and L-stable, but it uses solutions from two previous time levels, and is also less accurate than TR.

For drift-diffusion calculations, ATLAS uses a composite TR-BDF2 scheme that was developed by Bank et. al.[74]. This method is one-step, second order, and both A-stable and L-stable. An estimate of the LTE is obtained at each timestep, and this estimate is used to automatically adapt the timestep.

Different schemes are used for transient solutions that include lattice heating or energy balance. If lattice heating is included the block iterative procedure is organized at each time step in the same way as for the steady state case. If energy balance is selected, the absolutely stable half-implicit scheme [76] is used. Automatic timestep selection with local error control is implemented in this case. The tolerance may be specified using the `TOL.TIME` parameter in the `METHOD` statement.

---

**Note:** You normally specify only the initial timestep with the `TSTEP` parameter of the `SOLVE` statement. After this, time steps are derived from the LTE and will typically increase.

---

## 17.9: Small Signal and Large Signal Analysis

There are several ways to predict the small-signal and large-signal high-frequency properties of semiconductor devices (review of these different techniques was presented by Laux [75]). Frequency domain perturbation analysis can be used to determine the small-signal characteristics while Fourier analysis of transient responses (FATR) can be used for both small-signal and large signal response.

You can also use charge partitioning models [60] but these methods have been dropped because they can only be applied to insulated contacts, where there is only displacement current, and are strictly quasi-static (low frequency).

### 17.9.1: Frequency Domain Perturbation Analysis

Frequency-domain perturbation analysis of a DC solution can be used to calculate small-signal characteristics at any user-specified frequency [75]. This scheme works for both 2D and 3D. The calculation proceeds in the following manner:

1. Variables are represented as the sum of the known DC component and a small unknown sinusoidal AC component.
2. All equations are expanded.
3. Differentiation in time becomes multiplication by the value of  $j\omega$  ( $\omega = 2\pi$  frequency).
4. Products of AC quantities are neglected since they are small with respect to other quantities
5. The DC solution is subtracted.

What remains is a complex linear system whose unknowns are the AC components of the solution. Solving this linear system with appropriate boundary conditions yields small-signal characteristics.

The coefficient matrix of the complex linear system is simply the Jacobian associated with the DC operating point, with some terms on the leading diagonal supplemented by  $j\omega$ . The Jacobian is available 'for free' if the DC solution was calculated using Newton iteration. This is a very attractive feature of the Newton method. The resulting linear complex system can be solved by an iterative or a direct method. A form of successive over relaxation (SOR) works well for frequencies significantly below the cutoff frequency, but fails at higher frequencies. More sophisticated iterative techniques can be used at higher frequencies, but it is simpler and more reliable to switch to direct sparse matrix methods if SOR fails to converge.

Frequency domain perturbation analysis is extremely attractive when the full Newton method is used to calculate a DC solution. The method works for all frequencies. It requires a predictable amount of computation which is quite low with respect to other calculations, since only a single linear system is solved.

Frequency domain perturbation analysis is invoked in ATLAS by specifying the appropriate parameters in the SOLVE statement. The AC.ANALYSIS parameter specifies that this analysis is to be performed. TERMINAL specifies the contact whose terminal voltage is to be perturbed. A full characterization requires that all but one of the device terminals is perturbed. FREQUENCY, FSTEP, and NFSTEPS determine the frequencies for which solutions are obtained. FREQUENCY specifies the initial frequency. FSTEP and NFSTEPS define a loop on frequencies. If MULT.FREQ is specified, the frequency is multiplied by FSTEP at each increment. This is useful for characterizing the small-signal response over several decades of frequency. The solution method can be specified using the SOR, DIRECT, and AUTO parameters. AUTO starts out using SOR but switches to DIRECT if convergence problems are encountered.

## 17.9.2: Fourier Analysis Of Transient Responses

FATR is a post-processing step which must be performed on a LOG file which contains transient data. The FOURIER statement performs a Fast Fourier Transform (FFT) on the time domain data transforming it into the frequency domain.

The syntax of the FOURIER statement is shown in Table 17-2. For more information about the FOURIER statement, see Chapter 18: “Statements”, Section 18.14: “FOURIER”.

| Statement | Parameter      | Default |
|-----------|----------------|---------|
| FOURIER   | INFILE         |         |
| FOURIER   | OUTFILE        |         |
| FOURIER   | T.START        |         |
| FOURIER   | T.STOP         |         |
| FOURIER   | FUNDAMENTAL    |         |
| FOURIER   | MAX.HARMONIC   |         |
| FOURIER   | NUM.SAMPLES    | 64      |
| FOURIER   | INTERPOLATE    | FALSE   |
| FOURIER   | COMPLEX.VALUES | FALSE   |

The explanation for the FOURIER parameters are as follows:

- INFILE – input log file. This should contain data from a transient simulation.
- OUTFILE – file output file for the Fourier transform.

The following parameters are optional:

- T.START – start of time data to be used for the FFT. The default value is the first time point in the input log file.
- T.STOP – end of time data to be used for the FFT. The default value is the last time point in the input log file.
- FUNDAMENTAL – fundamental frequency. If this is not specified, then the fundamental frequency is set to  $1/(T.STOP - T.START)$ . If the fundamental frequency is specified then T.STOP is set to  $T.START + 1/FUNDAMENTAL$ .
- MAX.HARMONIC – maximum harmonic frequency that the FFT should calculate. This will automatically calculate the correct number of samples (NUM.SAMPLES) required to generate this frequency. FUNDAMENTAL must be specified when MAX.HARMONIC is used.
- NUM.SAMPLES – number of samples. This should be an integer power of 2, i.e.  $2^n$ , where n is a positive integer. The default value is 64 unless the MAX.HARMONIC parameter is specified. In this case, the number of samples is set to the nearest integer power of 2 which will generate this frequency.
- INTERPOLATE – performs linear interpolation on input data with non-uniform timesteps. This interpolates the data on to uniform timesteps. Interpolation of data can introduce addition (inaccurate) harmonic values into the FFT, which would not occur if uniform time is taken. INTERPOLATE must be used if the log file contains non-uniform time steps.
- COMPLEX.VALUES – prints the real and imaginary components to file, as well as the magnitude and phase.

**Note:** FFT works best with uniform time steps, therefore `DT . MIN` and `DT . MAX` on the `METHOD` statement should be set to the same value. The time step should be set to:  $\text{time step} = 1/(\text{number of samples} * \text{fundamental frequency})$ .

---

The FFT can then calculate harmonic frequencies up to:

$(\text{number of samples}/2 - 1) * \text{fundamental frequency}$ .

Small-signal data at high frequencies can be obtained by calculating the terminal current responses to terminal voltage perturbations. The currents and voltages should then Fourier analyzed. Their ratio at each frequency provides admittance data for that frequency. The voltage perturbations are normally selected to have an analytic form with a known Fourier transform. Care must be taken to self-consistently account for geometric capacitances when step function voltage perturbations are used. The advantages of this technique are that it can be used whenever transient calculations are possible, and each transient solution gives information over a broad range of frequencies. The main disadvantage is that transients become very long when low frequency effects are investigated.

### 17.9.3: Overall Recommendations

Use frequency-domain perturbation analysis when it is available. The method works for arbitrary frequencies and does not require transient calculations.

Use Fourier analysis of transient responses for high frequencies when is not available but transient calculations are possible.

## 17.10: Differences Between 2D and 3D Numerics

With respect to numerical techniques there are several differences between 2D and 3D simulations.

First, with respect to the nonlinear iteration strategies, all three strategies, `NEWTON`, `GUMMEL` and `BLOCK` are supported in 2D simulation, whereas, only `NEWTON` and `GUMMEL` are supported for 3D simulations. Implementation of the `BLOCK` strategy is expected in a future release.

Second, solution of the linear subproblem is handled differently for 2D and 3D simulations. As previously noted the computational burden of solving the linear subproblem increases with the size of the solution domain. For smaller problems direct methods are quicker while for larger problems iterative methods are preferred. It turns out that the point at which the iterative methods become less burdensome roughly coincides with the transition between 2D and 3D domains. As such the default method for 2D simulations is a direct solver. For 3D simulations, the default method is an iterative solver. By default `ILUCGS` is applied to 3D simulations. `ILUCGS` is an acronym for incomplete lower upper decomposition conjugate gradient squared. Two alternative iterative solvers are also available for 3D simulations. `BICGST` (`BICGST` on the `METHOD` statement) is an acronym for biconjugate gradient squared stabilized. `GMRES` (`GMRES` on the `METHOD` statement) is an acronym for generalized minimum residual. Direct methods can be used for 3D simulation by specifying `DIRECT` on the `METHOD` statement. Practical experience shows that for 3D simulations either of the iterative methods are faster than the direct method. But in some cases, the accuracy produced by the iterative methods can prevent convergence in the nonlinear outer loop. For 2D simulations only direct methods are supported.

The DC curve tracer algorithm and small signal AC analysis are also not currently supported for 3D simulations.

## 18.1: Input Language

This chapter contains a complete description (in alphabetical order) of every statement and parameter used by any of the ATLAS products, except for MIXEDMODE. (MIXEDMODE specific parameters are described in Chapter 12: “MixedMode: Mixed Circuit and Device Simulator”). Descriptions for the statements in this chapter are as follows:

- The statement name.
- The product for which the statement is applicable.
- The syntax of the statement.
- A list of all statement parameters, their type, default value, and units.
- A description of each parameter.
- An example of the correct usage of each statement.

---

**Note:** An error message will be generated if you attempt to specify a statement for a simulator that you haven't purchased. For example, the BEAM statement can only be used if you have purchased LUMINOUS or LUMINOUS 3D.

---

### 18.1.1: Syntax Rules

An input deck line is referred to as a statement (or statement line). Since statements and parameters are not case sensitive, they can be entered using either uppercase or lowercase letters.

A statement is specified in the general format:

```
<STATEMENT> <PARAMETER>=<VALUE>
```

where STATEMENT is the statement name, PARAMETER is the parameter name, and VALUE is the parameter value. The space character is used to separate the parameters in a statement.

The words and numbers, which follow a statement, are parameters of that statement. A word is an alphanumeric string, which is terminated either by a space or by a carriage return. A number is a numeric or alphanumeric string which is terminated either by a space or by a carriage return. Numerical values may range from  $10^{-38}$  to  $10^{38}$ . A number may contain the symbols + (positive), - (negative), and/or E (decimal notation). For example:

```
+10 -1.234E5 .003 -.12E+10
```

Four types of parameters are used by the ATLAS products. These are: real, integer, logical, and character. Table 18-1 explains these parameter types.

| Table 18.1. Types of Parameters |                           |                |                 |
|---------------------------------|---------------------------|----------------|-----------------|
| Parameter                       | Description               | Value Required | Example         |
| Character                       | Any character string      | Yes            | INFILE=NMOS.DOP |
| Integer                         | Any whole number          | Yes            | REGION=2        |
| Logical                         | A true or false condition | No             | GAUSSIAN        |
| Real                            | Any real number           | Yes            | X.MIN=0.52      |

Any parameter that doesn't have a logical value must be specified in the form: `PARAM=VAL`, where `PARAM` is the name of the parameter, and `VAL` is the value of the parameter. Logical parameters must be separated from other parameters or commands by a space.

For example, in the statement:

```
DOPING UNIFORM CONCENTRATION=1E16 P.TYPE
```

the `UNIFORM` and `P.TYPE` parameters have logical values and the `CONCENTRATION` parameter has a value of  $1 \times 10^{16}$  (real).

Logical parameters can be turned off (switched from true to false) by placing a caret (^) in front of the logical parameter. For example, in the statement:

```
DOPING UNIFORM CONCENTRATION=1E16 ^P.TYPE
```

the `P.TYPE` parameter has been set to false.

## Mnemonics

It is not always necessary to input the entire statement or parameter name. ATLAS only requires that you input enough letters to distinguish that command or parameter from other commands or parameters. For example, `DOP` may be used to abbreviate the `DOPING` command. Excessive truncation is not recommended, since future ATLAS syntax might make short abbreviations become ambiguous.

## Continuation Lines

Since it may be necessary for a statement line to contain more than 256 characters, ATLAS allows you to specify continuation lines. To continue a line, put a backslash (\) character at the end of the line that is to be continued. When ATLAS encounters the backslash, it will interpret the next line to be a continuation of the current line. The PISCES-II continuation of using a (+) at the start of the subsequent line is not supported in ATLAS.

## Comments

Comments are indicated either by `COMMENT` command, or by a pound sign (#). All characters on a line, which follow a comment indicator (`COMMENT` or #) will not be analyzed by ATLAS.

## Synonyms

Some parameters have synonyms. These are parameters that have a different name but the same functionality. A parameter's synonym is listed in the parameter descriptions of the statements.

## Pseudonyms

Throughout the statement descriptions, pseudonyms are used either to indicate a group of parameters or to indicate the value of a particular parameter. A < symbol indicates the start of a pseudonym(s). A > symbol indicates the end of a pseudonym(s). Pseudonyms will be separated from one another by a space character ( ). For example, `LOC` might indicate a group of location parameters, and `FILENAME` might indicate the name of a file that must be specified.

## Symbols

The following symbols are used in the statement descriptions:

- < Indicates the start of a list of pseudonyms.
- > Indicates the end of a list of pseudonyms.
- | Separates parameters or pseudonyms which are mutually exclusive. Only one of these parameters may be used in a statement.
- [ Indicates the start of an optional command, parameter, or pseudonym.



- ] Indicates the end of an optional command, parameter, or pseudonym.

## Expressions

ATLAS does not support arithmetic expressions in the syntax. You can, however, evaluate and use expressions by using the `SET` or `EXTRACT` statements.

## 18.2: BEAM

BEAM specifies an optical input signal in the form of a collimated beam of light. This statement is used with LUMINOUS or LUMINOUS 3D.

### Syntax

BEAM <parameters>

| Parameter     | Type      | Default | Units   |
|---------------|-----------|---------|---------|
| AMBIENT.INDEX | Real      | 1.0     |         |
| ANGLE         | Real      | 0.0     | Degrees |
| BACK.REFL     | Logical   | False   |         |
| BPM           | Logical   | False   |         |
| CIRCULAR      | Logical   | False   |         |
| DEVICE        | Character |         |         |
| ELLIPTICAL    | Logical   | False   |         |
| F.RADIATE     | Character |         |         |
| F3.RADIATE    | Character |         |         |
| F.REFLECT     | Character |         |         |
| FRONT.REFL    | Logical   | False   |         |
| GAUSSIAN      | Logical   | False   |         |
| INTEGRATE     | Logical   | True    |         |
| ITERATION     | Integer   | 20      |         |
| LENS.HEIGHT   | Real      | 0.0     | microns |
| LENS.INDEX    | Real      | 1.0     |         |
| LENS.PLANE    | Real      | 0.0     | μm      |
| LENS.RADIUS   | Real      | 0.0     | μm      |
| LENS.WIDTH    | Real      |         | microns |
| LENS.X        | Real      | 0.0     | μm      |
| LENS.XMAX     | Real      | 0.0     | microns |
| LENS.XMIN     | Real      | 0.0     | microns |
| LENS.Y        | Real      | 0.0     | μm      |
| LENS.Z        | Real      | 0.0     | μm      |
| LENS.ZMAX     | Real      | 0.0     | microns |
| LENS.ZMIN     | Real      | 0.0     | microns |

| Parameter     | Type      | Default               | Units                  |
|---------------|-----------|-----------------------|------------------------|
| LONGIT.STEP   | Real      | 0.0                   |                        |
| MAX.WINDOW    | Real      | $1.0 \times 10^{20}$  | $\mu\text{m}$          |
| MEAN          | Character | 0.0                   | $\mu\text{m}$          |
| METAL.REFLECT | Logical   | False                 |                        |
| MIN.POWER     | Real      | 0.0                   | $\text{W}/\text{cm}^2$ |
| MIN.WINDOW    | Real      | $-1.0 \times 10^{20}$ | $\mu\text{m}$          |
| NUMBER        | Integer   | 1                     |                        |
| NX            | Integer   | 10                    |                        |
| NZ            | Integer   | 10                    |                        |
| PERIODIC      | Logical   | False                 |                        |
| PHI           | Real      | 0.0                   | Degrees                |
| POLARIZE      | Real      | 0.0                   | Degrees                |
| POWER.FILE    | Character |                       |                        |
| POWER.SCAL    | Real      | 1.0                   |                        |
| QUANTUM.EFF   | Real      | 1.0                   |                        |
| RAY.CHECK     | Logical   | False                 |                        |
| RAYS          | Integer   | 1                     |                        |
| RAYTRACE      | Character |                       |                        |
| REFLECTS      | Integer   | 1                     |                        |
| REL.POWER     | Real      | 1.0                   |                        |
| SIGMA         | Real      | 0.0                   | $\mu\text{m}$          |
| THETA         | Real      | 0.0                   | Degrees                |
| THINEST       | Real      | 0.0                   | $\mu\text{m}$          |
| TRANSV.STEP   | Real      | 0.0                   |                        |
| USER.SPECTRUM | Logical   | False                 |                        |
| VERBOSE       | Logical   | False                 |                        |
| WAVELENGTH    | Real      | 0.623                 | $\mu\text{m}$          |
| WAVEL.END     | Real      | 0.0                   | $\mu\text{m}$          |
| WAVEL.NUM     | Integer   | 1                     |                        |
| WAVEL.SCAL    | Real      | 1.0                   |                        |
| WAVEL.START   | Real      | 0.0                   | $\mu\text{m}$          |

| Parameter  | Type    | Default               | Units   |
|------------|---------|-----------------------|---------|
| X.CENTER   | Real    | 0.0                   | μm      |
| X.GAUSSIAN | Logical | False                 |         |
| X.MEAN     | Real    | 0.0                   | μm      |
| X.ORIGIN   | Real    | 0.0                   | μm      |
| X.RADIUS   | Real    | 0.0                   | μm      |
| X.SEMIAxis | Real    | 0.0                   | microns |
| X.SIGMA    | Real    | 0.0                   | μm      |
| XCENTER    | Real    | 0.0                   | μm      |
| XGAUSSIAN  | Logical | False                 |         |
| XMAX       | Real    | $-1.0 \times 10^{20}$ | μm      |
| XMEAN      | Real    | 0.0                   | μm      |
| XMIN       | Real    | $1.0 \times 10^{20}$  | μm      |
| XRADIUS    | Real    | 0.0                   | μm      |
| XSIGMA     | Real    | 0.0                   | μm      |
| Y.ORIGIN   | Real    | 0.0                   | μm      |
| Y.SEMIAxis | Real    | 0.0                   | microns |
| Z.CENTER   | Real    | 0.0                   | μm      |
| Z.GAUSSIAN | Logical | False                 |         |
| Z.MEAN     | Real    | 0.0                   | μm      |
| Z.ORIGIN   | Real    | 0.0                   | μm      |
| Z.RADIUS   | Real    | 0.0                   | μm      |
| Z.SEMIAxis | Real    | 0.0                   | microns |
| Z.SIGMA    | Real    | 0.0                   | μm      |
| ZCENTER    | Real    | 0.0                   | μm      |
| ZGAUSSIAN  | Logical | False                 |         |
| ZMEAN      | Real    | 0.0                   | μm      |
| ZMAX       | Real    | $-1.0 \times 10^{20}$ | μm      |
| ZMIN       | Real    | $1.0 \times 10^{20}$  | μm      |
| ZRADIUS    | Real    | 0.0                   | μm      |
| ZSIGMA     | Real    | 0.0                   | μm      |

## Description

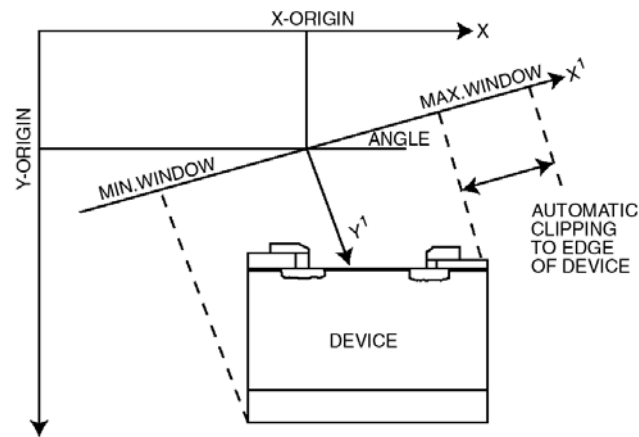


Figure 18-1: LUMINOUS Optical Source Coordinate System

**AMBIENT.INDEX** specifies the index of refraction of domain outside of all meshed regions.

**ANGLE** is the angle of propagation of the optical beam (see Figure 18-1 and Chapter 6: “3D Device Simulator”, Figure 6-6-1).  $ANGLE=90$  is vertical illumination from the top of the device. The synonym for this parameter is **PHI**.

**BACK.REFL** specifies that back side reflections are to be taken into account. When **BACK.REFL** is specified, the area outside the device domain is assumed to be a vacuum (i.e.,  $n = 1.0$ ,  $k = 0.0$ ).

**BPM** (LUMINOUS2D) use the Beam Propagation Method instead of Ray-Tracing for analysis of light propagation in the device. Use **BPM** when diffraction of light or coherent effects are important (see Chapter 10: “Luminous: Optoelectronic Simulator”, Section 10.6: “Beam Propagation Method in 2D”). **BEAM** parameters related specifically to ray tracing (such as **RAYTRACE**, **RAYS**, **THINEST**, **MAX.WINDOW**, **MIN.WINDOW**) are ignored when **BPM** is specified.

**DEVICE** specifies the name of a device in **MIXEDMODE** to identify to which device the beam is directed.

**CIRCULAR** is the synonym for **ELLIPTICAL**.

**ELLIPTICAL** specifies that an elliptical source is to be used in LUMINOUS 3D. When the **ELLIPTICAL** parameter is specified, the **X.CENTER**, **Z.CENTER**, **X.RADIUS**, and **Z.RADIUS** should also be specified. The synonym for this parameter is **CIRCULAR**.

**F.REFLECT** specifies the name of a file containing a C-INTERPRETER function for specifying reflection coefficient models as a function of wavelength, position, and angle incidence (LUMINOUS only).

**F.RADIATE** specifies the name of a file containing a C-INTERPRETER function for specifying generation rate as a function of position and optionally time. This function can be used to simulate single event upset (LUMINOUS2D only).

**F3.RADIATE** is the same as the **F.RADIATE** parameter but is applied in 3-D. This is typically used for single event or photogeneration simulations with LUMINOUS 3D.

**FRONT.REFL** specifies that front side reflections are to be taken into account. When **FRONT.REFL** is specified, the area outside the device domain is assumed to be a vacuum (i.e.,  $n=1.0$ ,  $k= 0.0$ ).

**GAUSSIAN** is the synonym for **X.GAUSSIAN**.

**INTEGRATE** specifies whether the user-specified spectrum (contained in the file identified by the **POWER.FILE** parameter) should be numerically integrated and averaged over the wavelength sampling or if the samples should be interpolated directly from the table.

**LENS.HEIGHT** specifies an attribute of the composite lenslet (see Chapter 10: “Luminous: Optoelectronic Simulator”, Figure 10-8).

**LENS.INDEX** specifies the index of refraction of a lenslet (LUMINOUS 3D only).

**LENS.PLANE** specifies the minimum y-coordinate of the lenslet sphere (LUMINOUS 3D only).

**LENS.RADIUS** specifies the radius of the sphere defining a lenslet (LUMINOUS 3D only).

**LENS.WIDTH** specifies an attribute of the composite lenslet (see Chapter 10: “Luminous: Optoelectronic Simulator”, Figure 10-8).

**LENS.X** specifies the x coordinate of the center of the sphere defining a lenslet (LUMINOUS 3D only).

**LENS.Y** specifies the y coordinate of the center of the sphere defining a lenslet (LUMINOUS 3D only).

**LENS.Z** specifies the z coordinate of the center of the sphere defining a lenslet (LUMINOUS 3D only).

**LENS.XMIN, LENS.XMAX, LENS.ZMIN, LENS.ZMAX** specify attributes of the composite lenslet (see Chapter 10: “Luminous: Optoelectronic Simulator”, Figure 10-8).

**LONGIT.STEP** sets the mesh size in the longitudinal direction when using BPM. The default value is WAVELENGTH/16.0.

**MAX.WINDOW** specifies the maximum x-value of the illumination window relative to the coordinate system of the optical beam (see Figure 18-1). The illumination window is always clipped to the device domain. The synonym for this parameter is XMAX.

**MEAN** is the synonym for X.MEAN.

**METAL.REFLECT** specifies that all metals are to be treated as perfect reflectors.

**MIN.POWER** specifies the minimum intensity relative to the source that a given ray will be traced. This is useful for limiting the numbers of rays traced.

**MIN.WINDOW** specifies the minimum x-value of the illumination window relative to the coordinate system of the optical beam. The synonym for this parameter is XMIN.

**NUMBER** specifies the beam number (from 1 to 10). This number is used by the SOLVE statement to specify the relative intensity of different beams. You may specify beam numbers in any order that you desire.

**NX** specifies the number of rays traced along the source beam's x axis for LUMINOUS 3D (see Chapter 6: “3D Device Simulation”, Figure 6-6-3).

**NZ** specifies the number of rays traced along the source beam's z axis for LUMINOUS 3D (see Chapter 6: “3D Device Simulator”, Figure 6-6-3).

**PERIODIC** specifies that for ray tracing, the structure is to be treated as periodic in the x and z directions. Rays exiting the sides of the device are wrapped around to the other side of the device (LUMINOUS 3D only).

**PHI** is the synonym for ANGLE.

**POLARIZE** specifies the polarization of the optical beam at the origin. The polarization angle is the angle between the E vector and the device plane.

**POWER.SCALE** specifies a scale factor. This factor is multiplied by each of the relative powers in the spectrum file when multi-spectral simulations are performed. The POWER.SCALE parameter can be used to perform unit conversions.

**POWER.FILE** specifies the filename of a spectrum file. The spectrum file must be in the following format:

```
number of pairs
wavelength_1 power_1
```

---

```

wavelength_2  power_2
. . .        . . .
. . .        . . .
wavelength_n  power_n

```

---

**Note:** The power file must contain at least two power/wavelengths pairs.

---

**QUANTUM.EFF** is a quantum efficiency factor which specifies the number of carrier pairs generated per photon absorbed.

**RAYTRACE** specifies the name of a file where the results of a ray trace are saved. The ray trace may be viewed using TONYPLOT3D (LUMINOUS 3D only).

**RAY.CHECK** enables diagnostic printing during ray tracing.

**RAYS** specifies the number of rays you want to split the optical beam. LUMINOUS will automatically split the beam into enough rays to resolve the geometry. Use of the number parameter will cause further splitting of the optical beam (LUMINOUS only).

**REFLECTS** specifies the number of reflections that will be traced. When the value of the REFLECTS parameter is increased, the total number of rays traced increases non-linearly. We recommend that this parameter be used wisely. For example, a single ray incident on three material layers will produce 4 rays if REFLECTS=0 is specified, 10 rays if REFLECTS=1 is specified, and 24 rays if REFLECTS=2 is specified.

**REL.POWER** specifies the relative power in the beam when mono-spectral simulations are performed. This factor is multiplied by the power parameters specified in the SOLVE statement to give the total optical power in the beam.

**SIGMA** is the synonym for X.SIGMA.

**THETA** specifies the angle of rotation for the source beam direction of propagation relative to the x-y plane (see Chapter 6: “3D Device Simulator”, Figure 6-6-2) (LUMINOUS 3D only).

**THINEST** specifies the width of the thinnest ray to be traced (LUMINOUS only).

**TRANSV.STEP** sets the mesh size in the transverse direction when using BPM. The default value is WAVELENGTH/16.0.

**USER.SPECTRUM** specifies that sampling in wavelength used for simulation is the same as that contained in the POWER.FILE.

**VERBOSE** enables a higher level of diagnostic run-time printing.

**WAVELENGTH** specifies the optical wavelength of the source beam (in the vacuum) for mono-spectral simulations.

**WAVEL.END** specifies the maximum wavelength of the source beam (in the vacuum) when multi-spectral simulations are performed.

**WAVEL.NUM** specifies the number of wavelengths which will be used when multi-spectral simulations are performed. Spectral illumination is selected when the WAVEL.NUM parameter is greater than 1. Once multi-spectral simulations are selected, you must specify the POWER.FILE, WAVEL.START, and WAVEL.END parameters.

**WAVEL.SCAL** specifies the scale factor for the wavelengths which are used in multi-spectral simulations. Each of the wavelengths in the spectrum file is multiplied by this scale factor.

**WAVEL.START** specifies the minimum wavelength of the source beam (in the vacuum) when multi-spectral simulations are performed.

**X.CENTER** specifies the X coordinate of the center of an elliptical source related to the beam coordinate system (which is centered at the beam origin) for LUMINOUS 3D. Note that to enable elliptical sources, the ELLIPTICAL parameter should also be specified. The synonym for this parameter is XCENTER.

**X.GAUSSIAN** specifies that a LUMINOUS 3D source is to have a Gaussian intensity profile in the X direction related to the beam coordinate system (which is centered at the beam origin). When X.GAUSSIAN is specified, X.MEAN and X.SIGMA should also be specified. The synonyms for this parameter are XGAUSSIAN and GAUSSIAN.

**X.MEAN** specifies the location of the mean value of a Gaussian source in the X direction related to the beam coordinate system (i.e., from the X.CENTER position). When X.MEAN is specified, X.GAUSSIAN and X.SIGMA should also be specified. The synonyms for this parameter are XMEAN and MEAN.

**X.ORIGIN** specifies the x coordinate of the optical beam origin (see Figure 18-1 and Chapter 6: “3D Device Simulator”, Figure 6-6-1). The beam must originate outside all device regions.

**X.RADIUS** specifies the X axis radius of an elliptical source related to the beam coordinate system (which is centered at the beam origin) for LUMINOUS 3D. Note that to enable elliptical sources, the ELLIPTICAL should also be specified. The synonym for this parameter is XRADIUS.

**X.SEMIAxis, Y.SEMIAxis, Z.SEMIAxis** specify attributes of the elliptical lens (see Chapter 10: “Luminous: Optoelectronic Simulator”, Equation 10-27).

**X.SIGMA** specifies the standard deviation in the X direction of the beam coordinate system for a Gaussian source in LUMINOUS 3D. When X.SIGMA is specified, X.GAUSSIAN and X.MEAN should also be specified. The synonym for this parameter is XSIGMA.

**XMAX** specifies the maximum x coordinate in the source beam coordinate system for ray tracing in LUMINOUS 3D (see Chapter 6: “3D Device Simulator”, Figure 6-6-3).

**XMIN** specifies the minimum x coordinate in the source beam coordinate system for ray tracing in LUMINOUS 3D (see Chapter 6: “3D Device Simulator”, Figure 6-6-3).

**Y.ORIGIN** specifies the y coordinate of the optical beam origin (see Figure 18-1 and Chapter 6: “3D Device Simulator”, Figure 6-6-1). The beam must originate outside all device regions.

**Z.CENTER** specifies the Z coordinate of the center of an elliptical source related to the beam coordinate system (which is centered at the beam origin). Note that to enable elliptical sources, the ELLIPTICAL parameter should also be specified. The synonym for this parameter is ZCENTER.

**Z.GAUSSIAN** specifies that a LUMINOUS 3D source is to have a Gaussian intensity profile in the Z direction related to the beam coordinate system (which is centered at the beam origin). When Z.GAUSSIAN is specified, Z.MEAN and Z.SIGMA should also be specified. The synonym for this parameter is ZGAUSSIAN.

**Z.MEAN** specifies the location of the mean value of a Gaussian source in the Z direction related to the beam coordinate system. When Z.MEAN is specified, Z.GAUSSIAN and Z.SIGMA should also be specified. The synonym for this parameter is ZMEAN.

**Z.RADIUS** specifies the X axis radius of an elliptical source related to the beam coordinate system. When Z.MEAN is specified, Z.GAUSSIAN and Z.SIGMA should also be specified. The synonym for this parameter is ZRADIUS.

**Z.SIGMA** specifies the standard deviation in the Z direction of the beam coordinate system for a Gaussian source in LUMINOUS 3D. When Z.SIGMA is specified, Z.GAUSSIAN and Z.MEAN should also be specified. The synonym for this parameter is ZSIGMA.

**ZMAX** specifies the maximum z coordinate in the source beam coordinate system for ray tracing in LUMINOUS 3D (see Chapter 6: “3D Device Simulator”, Figure 6-6-1).

**ZMIN** specifies the minimum z coordinate in the source beam coordinate system for ray tracing in LUMINOUS 3D (see Chapter 6: “3D Device Simulator”, Figure 6-6-1).



**Z.ORIGIN** specifies the z coordinate of the optical beam origin (see Chapter 6: “3D Device Simulator”, Figure 6-6-1). The beam must originate outside all device regions (LUMINOUS 3D only).

### Monochromatic Beam Example

This beam has a monochromatic spectrum with a wavelength of 0.6  $\mu\text{m}$ . The beam originates at  $x=0.5$  and  $y=-2.0$ . It has a 90 degree propagation angle and a beam width of 0.2  $\mu\text{m}$  which is centered at the beam origin. During the ray trace calculation the rays will be terminated when the power level along the ray falls to 5% of the original power.

```
BEAM NUM=1 WAVELENGTH=0.6 X=0.5 Y=-2.0 ANG=90.0 MIN=-0.1 MAX=0.1 \
MIN.POWER=0.05
```

### Multi-spectral Beam Example

A multi-spectral beam (at a 45 degree angle) which originates at  $x=0.0$  and  $y=-1.0$ . The multi-spectral source is imported from the spectrum file, *source.spc*. The spectrum is discretized into our wavelengths between 0.4  $\mu\text{m}$  and 0.6  $\mu\text{m}$ .

```
BEAM NUM=2 X=0.0 Y=-1.0 ANG=45.0 \
POWER.FILE=SOURCE.SPC WAVEL.START=0.4 \
WAVEL.END=0.6 WAVEL.NUM=4
```

### LUMINOUS3D Lens Example

```
BEAM NUM=1 X.ORIGIN=2.5 Y.ORIGIN=-1.0 Z.ORIGIN = 2.5 ANG=90.0 WAVEL=0.6 \
NX=10 NZ=10 LENS.X=2.5 LENS.Y=-0.5 LENS.Z=2.5 \
LENS.INDEX=2.03 LENS.RADIUS=0.25 LENS.PLANE=-0.5
```

### Gaussian Intensity Profile Example

The following beam statement will define a beam window 2  $\mu\text{m}$  wide that is centred at (X.ORIGIN, Y.ORIGIN) with a Gaussian peak of 0.01  $\text{W}/\text{cm}^2$  with a standard deviation of 0.05  $\mu\text{m}$ .

```
beam num=1 x.origin=5.0 y.origin=-1.0 angle=90.0 wavelength=0.6 \
xmin=-1 xmax=1 GAUSSIAN MEAN=0 SIGMA=0.05 RAYS=200
SOLVE B1=1E-2
```

---

**Note:** It is recommended that you use the RAYS parameter to define a large number of rays across the beam to ensure that the Gaussian profile is adequately reproduced. The rays are evenly spaced across the beam so it is necessary to use a large number of them.

---

## 18.3: COMMENT, #

COMMENT allows comments to be placed in an ATLAS input file. ATLAS will print and display comment lines.

### Syntax

```
COMMENT [<string>]
      # [<string>]
```

**string** is any alphabetic, numeric, or alphanumeric sequence of characters. The synonym for this parameter for #.

### Example

```
COMMENT  ATLAS is a copyright of Silvaco International
#        ATLAS is a copyright of Silvaco International
```

---

**Note:** The \$ was allowed as a comment character in previous versions of ATLAS. This should be avoided and replaced by the # or COMMENT statement.

---

## 18.4: CONTACT

CONTACT specifies the physical attributes of an electrode.

**Note:** If the CONTACT statement is not used for a given electrode, the electrode is assumed to be charge-neutral (Ohmic).

### Syntax

CONTACT NUMBER=<n> | NAME=<ename> | ALL [<wfp>] [<bc>] [<lcr>] [<link>]

| Parameter     | Type      | Default | Units                              |
|---------------|-----------|---------|------------------------------------|
| ALL           | Logical   | False   |                                    |
| ALPHA         | Real      | 0       | cm                                 |
| ALUMINUM      | Logical   | False   |                                    |
| BARRIER       | Logical   | False   |                                    |
| CAPACITANCE   | Real      | 0       | F/ $\mu\text{m}$                   |
| COMMON        | Character |         |                                    |
| CON.RESIST    | Real      | 0       | $\Omega \cdot \text{cm} \cdot \mu$ |
| CURRENT       | Logical   | False   |                                    |
| DEVICE        | Character |         |                                    |
| E.TUNNEL      | Logical   | False   |                                    |
| ELE.CAP       | Integer   |         |                                    |
| EXT.ALPHA     | Real      | 0       | W/( $\text{cm}^2\text{K}$ )        |
| EXT.TEMP      | Real      | 300     | K                                  |
| F.ETUNNEL     | Character |         |                                    |
| FACTOR        | Real      | 0       |                                    |
| FLOATING      | Logical   | False   |                                    |
| FG.CAP        | Real      | 0.0     | F/ $\mu\text{m}$                   |
| INDUCTANCE    | Real      | 0       | H $\cdot\mu\text{m}$               |
| ME.TUNNEL     | Real      | 1.0     |                                    |
| MO.DISILICIDE | Logical   | False   |                                    |
| MOLYBDENUM    | Logical   | False   |                                    |
| MULT          | Logical   | False   |                                    |
| NAME          | Character |         |                                    |
| NEUTRAL       | Logical   | True    |                                    |

| Parameter     | Type    | Default         | Units                      |
|---------------|---------|-----------------|----------------------------|
| N.POLYSILICON | Logical | False           |                            |
| NUMBER        | Integer |                 |                            |
| P.POLYSILICON | Logical | False           |                            |
| REFLECT       | Logical | False           |                            |
| RESISTANCE    | Real    | 0               | $\Omega \cdot \mu\text{m}$ |
| SHORT         | Logical | False           |                            |
| SURF.REC      | Logical | False           |                            |
| TU.DISILICIDE | Logical | False           |                            |
| TUNGSTEN      | Logical | False           |                            |
| VSURFN        | Real    | see description | cm/s                       |
| VSURFP        | Real    | see description | cm/s                       |
| WORKFUN       | Real    | 0               | V                          |

## Description

**NAME** specifies the name of a previously defined electrode. See Section 18.10: “ELECTRODE” for more information.

**NUMBER** specifies the contact number to be defined. It must be the number of a previously defined electrode. It is recommended that electrode names be used rather than numbers.

**ALL** defines the same properties for all electrodes.

**DEVICE** specifies which device the CONTACT statement applies to in MIXEDMODE.

**wfp** is one of the work function parameters described below. It is permitted to either specify the name of a material or a work function value (WORKFUN parameter).

**bc** is one or more of the boundary condition parameters.

**lcr** is one or more of the external parasitic element parameters.

**link** is one or more of a set of parameters that allow you to associate two or more electrodes electrically.

## Workfunction Parameters

**ALUMINUM** specifies aluminum as the contact material for the electrode. This sets the workfunction to 4.10V. Note that this parameter should not be set if an Ohmic contact is required.

**MOLYBDENUM** specifies molybdenum as the contact material for the electrode. This sets the work function of the electrode to 4.53V.

**MO.DISILICIDE** specifies molybdenum disilicide as the contact material for the electrode. This sets the work function of the electrode to 4.80V.

**NEUTRAL** specifies that the electrode is Ohmic. This is the default characteristic of an electrode.

**N.POLYSILICON** specifies n+ doped polysilicon as the contact material for the electrode. This sets the work function to 4.17V.

**P.POLYSILICON** specifies p+ polysilicon as the contact material for the electrode. This sets the work function to  $4.17V + E_g(\text{Si})$ .

**TU.DISILICIDE** specifies tungsten disilicide as the contact material for the electrode. This sets the work function to 4.80V.

**TUNGSTEN** specifies tungsten as the contact material for the electrode. This sets the work function to 4.63V.

**WORKFUN** specifies the work function of the electrode in V. This parameter must be specified in the form `WORKFUN=n` where **n** is a real number. This specification is absolute workfunction and not workfunction difference to the semiconductor.

---

**Note:** If no `WORKFUN` or material type parameter is specified, the electrode is assumed to be an Ohmic contact

---

## Boundary Conditions

**CURRENT** specifies current boundary conditions. If specified, `CAPACITANCE`, `CON.RESIST`, `INDUCTANCE`, or `RESISTANCE` may not be specified.

**FLOATING** specifies a charge boundary condition. This parameter is used to specify the floating gate in EPROM devices. This parameter can only be used for insulated contacts. If specified, `CAPACITANCE`, `CON.RESIST`, `INDUCTANCE`, or `RESISTANCE` may not be specified, but special syntax exists for adding capacitances to a floating contact. See `EL<n>.CAP` and `FG<n>.CAP`. **The synonym for this parameter is** `CHARGE`.

**ALPHA** specifies the linear, dipole lowering coefficient. This parameter has no effect unless the `BARRIER` parameter has been specified.

**BARRIER** turns on the barrier lowering mechanism for Schottky contacts.

**E.TUNNEL** specifies that the Schottky tunnelling model for electrons will be used. `E.TUNNEL` will also enable the `SURF.REC` boundary condition which models the thermionic emission in a Schottky contact.

**EXT.ALPHA** specifies the inverse value of the thermal resistance that can be applied to a contact when performing energy balance simulations. Basically, the thermal resistance allows the carrier energy boundary condition at a contact to be a value other than the ambient temperature.

**EXT.TEMP** specifies the external temperature, or carrier energy, of an electrode when performing energy balance simulations.

**F.ETUNNEL** specifies the name of a file containing a `C-INTERPRETER` function that specifies electron tunnelling at a Schottky contact.

**ME.TUNNEL** specifies the relative effective mass for use in the electron tunneling mode (see `E.TUNNEL`).

**REFLECT** specifies that for Energy Balance and Hydrodynamic simulation using a Neumann (reflective) boundary condition for carrier temperature equations. By default, contacts are handled as Dirichlet boundaries with carrier temperature equal to lattice temperature.

**SURF.REC** specifies that finite surface recombination velocities are used at the respective contact. This parameter must be specified in the form `SURF.REC [VSURFN=<n>] [VSURFP=<p>]`, where **n** and **p** are real numbers.

**VSURFN** specifies the actual surface recombination velocities for electrons ( $V_{sn}$ ). If this parameter is not specified, its default value is calculated by Equation 18-1.

$$V_{sn} = \frac{ARICHN \cdot T_L^2}{qN_C} \quad 18-1$$

where **ARICHN** is the effective Richardson constant for electrons. This constant accounts for quantum mechanical reflections and tunneling.

**VSURFP** specifies the actual surface recombination velocities for holes ( $V_{sp}$ ). If this parameter is not specified, its default value is calculated by Equation 15-2.

$$V_{sp} = \frac{ARICHPT^2}{qN_V} \quad 18-2$$

where **ARICHPT** is the effective Richardson constants for holes. This constant accounts for quantum mechanical reflections and tunneling.

## Contact Parasitics

**RESISTANCE** specifies a lumped resistance value. You may not specify both **RESISTANCE** and **CON.RESIST**.

**INDUCTANCE** specifies an external inductance which is related to the specified electrode. A synonym is **L**.

**CAPACITANCE** specifies a lumped capacitance value to be attached to the contact.

**CON.RESIST** specifies a distributed contact resistance. You cannot specify both **CON.RESIST** and **RESIST**.

---

**Note:** There are restrictions on the allowed numerical methods and types of analysis possible when any form of parasitic element is attached to a contact. See the Getting Started section for details.

---

## Electrode Linking Parameters

These parameters allow one electrode to be biased as a function of another electrode. This allows separate regions of the same physical contact to be linked together. For example, in the statement:

```
CONTACT NAME=MYDRAIN COMMON=DRAIN FACTOR=4.6
```

The electrode, **MYDRAIN**, is linked to the electrode, **DRAIN**. The bias on **MYDRAIN** will always be equal to the bias on the drain plus 4.6. If the optional **MULT** parameter had been specified, the bias on **MYDRAIN** would be equal to the bias on the drain multiplied by 4.6.

**COMMON** specifies the electrode name to which the contact referred to by **NAME** is linked. Although the electrodes are linked, separate currents will be saved for both electrodes unless **SHORT** is also specified. The electrode referred to in **NAME** should not appear on any **SOLVE** statements since its bias is now determined as a function of the electrode referred to by **COMMON**.

**SHORT** specifies that the electrode referred to by **NAME** is shorted to the electrode specified by the **COMMON** parameter. This implies that the two electrodes will be treated as one and only one value will be written to log files and in the run time output.

**FACTOR** specifies the constant offset voltage (or current) between the electrodes referred by **NAME** and **COMMON**. By default, **FACTOR** is added the defined voltage.

**MULT** specifies that **FACTOR** is a multiplier.

## Floating Gate Capacitance Parameters

In some cases, you may want to simulate floating gate structures, in 2D, which have control gates that are longer in the unsimulated dimension than the floating gate. In these cases, specify the following parameters to account for additional capacitance between the floating gate and the control gate and other electrodes. Up to four extra capacitances are allowed so in the following **<n>** is an integer number between 1 and 4.

**EL<n>.CAP** specifies the name of the electrode to which the extra capacitance is linked.

**FG<n>.CAP** specifies the additional capacitance per unit length to be added between the floating gate and electrode specified in **EL<n>.CAP**.

## Schottky Barrier and Surface Recombination Example

This example defines all electrodes except number 2 (aluminum) to be neutral. Electrode number 2 also includes finite surface recombination velocities and barrier lowering. A definition in the second statement overrides that definition in the first statement.

```
CONTACT ALL NEUTRAL
CONTACT NUMBER=2 ALUMINUM SURF.REC BARRIER
```

## Parasitic Resistance Example

This example attaches a lumped resistor with a value of  $10^5 \Omega \mu\text{m}$  to the substrate. A distributed contact resistance of  $10^{-6} \Omega \cdot \text{cm}^2$  is included on the drain.

```
CONTACT NAME=substrate RESISTANCE=1E5
CONTACT NAME=drain CON.RESIST=1E-6
```

## Floating Gate Example

This syntax defines a floating contact with a workfunction equal to 4.17eV. An extra 1fF/um capacitance is added between this electrode and the electrode named cgate.

```
CONTACT NAME=fgate FLOATING N.POLY EL1.CAP=cgate FG1.CAP=1e-15
```

---

**Note:** The **MODELS PRINT** command can be used to echo the back contact workfunction and parasitic elements settings to the run-time output.

---

## 18.5: CURVETRACE

CURVETRACE sets the parameters for the automatic curve tracing routine.

### Syntax

CURVETRACE <params>

| Parameter    | Type      | Default               | Units    |
|--------------|-----------|-----------------------|----------|
| ANGLE1       | Real      | 5                     |          |
| ANGLE2       | Real      | 10                    |          |
| ANGLE3       | Real      | 15                    |          |
| BEG.VAL      | Real      | 0.0                   | V        |
| CONTROLRES   | Real      | $1.0 \times 1.0^{10}$ | $\Omega$ |
| CONTR.ELEC   | Integer   |                       |          |
| CONTR.NAME   | Character |                       |          |
| CURR.CONT    | Logical   |                       |          |
| END.VAL      | Real      |                       |          |
| MAXDV1       | Real      | 0.1                   | V        |
| MAXDV2       | Real      | 1.0                   | V        |
| MINCUR       | Real      |                       |          |
| MINDL        | Real      | 0.1                   |          |
| NEXTST.RATIO | Real      | 2.0                   |          |
| STEP.CONT    | Logical   |                       |          |
| STEP.INIT    | Real      | 0.1                   | V        |
| STEPS        | Real      | 0.1                   |          |
| TURNINGPOINT | Logical   | False                 |          |
| VOLT.CONT    | Logical   | False                 |          |

---

**Note:** The CURVETRACE function of ATLAS creates several temporary files in the local directory where it is run. Two simultaneous ATLAS runs using `curvetrace` in the same directory will interfere with each other.

---

### Description

ANGLE1, ANGLE2, and ANGLE3 are critical angles (in degrees) affecting the smoothness and step size of the trace. If the difference in slopes of the last two solution points is less than ANGLE1, the step size will be increased for the next projected solution. If the difference lies between ANGLE1 and ANGLE2, the step size remains the same. If the difference is greater than ANGLE2, the step size is



reduced. **ANGLE3** is the maximum difference allowed, unless overridden by the **MINDL** parameter. **ANGLE2** should always be greater than **ANGLE1** and less than **ANGLE3**.

**BEG.VAL** is the value of the voltage at the starting point of the curve trace for the controlling electrode.

**CONTR.ELEC** is the number of the electrode that is designated as a control electrode.

**CONTR.NAME** is the name of the control electrode.

**CURR.CONT** denotes that a maximum current on the control electrode, specified by **END.VAL** is used as the upper bound on the trace.

**CONTROLRES** specifies the control resistance value to be set at the control electrode after the current at the control electrode becomes greater than the value specified by the **MINCUR** parameter. Using a large value of the control resistance allows you to set the value of the current (instead of the internal voltage) on the control electrode. A large value of the control resistance is suitable for electron devices where the shape of the characteristic curve is vertical or exhibits the presence of turning points (where it is required to switch the electrode control from voltage to current).

**END.VAL** is used to stop tracing if the voltage or current of control electrode equals or exceeds **END.VAL**.

**MAXDV1** specifies maximum value of the voltage bias step at the beginning of the **CURVETRACE** algorithm. This limitation is used until the current at the control electrode is greater than the value specified by the **MINCUR** parameter.

**MAXDV2** specifies maximum value of the voltage bias step to be used after the current at the control electrode becomes greater than the value specified by the **MINCUR** parameter.

**MAXDV1** and **MAXDV2** control (together with **NEXTST.RATIO**) the maximum voltage step at each point of the IV curve. Using large values for them means that few points are used to trace the curve. This results in a faster simulation but can affect the stability of the tracing algorithm and decrease the accuracy of the IV curve.

**MINCUR** may be used to set a small current value in order to switch from internal control electrode bias ramping to external ramping with load resistor. This parameter is recommended for small current breakdown simulation.

**MINDL** is the minimum normalized step size allowed in the trace. Usually, you don't need to adjust this parameter. Increasing **MINDL** will reduce the smoothness of the trace by overriding the angle criteria, resulting in more aggressive projection and fewer simulation points. Reducing **MINDL** will enhance the smoothness and increase the number of points in the trace.

**NEXTST.RATIO** specifies which factor to use to increase the voltage step on the smooth parts of the I-V curve.

**STEPS** is the number of operational points on a trace if **STEP.CONT** was specified.

**STEP.CONT** specifies that the trace will proceed for a certain number of simulation points.

**STEP.INIT** specifies initial voltage step size.

---

**Note:** To set a sweep of increasingly negative voltage in **CURVETRACE**, you only need to set **STEP.INIT** to be negative. Since all parameters are multiplier of **STEP.INIT**, the whole voltage sweep will be negative.

---

**TURNINGPOINT** specifies that binary output solution files will be saved whenever the slope of the IV curve changes sign (i.e., there is a turning point). The name of the output file is *soln.num*, where *num* is the number of the current solution.

**VOLT.CONT** denotes that a maximum voltage on the control electrode, specified by `END.VAL` is used as the upper bound on the trace.

### Diode Breakdown Example

To trace a diode breakdown curve using current value as a termination criteria, the following statement may be used:

```
CURVETRACE CURR.CONT END.VAL=0.01 CONTR.NAME=anode \  
MINCUR=5E-12 NEXTST.RATIO=1.1 STEP.INIT=0.1  
SOLVE CURVETRACE
```

## 18.6: DBR

The DBR statement is used to define Distributed Bragg Reflectors (DBR). DBRs are periodic structures composed of alternating layers of two different materials.

### Syntax

DBR <parameters>

| Parameter    | Type      | Default | Units            |
|--------------|-----------|---------|------------------|
| BOTTOM       | Logical   | False   |                  |
| CALC1.STRAIN | Logical   | False   |                  |
| CALC2.STRAIN | Logical   | False   |                  |
| HALF.CYCLES  | Real      | 2       |                  |
| LAYERS       | Real      | 2       |                  |
| LED1         | Logical   | False   |                  |
| LED2         | Logical   | False   |                  |
| MAT1         | Character |         |                  |
| MAT2         | Character |         |                  |
| N1           | Real      | 0       |                  |
| N2           | Real      | 0       |                  |
| NA1          | Real      | 0.0     | cm <sup>-3</sup> |
| NA2          | Real      | 0.0     | cm <sup>-3</sup> |
| ND1          | Real      | 0.0     | cm <sup>-3</sup> |
| ND2          | Real      | 0.0     | cm <sup>-3</sup> |
| NU12         | Integer   | 5       |                  |
| NU21         | Integer   | 5       |                  |
| POLARIZ1     | Logical   | False   |                  |
| POLARIZ2     | Logical   | False   |                  |
| POLAR1.SCALE | Real      | 1.0     |                  |
| POLAR2.SCALE | Real      | 1.0     |                  |
| QWELL1       | Logical   | False   |                  |
| QWELL2       | Logical   | False   |                  |
| SPA1         | Real      | 0.0     | microns          |
| SPA2         | Real      | 0.0     | microns          |
| STRAIN1      | Real      | 0.0     |                  |

|             |         |       |         |
|-------------|---------|-------|---------|
| STRAIN2     | Real    | 0.0   |         |
| TH12        | Real    |       |         |
| TH21        | Real    |       |         |
| THICK1      | Real    | 0.0   | microns |
| THICK2      | Real    | 0.0   | microns |
| TOP         | Logical | False |         |
| WELL1.CNBS  | Integer | 1     |         |
| WELL2.CNBS  | Integer | 1     |         |
| WELL1.FIELD | Logical | True  |         |
| WELL2.FIELD | Logical | True  |         |
| WELL1.GAIN  | Real    | 1.0   |         |
| WELL2.GAIN  | Real    | 1.0   |         |
| WELL1.NX    | Integer | 10    |         |
| WELL2.NX    | Integer | 10    |         |
| WELL1.NY    | Integer | 10    |         |
| WELL2.NY    | Integer | 10    |         |
| WELL1.VNBS  | Integer | 1     |         |
| WELL2.VNBS  | Integer | 1     |         |
| Y.START     | Real    | 0.0   | microns |
| Y.FINISH    | Real    | 0.0   | microns |
| Y.FINAL     | Real    | 0.0   | microns |
| Y.END       | Real    | 0.0   | microns |
| Y1.COMP     | Real    | 0.0   |         |
| Y2.COMP     | Real    | 0.0   |         |
| X1.COMP     | Real    | 0.0   |         |
| X2.COMP     | Real    | 0.0   |         |

## Description

The DBR statement is a short cut for specifying a set of REGION statements, which specifies a stack of alternating layers of two materials. The material compositions of the layers are specified by the MAT1, MAT2, NA1, NA2, ND1, ND2, STRAIN1, STRAIN2, X1.COMP, X2.COMP, Y1.COMP, and Y2.COMP parameters. The number of layers are specified by the HALF.CYCLES parameter. The locations of the layers are specified by the Y.START, Y.FINISH or the TOP/BOTTOM parameters. The meshing of the layers is specified by the N1, N2 or the SPA1, SPA2 parameters.

For more information about DBR, see Chapter 9: "VCSEL Simulator", the "Specifying Distributed Bragg Reflectors" Section on page 9-10.

**BOTTOM** specifies that the DBR is to be added at the bottom (starting at the maximum previously specified Y coordinate and extending in the positive Y direction) of the structure.

**CALC1.STRAIN, CALC2.STRAIN** specifies that the strain in the region/cycle is calculated from the lattice mismatch with adjacent regions.

**HALF.CYCLES** specifies the total number of layers. Note that if **HALF.CYCLES** is odd, there will be more layers of one material than the other. Its alias is **LAYERS**.

---

**Note:** Don't confuse **HALD.CYCLES** with fractions of the optical emission wavelength. **HALF.CYCLES** relates to layers.

---

**LED1, LED2** specifies that the region/cycle is to be treated as a light emitting region and included in postprocessing for LED analysis. See Chapter 11: "LED: Light Emitting Diode Simulator".

**MAT1** specifies the material name for layers of material 1.

**MAT2** specifies the material name for layers of material 2.

**N1** specifies the integer number of mesh lines per layer of material 1. Note that if **N1** is specified, then **SPA1** shouldn't be specified.

**N2** specifies the integer number of mesh lines per layer of material 2. Note that if **N2** is specified, then **SPA2** shouldn't be specified.

**NA1** specifies the ionized acceptor concentration in layers of material 1.

**NA2** specifies the ionized acceptor concentration in layers of material 2.

**ND1** specifies the ionized donor concentration in layers of material 1.

**ND2** specifies the ionized donor concentration in layers of material 2.

**NU12** is the number of grid lines in the graded region between the 1st and 2nd half cycle in the direction specified by the **BOTTOM** or **TOP** parameters.

**NU21** is the number of grid lines in the graded region between the 2nd and 1st half cycle in the direction specified by the **BOTTOM** or **TOP** parameters.

**POLARIZ1, POLARIZ2** enables the automatic calculation of added interface charge due to spontaneous and piezoelectric polarization. See Chapter 3: "Physics", Section 3.6.8: "Polarization in Wurtzite Materials".

**POLAR1.SCALE, POLAR2.SCALE** specifies a constant scale factor multiplied by the calculated spontaneous and piezoelectric polarization charges when you enable polarization by setting the **POLARIZATION** parameter of the DBR statement. See Chapter 3: "Physics", Section 3.6.8: "Polarization in Wurtzite Materials".

**QWELL1, QWELL2** specifies that the region/cycle is treated as a quantum well for calculation of radiative recombination or gain or both for certain optoelectronic models.

**SPA1** specifies the spacing between mesh lines in layers of material 1. Note that this should be smaller than or equal to **THICK1**.

**SPA2** specifies the spacing between mesh lines in layers of material 2. Note that this should be smaller than or equal to **THICK2**.

**STRAIN1** specifies the strain in the layer of material 1.

**STRAIN2** specifies the strain in the layer of material 2.

**TOP** specifies that the DBR is to be added at the top (starting at the minimum previously specified Y coordinate and extending in the negative Y direction) of the structure.

**TH12** is the thickness of grading region between 1st half cycle and 2nd half cycle going in the direction specified by the **BOTTOM** or **TOP** parameters.

**TH21** is the thickness of grading region between 2nd half cycle and 1st half cycle going in the direction specified by the **BOTTOM** or **TOP** parameters.

**THICK1** specifies the thickness of each layer of material 1.

**THICK2** specifies the thickness of each layer of material 2.

**WELL1.CNBS**, **WELL2.CNBS**, **WELL1.VNBS**, **WELL2.VNBS** specify the number of bound states retained for calculation of radiative recombination or gain if the region/cycle is treated as a quantum well as specified by the **QWELL1**, **QWELL2** parameters.

**WELL1.FIELD**, **WELL2.FIELD**, when enabled, specify that the calculations of bound state energies should include the effects of the local field.

**WELL1.GAIN**, **WELL2.GAIN** specify a constant scale factor multiplied by the calculated gain to give the net gain used for certain optoelectronic calculations.

**WELL1.NX**, **WELL2.NX**, **WELL1.NY**, **WELL2.NY** specify the number of slices (**WELL#.NX**) and the number of samples per slice (**WELL#.NY**) are used in the solution of Schrodinger's equation to obtain the local bound state energies for calculation of radiative recombination or gain or both for certain optoelectronic models.

**Y.START** specifies the starting location of a DBR that begins with a layer of material 1 and alternates materials in an increasing Y direction.

**Y.FINISH** specifies the starting location of a DBR that begins with a layer of material 1 and alternates materials in an decreasing Y direction.

**Y.FINAL** and **Y.END** are aliases for **Y.FINISH**.

**Y1.COMP** specifies the composition fraction y in layers of material 1.

**Y2.COMP** specifies the composition fraction y in layers of material 2.

**X1.COMP** specifies the composition fraction x in layers of material 1.

**X2.COMP** specifies the composition fraction x in layers of material 2.

---

**Note:** DBR statements can be intermixed with **X.MESH**, **Y.MESH**, and **REGION** statements.

---

## 18.7: DEFECTS

DEFECTS activates the band gap defect model and sets the parameter values. This model can be used when thin-film transistor simulations are performed using the TFT product.

### Syntax

DEFECTS [<parameters>]

| Parameter  | Type      | Default               | Units                      |
|------------|-----------|-----------------------|----------------------------|
| AFILE      | Character |                       |                            |
| CONTINUOUS | Logical   | False                 |                            |
| DEVICE     | Character |                       |                            |
| DFILE      | Character |                       |                            |
| EGA        | Real      | 0.4                   | eV                         |
| EGD        | Real      | 0.4                   | eV                         |
| F.TFTACC   | Character |                       |                            |
| F.TFTDON   | Character |                       |                            |
| FILE.INT   | Logical   | False                 |                            |
| INT_LIM1   | Real      | 0                     | eV                         |
| INT_LIM2   | Real      | 0                     | eV                         |
| MATERIAL   | Character |                       |                            |
| NGA        | Real      | $5.0 \times 10^{17}$  | $\text{cm}^{-3}$           |
| NGD        | Real      | $1.5 \times 10^{18}$  | $\text{cm}^{-3}$           |
| NTA        | Real      | $1.12 \times 10^{21}$ | $\text{cm}^{-3}/\text{eV}$ |
| NTD        | Real      | $4.0 \times 10^{20}$  | $\text{cm}^{-3}/\text{eV}$ |
| NUMBER     | Real      | All                   |                            |
| NUMA       | Real      | 12                    |                            |
| NUMD       | Real      | 12                    |                            |
| SIGGAE     | Real      | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGGAH     | Real      | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SIGGDE     | Real      | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SIGGDH     | Real      | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGTAE     | Real      | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGTAH     | Real      | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |

| Parameter | Type      | Default               | Units           |
|-----------|-----------|-----------------------|-----------------|
| SIGTDE    | Real      | $1.0 \times 10^{-14}$ | cm <sup>2</sup> |
| SIGTDH    | Real      | $1.0 \times 10^{-16}$ | cm <sup>2</sup> |
| TFILE     | Character |                       |                 |
| WGA       | Real      | 0.1                   | eV              |
| WGD       | Real      | 0.1                   | eV              |
| WTA       | Real      | 0.025                 | eV              |
| WTD       | Real      | 0.05                  | ev              |

## Description

The DEFECTS statement is used to describe the density of defect states in the band gap. You can specify up to four distributions, two for donor-like states and two for acceptor-like states. Each type of state may contain one exponential (tail) distribution and one Gaussian distribution.

**AFILE** specifies the file name where the acceptor state density distribution, as a function of energy, will be stored. You can examine this file by using TONYPLOT.

**CONTINUOUS** specifies that the continuous defect integral model will be used.

**DEVICE** specifies which device the statement applies in mixed mode simulation

**DFILE** specifies the file name where the donor state density distribution, as a function of energy, will be stored. You can examine this file by using TONYPLOT.

**EGA** specifies the energy that corresponds to the Gaussian distribution peak for acceptor-like states. This energy is measured from the conduction band edge.

**EGD** specifies the energy that corresponds to the Gaussian distribution peak for donor-like states. This energy is measured from the valence band edge.

**F.TFTACC** specifies the name of a file containing a C-INTERPRETER function, describing the distribution of acceptor state densities as a function of energy.

**F.TFTDON** specifies the name of a file containing a C-INTERPRETER function, describing the distribution of donor state densities as a function of energy.

**FILE.INT** specifies the integrated density of states with respect to energy will be stored in the AFILE, DFILE, and TFILE files for discrete defects.

**INT\_LIM1** specifies the lower limit for the numerical integration of the CONTINUOUS method.

**INT\_LIM2** specifies the upper limit for the numerical integration of the CONTINUOUS method.

**MATERIAL** specifies which material from the table in Appendix B: "Material Systems" will apply to the DEFECT statements. If a material is specified, then the regions defined as being composed of that material will be affected.

**NGA** specifies the total density of acceptor-like states in a Gaussian distribution.

**NGD** specifies the total density of donor-like states in a Gaussian distribution.

**NTA** specifies the density of acceptor-like states in the tail distribution at the conduction band edge.

**NTD** specifies the density of donor-like states in the tail distribution at the valence band edge.

**NUMBER** or **REGION** specifies the region index to which the DEFECT statement applies.



**NUMA** specifies the number of discrete levels that will be used to simulate the continuous distribution of acceptor states.

**NUMD** specifies the number of discrete levels that will be used to simulate the continuous distribution of donor states.

**SIGGAE** specifies the capture cross-section for electrons in a Gaussian distribution of acceptor-like states.

**SIGGAH** specifies the capture cross-section for holes in a Gaussian distribution of acceptor-like states.

**SIGGDE** specifies the capture cross-section for electrons in a Gaussian distribution of donor-like states.

**SIGGDH** specifies the capture cross-section for holes in a Gaussian distribution of donor-like states.

**SIGTAE** specifies the capture cross-section for electrons in a tail distribution of acceptor-like states.

**SIGTAH** specifies the capture cross-section for holes in a tail distribution of acceptor-like states.

**SIGTDE** specifies the capture cross-section for electrons in a tail distribution of donor-like states.

**SIGTDH** specifies the capture cross-section for holes in a tail distribution of donor-like states.

**TFILE** specifies the file name where the acceptor and donor state density distributions, such as function of energy, referenced from eV will be stored. You can examine this file by using TONYPLOT.

**WGA** specifies the characteristic decay energy for a Gaussian distribution of acceptor-like states.

**WGD** specifies the characteristic decay energy for a Gaussian distribution of donor-like states.

**WTA** specifies the characteristic decay energy for the tail distribution of acceptor-like states.

**WTD** specifies the characteristic decay energy for the tail distribution of donor-like states.

### TFT Example

The following statement lines specify distributed defect states which would typically be used for polysilicon.

```
DEFECTS NTA=1.E21 NTD=1.E21 WTA=0.033 WTD=0.049 \  
        NGA=1.5E15 NGD=1.5E15 EGA=0.62 EGD=0.78 \  
        WGA=0.15 WGD=0.15 SIGTAE=1.E-17 \  
        SIGTAH=1.E-15 SIGTDE=1.E-15 SIGTDH=1.E-17 \  
        SIGGAE=2.E-16 SIGGAH=2.E-15 SIGGDE=2.E-15 \  
        SIGGDH=2.E-16
```

## 18.8: DEGRADATION

DEGRADATION specifies parameters for MOS device degradation modeling.

### Syntax

```
DEGRADATION <params>
```

| Parameter | Type | Default              | Units            |
|-----------|------|----------------------|------------------|
| F.NTA     | Char |                      |                  |
| F.NTD     | Char |                      |                  |
| F.NTD     | Char |                      |                  |
| F.SIGMAE  | Char |                      |                  |
| F.SIGMAH  | Char |                      |                  |
| NTA       | Real | $1.0 \times 10^{11}$ | $\text{cm}^{-2}$ |
| NTD       | Real | $1.0 \times 10^{10}$ | $\text{cm}^{-2}$ |
| SIGMAE    | Real | $1.0 \times 10^{17}$ | $\text{cm}^{-2}$ |
| SIGMAH    | Real | $1.0 \times 10^{17}$ | $\text{cm}^{-2}$ |

### Description

**NTA** specifies the uniform acceptor-like trap density on the interface.

**NTD** specifies the uniform donor-like trap density on the interface.

**SIGMAE** specifies the acceptor-like trap capture cross section.

**SIGMAH** specifies the donor-like trap capture cross section.

**F.NTA** specifies the file name for a C-INTERPRETER function that specifies arbitrary density distribution of the acceptor-like traps on the interface.

**F.NTD** specifies the file name for a C-INTERPRETER function that specifies arbitrary density distribution of the donor-like traps on the interface.

**F.SIGMAE** specifies the name of a file containing a C-INTERPRETER function specifying the distribution of acceptor trap cross-sections.

**F.SIGMAH** specifies the name of a file containing a C-INTERPRETER function specifying the distribution of donor trap cross-sections.

### MOS Interface State Example

```
DEGRADATION NTA=1.E-12 SIGMAE=5.E-18
```

This syntax defines a density of acceptor states uniformly distributed along the silicon-oxide interface. The trapping cross section is also defined. Traps will be filled by gate current in transient mode simulations leading to a shift in device parameters.

## 18.9: DOPING

DOPING specifies doping profiles either analytically or from an input file.

### Syntax

```
DOPING <prof>[<psp>][<bound>][<loc>][<sprea>>][OUTFILE= <fn>][<trps>]
```

| Parameter      | Type      | Default | Units            |
|----------------|-----------|---------|------------------|
| 2D.ASCII       | Logical   | False   |                  |
| ACTIVE         | Logical   | True    |                  |
| ANTIMONY       | Logical   | False   |                  |
| ARSENIC        | Logical   | False   |                  |
| ASCII          | Logical   | False   |                  |
| ATHENA         | Logical   | False   |                  |
| ATHENA.1D      | Logical   | False   |                  |
| BACKDOPE       | Real      | none    | cm <sup>-3</sup> |
| BORON          | Logical   | False   |                  |
| CHARACTERISTIC | Real      |         | μm               |
| CHEMICAL       | Logical   | False   |                  |
| CONCENTRATION  | Real      | 0       | cm <sup>-3</sup> |
| DEGEN          | Real      |         |                  |
| DEVICE         | Char      |         | 1                |
| DIRECTION      | Character | y       |                  |
| DOP.SEED       | Integer   | -10     |                  |
| DOP.SIGMA      | Real      | 0.0     | cm <sup>-3</sup> |
| DOPOFF         | Real      | 0       | cm <sup>-3</sup> |
| DOSE           | Real      |         | cm <sup>-2</sup> |
| ERFC.LATERAL   | Logical   | False   |                  |
| E.LEVEL        | Real      |         | eV               |
| F.COMPOSIT     | Character |         |                  |
| F.DOPING       | Character |         |                  |
| F3.DOPING      | Character |         |                  |
| GAUSSIAN       | Logical   | False   |                  |
| INDIUM         | Logical   | False   |                  |

| Parameter     | Type      | Default | Units         |
|---------------|-----------|---------|---------------|
| INFILE        | Character |         |               |
| INT.LIN       | Logical   | False   |               |
| INT.LOG       | Logical   | True    |               |
| INT.OPTM      | Logical   | False   |               |
| JUNCTION      | Real      |         | $\mu\text{m}$ |
| LAT.CHAR      | Real      |         | $\mu\text{m}$ |
| MASTER        | Logical   | False   |               |
| N.TYPE        | Logical   | False   |               |
| NET           | Logical   | False   |               |
| NOROLLOFF     | Logical   | False   |               |
| NOXROLLOFF    | Logical   | False   |               |
| NOYROLLOFF    | Logical   | False   |               |
| OUTFILE       | Character |         |               |
| PHOSPORUS     | Logical   | False   |               |
| P.TYPE        | Logical   | False   |               |
| RATIO.LATERAL | Real      | 0.7     |               |
| RESISTI       | Real      |         |               |
| OX.CHARGE     | Logical   | False   |               |
| REGION        | Integer   | All     |               |
| SIGN          | Real      |         | $\text{cm}^2$ |
| SIGP          | Real      |         | $\text{cm}^2$ |
| SLICE.LAT     | Real      |         | $\mu\text{m}$ |
| START         | Real      | 0       |               |
| SUPREM3       | Logical   | False   |               |
| TAUN          | Real      |         |               |
| TAUP          | Real      |         |               |
| TRAP          | Logical   | False   |               |
| UNIFORM       | Logical   | False   |               |
| X1            | Real      | 0       | $\mu\text{m}$ |
| X2            | Real      | 0       | $\mu\text{m}$ |
| XY            | Logical   | True    |               |

| Parameter  | Type    | Default             | Units         |
|------------|---------|---------------------|---------------|
| XZ         | Logical | False               |               |
| X.COMP     | Logical | False               |               |
| X.DIR      | Logical | False               |               |
| X.LEFT     | Real    | left of structure   | $\mu\text{m}$ |
| X.MAX      | Real    |                     | $\mu\text{m}$ |
| X.MIN      | Real    |                     | $\mu\text{m}$ |
| X.RIGHT    | Real    | right of structure  | $\mu\text{m}$ |
| Y.BOTTOM   | Real    | bottom of structure | $\mu\text{m}$ |
| Y1         | Real    | 0                   | $\mu\text{m}$ |
| Y2         | Real    | 0                   | $\mu\text{m}$ |
| YX         | Logical | True                |               |
| YZ         | Logical | False               |               |
| Y.COMP     | Logical | False               |               |
| Y.DIR      | Logical | False               |               |
| Y.MAX      | Real    |                     | $\mu\text{m}$ |
| Y.MIN      | Real    |                     | $\mu\text{m}$ |
| Y.TOP      | Real    | top of structure    |               |
| Z1         | Real    | 0                   | $\mu\text{m}$ |
| Z2         | Real    | 0                   | $\mu\text{m}$ |
| ZY         | Logical | False               |               |
| ZX         | Logical | False               |               |
| Z.BACK     | Real    |                     |               |
| Z.DIR      | Logical | False               |               |
| Z.FRONT    | Real    |                     |               |
| Z.MIN      | Real    |                     | $\mu\text{m}$ |
| Z.MAX      | Real    |                     | $\mu\text{m}$ |
| ZLAT.CHAR  | Real    |                     |               |
| ZSLICE.LAT | Real    |                     |               |
| ZRATIO.LAT | Real    | 0.7                 |               |

## Description

The **DOPING** statement is used to define doping profiles in the device structure. Typically a sequence of **DOPING** statements is given each building on the others.

**OUTFILE** specifies the name of an output file for use with **REGRID**. The first **DOPING** statement should use this parameter to specify a filename. All doping information from the first **DOPING** statement and all subsequent **DOPING** statements in the input file are saved to this file. The **REGRID** statement can read this file and interpolate doping on the new grid.

---

**Note:** The file from **OUTFILE** cannot be used in **TONYPLOT** or in the **MESH** statement. The **SAVE** command should be used after all of the **DOPING** commands required to save a file for plotting the doping profile.

---

## Analytical Profile Types

These parameters specify how **ATLAS** will generate a doping profile from analytical functions.

**DOP.SIGMA** specifies the variance for random gaussian dopant distribution.

**DOP.SEED** specifies a seed value for random gaussian dopant distribution.

**GAUSSIAN** specifies the use of a gaussian analytical function to generate the doping profile. If **GAUSSIAN** is specified, the following parameters must also be specified:

- Polarity parameters **N.TYPE** or **P.TYPE**
- One of the following groups of profile specifications:
  - Group 1: **CONCENTRATION** and **JUNCTION**
  - Group 2: **DOSE** and **CHARACTERISTIC**
  - Group 3: **CONCENTRATION** and **CHARACTERISTIC**

**UNIFORM** specifies the use of uniform (constant) analytical functions to generate the doping profile. If **Uniform** is specified, the **N.TYPE**, **P.TYPE**, and **CONCENTRATION** parameters must be specified. Doping is introduced into a box defined by the boundary parameters (see the "Boundary Conditions" Section on page 18-15). The box by default includes the entire region.

**F.DOPING** specifies the name of a file containing a **C-INTERPRETER** function specifying the spatial distribution of dopants.

**F3.DOPING** specifies the name of a file containing a **C-INTERPRETER** function specifying the spatial distribution of dopants for a 3D device.

## File Import Profile Types

These parameters specify how **ATLAS** will generate a doping profile from a file. Files can be user-defined or from process simulation.

**2D.ASCII** specifies that a 2D doping profile, which is defined on a rectangular Cartesian grid, should be loaded from a file specified by **INFILE**. **2D.ASCII** must be specified along with either the **N.TYPE**, **P.TYPE** or **NET** parameters. This first column of the file should contain the x coordinates. The second column should contain the y coordinates. The third column should contain the doping data.

**INFILE** specifies the name of the appropriate input file.

**ASCII** has two separate meanings. The first meaning is that it specifies the file type as **ASCII** when it's combined with other format parameters. The second meaning is when this parameter is used alone, it specifies **ASCII** data files containing concentration versus depth information.

In the second meaning, this parameter must be written in the form:

```
ASCII INFILE=<filename>
```

where `filename` is the name of the ASCII input file. The data file must be in the following format:

```
depth    concentration
depth    concentration
depth    concentration
...
```

where `depth` is specified in  $\mu\text{m}$  and `concentration` is specified in  $\text{cm}^{-3}$ . An input file name, a dopant type, and boundary parameters must be specified. Positive concentrations are assumed to be n-type and negative concentrations are assumed to be p-type unless the `N.TYPE` or `P.TYPE` parameters are used.

**MASTER** specifies that the `INFILE` is written in the Silvaco standard structure file (SSF) format. This file format is the default output format of ATHENA and SSUPREM3. This parameter is typically combined with the `SSUPREM3`, `ATHENA 1D`, or `ATHENA` parameters. If neither of these are used the default is `SUPREM3`.

**SUPREM3** specifies the `INFILE` was produced by `SSUPREM3` in standard structure file (SSF) format or binary or an ASCII export format. If this profile type is used, an input file name, a dopant, and boundary parameters must be specified. When `SSUPREM3` produces an output file, the doping profiles are stored by dopant. Therefore, a dopant parameter should be specified in order to import the correct doping profile into ATLAS. If a specific dopant is not specified the total donors and acceptor concentrations are loaded.

---

**Note:** Files containing 1D doping profiles can be loaded into `BLAZE`, `BLAZE3D`, `DEVICE3D`, or `S-PISCES`. Files containing 2D doping profiles can only be loaded into `S-PISCES`.

---

**ATHENA.1D** specifies that the doping file is a `ATHENA 1D` export file. This parameter acts in a similar way to the `SSUPREM3` parameter.

**ATHENA** reads 2D doping information from `ATHENA` standard structure file (SSF) or `PISCES-II` format files. The `PISCES-II` format is an obsolete file format. Doping information obtained from this file will be added to each point of the current ATLAS mesh. If points in the ATLAS mesh do not coincide with points in the `ATHENA` mesh, doping for ATLAS mesh points will be interpolated from `ATHENA` doping information. If this profile type is used, the `INFILE` parameter must also be specified.

---

**Note:** The `X.STRETCH` function available in previous versions of ATLAS has been replaced by similar more powerful functions in `DEVEDIT`. This feature should no longer be used in ATLAS.

---

## Dopant Type Specification Parameters

These parameters give information about the dopant species or type to be used in the specified profile. Different profile types require different profile specifications.

**ACTIVE** specifies that for the dopant specified the active concentration as opposed to the chemical concentration is added. This is true by default. Files from `ATHENA` or `SSUPREM3` contain both active and chemical concentrations for each dopant.

**ANTIMONY** specifies that antimony dopant information be extracted from an imported file.

**ARSENIC** specifies that arsenic dopant information be extracted from an imported file.

**BORON** specifies that boron dopant information be extracted from an imported file.

**CHEMICAL** specifies that the chemical concentration (as opposed to the active concentration) will be read from the imported file. This is generally not advisable.

**DOPOFF** subtracts a background doping value from the ATHENA or SSUPREM3 doping.

**E.LEVEL** sets the energy of the discrete trap level. For acceptors, **E.LEVEL** is relative to the conduction band edge. For donors, it is relative to the valence band edge.

**INDIUM** specifies that indium dopant information be extracted from an imported file.

**NET** specifies that net doping information be extracted from an imported file. This is usually not advisable. It is better to use several DOPING statements to extract data dopant by dopant from a file.

**N.TYPE, DONOR** specifies an n-type or donor dopant. This parameter may be used with GAUSSIAN and UNIFORM profile types.

**P.TYPE, ACCEPTOR** specifies a p-type or acceptor dopant. This parameter may be used with GAUSSIAN and UNIFORM profile types.

**PHOSPHORUS** specifies that phosphorus dopant information be extracted from an imported file.

**TRAP** specifies that the dopant concentration is to be treated as a trap state density.

**OX.CHARGE** specifies a fixed oxide charge profile. Oxide charge can only be placed in any insulator region. The **N.TYPE/P.TYPE** parameters are not used hence a negative concentration implies a negative charge.

**X.COMP** specifies a profile of composition fraction  $x$  as defined in Appendix B: "Material Systems". This profile can be used to change the composition fraction of cations in ternary and quaternary materials over a spatial distribution.

**Y.COMP** specifies a profile of composition fraction  $y$  as defined in Appendix B: "Material Systems". This profile can be used to change the composition fraction of anions in ternary and quaternary materials over a spatial distribution.

**RESISTI** can be used to specify resistivity, which is converted to carrier concentration in silicon (i.e., this parameter replaces the **CONC** parameter). This conversion uses tables of resistivity versus concentration for donors and acceptors. These tables currently make no distinction between specific changes of the same type. The Arora mobility model is the basis of these tables.

## Vertical Distribution Parameters

**CHARACTERISTIC** specifies the principal characteristic length of the implant. If this parameter is left unspecified, the principal characteristic can be computed from the values of the

- Polarity Parameters
- Boundary Parameters
- Concentration and Junction parameters

**CONCENTRATION** specifies the peak concentration when a Gaussian profile is used. If this parameter is not specified, peak concentration may be computed from the values of the polarity, boundary, **DOSE**, or **RESISTI**, **CHARACTERISTIC** concentrations. When a uniform profile is specified, the **CONCENTRATION** parameter sets the value of the uniform doping level. Concentrations must be positive.

**DOSE** specifies the total dose for a Gaussian profile.

**JUNCTION** specifies the location of a p-n junction within the silicon region of a Gaussian profile. When **JUNCTION** is specified, the characteristic length is computed by examining the doping at a point halfway between the end of the constant box and the given depth. The **JUNCTION** location is evaluated



considering all previous DOPING statements only. This means that in some cases the order of DOPING statements is important.

**PEAK** specifies the depth location of the peak doping in a Gaussian profile.

### Location Parameters

**DIRECTION** specifies the axis along which a one-dimensional profile is directed in a two-dimensional device (x or y). **DIR=Y** will typically be used for implanted profiles.

**REGION** specifies the region number where doping is to be added.

**START** specifies the depth in the y direction where the profile should start.

### Lateral Extent Parameters

These parameters must be specified when a 1-D doping profile type is used (**MASTER**, **GAUSSIAN**, or **ASCII**). These boundary parameters set the doping boundaries before applying lateral spreading. This is equivalent to setting implant mask edges.

**X.MIN**, **X.MAX**, **Y.MIN**, **Y.MAX**, **Z.MIN** and **Z.MAX** specify the x, y and z bounds of a rectangular shaped region or box in the device. The dopant profile within this box will be constant with a density equal to the value specified by the **CONC** parameter. Outside this box the profile decreases from the peak, **CONC**, with distance, from the box along the principal axes. The relationship between the concentration, outside the box, to distance will depend upon the profile type as specified by the **GAUSSIAN**, **MASTER**, **ATHENA**, **ATLAS**, and **UNIFORM** parameters.

**X.LEFT**, **X.MIN** specifies the left boundary of a vertical 1-D profile.

**X.RIGHT**, **X.MAX** specifies the right boundary of a vertical 1-D profile.

**Y.BOTTOM**, **Y.MAX** specifies the bottom boundary of a horizontal 1-D profile.

**Y.TOP**, **Y.MIN** specifies the top boundary of a horizontal 1-D profile.

**Z.BACK**, **Z.MIN** specifies the back boundary of a z directed 1-D or 2-D profile.

**Z.FRONT**, **Z.MAX** specifies the front boundary of a z directed 1-D or 2-D profile.

### Lateral Distribution Parameters

These parameters specify how a vertical 1-D profile is extended outside the box defined by the lateral extent parameters.

**BACKDOPE** specifies the value to which the doping profile specified from the 1D profile will roll-off to outside its lateral and vertical extents. If this value is not specified, then the last doping value in the ASCII file is used as the background doping level, regardless of windowing in the y-direction. If **NOXROLLOFF** is used, then **BACKDOPE** will be ignored for the x-direction. If **NOYROLLOFF** is used, then **BACKDOPE** will be ignored for the y-direction. If **NOROLLOFF** is used, then **BACKDOPE** will be completely ignored.

**ERFC.LATERAL** specifies an error function used for lateral spreading. If two-dimensional spreading parameters are used in conjunction with a Gaussian profile, the lateral impurity profile may be transformed into an error function.

**LAT.CHAR** specifies the characteristic length of the lateral profile. If this parameter is not specified, the characteristic length is defined by:

$$CL = RL \times OCL \quad 18-3$$

where:

- CL is the lateral characteristic length in the x direction.
- RL is the value of **RATIO.LATERAL**.
- OCL is the characteristic length of the original profile in the y direction.

**NOXROLLOFF** causes the doping level to abruptly change to zero outside the x-limits.

**NOYROLLOFF** causes the doping level to abruptly change to zero outside the y-limits.

**NOROLLOFF** is the same as setting both **NOXROLLOFF** and **NOYROLLOFF**.

**RATIO.LATERAL** is the ratio of characteristic lengths in the x and y directions.

**SLICE.LAT** specifies the point at which the doping is examined to compute the characteristic length of a Gaussian profile after **JUNCTION** has been specified. The default for this parameter is a point halfway between the end of the constant box and the given depth.

**ZLAT.CHAR** specifies the characteristic length of the lateral profile in the z direction. See also **LAT.CHAR**.

**ZRATIO.LATERAL** is used analogously to **RATIO.LATERAL** but applies to lateral spreading in the z direction. See also **LAT.CHAR**.

**ZSLICE.LAT** is similar to **SLICE.LAT** but applies to profiles in the z direction.

### Trap Parameters

**DEVICE** specifies which device the statement applies to in **MIXEDMODE** simulation.

**REGION** specifies which region the traps apply to. If unspecified, the traps apply to all regions.

**E.LEVEL** sets the energy of the discrete trap level. For acceptors, **E.LEVEL** is relative to the conduction band edge, for donors it is relative to the valence band edge.

**DEGEN.FAC** specifies the degeneracy factor of the trap level used to calculate the density.

**SIGN** specifies the capture cross section of the trap for electrons.

**SIGP** specifies the capture cross section of the trap for holes.

**TAUN** specifies the lifetime of electrons in the trap level.

**TAUP** specifies the lifetime of holes in the trap level.

---

**Note:** See Section 18.48: "TRAP" for more information on each of these parameters

---

### Angled Distribution Parameters

**X1,Y1,X2,Y2** specify the X and Y coordinates of the ends of the line segment describing the location of the specified angled profile.

**X.DIR** and **Y.DIR** specify the direction in which the angled profile is extended.

In **DEVICE3D**, (see Chapter 6: "3D Device Simulator" for more information about this simulator), dopants can be added along angled segments in the X-Y plane. The start and ending coordinates of the line segment are defined by the **X1**, **Y1**, **X2**, and **Y2** parameters. You can then specify whether a 2D profile is extended from the line segment in either the X or the Y direction. To specify it, set the **X.DIR** or **Y.DIR** parameter. You can then specify a 2D doping profile in the same **DOPING** statement. The profile can be an analytic, **SUPREM**, **ASCII**, or **SUPREM4**.

The dopants are placed relative to the defined line segment, according to the setting of **X.DIR** or **Y.DIR**. If **X.DIR** is specified, then the effective Y coordinate of the profile is the device Z coordinate and the effective X coordinate of the profile is the distance in the X direction from the center of the line segment. No dopants are added if the device Y coordinate is outside of the Y coordinates of the line segment. If **Y.DIR** is specified, then the effective Y coordinate of the profile is the device Z coordinate and the effective X coordinate of the profile is the distance in the Y direction from the of the line

segment. No dopants are added if the device X coordinate is outside the X coordinates of the line segment.

### Analytical Doping Definition Example

This example describes a 1.0 $\mu\text{m}$  n-channel MOSFET using Gaussian source and drain profiles. The lateral extent of the source is given by X.RIGHT=2. This corresponds to the mask edge for the implant. Sub-diffusion is determined by an error function based on the RATIO.LAT and JUNCTION parameters. For both source and drain, the n+ doping is added to the uniform p-well concentration to ensure a junction depth of 0.3 $\mu\text{m}$ .

```
DOP UNIF CONC=1E16 P.TYPE
DOP GAUSS CONC=9E19 N.TYPE X.RIGHT=2 JUNC=0.3 RATIO.LAT=0.6 ERFC.LAT
DOP GAUSS CONC=9E19 N.TYPE X.LEFT=3 JUNC=0.3 RATIO.LAT=0.6 ERFC.LAT
```

### 1D ATHENA or SSUPREM3 Interface Example

This example reads a 1D ATHENA bipolar profile and adds it to a uniform substrate concentration. The base and emitter doping are loaded from the same file by specifying the impurity required for each area (boron in the base and arsenic in the emitter).

The DOPOFF parameter is used to subtract the substrate arsenic dopant out of the 1-D profile that is loaded since this dopant was already specified in the substrate doping line.

Versions of SSUPREM3 later than 5.0 use standard structure files as default when saving data. These can be loaded in ATLAS with the syntax below by replacing ATHENA.1D with SSUPREM3.

```
# SUBSTRATE
DOP REGION=1 UNIF CONC=1E16 N.TYPE
# BASE
DOP REGION=1 MASTER ATHENA.1D BORON RATIO.LAT=0.7 INF=bipolar.exp
# EMITTER
DOP REGION=1 MASTER ATHENA.1D ARSENIC RATIO.LAT=0.6 \
INF=bipolar.exp X.LEFT=12.0 X.RIGHT=13.0 DOPOFF=1e16
```

### Athena Doping Interface Example

This example demonstrates how to use an SSF format ATHENA file to interpolate doping onto a ATLAS grid and save the doping information for subsequent regrid operations. This is an alternative to the ATHENA/ATLAS interface, which is described in Chapter 2: “Getting Started with ATLAS”, Section 2.6.1: “Interface From ATHENA”.

```
DOPING ATHENA MASTER INFILE=NMOS.DOP OUTFILE=NMOS.DOP
REGRID DOPING ABS LOG RATIO=4 OUTFILE=NMESH1.STR DOPFILE=NMOS.DOP
```

### 3D Doping Definition Example

The following example illustrates the formation of a Gaussian highly doped n-type area in a three-dimensional structure.

```
DOPING GAUSS N.TYPE CONC=1e20 PEAK=0.0 CHAR=0.2 X.LEFT=0.5 \
X.RIGHT=1.0 Z.LEFT=0.5 Z.RIGHT=1.0
```

### 3D Doping From ASCII 1D File

You can read a 1D doping profile from an ASCII file and apply it to the entire or part of a 3-D device. The `X.DIR`, `Y.DIR`, or `Z.DIR` parameters specify the direction of the profile as applied in the 3-D device. The starting position of the doping profile will be set by the relevant `X.MIN`, `Y.MIN`, or `Z.MIN` parameter. The ending position of the doping profile will be the minimum of the relevant `X.MIN`, `Y.MIN`, or `Z.MIN` plus the spatial extent of the doping profile in the ASCII file, or the `X.MAX`, `Y.MAX`, `Z.MAX` parameter or a physical boundary of the device. You can specify a general parallelogram in the plane perpendicular to the direction of doping direction. To specify it, use the appropriate combination of `X1`, `X2`, `Y1`, `Y2`, `Z1`, `Z2`, `X.MIN`, `X.MAX`, `Y.MIN`, `Y.MAX`, `Z.MIN`, `Z.MAX`. For example, we consider the `Y.DIR` parameter specified. We can then specify a parallelogram in the X-Z plane as shown in Figure 18-2.

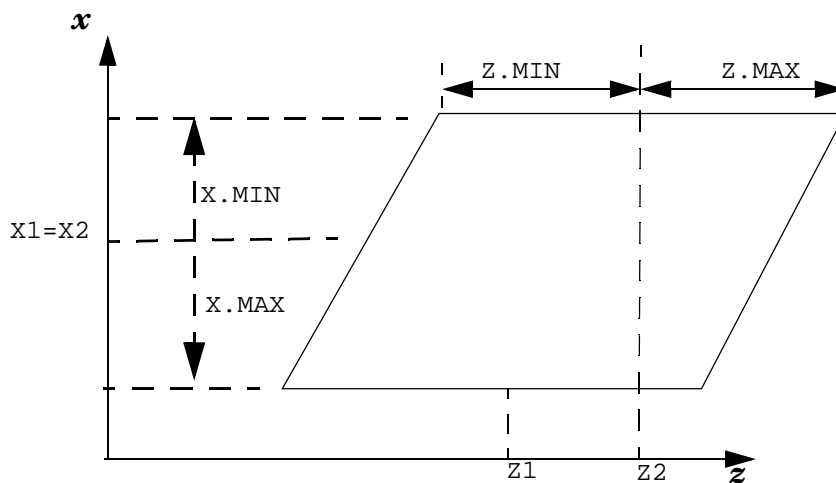


Figure 18-2: Parallelogram Geometry Example

In the figure, two sides are parallel to the Z-axis. `Z1` and `Z2` specify the Z-coordinate of the midpoints of these two sides. `Z.MIN` and `Z.MAX` together specify the lengths of the sides, and `Z.MIN` will be negative and equal to  $-Z.MAX$ . (In fact, the positions are evaluated as  $Z1+Z.MIN$  and  $Z1+Z.MAX$  for one side and  $Z2+Z.MIN$  and  $Z2+Z.MAX$  for the other. Therefore, having `Z1` and `Z2` and so on refer to the side midpoint is just a convenient convention.)

You must specify `X1` and `X2` as having the same value, and specify `X.MIN` and `X.MAX` the side lengths the same way as for `Z.MIN` and `Z.MAX`.

Setting `Z1` and `Z2` to the same value will result in a rectangle. By then changing `X1` and `X2` so they are not equal will result in a parallelogram with sides parallel to the x-axis. If a different direction of doping variation is defined, then a parallelogram can be set up in the plane perpendicular to it in analogously to the above example.

Outside the specified parallelogram the doping level will be either the value of the last point in the ASCII file, or the value specified by the `BACKDOPE` parameter. A smooth transition of the doping from the value inside the parallelogram to the value outside can be applied elsewhere using the `LAT.CHAR` or `RATIO.LAT` parameters.

**X1, X2, Y1, Y2, Z1, Z2**, by convention, specify the midpoints of the sides making up the parallelogram.

**X.MIN, X.MAX** determine the X-coordinate of the start and end points of the placement of the doping profile read in from an ASCII file (if you specify `X.DIR`). Otherwise, they specify the lateral extent of the parallelogram sides defining the location of the doping in a plane perpendicular to the specified

direction of the doping variation. In this case, they are added to `X1` and to `X2` to determine the coordinates of the ends of sides.

**Y.MIN, Y.MAX, Z.MIN, Z.MAX** are the same as `X.MIN` and `X.MAX` except they apply to the y and z-directions respectively.

**Example:**

```
doping ascii inf=ydop.dat y.dir n.type x1=6.0 x2=4.0 x.min=-2 x.max=2
z.min=3.0 z.max=7.0 y.min=2.0 y.max=10.0 lat.char=0.005 backdope=0.0
```

This will apply the doping profile specified in `ydop.dat` as n-type doping in the y-direction between the positions `y=2` microns and `y=10` microns (unless the length range in `ydop.dat` is less than this distance). In the x-z plane, it will be applied to a parallelogram with sides parallel to the x-direction of length 4 microns. The z-coordinates of these sides are 3.0 microns and 7.0 microns. The doping will transition from the value inside the parallelogram to 0.0 outside on a length scale of 0.005 microns.

## Using 2D ATHENA Master Files for Doping in ATLAS

In a 2D ATHENA master file, the doping profile is defined over a box in two dimensions. This doping is put over 2D-sections normal to the plane of a parallelogram to be defined in the doping statement. This parallelogram must lie in one of the xy, yz, and xz planes and have two edges parallel to one of the coordinate axes.

As the mesh in the ATHENA master file doesn't necessarily coincide with the three-dimensional mesh in ATLAS, an interpolation routine is required to import the doping in ATLAS. You can then choose between a linear and a logarithmic interpolation algorithm.

Here's a list of the parameters that are used for this kind of doping.

**INT.LIN** specifies that a linear interpolation is to be used to import doping from ATHENA into ATLAS.

**INT.LOG** specifies that the ATHENA doping is imported in ATLAS by using a logarithmic interpolation algorithm.

**INT.OPTM** enables an optimized interpolation routine, which attempts to reduce CPU time due to the doping interpolation.

**LAT.CHAR** defines the characteristic length, `CL`, of the lateral spreading (in the `y>y2` and `y<y1` planes). If `RATIO.LAT` is used instead, then the characteristic length is assumed to come from this parameter by the height of the parallelogram (i.e., `CL=RL X OCL`, `OCL` being the height of the parallelogram (`y2-y1` in this case)). If both `LAT.CHAR` and `RATIO.LAT` aren't specified, then no lateral spreading is done.

**XY** specifies that the parallelogram containing doping in ATLAS3D is in the xy plane.

**YX** is a synonym for `XY`.

**YZ** specifies that a parallelogram containing doping in ATLAS3D is in the yz plane.

**ZY** is a synonym for `YZ`.

**XZ** specifies that a parallelogram containing doping in ATLAS3D is in the xz plane.

**ZX** is a synonym for `XZ`.

**X1, X2, Y1, Y2, Z1, Z2** specify an average segment in one of the three coordinate planes defining the orientation of the parallelogram.

**X.DIR, Y.DIR, Z.DIR** specify that a parallelogram containing doping in ATLAS3D has two edges in the x direction, y direction, and z direction.

**X.MIN, X.MAX** define the minimum and maximum lateral extent of a parallelogram along the x direction lying in the xy or xz plane, starting from its average segment (they must be specified with

$x_1$  and  $x_2$ ). If a parallelogram is defined in the  $yz$  plane,  $X.MIN$  can then be used to specify the initial coordinate to start the doping along the  $x$  direction.

**Y.MIN, Y.MAX** define the minimum and maximum lateral extent of a parallelogram along the  $y$  direction lying in the  $xy$  or  $yz$  plane, starting from its average segment (they must be specified with  $Y1$  and  $Y2$ ). If a parallelogram is defined in the  $zx$  plane,  $Y.MIN$  can then be used to specify the initial coordinate to start the doping along the  $y$  direction.

**Z.MIN, Z.MAX** define the minimum and maximum lateral extent of a parallelogram along the  $z$  direction lying in the  $yz$  or  $zx$  plane, starting from its average segment (they must be specified with  $Z1$  and  $Z2$ ). If a parallelogram is defined in the  $xy$  plane,  $Z.MIN$  can then be used to specify the initial coordinate to start the doping along the  $z$  direction.

The following three cases, which correspond to the parallelograms in the  $xy$ ,  $yz$  and  $zx$  planes, describe how the doping from the ATHENA master file is put into the ATLAS structure .

### First Case: Parallelogram In The XY Plane

#### SUB-CASE A: Parallelogram along the x direction.

Sections of the ATLAS structure in  $zx$  planes are considered, which intersect for  $y_1 < y < y_2$ , the segment  $(x_a, x_b)$  inside the parallelogram. Each of these sections defines a box where the 2D doping is imported from ATHENA. Particularly, all the coordinates in ATHENA are scaled and translated so that the edge  $(x_c, x_d)$  of the ATHENA box containing the doping coincide with the segment  $(x_a, x_b)$  of the ATLAS box. This is done for all the sections inside the parallelogram. See Figure 18-3.

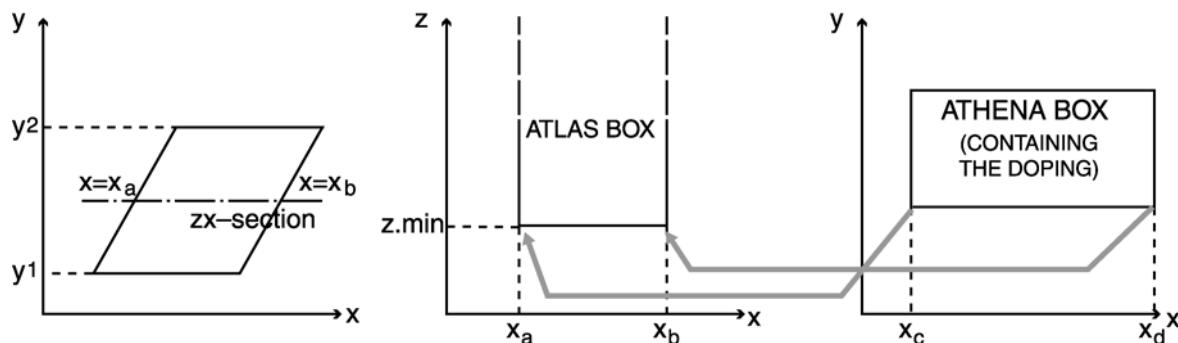


Figure 18-3: Parallelogram in the XY plane in the X direction and doping from the ATHENA2D master file

#### Examples:

```
doping athena master inf=athena.str boron xy \
x1=2.0 x2=3.0 y1=1.5 y2=4.0 x.dir \
x.min=-2.0 x.max=1.0 z.min=0.6 lat.char=0.05 int.log int.optm
```

For the  $z$  coordinate,  $z.min$  is used to specify the minimum value where to start putting the doping into the  $zx$ -sections (which properly defines the segment  $(x_a, x_b)$  in this plane).

In addition, a lateral spreading can be partially accomplished by extending the parallelogram into the planes,  $y > y_2$  and  $y < y_1$ , where the doping is spread out according to a Gaussian law.

#### SUB-CASE B: Parallelogram along the Y direction

Sections of the ATLAS structure are considered in the  $yz$  planes. A transformation of coordinates in ATHENA is accomplished in order to place the ATHENA segment  $(y_c, y_d)$  into the ATLAS one  $(y_a, y_b)$ . See Figure 18-4.

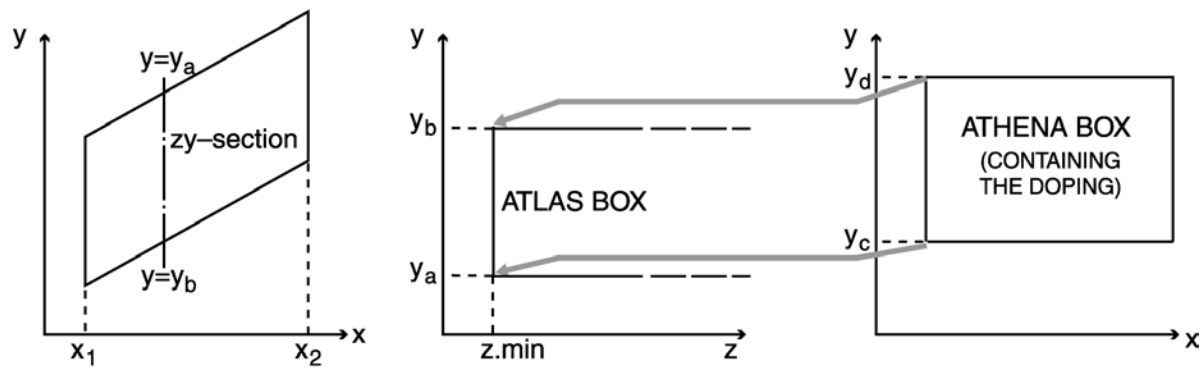


Figure 18-4: Parallelogram in the XY plane in the Y direction and doping from the ATHENA2D master file

#### Examples:

```
doping athena master inf=athena.str boron xy \
x1=2.0 x2=3.0 y1=1.5 y2=4.0 y.dir \
y.min=-2.0 y.max=1.0 z.min=0.6 lat.char=0.05 int.lin int.optm
```

#### Second Case: YZ Plane

The yz plane containing the parallelogram is defined by the yz parameter (or zy) in the DOPING statement.

If parallelograms along the z direction are defined (specify Z.DIR in doping statement), the doping from ATHENA is put over sections in the zx planes. If the parallelograms along the y direction are defined (using Y.DIR in doping statement), the doping from ATHENA is put over sections in the xy planes.

The minimum x coordinate in ATLAS to start adding doping can be specified by X.MIN in DOPING statement.

#### Examples:

```
doping athena master inf=athena.str boron zy z.dir \
z1=0.3 z2=0.6 y1=0.35 y2=0.25 z.min=-0.2 z.max=0.6 \
x.min=0.2 ratio.lat=0.05
```

```
doping athena master inf=athena.str boron zy y.dir \
z1=0.3 z2=0.6 y1=0.35 y2=0.25 y.min=-0.2 y.max=0.6 \
x.min=0.2 ratio.lat=0.05
```

#### Third Case: ZX Plane

The zx plane containing the parallelogram is defined by the zx parameter (or xz) in DOPING statement. If parallelograms along the z direction are defined (using Z.DIR in the DOPING statement), the doping from ATHENA is placed over sections in the yz planes.

If the parallelograms along the x direction are defined (using X.DIR in DOPING statement), the doping from ATHENA is placed over the sections in the xy planes.

The minimum y coordinate in ATLAS to start adding doping can be specified by Y.MIN in doping statement.

**Examples:**

```
doping athena master inf=athena.str boron int.lin \  
xz z.dir z1=0.45 z2=0.55 x1=0.2 x2=0.7 x.min=-0.4 \  
x.max=0.2 y.min=0.0 lat.char=0.02  
doping athena master inf=athena.str boron int.lin \  
xz x.dir z1=0.4 z2=0.8 x1=0.2 x2=0.7 z.min=-0.4 \  
z.max=0.2 y.min=0.5 ratio.lat=0.5
```



## 18.10: ELECTRODE

ELECTRODE specifies the locations and names of electrodes in a previously defined mesh.

### Syntax

```
ELECTRODE NAME=<en> [NUMBER=<n>] [SUBSTRATE] <pos> <reg>
```

| Parameter | Type      | Default                  | Units |
|-----------|-----------|--------------------------|-------|
| BOTTOM    | Logical   | False                    |       |
| IX.HIGH   | Integer   | right side of structure  |       |
| IX.LOW    | Integer   | left side of structure   |       |
| IY.HIGH   | Integer   | IY.LOW                   |       |
| IY.LOW    | Integer   | top of structure         |       |
| IZ.HIGH   | Real      |                          |       |
| IZ.LOW    | Real      |                          |       |
| LEFT      | Logical   | False                    |       |
| LENGTH    | Real      | length of structure      | μm    |
| MATERIAL  | Character | Contact                  |       |
| NAME      | Character |                          |       |
| NUMBER    | Integer   | defined #(electrodes)+ 1 |       |
| RIGHT     | Logical   | False                    |       |
| SUBSTRATE | Logical   | False                    |       |
| TOP       | Logical   | False                    |       |
| X.MAX     | Real      | right side of structure  | μm    |
| X.MIN     | Real      | left side of structure   | μm    |
| Y.MAX     | Real      | Y.MIN                    | μm    |
| Y.MIN     | Real      | top of the structure     | μm    |
| Z.MIN     | Real      |                          | μm    |
| Z.MAX     | Real      |                          | μm    |

### Description

**MATERIAL** specifies a material for the electrode (see Appendix B: “Material Systems”, Table B-1). This material will be displayed in TONYPLOT. The electrode material can also be used to define the electrode thermal characteristics (thermal conductivity) and optical characteristics (complex index of refraction). Setting the material here does not apply any electrical property such as workfunction to the terminal. All electrical properties of electrodes are set on the CONTACT statement.

**NAME** specifies an electrode name.

The electrode name can be referenced by other ATLAS statements to modify characteristics of the specified electrode. For reference by the CONTACT or THERMALCONTACT statements any valid character string can be used and properly cross-referenced. But when setting voltages, currents and charge from the SOLVE statement certain electrode names are recognized in a simplified syntax. By prepending the electrode name with "V" for voltage, "I" for current and "Q" for charge, you can directly and conveniently set the electrode bias, current or charge respectively. For example:

```
SOLVE VGATE=1.0
```

can be used to assign 1 volt bias to the electrode named "GATE". In such a manner, the following list of names can be used to set voltage, current or charge.

- GATE
- FGATE
- CGATE
- NGATE
- PGATE
- VGG

The following list of names can be used to assign only voltage or current.

- DRAIN
- SOURCE
- BULK
- SUBSTRATE
- EMITTER
- COLLECTOR
- BASE
- ANODE
- CATHODE
- WELL
- NWELL
- PWELL
- CHANNEL
- GROUND
- NSOURCE
- PSOURCE
- NDRAIN
- PDRAIN
- VDD
- VSS
- VEE
- VCC

**NUMBER** specifies an electrode number from 1 to 50. Electrode numbers may be specified in any order. If NUMBER is not specified, electrodes will be automatically numbered in sequential order. This parameter cannot re-number electrodes already defined in ATLAS or other programs.

**SUBSTRATE** places the specified electrode at the bottom of the device and names the electrode, substrate.

**pos** is one of the position parameters described below.

**reg** is a set of the region parameters described on the next page.

### Position Parameters

**BOTTOM** or **SUBSTRATE** specifies that the electrode is positioned along the bottom of the device.

**LEFT** specifies that the electrode starts at the left-hand edge of the device. The electrode will be positioned from left to right along the top of the device.

**RIGHT** specifies that the electrode starts at the right-hand edge of the device. The electrode will be positioned from right to left along the top of the device.

**TOP** specifies that the electrode is positioned along the top of the device.

### Region Parameters

Device coordinates may be used to add regions to both rectangular and irregular meshes. In either case, boundaries must be specified with the **X.MAX**, **X.MIN**, **Y.MAX**, and **Y.MIN** parameters.

**LENGTH** specifies the length of the electrode in the x direction. It is not necessary to specify **X.MIN**, **X.MAX**, and **LENGTH**. If two of these parameters are specified, the value of the third parameter will be calculated.

**X.MAX** specifies the maximum x-boundary of the electrode.

**X.MIN** specifies the minimum x-boundary of the electrode.

**Y.MAX** specifies the maximum y-boundary of the electrode.

**Y.MIN** specifies the minimum y-boundary of the electrode.

**Z.MIN** specifies the minimum z-boundary of the electrode.

**Z.MAX** specifies the maximum z-boundary of the electrode.

---

**Note:** If an electrode has been shortened to fit the current mesh, a warning message will be generated by ATLAS. Electrode placement can only occur at previously defined mesh nodes.

---

### Grid Indices

As an alternative to the region parameters, you can use grid indices to define a region only when the mesh is rectangular although these parameters are not recommended. To define a region with a rectangular mesh:

1. Use the **X.MESH** and **Y.MESH** statements to specify grid indices.
2. Use the **IX.HIGH**, **IX.LOW**, **IY.HIGH**, and **IY.LOW** parameters to specify x and y values.

**IX.HIGH** specifies the maximum x-value of the grid index.

**IX.LOW** specifies the minimum x-value of the grid index.

**IY.HIGH** specifies the maximum y-value of the grid index

**IY.LOW** specifies the minimum y-value of the grid index.

Nodes, which have x and y grid indices, between **IX.LOW** and **IX.HIGH** and between **IY.LOW** and **IY.HIGH** are designated electrode nodes. Normally, horizontal planar electrodes will be used. In this case, **IY.LOW** equals **IY.HIGH**.

**IZ.HIGH** specifies the maximum z-value of the grid index.

**IZ.LOW** specifies the minimum z-value of the grid index.

### MOS Electrode Definition Example

This example defines electrodes for a typical MOS structure.

```
ELEC X.MIN=0.5 LENGTH=0.25 NAME=gate
ELEC LENGTH=0.25 Y.MIN=0 LEFT NAME=source
ELEC LENGTH=0.25 Y.MIN=0 RIGHT NAME=drain
ELEC SUBSTRATE
```

### 3D Electrode Definition Example

The following example illustrates electrode definition for a 3-D structure.

```
ELECTRODE NAME=ANODE X.MIN=0.5 X.MAX=1.0 \
Z.MIN=0.5 Z.MAX=1.0
```

---

**Note:** In ATLAS, it is preferred to refer to ELECTRODES by name rather than number. Some functions, however, may require the electrode number. The syntax, `MODELS PRINT`, can be used to echo electrode numbers to the run-time output.

---

## 18.11: ELIMINATE

ELIMINATE terminates mesh points along lines in a rectangular grid defined within ATLAS in order to reduce the local mesh density.

### Syntax

```
ELIMINATE X.DIRECTION|Y.DIRECTION [<boundary>]
```

| Parameter | Type    | Default | Units |
|-----------|---------|---------|-------|
| COLUMNS   | Logical | False   |       |
| IX.LOW    | Integer |         |       |
| IX.HIGH   | Integer |         |       |
| IY.LOW    | Integer |         |       |
| IY.HIGH   | Integer |         |       |
| ROWS      | Logical | False   |       |
| X.MIN     | Real    |         | μm    |
| X.MAX     | Real    |         | μm    |
| Y.MIN     | Real    |         | μm    |
| Y.MAX     | Real    |         | μm    |

### Description

The ELIMINATE statement is used to remove points along every other line within the chosen range. Successive eliminations of the same range remove points along every fourth line. For horizontal elimination, the vertical bounds should be decreased by one at each re-elimination of the same region. For vertical elimination, the horizontal bounds should be decreased by one at each re-elimination of the same region.

**ROWS** or **X.DIR** eliminates points along horizontal lines.

**COLUMNS** or **Y.DIR** eliminates points along vertical lines.

### Boundary Parameters

**X.MIN**, **X.MAX**, **Y.MIN**, and **Y.MAX** specify the location of the boundaries of an area in coordinates, where the elimination is applied.

The following are provided for backward compatibility only. Their use is not recommended.

**IX.HIGH** specifies the mesh line number high boundary in the x direction.

**IX.LOW** specifies the mesh line number low boundary in the x direction.

**IY.HIGH** specifies the mesh line number high boundary in the y direction.

**IY.LOW** specifies the mesh line number low boundary in the y direction.

### Substrate Mesh Reduction Example

This example removes vertical points between the depth of 10 $\mu$ m and 20 $\mu$ m.

```
ELIM Y.DIR Y.MIN=10 Y.MAX=20 X.MIN=1 X.MAX=8
```

```
ELIM Y.DIR Y.MIN=10 Y.MAX=20 X.MIN=1 X.MAX=7
```

---

**Note:** In some cases, applications of the `ELIMINATE` statement can cause internal inconsistencies in the mesh. When this occurs, an error message will appear, warning you that there are triangles that are not associated with any region.

---

---

**Note:** The `ELIMINATE` statement only works on meshes defined using `ATLAS` syntax. You can eliminate mesh points on arbitrary meshes in `DEVEDIT`

---

---

## 18.12: EXTRACT

EXTRACT statements are used to measure parameters from both log and solution files.

---

**Note:** These commands are executed by DECKBUILD. This statement is documented in the VWF INTERACTIVE TOOLS MANUAL, VOLUME 1.

---

### Terminal Current Extraction Example

By default, EXTRACT works on the currently open log file. For example, to extract peak drain current from a run immediately after solution, type:

```
LOG OUTF=myfile.log
SOLVE .....
EXTRACT NAME="peak Id" max(i."drain")
```

### Extraction Example from Previously Generated Results

To extract the same data from a previously run simulation, use the INIT parameter.

```
EXTRACT INIT INFILE="myfile.log"
EXTRACT NAME="peak Id" max(i."drain")
```

### Solution Quantities Extraction Example

To use EXTRACT with solution files, use the INIT parameter. To find the integrated number of electrons in a 1D slice at X=1.0, use:

```
SAVE OUTF=mysolve.str or SOLVE ..... MASTER OUTF=mysolve.str
EXTRACT INIT INFILE="mysolve.str"
EXTRACT NAME="integrated e-" area from curve(depth,n.conc \
material="Silicon" mat.occno=1 x.val=1.0)
```

---

**Note:** EXTRACT commands are generally case sensitive.

---

## 18.13: EYE.DIAGRAM

`EYE.DIAGRAM` specifies that an eye diagram should be generated from the specified log file. An eye diagram is created by dividing up transient data in periods of fixed size and then overlaying it.

### Syntax

```
EYE.DIAGRAM INFILE OUTFILE PERIOD + [OPTIONAL PARAMETERS]
```

| Parameter | Type      | Default | Units |
|-----------|-----------|---------|-------|
| INFILE    | Character |         |       |
| OUTFILE   | Character |         |       |
| PERIOD    | Real      |         | s     |
| T.START   | Real      |         | s     |
| T.STOP    | Real      |         | s     |

### Description

**INFILE** specifies the input log file. This should contain data from a transient simulation.

**OUTFILE** specifies the file output file for the eye diagram.

**PERIOD** specifies the window period.

**T.START** specifies the initial time value to be used. The default value is the first time point in the input log file.

**T.STOP** specifies the final time value to be used. The default value is the last time point in the input log file.

### Examples

```
EYE.DIAGRAM INFILE=laser.log OUTFILE=eye.log PERIOD=2e-10 T.START=1.5e-9
```

In this example, `laser.log` is a log file from the transient simulation of a buried heterostructure laser when it is biased using a pseudo-random bit sequence. The data values from time=1.5ns onwards are used to create the eye diagram with a data period of 0.2ns. The results are then saved to the log file, `eye.log`. Figure 18-5 shows the eye diagram in TONYPLOT.



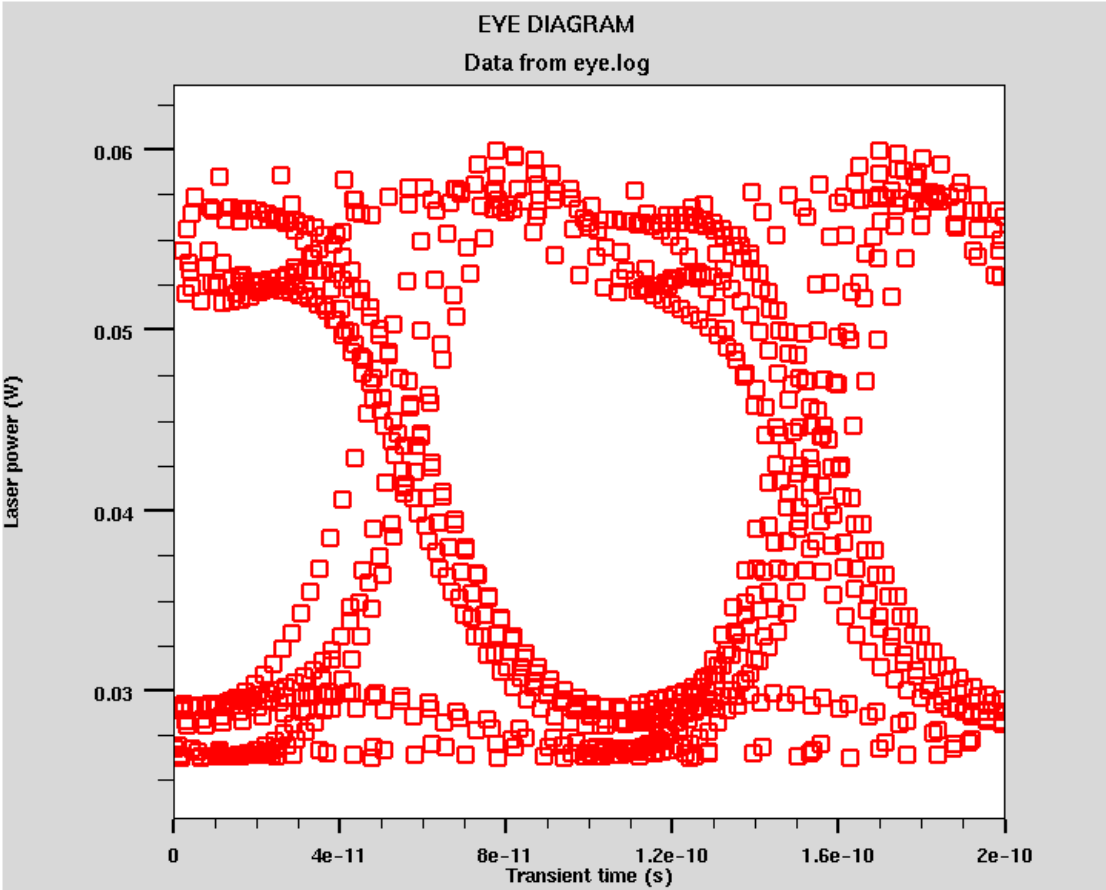


Figure 18-5: Eye diagram for BH Laser diode with a psuedo-random bit sequence input

## 18.14: FOURIER

FOURIER enables you to do Fourier transformations.

### Syntax

```
FOURIER INFILE OUTFILE + [ OPTIONAL PARAMETERS ]
```

| Parameter      | Type      | Default | Units |
|----------------|-----------|---------|-------|
| COMPLEX.VALUES | Logical   | False   |       |
| FUNDAMENTAL    | Real      |         | Hz    |
| INFILE         | Character |         |       |
| INTERPOLATE    | Logical   | False   |       |
| MAX.HARMONIC   | Real      |         | Hz    |
| NUM.SAMPLES    | Integer   | 64      |       |
| OUTFILE        | Character |         |       |
| T.START        | Real      |         | s     |
| T.STOP         | Real      |         | s     |

### Description

The FOURIER statement performs a Fast Fourier Transform on log file data.

**COMPLEX.VALUES** specifies that the real and imaginary components are saved to file as well as the magnitude and phase values. The synonym for this parameter is **REAL.VALUES**.

**FUNDAMENTAL** specifies the fundamental frequency. If the fundamental frequency is specified, **T.STOP** is set to **T.START + 1/FUNDAMENTAL**. If this is not specified, the fundamental frequency is set to  $(T.STOP - T.START) / NUM.SAMPLES$ .

**INFILE** specifies the input log file. This should contain data from a transient simulation.

**INTERPOLATE** specifies that the input data should be linearly interpolated such that data at uniform time steps are created. Interpolation of data can introduce additional (inaccurate) harmonic values into the Fourier transform. **INTERPOLATE** must be used if the log file contains non-uniform time steps.

**MAX.HARMONIC** specifies the maximum harmonic frequency that the Fourier transform should calculate. This will automatically calculate the correct number of samples (**NUM.SAMPLES**) required to generate this frequency. **FUNDAMENTAL** must be specified when **MAX.HARMONIC** is used.

**NUM.SAMPLES** specifies the number of discrete samples. This should be an integer power of 2 (i.e.,  $2^n$  where  $n$  is a positive integer). The default value is 64 unless the **MAX.HARMONIC** parameter is specified. In this case the number of samples is set to the nearest integer power of 2 which will generate this frequency.

**OUTFILE** specifies the output file for the Fourier transform data.

**T.START** specifies the start of time data to be used for the Fourier transform. The default value is the first time point in the input log file.

**T.STOP** specifies the end of time data to be used for the Fourier transform. The default value is the last time point in the input log file.

### Example 1

In this example, the transient data previously written to log file, *hemt1.log*, is transformed from the time domain to the frequency domain. The fundamental frequency is set to 0.5 GHz, and harmonic frequencies up to 16 GHz are calculated. Since the data in *hemt1.log* has non-uniform time steps, the **INTERPOLATE** flag must be enabled. The complex values as well as the magnitude and phase values are stored in *fftout1.log*.

```
FOURIER INFILE=hemt1.log FUNDAMENTAL=5e8 MAX.HARMONIC=1.6E10 \  
        OUTFILE=fftout1.log INTERPOLATE COMPLEX.VALUES
```

### Example 2

In this example, the log file values between 31.25 ps and 2ns are transformed into the frequency domain. The fundamental frequency is automatically determined from the time period set by **T.START** and **T.STOP**. The data values from this time period are interpolated into 64 samples, giving a maximum harmonic frequency of 15.5 GHz. The magnitude and phase values are then stored in *fftout2.log*.

```
FOURIER INFILE=hemt1.log T.START=3.125e-11 T.STOP=2e-9 NUM.SAMPLES=64 \  
        OUTFILE=fftout2.log INTERPOLATE
```

## 18.15: GO

GO quits and restarts ATLAS and also defines certain global parameters for ATLAS execution

---

**Note:** This command is executed by DECKBUILD. This statement is documented in the VWF INTERACTIVE TOOLS MANUAL VOLUME ONE.

---

### Example starting a given ATLAS Version

To start a given version of ATLAS the syntax is set by the `simflags` argument. To start version 4.3.0.R, type:

```
go atlas simflags="-V 4.3.0.R"
```

### Parallel ATLAS Example

To define the number of processors to be used in parallel ATLAS, use the `P` flag. For example, to start parallel ATLAS use four processors. For example:

```
go atlas simflags="-V 4.3.2.C -P 4"
```

## 18.16: IMPACT

IMPACT specifies and set parameters for impact ionization models.

### Syntax

IMPACT <model>

| Parameter | Type      | Default               | Units            |
|-----------|-----------|-----------------------|------------------|
| A.NT      | Real      | 0.588                 |                  |
| A.PT      | Real      | 0.588                 |                  |
| AN1       | Real      | $7.03 \times 10^5$    | $\text{cm}^{-1}$ |
| AN2       | Real      | $7.03 \times 10^5$    | $\text{cm}^{-1}$ |
| AP1       | Real      | $6.71 \times 10^5$    | $\text{cm}^{-1}$ |
| AP2       | Real      | $1.682 \times 10^6$   | $\text{cm}^{-1}$ |
| B.NT      | Real      | 0.248                 |                  |
| B.PT      | Real      | 0.248                 |                  |
| BETAN     | Real      | 1.0                   |                  |
| BETAP     | Real      | 1.0                   |                  |
| BN1       | Real      | $1.231 \times 10^6$   | V/cm             |
| BN2       | Real      | $1.231 \times 10^6$   | V/cm             |
| BP1       | Real      | $1.231 \times 10^6$   | V/cm             |
| BP2       | Real      | $2.036 \times 10^6$   | V/cm             |
| C0        | Real      | $2.5 \times 10^{-10}$ |                  |
| CHIA      | Real      | $3.0 \times 10^5$     |                  |
| CHIB      | Real      | $5.0 \times 10^4$     |                  |
| CHI.HOLES | Real      | $4.6 \times 10^4$     |                  |
| CROWELL   | Logical   | False                 |                  |
| CSUB.N    | Real      | $2.0 \times 10^{14}$  |                  |
| CSUB.P    | Real      | $4.0 \times 10^{12}$  |                  |
| DEVICE    | Character |                       |                  |
| E.DIR     | Logical   | True                  |                  |
| E.SIDE    | Logical   | False                 |                  |
| E.VECTOR  | Logical   | False                 |                  |

| Parameter  | Type      | Default               | Units             |
|------------|-----------|-----------------------|-------------------|
| EGRAN      | Real      | $4.0 \times 10^5$     | V/cm              |
| ENERGY     | Real      | 0.0025                |                   |
| ETH.N      | Real      | 1.8                   | eV                |
| ETH.P      | Real      | 3.5                   | eV                |
| F.EDIIN    | Character |                       |                   |
| F.EDIIP    | Character |                       |                   |
| GRANT      | Logical   | False                 |                   |
| ICRIT      | Real      | $4.0 \times 10^{-3}$  | A/cm <sup>2</sup> |
| INFINITY   | Real      | 0.001                 |                   |
| LAMDAE     | Real      | $6.2 \times 10^{-7}$  | cm                |
| LAMDAH     | Real      | $3.8 \times 10^{-7}$  | cm                |
| LENGTH.REL | Logical   | False                 |                   |
| LREL.EL    | Real      | $3.35 \times 10^{-2}$ | μm                |
| LREL.HO    | Real      | $2.68 \times 10^{-2}$ | μm                |
| M.ANT      | Real      | 1.0                   |                   |
| M.APT      | Real      | 1.0                   |                   |
| M.BNT      | Real      | 1.0                   |                   |
| M.BPT      | Real      | 1.0                   |                   |
| MATERIAL   | Character |                       |                   |
| NAME       | Character |                       |                   |
| NEW        | Logical   | False                 |                   |
| OLD        | Logical   | False                 |                   |
| REGION     | Integer   |                       |                   |
| SELB       | Logical   | False                 |                   |
| TAUSN      | Real      | $0.4 \times 10^{-12}$ | s                 |
| TAUSP      | Real      | $0.4 \times 10^{-12}$ | s                 |
| TOYABE     | Logical   | False                 |                   |
| VALDINOCI  | Logical   | False                 |                   |
| VAL.AN0    | Real      | 4.3383                |                   |
| VAL.AN1    | Real      | -2.42e-12             |                   |

| Parameter | Type | Default    | Units |
|-----------|------|------------|-------|
| VAL.AN2   | Real | 4.1233     |       |
| VAL.BN0   | Real | 0.235      |       |
| VAL.BN1   | Real | 0.0        |       |
| VAL.CN0   | Real | 1.6831e4   |       |
| VAL.CN1   | Real | 4.3796     |       |
| VAL.CN2   | Real | 1.0        |       |
| VAL.CN3   | Real | 0.13005    |       |
| VAL.DN0   | Real | 1.233735e6 |       |
| VAL.DN1   | Real | 1.2039e3   |       |
| VAL.DN2   | Real | 0.56703    |       |
| VAL.AP0   | Real | 2.376      |       |
| VAL.AP1   | Real | 0.01033    |       |
| VAL.AP2   | Real | 1.0        |       |
| VAL.BP0   | Real | 0.17714    |       |
| VAL.BP1   | Real | -0.002178  |       |
| VAL.CP0   | Real | 0.0        |       |
| VAL.CP1   | Real | 0.00947    |       |
| VAL.CP2   | Real | 2.4924     |       |
| VAL.CP3   | Real | 0.0        |       |
| VAL.DP0   | Real | 1.4043e6   |       |
| VAL.DP1   | Real | 2.9744e3   |       |
| VAL.DP2   | Real | 1.4829     |       |

## Description

The impact ionization model for continuity equations allows the accurate prediction of avalanche breakdown for many devices. Since impact ionization is a two-carrier process, the following statement must be specified after setting impact ionization models.

```
METHOD CARRIERS=2
```

## Model Selection Flags

**CROWELL** specifies the Crowell and Sze formulae [8].

**GRANT** selects Grant's impact ionization model [29] (see Chapter 3: "Physics", Equations 3-273 through 3-277).

**SELB** selects the impact ionization model described by Selberherr [2].

**N.CONCANNON, P.CONCANNON** set the Concannon substrate current model.

**TOYABE** is a synonym for **SELB**.

---

**Note:** If no model selection flag is set, the model parameters from Grant [29] are used. See Chapter 3: “Physics”, “Grant’s Impact Ionization Model” Section on page 3-74.

---

## Electric Field Model Selection Flags

The default electric field to use for ionization rate calculations is calculated as the modulus of the electric field over a triangle. In ATLAS3D, this is combined with the z-component of the field at each corner of the prism to give an overall field modulus at each node. This corresponds to Equation 3-257 in Chapter 3: “Physics” for a triangle.

**E.DIR** specifies that the impact ionization rate will be calculated as a function of the electric field in the direction of the current (see Equation 3-259 in Chapter 3: “Physics”). Its alias is **NEW**.

**E.SIDE** specifies that the impact ionization rate will be calculated as a function of the electric field along the side of the triangle (see Equation 3-258 in Chapter 3: “Physics”). This model is only supported in ATLAS2D. Its alias is **OLD**.

**E.VECTOR** specifies that the vector electric field will be used in the calculated of the impact ionization rate (see Equation 3-257 in Chapter 3: “Physics”).

**OLD** is the model that corresponds to Equation 3-258 in Chapter 3: “Physics” and is only supported in ATLAS2D.

**NEW** is the model that corresponds to Equation 3-259 in Chapter 3: “Physics”, where the component of the field in the direction of the current is used in the ionisation rate calculation. It is implemented in both ATLAS2D and ATLAS3D. If the dot product of  $E$  and  $J$  is negative, then the field component is taken as 0. Consequently, impact ionisation may only occur when a current is dominated by the drift term.

## Model Localization Parameters

**DEVICE** specifies the device in MIXEDMODE simulation to which the statement should apply.

**MATERIAL** specifies what material from Appendix B: “Material Systems”, Table B-1 the statement should apply. If a material is specified then all regions defined as being composed of that material will be affected.

**NAME** specifies what region that the IMPACT statement should apply. Note that the name must match the name specified in the NAME parameter of the REGION statement.

**REGION** specifies that index of the region to which the impact parameters apply.

## Valdinoci Model Parameters

**VAL.AN0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.AN1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.AN2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.BN0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.



**VAL.BN1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.CN0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.CN1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.CN2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.CN3** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.DN0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.DN1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.DN2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-270.

**VAL.AP0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.AP1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.AP2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.BP0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.BP1** specifies the value of a temperature dependent impact ionization parameter in Chapter 33: “Physics”, Equation 3-271

**VAL.CP0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.CP1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.CP2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.CP3** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.DP0** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.DP1** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

**VAL.DP2** specifies the value of a temperature dependent impact ionization parameter in Chapter 3: “Physics”, Equation 3-271.

## Crowell Model Parameters

**LAMBDAE** specifies the mean free path for electrons

**LAMDAH** specifies the mean free path for holes .

## Selberherr Model Parameters

**AN1**, **AN2**, **BN1**, **BN2**, **EGRAN** specify the basic set of parameters for Selberherr's impact ionization model. Index 1 (**AP1**, **BP1**, **AN1**, and **BN1**) corresponds to field values less than **EGRAN**, and index 2 (**AP2**, **BP2**, **AN2**, and **BN2**) corresponds to field values greater than **EGRAN**.

**BETAN** for electrons and **BETAP** for holes correspond to coefficients for the power of **ECRIT/E**

## Temperature Dependence Parameters

**A.NT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-269.

**A.PT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-270.

**B.NT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-271.

**B.PT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-272.

**M.ANT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-269.

**M.APT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-270.

**M.BNT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-271.

**M.BPT** specifies the value of the temperature-dependent parameter in Chapter 3: "Physics", Equation 3-272.

## Parameters for use with Energy Balance

**F.EDIIN** specifies the name of the file containing a C-INTERPRETER function describing the values of the parameters in Chapter 3: "Physics", Equation 3-267 as a function of electron temperature.

**F.EDIIP** specifies the name of the file containing a C-INTERPRETER function describing the values of the parameters in Chapter 3: "Physics", Equation 3-268 as a function of hole temperature.

**LENGTH.REL** specifies the use of energy relaxation length for the impact ionization model with the energy balance model.

**LREL.EL** specifies an energy relaxation length for electrons if **LENGTH.REL** is specified.

**LREL.HO** specifies an energy relaxation length for holes if **LENGTH.REL** is specified.

**TAUSN** specifies the relaxation time for electrons in the temperature dependent impact model.

**TAUSP** specifies the relaxation time for holes in the temperature dependent impact model.

---

**Note:** When energy balance simulations are run, the Toyabe impact ionization model is used. This model is used regardless of the **SELB** or **CROWELL** settings. See Chapter 3: "Physics", "Toyabe Impact Ionization Model" Section on page 3-76 for more information about this model.

---

## Concannon Model Parameters

**CSUB.N** is an empirical tuning factor used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-296) for electrons.

**CSUB.P** is an empirical tuning factor used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-297) for holes.

**ETH.N** specifies the ionization threshold energy for electrons used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-296).

**ETH.P** specifies the ionization threshold energy for holes used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-297).

**C0** specifies the electron distribution weight factor used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-300).

**CHIA** specifies the electron distribution function constant used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-300).

**CHIB** specifies the electron distribution function constant used in Concannon's Substrate Current Model (see Chapter 33: "Physics", Equation 3-300).

**CHI.HOLES** specifies the hole distribution function constant used in Concannon's Substrate Current Model (see Chapter 3: "Physics", Equation 3-301).

**ENERGY.STEP** specifies the energy step for numeric integration used in Concannon's Substrate Current Model

**INFINITY** specifies the limit for the highest energy in numeric integration used in Concannon's Substrate Current Model.

## Selberrherr Model Example

This example shows an IMPACT statement which specifies all parameters used by the model selected by the SELB parameter. In this case, only parameters for holes are field dependent. The AP1 and BP1 parameters correspond to parameters at field values more than EGRAN. The AP2 and BP2 parameters correspond to field values less than EGRAN. Coefficients for electrons should be repeated.

```
IMPACT SELB AN1=7.03E5 AN2=7.03E5 BN1=1.231E6 \
          BN2=1.231E6 AP1=6.71E5 AP2=1.58E6 BP1=1.693E6 \
          BP2=2.036E6 BETAN=1 BETAP=1 EGRAN=4.0E5
```

## 18.17: INTDEFECTS

INTDEFECTS activates the band gap interface defect model and sets the parameter values. This model can be used when thin-film transistor simulations are performed using the TFT product.

### Syntax

INTDEFECTS [<parameters>]

| Parameter  | Type       | Default               | Units                      |
|------------|------------|-----------------------|----------------------------|
| AFILE      | Character  |                       |                            |
| CONTINUOUS | Logical    | True                  |                            |
| DEVICE     | Character  |                       |                            |
| DFILE      | Characater |                       |                            |
| EGA        | Real       | 0.4                   | eV                         |
| EGD        | Real       | 0.4                   | eV                         |
| F.TFTACC   | Character  |                       |                            |
| F.TFTDON   | Character  |                       |                            |
| NGA        | Real       | $5.0 \times 10^{17}$  | $\text{cm}^{-3}$           |
| NGD        | Real       | $1.5 \times 10^{18}$  | $\text{cm}^{-3}$           |
| NTA        | Real       | $1.12 \times 10^{21}$ | $\text{cm}^{-3}/\text{eV}$ |
| NTD        | Real       | $4.0 \times 10^{20}$  | $\text{cm}^{-3}/\text{eV}$ |
| NUMBER     | Real       | All                   |                            |
| NUMA       | Real       | 12                    |                            |
| NUMD       | Real       | 12                    |                            |
| SIGGAE     | Real       | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGGAH     | Real       | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SIGGDE     | Real       | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SIGGDH     | Real       | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGTAE     | Real       | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| SIGTAH     | Real       | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SIGTDE     | Real       | $1.0 \times 10^{-14}$ | $\text{cm}^2$              |
| SOGTDH     | Real       | $1.0 \times 10^{-16}$ | $\text{cm}^2$              |
| WGA        | Real       | 0.1                   | eV                         |
| WGD        | Real       | 0.1                   | eV                         |

| Parameter | Type | Default             | Units         |
|-----------|------|---------------------|---------------|
| WTA       | Real | 0.025               | eV            |
| WTD       | Real | 0.05                | ev            |
| X.MIN     | Real | left of structure   | $\mu\text{m}$ |
| X.MAX     | Real | right of structure  | $\mu\text{m}$ |
| Y.MIN     | Real | top of structure    | $\mu\text{m}$ |
| Y.MAX     | Real | bottom of structure | $\mu\text{m}$ |
| Z.MIN     | Real | back of structure   | $\mu\text{m}$ |
| Z.MAX     | Real | front of structure  | $\mu\text{m}$ |

## Description

The INTDEFECTS statement is used to describe the density of defect states in the band gap at semiconductor interfaces. You can specify up to four distributions, two for donor-like states and two for acceptor-like states. Each type of state may contain one exponential (tail) distribution and one Gaussian distribution.

**AFILE** specifies the file name where the acceptor state density distribution, as a function of energy, will be stored. You can examine this file by using TONYPLOT.

**CONTINUOUS** specifies that the continuous defect integral model will be used.

**DEVICE** specifies which device the statement applies in mixed mode simulation.

**DFILE** specifies the file name where the donor state density distribution, as a function of energy, will be stored. You can examine this file by using TONYPLOT.

**EGA** specifies the energy that corresponds to the Gaussian distribution peak for acceptor-like states. This energy is measured from the conduction band edge.

**EGD** specifies the energy that corresponds to the Gaussian distribution peak for donor-like states. This energy is measured from the valence band edge.

**F.TFTACC** specifies the name of a file containing a C-INTERPRETER function, describing the distribution of acceptor state densities as a function of energy.

**F.TFTDON** specifies the name of a file containing a C-INTERPRETER function, describing the distribution of donor state densities as a function of energy.

**NGA** specifies the total density of acceptor-like states in a Gaussian distribution.

**NGD** specifies the total density of donor-like states in a Gaussian distribution.

**NTA** specifies the density of acceptor-like states in the tail distribution at the conduction band edge.

**NTD** specifies the density of donor-like states in the tail distribution at the valence band edge.

**NUMBER** or **REGION** specifies the region index to which the DEFECT statement applies.

**NUMA** specifies the number of discrete levels that will be used to simulate the continuous distribution of acceptor states.

**NUMD** specifies the number of discrete levels that will be used to simulate the continuous distribution of donor states.

**SIGGAE** specifies the capture cross-section for electrons in a Gaussian distribution of acceptor-like states.

**SIGGAH** specifies the capture cross-section for holes in a Gaussian distribution of acceptor-like states.

**SIGGDE** specifies the capture cross-section for electrons in a Gaussian distribution of donor-like states.

**SIGGDH** specifies the capture cross-section for holes in a Gaussian distribution of donor-like states.

**SIGTAE** specifies the capture cross-section for electrons in a tail distribution of acceptor-like states.

**SIGTAH** specifies the capture cross-section for holes in a tail distribution of acceptor-like states.

**SIGTDE** specifies the capture cross-section for electrons in a tail distribution of donor-like states.

**SIGTDH** specifies the capture cross-section for holes in a tail distribution of donor-like states.

**WGA** specifies the characteristic decay energy for a Gaussian distribution of acceptor-like states.

**WGD** specifies the characteristic decay energy for a Gaussian distribution of donor-like states.

**WTA** specifies the characteristic decay energy for the tail distribution of acceptor-like states.

**WTD** specifies the characteristic decay energy for the tail distribution of donor-like states.

**X.MIN** specifies the left boundary of a box, where an interface must exist, where defects are to be applied.

**X.MAX** specifies the right boundary of a box, where an interface must exist, where defects are to be applied.

**Y.MIN** specifies the top boundary of a box, where an interface must exist, where defects are to be applied.

**Y.MAX** specifies the bottom boundary of a box, where an interface must exist, where defects are to be applied.

**Z.MIN** specifies the back boundary of a box, where an interface must exist, where defects are to be applied.

**Z.MAX** specifies the front boundary of a box, where an interface must exist, where defects are to be applied.

## 18.18: INTERFACE

INTERFACE specifies interface parameters at semiconductor/insulator boundaries. All parameters apply only at the boundary nodes except where stated.

### Syntax

```
INTERFACE [<params>]
```

| Parameter  | Type    | Default                      | Units            |
|------------|---------|------------------------------|------------------|
| AR.ABSORB  | Real    | 0.0                          | cm <sup>-1</sup> |
| AR.INDEX   | Real    | 1                            | none             |
| AR.THICK   | Real    | 0                            | μm               |
| CHARGE     | Real    | 0.0                          | cm <sup>-2</sup> |
| COATING    | Integer | 1                            |                  |
| DEVICE     | Char    |                              | cm/s             |
| DD.TUNNEL  | Real    | 0.1                          |                  |
| DY.TUNNEL  | Real    | 0.1                          |                  |
| F.QF       | Char    |                              |                  |
| LAYER      | Integer | 1                            |                  |
| S.N        | Real    | 0.0                          | cm/s             |
| S.P        | Real    | 0.0                          | cm/s             |
| QF         | Real    | 0.0                          | cm <sup>-2</sup> |
| REGION     | Integer |                              |                  |
| S.I.       | Logical | True                         |                  |
| S.S.       | Logical | False                        |                  |
| S.X.       | Logical | False                        |                  |
| THERMIONIC | Logical | False                        |                  |
| TUNNEL     | Logical | False                        |                  |
| X.MAX      | Real    | right hand side of structure | μm               |
| X.MIN      | Real    | left hand side of structure  | μm               |
| Y.MAX      | Real    | bottom of structure          | μm               |
| Y.MIN      | Real    | top of structure             | μm               |
| Z.MIN      | Real    |                              | μm               |
| Z.MAX      | Real    |                              | μm               |
| Pl.X       | Real    |                              | μm               |

| Parameter | Type | Default | Units         |
|-----------|------|---------|---------------|
| P2.X      | Real |         | $\mu\text{m}$ |
| P1.Y      | Real |         | $\mu\text{m}$ |
| P2.Y      | Real |         | $\mu\text{m}$ |

## Description

The `INTERFACE` statement consists of a set of boundary condition parameters for the interface and a set of parameter to localize the effect of these parameters.

## Boundary Condition Parameters

**AR.ABSORB** specifies the absorption coefficient of a anti-refractive coating layer (also called extinction coefficient). Default value is  $0.0 \text{ cm}^{-1}$ .

**AR.INDEX** specifies the real component refractive index for the anti-reflective coating model in `LUMINOUS`. This model assumes the imaginary component of refractive index is zero so that the layer is non-absorbing. This model is only applicable for normal illumination. See Chapter 10: “Luminous: Optoelectronic Simulator”, “Anti-Reflective Coatings” on page 10-7 for more information about the anti-reflective coating model.

**AR.THICK** specifies the thickness of an anti-reflective coating layer for the reflection model in `LUMINOUS`. This layer should generally not exist in the device mesh structure. See Chapter 10: “Luminous: Optoelectronic Simulator”, “Anti-Reflective Coatings” on page 10-7 for more information about the anti-reflective coating model.

**CHARGE** specifies interface charge density ( $\text{cm}^{-2}$ ) applied between two materials. The additional parameters (`S.I`, `S.S`, and `S.X`) allow this value to be applied at semiconductor-insulator, semiconductor-semiconductor, and semiconductor-domain edges respectively. A value of  $1\text{e}10 \text{ cm}^{-2}$  represents  $1\text{e}10$  electronic charges per  $\text{cm}^{-2}$  at the interface. A positive value will introduce a positive charge value and a negative value will introduce a negative charge value.

**COATING** specifies the number of a multilayer anti-reflective coating (ARC) referred to in the `INTERFACE` statement. If the `COATING` parameter is not set, the first coating is assumed. You must specify coatings in order (i.e., you must define `COATING=2` before you define `COATING=3`). Different coatings should not overlap. If this occurs, the later coating is assumed in the overlapping part. For more information about ARC, see Chapter 10: “Luminous: Optoelectronic Simulator”, “Anti-Reflective Coatings” on page 10-7.

**DD.TUNNEL** controls the numerical integration in Equation 5-47. The integral is considered converged when the argument of the outer integral is less than the value of `DD.TUNNEL`.

---

**Note:** The numerical integral starts at the peak of the barrier where the argument should be equal to 1.0. Reducing this value increases simulation time but may improve accuracy.

---

**DY.TUNNEL** controls the step size in the numerical integration in Equation 5-47. The value of `DY.TUNNEL` specifies the size of the energy step,  $dE_x$ . The energy step is chosen as the product of the value for `DY.TUNNEL` and the energy change over the first triangle adjacent to the edge at the location in question. Reducing this value increases simulation time but may improve accuracy.

**F.QF** specifies the name of a file containing a `C-INTERPRETER` function describing the density of the interface fixed charge as a function of position.



**LAYER** describes the order of layers in a coating. If **LAYER** is not specified, the first (top) layer is assumed. You must specify the layers in order (i.e., you must define **LAYER=2** before you define **LAYER=3**). Note that you only need to specify the coordinates of the interface for the first layer of each coating.

**QF** specifies fixed oxide charge density ( $\text{cm}^{-2}$ ) applied at a semiconductor to insulator interface. A value of  $1\text{e}10 \text{ cm}^{-2}$  represents  $1\text{e}10$  electronic charges per  $\text{cm}^{-2}$  at the interface. A positive value will introduce a positive charge value and a negative value will introduce a negative charge value.

**S.N** specifies the electron surface recombination velocity.

**S.P** specifies the hole surface recombination velocity.

**THERMIONIC** specifies that carrier transport across an interface is modeled by thermionic emission. This model will only be applied at semiconductor/semiconductor boundaries. See Chapter 5: “Blaze: Compound Material 2D Simulator”, Section 5.1.4: “The Thermionic Emission and Field Emission Transport Model” for more information on thermionic emission.

**TUNNEL** specifies that the carrier transport across the interface will account for thermionic field emission. When **TUNNEL** is specified, **THERMIONIC** should also be specified. See Chapter 5: “Blaze: Compound Material 2D Simulator”, Section 5.1.4: “The Thermionic Emission and Field Emission Transport Model” for more information on thermionic emission.

## Position Parameters

**X.MIN**, **X.MAX**, **Y.MIN**, and **Y.MAX** define a bounding box. Any semiconductor/insulator interfaces found within this region are charged. If there is only one interface in a device, a non-planar surface may be defined using a box which contains the whole device.

**X.MIN** specifies the left x coordinate of the bounding box.

**X.MAX** specifies the right x coordinate of the bounding box.

**Y.MIN** specifies the bottom y coordinate of the bounding box.

**Y.MAX** specifies the top y coordinate of the bounding box.

**Z.MIN** specifies the front z coordinate of the bounding box. It is used in 3-D modules only.

**Z.MAX** specifies the back z coordinate of the bounding box. It is used in 3-D modules only.

**P1.X**, **P1.Y**, **P2.X**, and **P2.Y** define a bounding box. Within this box must lie the interface that is to be represented as the anti-reflective coating. See Chapter 10: “Luminous: Optoelectronic Simulator”, the “Anti-Reflective Coatings” on page 10-7 for more information about the anti-reflective coating model.

---

**Note:** For anti-reflective coatings in Luminous3D, use **X . MIN**, **X . MAX**, **Y . MIN**, **Y . MAX**, **Z . MIN**, and **Z . MAX** to define the bounding box.

---

**P1.X** specifies the left x coordinate of the bounding box.

**P2.X** specifies the right x coordinate of the bounding box.

**P1.Y** specifies the bottom y coordinate of the bounding box.

**P2.Y** specifies the top y coordinate of the bounding box.

**DEVICE** specifies which device in a **MIXEDMODE** simulation applies to the statement.

**REGION** specifies which the region number applies to the statement.

## MOS Example

This example defines an interface with both fixed charge and recombination velocities.

```
INTERFACE X.MIN=-4 X.MAX=4 Y.MIN=-0.5 Y.MAX=4 \  
          QF=1E10 S.N=1E4 S.P=1E4
```

## SOI Example

To define different fixed charge on the front and back interfaces of an SOI transistor, you need two `INTERFACE` statements.

In the syntax below, the first statement will apply  $5.10^{10}$   $\text{cm}^{-2}$  charge to any silicon/oxide interface above  $Y=0.01\mu\text{m}$ . The second statement applied a higher charge to any interface below  $Y=0.01\mu\text{m}$ . Note that charges are only applied at the material interfaces so the  $y$  coordinate needs only to be somewhere within the silicon film.

```
INTERFACE Y.MAX-0.01 QF=5e10  
INTERFACE Y.MIN=0.01 QF=2e11
```

## Interface Charge for III-V Devices

By default, the `INTERFACE` statement is applied to semiconductor-insulator interfaces. Interface charge can, however, be added at the interfaces between two semiconductor regions or at the edges of semiconductor regions.

The `CHARGE` parameter defines the interface charge value in  $\text{cm}^{-2}$ . The `S.I`, `S.S`, and `S.X` parameters control whether the charge is placed between semiconductor-insulator regions, semiconductor-semiconductor regions, or at the semiconductor domain edges. You can control the location of the added charge by using the position parameters.

## 18.19: INTTRAP

INTTRAP activates interface defect traps at discrete energy levels within the bandgap of the semiconductor and sets their parameter values.

### Syntax

```
INTTRAP <type> E.LEVEL=<r> DENSITY=<r> <capture parameters>
```

| Parameter | Type    | Default             | Units            |
|-----------|---------|---------------------|------------------|
| ACCEPTOR  | Logical | False               |                  |
| DEGEN.FAC | Real    | 1                   |                  |
| DENSITY   | Real    |                     | cm <sup>-2</sup> |
| DEVICE    | Char    |                     |                  |
| DONOR     | Logical | False               |                  |
| E.LEVEL   | Real    |                     | eV               |
| F.DENSITY | Char    |                     |                  |
| REGION    | Integer |                     |                  |
| SIGN      | Real    |                     | cm2              |
| SIGP      | Real    |                     | cm2              |
| TAUN      | Real    |                     | s                |
| TAUP      | Real    |                     | s                |
| X.MIN     | Real    | left of structure   | μm               |
| X.MAX     | Real    | right of structure  | μm               |
| Y.MIN     | Real    | top of structure    | μm               |
| Y.MAX     | Real    | bottom of structure | μm               |
| Z.MIN     | Real    | back of structure   | μm               |
| Z.MAX     | Real    | front of structure  | μm               |

### Description

**DEVICE** specifies which device the statement applies to in MIXEDMODE simulation.

**DONOR** specifies a donor-type trap level.

**ACCEPTOR** specifies an acceptor-type trap level.

**DEGEN.FAC** specifies the degeneracy factor of the trap level used to calculate the density.

**DENSITY** sets the maximum density of states of the trap level.

**F.DENSITY** specifies the name of a file containing a C-INTERPRETER function describing the density of donor/acceptor interface traps as a function of position.

**E.LEVEL** sets the energy of the discrete trap level. It is equal to the energy distance between conductance band and trap level for acceptor trap, and to energy distance between trap level and valence band for donor trap.

**X.MIN** specifies the left boundary of a box, where an interface must exist and where traps are to be applied.

**X.MAX** specifies the right boundary of a box, where an interface must exist and where traps are to be applied.

**Y.MIN** specifies the top boundary of a box, where an interface must exist and where traps are to be applied.

**Y.MAX** specifies the bottom boundary of a box, where an interface must exist and where traps are to be applied.

**Z.MIN** specifies the back boundary of a box, where an interface must exist and where traps are to be applied.

**Z.MAX** specifies the front boundary of a box, where an interface must exist and where traps are to be applied.

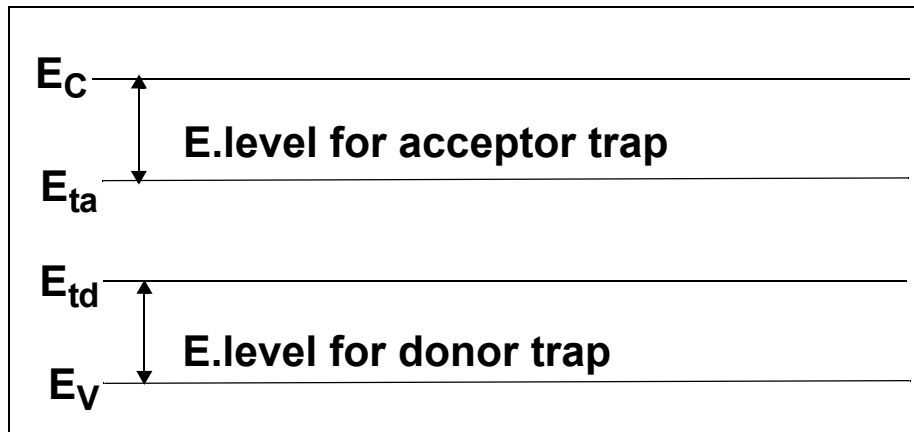


Figure 18-6: Acceptor and Donor Interface Trap Energy Levels

### Capture Parameters

Either the cross section or lifetime parameters should be used to define the capture parameters.

**SIGN** specifies the capture cross section of the trap for electrons.

**SIGP** specifies the capture cross section of the trap for holes.

**TAUN** specifies the lifetime of electrons in the trap level.

**TAUP** specifies the lifetime of holes in the trap level.

### Multiple Interface Trap States Example

The following example sets three discrete interface trap levels within the silicon bandgap. These trap levels will capture carriers, which slows down the switching speed of any device. In this example, the capture cross sections are used to define the properties of each trap.

```
intrtrap e.level=0.49 acceptor density=2.e10 degen=12 \
sign=2.84e-15 sigp=2.84e-14
intrtrap e.level=0.41 acceptor density=1.e10 degen=12 \
sign=7.24e-16 sigp=7.24e-15
```

```
inttrap e.level=0.32 donor density=1.e10 degen=1 \  
sign=1.00e-16 sigp=1.00e-17
```

---

**Note:** For semiconductor bulk trap levels, see Section 18.48: "TRAP".

---

## 18.20: LASER

LASER defines physical models and model parameters for laser and Vertical Cavity Surface-Emitting Lasers (VCSEL) simulation. For more information about VCSEL, see Chapter 9: "VCSEL Simulator".

### Syntax

LASER<parameters>

| Parameter     | Type      | Default | Units   |
|---------------|-----------|---------|---------|
| ABSORPTION    | Logical   | False   |         |
| ATRAP         | Real      | 0.5     |         |
| CAVITY.LENGTH | Real      | 100.0   | cm      |
| COUPLED       | Logical   | False   |         |
| DBR1.START    | Real      | 0.0     | microns |
| DBR1.FINAL    | Real      | 0.0     | microns |
| DBR2.START    | Real      | 0.0     | microns |
| DBR3.FINAL    | Real      | 0.0     | microns |
| EFINAL        | Real      | 0.0     | eV      |
| EINIT         | Real      | 0.0     | eV      |
| ESEP          | Real      | eV      |         |
| ETRANS        | Logical   | False   |         |
| F.MIRROR      | Character |         |         |
| FAR.NX        | Integer   | 100     |         |
| FAR.NY        | Integer   | 100     |         |
| FCARRIER      | Logical   | False   |         |
| INDEX.BOTTOM  | Real      | 1.0     |         |
| INDEX.MODEL   | Integer   | 0       |         |
| INDEX.TOP     | Real      | 1.0     |         |
| ITMAX         | Integer   | 30      |         |
| LOSSES        | Real      | 0       |         |
| MAXCH         | Real      | 2.5     |         |
| LMODES        | Logical   | False   |         |
| MAXTRAPS      | Integer   | 2       |         |
| MIRROR        | Real      | 90.0    | %       |
| MULTISAVE     | Logical   | True    |         |

|                 |           |                       |                 |
|-----------------|-----------|-----------------------|-----------------|
| NEAR.NX         | Integer   | 100                   |                 |
| NEAR.NY         | Integer   | 100                   |                 |
| NEFF            | Real      | 3.57                  |                 |
| NMODE           | Integer   | 1                     |                 |
| NX              | Integer   |                       |                 |
| NY              | Integer   |                       |                 |
| OMEGA           | Real      | $2.16 \times 10^{15}$ | Hz              |
| PHOTON.ENERGY   | Real      | 0                     | eV              |
| PROJ            | Logical   | False                 |                 |
| REFLECT         | Logical   | False                 |                 |
| RF              | Real      | 0.0                   | %               |
| RF.FILE         | Character |                       |                 |
| RR              | Real      | 0.0                   | %               |
| RR.FILE         | Character |                       |                 |
| SIN             | Real      | 100000                | cm <sup>2</sup> |
| SPEC.NAME       | Character |                       |                 |
| SPECSAVE        | Integer   | 1                     |                 |
| SPONTANEOUS     | Integer   | 1                     |                 |
| TAUSS           | Real      | 0.05                  |                 |
| TIMERATE        | Logical   | True                  |                 |
| TOLER           | Real      | 0.01                  |                 |
| TRANS_ENERGY    | Real      | eV                    |                 |
| TRAP            | Logical   | False                 |                 |
| VCSEL.CHECK     | Integer   | 1                     |                 |
| VCSEL.INCIDENCE | Integer   | False                 |                 |
| XMIN            | Real      | min. X                | microns         |
| XMAX            | Real      | max. X                | microns         |
| YMIN            | Real      | min. Y                | microns         |
| YMAX            | Real      | max. Y                | microns         |

## Description

**ABSORPTION** enables the absorption loss model in LASER.

**ATRAP** is the same as the `LAS.ATRAP` parameter in the `METHOD` statement.

**DBR1.START**, **DBR1.FINAL**, **DBR2.START**, and **DBR2.FINAL** parameters specify the locations of the front and rear DBR mirrors for a VCSEL device (See Figure 18-7). The reflectivity of front and rear DBR mirrors will be calculated from the optical intensity profile.

**CAVITY.LENGTH** specifies the cavity length in the longitudinal direction (in  $\mu\text{m}$ ).

**COUPLED** specifies that the solution process for the photon rate equation is fully coupled to the Jacobian of the drift-diffusion equations.

**EINIT**, **EFINAL** specify the lower and upper photon energies. LASER will calculate multiple longitudinal photon rates within this range. Using wide ranges can slow down simulation.

**ESEP** specifies the photon energy separation. If this isn't specified, LASER will automatically calculate the number of longitudinal modes based on the cavity length and the energy range.

**ETRANS** enables the selection of a specific transverse mode. The selected transverse mode will be the mode with the closest energy to `TRANS_ENERGY`.

**F.MIRROR** specifies the name of a file containing a C-Interpreter function that defines the front and rear mirror reflectivities as a function of wavelength.

**FAR.NX**, **FAR.NY** describe the number of samples to output for the far-field pattern in the X and Y directions. For more information about the far-field pattern, see Chapter 8: "Laser: Edge Emitting Simulator", Section 8.5.1: "Generation of Near-Field and Far-Field Patterns".

**FCARRIER** enables the free carrier loss model in LASER.

**INDEX.BOTTOM** specifies the refractive index of the medium below the structure. The default value is 1.0.

**INDEX.MODEL** specifies whether the simple refractive index model (`INDEX.MODEL=0`) or the more complex gain dependent refractive index (`INDEX.MODEL=1`) is used.

**INDEX.TOP** specifies the refractive index of the medium above the structure. The default value is 1.0.

---

**Note:** When using `INDEX.MODEL=1`, a complex value Eigenvalue solver is used. This requires a refined x direction LASER mesh and a refined y direction LASER mesh to ensure the accuracy of the solution. When the bulk refractive index model is used, only a refined y direction LASER mesh is required for the Eigenvalue solver.

---

**ITMAX** specifies the maximum number of iterations allowed for LASER simulation at each bias point.

**LMODES** specifies that multiple longitudinal models are to be accounted for during laser simulation.

**LOSSES** specifies the total losses in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-5.

**MAXCH** specifies the maximum allowed relative change in photon densities between iterations. Rapid changes of the photon densities can cause convergence problems.

**MAXTRAPS** specifies the number of transverse modes to be simulated.

**MIRROR** specifies the percentage facet reflectivity for the mirror loss in LASER. 100% reflectivity is equivalent to no mirror loss. Both facets are assumed to have this value of reflectivity.

**MULTISAVE** specifies the whether to save the transient laser spectrum as one file or multiple files.



**NEAR.NX**, **NEAR.NY** describe the number of samples to output for the near-field pattern in the X and Y directions. For more information about the near-field pattern, see Chapter 8: “Laser: Edge Emitting Simulator”, Section 8.5.1: “Generation of Near-Field and Far-Field Patterns”.

**NEFF** specifies the effective refractive index in Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-4.

**NMODE** is the same as the `LAS.NMODE` parameter in the `MODELS` statement.

**NSPEC** specifies the number of sampling points between `EINIT` and `EFINAL` in the reflectivity test. The default value is `NSPEC=100`.

**NX** defines the number of mesh divisions for the laser mesh in the X direction.

**NY** defines the number of mesh divisions for the laser mesh in the Y direction.

**PHOTON.ENERGY** specifies the energy of photons to be used in Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-1. If Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-2 is used for simulation, this parameter will only specify an initial estimate of the photon energy. If that’s the case, use the `LAS.OMEGA` parameter instead to specify the lasing frequency.

**PROJ** is the same as the `LAS.PROJ` parameter in the `METHOD` statement.

**OMEGA** specifies the lasing frequency to be used in Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-1. If model 2 is used for simulation, then this parameter will estimate the lasing frequency. If that’s the case, use the `PHOTON.ENERGY` parameter to specify photon energy instead.

**REFLECT** specifies that only half of the Laser structure is to be simulated. The axis of symmetry in this case is at  $x=0$ . Specify the laser mesh so that the minimum x coordinate is zero.

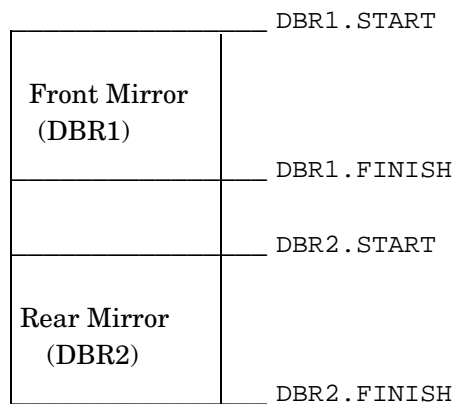
**RF** and **RR** specify the front and rear facet mirror reflectivities of Fabry-Perot type lasers. If these parameters aren’t specified, then they will be calculated from the average mirror loss parameter (`MIRROR.LOSS` parameter in the `LASER` or `MODELS` statements). If `MIRROR.LOSS` is used, then `RF` and `RR` shouldn’t be specified.

**RF.FILE** and **RR.FILE** specify the front and rear facet mirror reflectivity files. If `RF.FILE` is specified, the rear reflectivity will be read from the specified file. A linear interpolation algorithm will calculate value of the reflectivity from the tabulated values with the bounds given by the first and last wavelength value. The wavelength values in the file must be ascending order. The file format is as follows:

```

number of samples
wavelength (in microns)           reflectivity (in %)

```



**Figure 18-7: DBR Location Parameters**

The cavity length used in the mirror loss calculation is given by `DBR2.START - DBR1.FINISH`. If both DBR mirrors are not defined, then the mirror loss will set to 0.

**SIN** specifies an initial photon density in the fundamental lasing mode. This value provides an initial guess for subsequent iterations. This parameter is used only when the single frequency model has been selected.

**SPEC.NAME** specifies the name of a spectrum file, which LASER will produce for each bias point, if the `LMODES` parameter has been specified.

**SPECSAVE** the spectrum file will be saved after every `LAS.SPECSAVE` laser solution step.

**SPONTANEOUS** enables the Spontaneous Recombination Model (see Chapter 33: "Physics", Sections 3.9.1: "The General Radiative Recombination Model" and 3.9.2: "The Default Radiative Recombination Model").

**TAUSS** specifies the iteration parameter to be used for the photon rate equation. See Chapter 8: "Laser: Edge Emitting Simulator", Section 8.4.2: "Numerical Parameters" for more information.

**TIMERATE** specifies that the time dependent photon rate equation will be used in a transient laser simulation.

**TOLER** specifies the desired accuracy in photon areas.

**TRANS\_ENERGY** specifies the energy for selective a single transverse mode (see also `ETRANS`).

**TRAP** is the same as the `LAS.TRAP` parameter in the `METHOD` statement.

**VCSEL.CHECK** enables reflectivity test simulation of the VCSEL structure.

**VCSEL.INCIDENTCE** specifies the direction of light incident on the structure. `VCSEL.INCIDENTCE=1` is the light incident from the top. `VCSEL.INCIDENTCE=0` is the light incident from the bottom. `VCSEL.INCIDENTCE=2` or `>2` means both directions of light incidence are considered. By default, light is incident from the top of the structure.

**XMIN** defines the minimum X coordinate for the laser mesh. See also `LX.MESH`.

**XMAX** defines the maximum X coordinate for the laser mesh. See also `LX.MESH`.

**YMIN** defines the minimum Y coordinate for the laser mesh. See also `LY.MESH`.

**YMAX** defines the maximum Y coordinate for the laser mesh. See also `LY.MESH`.

## 18.21: LOAD

LOAD loads previous solutions from files as initial guesses to other bias points.

### Syntax

```
LOAD [ASCII|MASTER] [NO.CHECK] <files>
```

| Parameter | Type      | Default | Units |
|-----------|-----------|---------|-------|
| ASCII     | Logical   | False   |       |
| INFILE    | Character |         |       |
| INIFILE   | Character |         |       |
| IN2FILE   | Character |         |       |
| MASTER    | Logical   | False   |       |
| NO.CHECK  | Logical   | False   |       |
| TWOD      | Logical   | False   |       |

### Description

**ASCII** specifies that any original PISCES format files read or written by this statement will be in an ASCII rather than in a binary format.

**MASTER** specifies that any files read by this statement will be in a standard structure file rather than the original PISCES format. If you are using TONYPLOT to plot simulation results, this parameter should be specified.

**TWOD** allows loading of a 2-D solution into a 3-D structure. Note that the values from the 2-D solution are loaded uniformly in the Z direction.

**NO.CHECK** prevents checking material parameter differences between loaded binary files and the values set in the current input file.

### File Parameters

The LOAD statement requires that one of the following file parameter syntax be used.

```
LOAD INFILE=<filename>
```

or

```
LOAD IN1FILE=<filename> IN2FILE=<filename>
```

**INFILE** specifies a single input filename for solution data. This parameter should be used when you wish to load only one solution which is the most common case.

**IN1FILE** specifies a filename for present solution data. Use this parameter if two input files are needed to perform an extrapolation for an initial approximation (i.e., the PROJECT parameter of the SOLVE statement).

**IN2FILE** specifies an input filename for previous solution data. Use this parameter if two input files are needed to perform an extrapolation for an initial approximation (i.e., the PROJECT parameter of the SOLVE statement). The solution specified by this parameter is the first to be overwritten when new solutions are obtained.

## Simple Save and Load Examples

This example saves and loads the master format solution file, *SOL.STR*.

```
SAVE OUTF=SOL.STR.
```

```
....
```

```
LOAD INFILE=SOL.STR MASTER
```

As before but using the SOLVE syntax.

```
SOLVE OUTF=SOL.STR MASTER
```

```
..
```

```
LOAD INF=SOL.STR MASTER
```

When the save and load operations are not done within the same ATLAS run see the note below.

## Binary Format Example

Saving and loading using the binary format. This is quicker but these files cannot be plotted in TONYPLOT.

```
SOLVE OUTF=SOLVE_TMP
```

```
..
```

```
LOAD INF=SOLVE_TMP
```

---

**Note:** The function to calculate the difference between two files is now inside TONYPLOT. It has been discontinued from the LOAD statement

---

---

**Note:** The LOAD statement loads only the saved solution quantities into ATLAS. The mesh, electrodes, doping, regions, contact settings, material parameters, models, and numerical methods must all be specified in advance of any LOAD statement. See the Chapter 2: "Getting Started with ATLAS", "Re-initializing ATLAS at a Given Bias Point" Section on page 2-54.

---

## 18.22: LOG

LOG allows all terminal characteristics of a run to be saved to a file. Any DC, transient, or AC data generated by SOLVE statements after the LOG statement is saved. Any parameters specified by the PROBE statement are also stored in the logfile. If a log file is already open, the open log file is closed and a new log file is opened.

### Syntax

```
LOG [OUTFILE=<filename>] [MASTER] [acparams]
```

| Parameter   | Type      | Default | Units |
|-------------|-----------|---------|-------|
| ABCD.PARAM  | Logical   | False   |       |
| APPEND      | Logical   | False   |       |
| GAINS       | Logical   | False   |       |
| H.PARAM     | Logical   | False   |       |
| IMPEDANCE   | Real      | 50      | ohms  |
| INPORT      | Character |         |       |
| IN2PORT     | Character |         |       |
| J.DISP      | Logical   | False   |       |
| J.ELECTRON  | Logical   | False   |       |
| J.HOLE      | Logical   | False   |       |
| LCOMMON     | Real      | 0       | H     |
| LGROUND     | Real      | 0       | H     |
| LIN         | Real      | 0       | H     |
| LOUT        | Real      | 0       | H     |
| MASTER      | Logical   | True    |       |
| NOISE       | Logical   | False   |       |
| NOISE.ALL   | Logical   | False   |       |
| NOISE.I     | Logical   | False   |       |
| NOISE.IV    | Logical   | False   |       |
| NOISE.I.ALL | Logical   | False   |       |
| NOISE.V     | Logical   | False   |       |
| NOISE.VI    | Logical   | False   |       |
| NOISE.V.ALL | Logical   | False   |       |
| OFF         | Logical   | False   |       |
| OLD         | Logical   | False   |       |

| Parameter | Type      | Default | Units   |
|-----------|-----------|---------|---------|
| OUTPORT   | Character |         |         |
| OUT2PORT  | Character |         |         |
| OUTFILE   | Character |         |         |
| RCOMMON   | Real      | 0       | ohms    |
| RGROUND   | Real      | 0       | ohms    |
| RIN       | Real      | 0       | ohms    |
| ROUT      | Real      | 0       | ohms    |
| S.PARAM   | Logical   | False   |         |
| SIM.TIME  | Logical   | False   | s       |
| WIDTH     | Real      | 1       | microns |
| Y.PARAM   | Logical   | False   |         |
| Z.PARAM   | Logical   | False   |         |

### File Output Parameters

**OUTFILE** specifies the log file that will be used to store DC, AC, or transient I-V information.

**MASTER** specifies that AC data and I-V information will be saved in a standard structure file format. This is the default format.

**J.DISP** specifies that displacement currents are written to the log file.

**J.ELECTRON** specifies that electron currents are to be written into the log file.

**J.HOLE** specifies that hole currents are to be written into the log file.

**APPEND** specifies that the output I-V information should be appended to an existing log file. Make sure that the existing log files contain the same type of data (e.g., DC, AC, transient) as the subsequent SOLVE statements.

**OFF** specifies that any currently open log file will be closed and log file output is discontinued.

**OLD** specifies that AC data and IV information will be saved in the original PISCES-II file format. A synonym for this parameter is PISCES.

---

**Note:** The older `ACFILE` syntax is not supported and should not be used. AC results are stored in the file specified by `OUTFILE` as long as the first `SOLVE` statement after the `LOG` statement contains AC analysis.

---

### RF Analysis Parameters

If `S.PARAM`, `H.PARAM`, `Z.PARAM`, `GAINS`, or `ABCD.PARAM` is specified, the capacitance and conductance data will be converted into the requested set of AC parameters.

**S.PARAM** elects s parameter analysis. For S-parameter analysis, you can also choose to set any of the parasitic element parameters.

**H.PARAM** selects h parameter analysis.

**Y.PARAM** selects Y parameter analysis

**Z.PARAM** selects z parameter analysis.

**ABCD.PARAM** selects ABCD parameter analysis.

**GAINS** selects the calculation of several types of gains used in RF analysis [125]. These are the stability factor, unilateral power gain (GUm<sub>ax</sub>), maximum unilateral transducer power gain (GT<sub>max</sub>), maximum available power gain (G<sub>ma</sub>), and the maximum stable power gain (G<sub>ms</sub>). The magnitude of H<sub>21</sub> is also calculated.

**IMPEDANCE** specifies the matching impedance for s-parameter calculation.

**INPORT** specifies the electrode name for the primary input port used when performing any AC parameter calculations.

**IN2PORT** specifies the electrode name of the secondary input port.

**OUTPORT** specifies the electrode name for the output ports used when performing any AC parameter calculations.

**OUT2PORT** specifies the electrode n of the secondary output port

## NOISE Parameters

To perform noise analysis on a one-port device, define the INPORT. To perform noise analysis on a two-port device, define the INPORT and the OUTPORT.

**NOISE** selects  $F_{\min}$ ,  $Z_O$ , and  $g_n$  (the two-port noise figures of merit, 2pNFOM) for output.

**NOISE.ALL** selects all noise results for output. These are 2pNFOM, total and individual noise voltage sources, and total and individual noise current sources.

**NOISE.I** selects the 2pNFOM and the correlation of the total noise current sources.

**NOISE.I.ALL** selects the 2pNFOM, the correlation of the total noise current sources, and the correlation of the noise current sources from the individual noise mechanisms (GR, II, electron and hole diffusion; electron and hole flicker).

**NOISE.V** selects the 2pNFOM and the correlation of the total noise voltage sources.

**NOISE.VI** or **NOISE.IV** selects the 2pNFOM and the correlations of both the total noise voltage sources and the total noise current sources.

**NOISE.V.ALL** selects the 2pNFOM, the correlation of the total noise voltage sources, and the correlation of the noise voltage sources from the individual noise mechanisms (GR, II, electron and hole diffusion; electron and hole flicker).

---

**Note:** The 2pNFOM have no meaning for a one-port device and therefore don't output. If NOISE is the only parameter defined for a one-port device, then the correlation of the total noise voltage sources outputs (rather than outputting nothing).

---

## Parasitic Element Parameters

For RF parameter extraction, you can also set any of the parasitic element parameters. By setting the parasitic element parameters, you can apply lumped parasitic resistances or inductances to the terminal of the two-port device during the RF parameter extraction. These parameters will not affect the capacitance or conductance matrices calculated by ATLAS.

**RIN** specifies the lumped parasitic resistance on the input to the two port device for s-parameter extraction. The value of RIN is in Ohms.

**ROUT** specifies the lumped parasitic resistance on the output to the two port device for s-parameter extraction. The value of ROUT is in Ohms.

**RGROUND** specifies the lumped parasitic resistance on the ground or common side of the two port device for s-parameter extraction. The value of **RGROUND** is in Ohms. **RCOMMON** is an alias for **RGROUND**.

**LIN** specifies the lumped parasitic inductance on the input to the two port device for s-parameter extraction. The value of **LIN** is in Henrys.

**LOUT** specifies the lumped parasitic inductance on the output to the two port device for s-parameter extraction. The value of **LOUT** is in Henrys.

**LGROUND** specifies the lumped parasitic inductance on the ground or common side of the two port device for s-parameter extraction. The value of **LGROUND** is in henries. **LCOMMON** is an alias for **LGROUND**.

**SIM.TIME** saves the time taken for a bias point into the log file and measured in seconds. Note that if multiple jobs are using the same CPU that this method may not be a true reflection of processor speed.

**WIDTH** specified an output width (in z direction) to apply during the s-parameter calculation. Note that this parameter affects *only* the derived RF parameters and not currents, capacitances or conductances. The **WIDTH** parameter of the **MESH** statement can be used to scale these. Using both these **WIDTH** parameters will lead to a multiplication of the two widths for the RF parameters.

### Simple Logfile Definition Example

This example saves all I-V data in file, *myfile.log*.

```
LOG OUTF=myfile.log
```

Results should be plotted using **TONYPLOT**.

### RF Analysis Example

To generate s-parameters, assume the input is gate/source and the output is drain/source. A width of 100 microns is also defined along with 100ohm resistance on the input. For example:

```
LOG OUTF=myparams.log S.PARAM INPORT=gate OUTPORT=drain \  
IN2PORT=source OUT2PORT=source WIDTH=100 RIN=100
```

### Transient or AC Logfile Example

The contents of LOG files varies for different types of simulations (e.g., DC, transient, AC). The content is set by the first **SOLVE** statement after the **LOG** statement. Therefore, the following syntax is required.

```
SOLVE VDRAIN=0.5  
  
LOG OUTF=myfile.log  
  
SOLVE VDRAIN=3.0 RAMPTIME=1e-9 DT=1e-11 TSTOP=1e-7
```

Correct transient parameters would have not been stored, if the **LOG** statement had been placed before the first **SOLVE** statement, which is DC.



## 18.23: LX.MESH, LY.MESH

L<n>.MESH specifies the location of grid lines along the <n>-axis in a rectangular mesh used in LASER simulation. The syntax is equivalent for x and y directions.

### Syntax

```
LX.MESH NODE=<n> LOCATION=<n>
LX.MESH SPACING=<n> LOCATION=<n>
LY.MESH NODE=<n> LOCATION=<n>
LY.MESH SPACING=<n> LOCATION=<n>
```

| Parameter | Type    | Default | Units |
|-----------|---------|---------|-------|
| LOCATION  | Real    |         | μm    |
| NODE      | Integer |         |       |
| SPACING   | Real    |         | μm    |

### Description

**NODE** specifies the mesh line index. These mesh lines are assigned consecutively.

**LOCATION** specifies the location of the grid line.

**SPACING** specifies the mesh spacing at the mesh locations specified by the LOCATION parameter. If the SPACING parameter is specified, then the NODE parameter should not be specified.

### LASER Mesh Example

This syntax defines a mesh of 33x33 covering the area bounded by (0.3,0.0) to (2.4,1.0).

```
LX.M n=1 l=0.3
LX.M n=33 l=2.4
LY.M n=1 l=0.0
LY.M n=33 l=1.0
```

---

**Note:** The mesh defined in these statements for the Laser Helmholtz Solver is entirely separate from the electrical device simulation mesh defined on the MESH statement.

---

### Setting Locally Fine Grids Example

This example shows how to space grid lines closely around a topological feature such as a junction at  $y=0.85$  microns.

```
LY.MESH LOC=0.0 SPAC=0.2
LY.MESH LOC=0.85 SPAC=0.01
LY.MESH LOC=2 SPAC=0.35
```

## 18.24: MATERIAL

MATERIAL associates physical parameters with materials in the mesh. The parameter default values for standard semiconductors are shown in Appendix B: “Material Systems”.

### Syntax

```
MATERIAL <localization> <material_definition>
```

| Parameter      | Type | Default        | Units   |
|----------------|------|----------------|---|
| A.PASSLER      | Real | 3.18E-4        | eV/K  |
| A1             | Real | 0.0            |   |
| A2             | Real | 0.0            |   |
| A3             | Real | 0.0            |   |
| A4             | Real | 0.0            |   |
| A5             | Real | 0.0            |   |
| A6             | Real | 0.0            |   |
| ABSORPTION.SAT | Real | 1.0E7          |   |
| AC             | Real | 0.0            | eV  |
| AFFINITY       | Real | see Appendix B | eV  |
| ALATTICE       | Real | 0.0            | Å   |
| ALIGN          | Real | use AFFINITY   |   |
| ALPHAA         | Real | 0.0            |   |
| ALPHAR         | Real | 4.0            |   |
| ARICHN         | Real | see Appendix B | A/cm <sup>2</sup> /K <sup>2</sup>                   |
| ARICHP         | Real | see Appendix B | A/cm <sup>2</sup> /K <sup>2</sup>                   |
| ASTR           | Real | 0.0            |   |
| ASYMMETRY      | Real | 0.5            |   |
| AUGN           | Real | see Appendix B | cm <sup>6</sup> /s                                  |
| AUGP           | Real | see Appendix B | cm <sup>6</sup> /s                                  |
| AUGKN          | Num  | 0.0            | cm <sup>3</sup>                                     |
| AUGKP          | Num  | 0.0            | cm <sup>3</sup>                                     |
| AV             | Real | 0.0            | eV  |
| BBB            | Real | 0.0            | eV  |
| BB.A           | Real | 4.0E14         | eV <sup>-2</sup> *s <sup>-1</sup> *cm <sup>-1</sup> |

| Parameter  | Type      | Default              | Units                                |
|------------|-----------|----------------------|--------------------------------------|
| BB.B       | Real      | 1.97E7               | V/cm                                 |
| BB.GAMMA   | Real      | 2.5                  |                                      |
| BGN.C      | Real      | 0.5                  |                                      |
| BGN.N      | Real      | $1.0 \times 10^{17}$ | $\text{cm}^{-3}$                     |
| BGN.E      | Real      | $9.0 \times 10^{-3}$ | V                                    |
| BQP.NGAMMA | Real      | 1.2                  |                                      |
| BQP.NALPHA | Real      | 0.5                  |                                      |
| BQP.PGAMMA | Real      | 1.0                  |                                      |
| BQP.PALPHA | Real      | 0.5                  |                                      |
| BSTR       | Real      | 0.0                  |                                      |
| C11        | Real      | 0.0                  | GPa                                  |
| C12        | Real      | 0.0                  | GPa                                  |
| C13        | Real      | 0.0                  | GPa                                  |
| C33        | Real      | 0.0                  | GPa                                  |
| COPT       | Real      | 0.0                  | $\text{cm}^3/\text{s}$               |
| CSTR       | Real      | 0.0                  |                                      |
| D1         | Real      | 0.0                  | eV                                   |
| D2         | Real      | 0.0                  | eV                                   |
| D3         | Real      | 0.0                  | eV                                   |
| D4         | Real      | 0.0                  | eV                                   |
| DEGENERACY | Integer   | 2                    |                                      |
| DELTA1     | Real      | 0.0                  | eV                                   |
| DELTA2     | Real      | 0.0                  | eV                                   |
| DELTA3     | Real      | 0.0                  | eV                                   |
| DEVICE     | Character |                      |                                      |
| DGN.GAMMA  | Real      | 3.6                  |                                      |
| DGP.GAMMA  | Real      | 3.6                  |                                      |
| DINDEXDT   | Real      | 0.0                  | 1/K                                  |
| DRHODT     | Real      | 0.0                  | $\mu\Omega \cdot \text{cm}/\text{k}$ |
| DSTR       | Real      | 0.0                  |                                      |
| E31        | Real      | 0.0                  | C/m2                                 |

| Parameter       | Type      | Default        | Units            |
|-----------------|-----------|----------------|------------------|
| E33             | Real      | 0.0            | C/m <sup>2</sup> |
| EAB             | Real      | 0.045          | eV               |
| EDB             | Real      | 0.044          | eV               |
| EG300           | Real      | see Appendix B | eV               |
| EGALPHA         | Real      | see Appendix B | eV               |
| EGBETA          | Real      | see Appendix B | K                |
| EMISSION.FACTOR | Real      | 27.1728E-5     |                  |
| ESTR            | Real      | 0.0            |                  |
| ETRAP           | Real      | 0.0            | eV               |
| EPSINF          | Real      |                | eV/K             |
| F.ALPHAA        | Character |                |                  |
| F.BANDCOMP      | Character |                |                  |
| F.BGN           | Character |                |                  |
| F.CBDOSFN       | Character |                |                  |
| F.CONMUN        | Character |                |                  |
| F.CONMUP        | Character |                |                  |
| F.COPT          | Character |                |                  |
| F.EPSILON       | Character |                |                  |
| F.ENMUN         | Character |                |                  |
| F.ENMUP         | Character |                |                  |
| F.FERRO         | Character |                |                  |
| F.GAUN          | Character |                |                  |
| F.GAUP          | Character |                |                  |
| F.INDEX         | Character |                |                  |
| F.MNSNDIFF      | Character |                |                  |
| F.MNSPDIFF      | Character |                |                  |
| F.MNSNFLICKER   | Character |                |                  |
| F.MNSPFLICKER   | Character |                |                  |
| F.MUNSAT        | Character |                |                  |
| F.MUPSAT        | Character |                |                  |
| F.RECOMB        | Character |                |                  |
| F.TAUN          | Character |                |                  |

| Parameter  | Type      | Default               | Units               |
|------------|-----------|-----------------------|---------------------|
| F.TAUP     | Character |                       |                     |
| F.TAURN    | Character |                       |                     |
| F.TAURP    | Character |                       |                     |
| F.TCAP     | Character |                       |                     |
| F.TCOND    | Character |                       |                     |
| F.VBDOSFN  | Character |                       |                     |
| F.VSATN    | Character |                       |                     |
| F.VSATP    | Character |                       |                     |
| FCN        | Real      | $3.0 \times 10^{-18}$ | $\text{cm}^{-2}$    |
| FCP        | Real      | $7.0 \times 10^{-18}$ | $\text{cm}^{-2}$    |
| FERRO.EC   | Real      | 0.0                   | V/cm                |
| FERRO.EPSF | Real      | 1.0                   |                     |
| FERRO.PS   | Real      | 0.0                   | C/sqcm              |
| FERRO.PR   | Real      | 0.0                   | C/sqcm              |
| FSTR       | Real      | 0.0                   |                     |
| GAIN.SAT   | Real      | 1.0E7                 |                     |
| GAIN0      | Real      | 2000.0                | $\text{cm}^{-1}$    |
| GAIN00     | Real      | -200.0                | $\text{cm}^{-1}$    |
| GAIN1N     | Real      | 0                     | $\text{cm}^2$       |
| GAIN1P     | Real      | 0                     | $\text{cm}^2$       |
| GAIN1MIN   | Real      | $3.0 \times 10^{-16}$ | $\text{cm}^2$       |
| GAIN2NP    | Real      | 0                     | $\text{cm}^5$       |
| GAMMA      | Real      |                       |                     |
| GCB        | Real      | 2.0                   |                     |
| GN1        | Real      | $3.0 \times 10^{-16}$ | $\text{cm}^{-2}$    |
| GN2        | Real      | $4.0 \times 10^{-15}$ | $\text{cm}^{-2}$    |
| G.SURF     | Real      | 1.0                   | $\text{cm}^2$       |
| GVB        | Real      | 4.0                   |                     |
| HC.A       | Real      | See Appendix B        | J/K $\text{cm}^3$   |
| HC.B       | Real      | See Appendix B        | J/K $^2\text{cm}^3$ |

| Parameter  | Type      | Default                 | Units              |
|------------|-----------|-------------------------|--------------------|
| HC.C       | Real      | See Appendix B          | J/Kcm <sup>3</sup> |
| HC.D       | Real      | See Appendix B          | JKcm <sup>3</sup>  |
| HOOGEN     | Real      | 0.0                     |                    |
| HOOGEP     | Real      | 0.0                     |                    |
| IMAG.INDEX | Real      | See Appendix B          |                    |
| INDEX.FILE | Character |                         |                    |
| KSRHTN     | Real      | $2.5 \times 10^{-3}$    | s                  |
| KSRHTP     | Real      | $2.5 \times 10^{-3}$    | s                  |
| KSRHCN     | Real      | $3.0 \times 10^{-13}$   | cm <sup>3</sup>    |
| KSRHCP     | Real      | $11.76 \times 10^{-13}$ | cm <sup>3</sup>    |
| KSRHGN     | Real      | 1.77                    |                    |
| KSRHGP     | Real      | 0.57                    |                    |
| KAUGCEN    | Real      | $1.83 \times 10^{-31}$  | cm <sup>6</sup> /s |
| KAUGCP     | Real      | $2.78 \times 10^{-31}$  | cm <sup>6</sup> /s |
| KAUGDN     | Real      | 1.18                    |                    |
| KAUGDP     | Real      | 0.72                    |                    |
| LT.TAUN    | Real      | 0.0                     |                    |
| LT.TAUP    | Real      | 0.0                     |                    |
| LUTT1      | Real      | 0.0                     |                    |
| LUTT2      | Real      | 0.0                     |                    |
| LUTT3      | Real      | 0.0                     |                    |
| M.DSN      | Real      | See Appendix B          |                    |
| M.DSP      | Real      | See Appendix B          |                    |
| M.VTHN     | Real      |                         |                    |
| M.VTHP     | Real      |                         |                    |
| MATERIAL   | Character |                         |                    |
| MC         | Real      | 0.0                     |                    |
| MHH        | Real      | 0.49                    |                    |
| MINIMA     | Real      | 6                       |                    |
| ML         | Real      | 0.916                   |                    |
| MLH        | Real      | 0.16                    |                    |

| Parameter    | Type      | Default               | Units            |
|--------------|-----------|-----------------------|------------------|
| MSO          | Real      | 0.23                  |                  |
| MSTAR        | Real      | 0.0                   |                  |
| MTT          | Real      | 0.0                   |                  |
| MT1          | Real      | 0.191                 |                  |
| MT2          | Real      | 0.191                 |                  |
| MUN          | Real      | See Appendix B        |                  |
| MUP          | Real      | See Appendix B        |                  |
| MV           | Real      | 0.0                   |                  |
| MZZ          | Real      | 0.0                   |                  |
| NAME         | Character |                       |                  |
| NC300        | Real      | See Appendix B        | cm <sup>-3</sup> |
| NSRHN        | Real      | See Appendix B        | cm <sup>-3</sup> |
| NSRHP        | Real      | See Appendix B        | cm <sup>-3</sup> |
| NTRANSPARENT | Real      | 2.0×10 <sup>18</sup>  | cm <sup>-3</sup> |
| NUE . EXTR   | Real      |                       |                  |
| NUH . EXTR   | Real      |                       |                  |
| NV300        | Real      | See Appendix B        | cm <sup>-3</sup> |
| OXCH . ONLY  | Logical   | False                 |                  |
| P . PASSLER  | Real      | 2.33                  |                  |
| PERMITTIVITY | Real      | See Appendix B        | F/cm             |
| POWER        | Real      |                       |                  |
| PSP          | Real      | 0.0                   | C/m2             |
| REAL . INDEX | Real      | See Appendix B        |                  |
| REGION       |           | All regions           |                  |
| RESISTIVITY  | Real      |                       | μΩ·cm            |
| SEMICONDUC   | Logical   | False                 |                  |
| STABLE       | Integer   |                       |                  |
| T . PASSLER  | Real      | 406.0                 |                  |
| TAUMOB . EL  | Real      | 0.4×10 <sup>-12</sup> | s                |
| TAUMOB . HO  | Real      | 0.4×10 <sup>-12</sup> | s                |
| TAUN0        | Real      | See Appendix B        | s                |

| Parameter    | Type      | Default               | Units  |
|--------------|-----------|-----------------------|--------|
| TAUP0        | Real      | See Appendix B        | s      |
| TAUREL.EL    | Real      | $0.4 \times 10^{-12}$ | s      |
| TAUREL.HO    | Real      | $0.4 \times 10^{-12}$ | s      |
| TC.A         | Real      | See Appendix B        | W/cm·K |
| TC.B         | Real      | See Appendix B        | W/cm·K |
| TC.C         | Real      | See Appendix B        | W/cm·K |
| TC.C0        | Real      |                       | W/cm·K |
| TC.NPOW      | Real      |                       |        |
| TC.E         | Real      |                       |        |
| TC.D         | Real      |                       |        |
| TCON.CONST   | Logical   |                       |        |
| TCON.POWER   | Logical   |                       |        |
| TCON.POLYNOM | Logical   |                       |        |
| TCON.RECIPRO | Logical   |                       |        |
| TE.MODES     | Logical   | False                 |        |
| TMUN         | Real      |                       |        |
| TMUP         | Real      |                       |        |
| TRE.T1       | Real      |                       | s      |
| TRE.T2       | Real      |                       | s      |
| TRE.T3       | Real      |                       | s      |
| TRE.W1       | Real      |                       | eV     |
| TRE.W2       | Real      |                       | eV     |
| TRE.W3       | Real      |                       | eV     |
| TRH.T1       | Real      |                       | s      |
| TRH.T2       | Real      |                       | s      |
| TRH.T3       | Real      |                       | s      |
| TRH.W1       | Real      |                       | eV     |
| TRH.W2       | Real      |                       | eV     |
| TRH.W3       | Real      |                       | eV     |
| USER.DEFAULT | Character |                       |        |
| USER.GROUP   | Character | SEMICONDUCTOR         |        |



| Parameter   | Type | Default | Units |
|-------------|------|---------|-------|
| VSAT        | Real |         | cm/s  |
| VSATN       | Real |         | cm/s  |
| VSATP       | Real |         | cm/s  |
| WELL.DELTA  | Real | 0.341   | eV    |
| WELL.EPS    | Real | 0       | eV    |
| WELL.GAMMA0 | Real | 2E-3    | eV    |
| WELL.TAUIN  | Real | 3.3E-13 | s     |

## Description

The MATERIAL statement is used set basic material parameters related to band structure and parameters for certain mobility, recombination or carrier statistics models. Parameters for temperature dependence are noted in a separate section below.

## Localization of Material Parameters

**DEVICE** specifies which device the MATERIAL statement should apply to in MIXEDMODE simulation.

**MATERIAL** specifies which material from the table in Appendix B: “Material Systems” that the MATERIAL statement should apply. If a material is specified, then all regions defined as being composed of that material will be affected.

**NAME** specifies which region the MATERIAL statement should apply. Note that the name must match the name specified in the NAME parameter of the REGION statement.

**REGION** specifies the region number to which these parameters apply. If there is more than one semiconductor region, specification of different parameters for each region is allowed. If REGION is not specified, all regions in the structure are changed.

## Band Structure Parameters

**AFFINITY** specifies the electron affinity.

**ALIGN** specifies the fraction of the bandgap difference that is applied to the conduction band edge, relative to the minimum bandgap material in the device. Note that specifying this parameter overrides any electron affinity specification. See the Chapter 5: “Blaze: Compound Material 2D Simulator”, Section 5.1.2: “Alignment” for information on setting the band alignment.

**ARICHN** specifies the effective Richardson constant for electrons.

**ARICHP** specifies the effective Richardson constant for holes.

**EG300** specifies energy gap at 300K (see Chapter 3: “Physics”, Equation 3-38). All semiconductor materials in ATLAS must have a defined EG300.

**F.BANDCOMP** specifies the name of a file containing a C-INTERPRETER function that defines temperature and composition dependent band parameter models.

**F.CBDOSFN** specifies the C-Interpreter file for the Conduction band effective density of states as a function of Lattice/Electron temperature. This function is called `cbdofn`.

**F.TCAP** specifies the name of a file containing a C-INTERPRETER function that defines the lattice thermal capacity as a function of the lattice temperature, position, doping and fraction composition.

**F.TCOND** specifies the name of a file containing a C-INTERPRETER function that defines the lattice thermal conductivity as a function of the lattice temperature, position, doping and fraction composition.

**F.EPSILON** specifies the name of a file containing a C-INTERPRETER function that defines temperature and composition dependent static dielectric constant models.

**F.FERRO** specifies the name of a file containing a C-INTERPRETER function that defines dielectric permittivity as a function of electric field and position (x,y). You need a license to use this parameter.

**F.VBDOFSN** specifies the C-Interpreter file for the Valence band effective density of states as a function of Lattice/Hole temperature. This function is called `vbdosfn`.

**M.DSN** specifies the electron density of states effective mass. When specified, it is in Equation 3-31 in Chapter 3: "Physics" to calculate electron density of states.

**M.DSP** specifies the hole density of states effective mass. When specified it is in Equation 3-32 in Chapter 3: "Physics" to calculate hole density of states.

**M.VTHN** specifies the electron effective mass for calculation of thermal velocity in the thermionic heterojunction model (see Chapter 5: "Blaze: Compound Material 2D Simulator", Equation 5-45).

**M.VTHP** specifies the hole effective mass for calculation of thermal velocity in the thermionic heterojunction model (see Chapter 5: "Blaze: Compound Material 2D Simulator", Equation 5-46).

**NC300** specifies the conduction band density at 300K. (see Chapter 3: "Physics", Equation 3-31).

**NV300** specifies valence band density at 300K (see Chapter 3: "Physics", Equation 3-32).

**PERMITTIVITY** specifies dielectric permittivity of the material. All materials in an ATLAS structure must have a defined permittivity.

## BQP Parameters

**BQP.NGAMMA** and **BQP.PGAMMA** parameters allow you to set the  $\gamma$  parameter of the BQP model for electrons and holes respectively.

**BQP.NALPHA** and **BQP.PALPHA** parameters allow you to set the  $\alpha$  parameter of the BQP model for electrons and holes respectively.

## Mobility Model Parameters

**F.CONMUN** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature, composition and doping dependent electron mobility models.

**F.CONMUP** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature, composition and doping dependent hole mobility models.

**F.ENMUN** specifies a C-Interpreter file for the electron mobility as a function of Electron Temperature and perpendicular field as well as other choice variables. The function itself is named `endepmun` and only applies to ATLAS2D.

**F.ENMUP** specifies a C-Interpreter file for the hole mobility as a function of Hole Temperature and perpendicular field as well as other choice variables. The function itself is named `endepmup` and only applies to ATLAS2D.

**F.MUNSAT** specifies the name of a file containing a C-INTERPRETER function for the specification of parallel field dependent electron mobility model for velocity saturation.

**F.MUPSAT** specifies the name of a file containing a C-INTERPRETER function for the specification of parallel field dependent hole mobility model for velocity saturation.

**F.VSATN** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature and composition dependent electron saturation velocity models.

**F.VSATP** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature and composition dependent hole saturation velocity models.

**GSURF** specifies a factor by which mobility is reduced at the semiconductor surface. This is a simple but not accurate alternative to the transverse field dependent or surface mobility models set on the MODELS statement.

**MUN** specifies low-field electron mobility. This parameter is only used if no concentration dependent mobility model is specified.

**MUP** specifies low-field hole mobility. This parameter is only used if no concentration dependent mobility model is specified.

**VSATURATION** specifies the saturation velocity for the electric field dependent mobility.

**VSATN** specifies the saturation velocity for electrons.

**VSATP** specifies the saturation velocity for holes.

### Recombination Model Parameters

**AUGN** specifies the Auger coefficient,  $cn$  (see Chapter 3: "Physics", Equation 3-253).

**AUGP** Specifies the Auger coefficient,  $cp$  (see Chapter 3: "Physics", Equation 3-253).

**AUGKN** parameter of the narrow band-gap electron Auger recombination coefficient model.

**AUGKP** parameter of the narrow band-gap electron Auger recombination coefficient model.

**BB.A**, **BB.B** and **BB.GAMMA** specify the band-to-band tunneling parameters (see Chapter 3: "Physics", Equation 3-299).

**COPT** specifies the optical recombination rate for the material. This parameter has no meaning unless MODELS OPTR has been specified (see Chapter 3: "Physics", Equation 3-245).

**ETRAP** specifies the trap energy for SRH recombination

**F.COPT** specifies the name of a file containing a C-INTERPRETER function for the specification of composition and temperature dependence of the radiative recombination rate.

**F.GAUN** specifies the name of a file containing a C-INTERPRETER function for the specification of composition and temperature dependence of the electron Auger coefficient.

**F.GAUP** specifies the name of a file containing a C-INTERPRETER function for the specification of composition and temperature dependence of the hole Auger coefficient.

**F.RECOMB** specifies the name of a file containing a C-Interpreter function for the specification of temperature, composition, electron and hole concentration dependent recombination rate models.

**F.TAUN** specifies the name of a file containing a C-INTERPRETER function for the specification of position dependent electron lifetime models.

**F.TAUP** specifies the name of a file containing a C-INTERPRETER function for the specification of position dependent hole lifetime models.

**F.TAURN** specifies the name of a file containing a C-INTERPRETER function specifying the electron relaxation time as a function of electron energy.

**F.TAURP** specifies the name of a file containing a C-INTERPRETER function specifying the hole relaxation time as a function of hole energy.

## Klaassen Model parameters

**KSRHTN** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KSRHTP** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KSRHCN** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KSRHCP** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KSRHGN** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KSRHGP** coefficient for Klaassen's concentration and temperature dependent SRH lifetime model.

**KAUGCEN** coefficient for Klaassen's concentration dependent Auger model.

**KAUGCP** coefficient for Klaassen's concentration dependent Auger model.

**KAUGDN** coefficient for Klaassen's concentration dependent Auger model.

**KAUGDP** coefficient for Klaassen's concentration dependent Auger model.

**NSRHN** specifies the SRH concentration parameter for electrons (see Chapter 3: "Physics", Equation 3-242).

**NSRHP** specifies the SRH concentration parameter for holes (see Chapter 3: "Physics", Equation 3-243).

**TAUN0** specifies SRH lifetime for electrons (see Chapter 3: "Physics", Equation 3-242).

**TAUP0** specifies SRH lifetime for holes (see Chapter 3: "Physics", Equation 3-243).

See also Chapter 3: "Physics", Equations 3-244 and 3-245 and Equations 3-254 and 3-256 for more information about Klaassen models.

## Carrier Statistics Model Parameters

**ASYMMETRY** specifies the relative degree where band gap narrowing applies to the conduction band versus the valence band. The value of the **ASYMMETRY** parameter is multiplied by the total change in band gap due to band gap narrowing and that product is applied to the conduction band edge. For example, if the **ASYMMETRY** parameter has a value of 1.0, then the change in band gap due to band gap narrowing is applied only to the conduction band edge and the valence band edge remains unaffected.

**BGN.E**, **BGN.N** and **BGN.C** specify the parameters of the band gap narrowing model given in Chapter 3: "Physics", Equation 3-40.

**EAB** specifies acceptor energy level (see Chapter 3: "Physics", Equation 3-48).

**EDB** specifies donor energy level (see Chapter 3: "Physics", Equation 3-47).

**F.BGN** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature, composition and doping dependent bandgap narrowing models.

**GCB** specifies the conduction-band degeneracy factor (see Chapter 3: "Physics", Equation 3-47).

**GVB** specifies the valence-band degeneracy factor (see Chapter 3: "Physics", Equation 3-48).

## Energy Balance Parameters

**TAUMOB.EL** specifies the relaxation time for electrons in the temperature dependent mobility model (see Chapter 3: "Physics", Equation 3-119).

**TAUMOB.HO** specifies the relaxation time for holes in the temperature dependent mobility model (Chapter 3: "Physics", Equation 3-120).

**TAUREL.EL** specifies the relaxation time for electrons in the energy balance model (see Chapter 3: "Physics", Equation 3-113).

**TAUREL.HO** specifies the relaxation time for holes in the energy balance model (see Chapter 3: “Physics”, Equation 3-114).

**TRE.T1**, **TRE.T2**, **TRE.T3**, **TRE.W1**, **TRE.W2**, **TRE.W3**, **TRH.T1**, **TRH.T2**, **TRH.T3**, **TRH.W1**, **TRH.W2**, and **TRH.W3** are used in the temperature dependent energy relaxation time model based on table data from Laux-Fischetti Monte-Carlo simulation (see Chapter 3: “Physics”, Table 3-3-9).

### Lattice Temperature Dependence Parameters

**A.PASSLER** specifies a parameter of the Passler temperature dependent bandgap model given in Chapter 3: “Physics”, Equation 3-44.

**EGALPHA** specifies the alpha coefficient for temperature dependence of bandgap (see Chapter 3: “Physics”, Equation 3-38).

**EGBETA** specifies the beta coefficient for temperature dependence of bandgap (see Chapter 3: “Physics”, Equation 3-38).

**HC.A**, **HC.B**, **HC.C**, and **HC.D** specify the values of the four coefficient of the heat capacity equation (see Chapter 7: “Giga: Self-Heating Simulator”, Equation 7-6).

**LT.TAUN** specifies the temperature dependence for electron lifetimes (see Chapter 7: “Giga: Self-Heating Simulator”, Equation 7-19).

**LT.TAUP** specifies the temperature dependence for hole lifetimes (see Chapter 7: “Giga: Self-Heating Simulator”, Equation 7-20).

**P.PASSLER** specifies a parameter of the Passler temperature dependent bandgap model given in Chapter 33: “Physics”, Equation 3-44.

**POWER** specifies the value of thermal power generated in a power source associated with a region in THERMAL3D (see Chapter 13: “Thermal 3D: Thermal Packaging Simulator”).

**T.PASSLER** specifies a parameter of the Passler temperature dependent bandgap model given in Chapter 33: “Physics”, Equation 3-44.

**TC.A**, **TC.B**, and **TC.C** specify the three thermal conductivity coefficients (see Chapter 7: “Giga: Self-Heating Simulator”, Equation 7-4).

**TC.C0** specifies the equilibrium value of thermal conductivity,  $k(T_0)$ , in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”, Equation 16-2. The synonym for this parameter is **TC.CONST**.

**TC.D** specifies the value of the parameter D in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”, Equation 16-5.

**TC.E** specifies the value of the parameter E in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”, Equation 16-5.

**TCON.CONST** specifies that thermal conductivity should be modeled as constant with respect to temperature. The value of the thermal conductivity is given by the value of the **TC.C0** parameter.

**TCON.POWER** specifies that the temperature dependence of thermal conductivity should be modeled using Equation 16-3 in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”.

**TCON.POLY** specifies that the temperature dependence of thermal conductivity should be modeled using equation Equation 16-16-4 in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”.

**TCON.RECIP** specifies that the temperature dependence of thermal conductivity should be modeled using equation Equation 16-16-5 in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”.

**TC.NPOW** specifies the value of the coefficient of temperature dependence of thermal conductivity,  $n$ , in equation Equation 16-16-3 in Chapter 16: “Thermal 3D: Thermal Packaging Simulator”.

**TMUN** and **TMUP** specify the lattice temperature coefficients for the temperature dependence of electron lattice mobility, and of hole lattice mobility respectively.

## Oxide Material Parameters

**SEMICONDUCT** specifies that an oxide region is to be treated as a semiconductor.

**OXCH.ONLY** specifies that electron and hole concentrations are omitted from Poisson's Equation in oxides.

## Photogeneration Parameters

**F.INDEX** specifies the name of a file containing a C-INTERPRETER function for the specification of wavelength dependent complex index of refraction models.

**IMAG.INDEX** specifies the imaginary portion of the refractive index of the semiconductor (see Chapter 10: "Luminous: Optoelectronic Simulator", Equation 10-10-23). Wavelength dependent defaults exist for certain materials as documented in Appendix B: "Material Systems".

**INDEX.FILE** specifies the filename from which refractive indices for a material are read. This parameter is useful to load wavelength dependent refractive indices for use with both mono and multi-spectral light sources. The format of this file is:

```
<n>
wavelength(1) real index(1) imaginary index(1)
wavelength(2) real index(2) imaginary index(2)
...
wavelength(n) real index(n) imaginary index(n)
```

Where n is the number of lines to be read.

---

**Note:** The index file must be ordered by increasing wavelength.

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**REAL.INDEX** specifies the real portion of the refractive index of the semiconductor. Wavelength dependent defaults exist for certain materials as documented in Appendix B: "Material Systems".

## LASER Parameters

**ABSORPTION.SAT** specifies the absorption saturation intensity used in the non-linear absorption loss model given in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-16.

**ALPHAA** specifies the bulk absorption coefficient in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-2.

**ALPHAR** specifies the line width broadening factor in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-2.

**EMISSION.FACTOR** specifies a scale factor accounting the proportion of light directionally coupled into the lasing mode.

**EPSINF** specifies the high frequency relative dielectric permittivity ( $\epsilon_\infty$ ) (see Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-2). If this parameter is not specified, it will be set equal to the static dielectric permittivity of the material.

**F.ALPHAA** specifies the name of a file containing a C-INTERPRETER function for the bulk absorption coefficient.

**FCN** is the free-carrier loss model parameter in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-3.

**FCP** is the free-carrier loss model parameter in Chapter 8: "Laser: Edge Emitting Simulator", Equation 8-3.

**GAIN.SAT** specifies the non-linear gain saturation factor used in Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-14.

**GAIN0** specifies the parameter in Chapter 33: “Physics”, Sections 3.9.2: “The Default Radiative Recombination Model” and 3.9.3: “The Standard Gain Model”.

**GAIN00** specifies the parameter in Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”.

**GAIN1N** specifies the parameter in Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”.

**GAIN1P** specifies the parameter in Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”.

**GAIN1MIN** specifies the parameter in Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”.

**GAIN2NP** specifies the parameter in Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”.

**GAMMA** specifies the parameter in Chapter 33: “Physics”, Sections 3.9.2: “The Default Radiative Recombination Model” and 3.9.3: “The Standard Gain Model”. If this parameter is not specified, it will be calculated using Equation 3-354.

**GN1** specifies the parameter in Chapter 33: “Physics”, Section 3.9.5: “Tayamaya's Gain Model”.

**GN2** specifies the parameter in Chapter 33: “Physics”, Section 3.9.5: “Tayamaya's Gain Model”.

**NTRANSPARENT** specifies the parameter in Chapter 33: “Physics”, Section 3.9.5: “Tayamaya's Gain Model”.

## NOISE Parameters

**F.MNSNDIFF** specifies the name of a file containing a C-Interpreter function for the microscopic noise source for electron diffusion noise.

**F.MNSPDIFF** specifies the name of a file containing a C-Interpreter function for the microscopic noise source for hole diffusion noise.

**F.MNSNFLICKER** specifies the name of a file containing a C-Interpreter function for the microscopic noise source for electron flicker noise.

**F.MNSPFlicker** specifies the name of a file containing a C-Interpreter function for the microscopic noise source for hole flicker noise.

**HOOGEN** specifies the Hooge constant for electron flicker noise.

**HOOGEP** specifies the Hooge constant for hole flicker noise.

## Miscellaneous Material Parameters

**A1, A2, A3, A4, A5** and **A6** specify valence band effective mass parameters.

**AC, AV** and **BBB** specify cubic deformation potentials.

**ALATTICE** specifies the in plane lattice constant.

**ASTR, BSTR, CSTR, DSTR, ESTR** and **FSTR** are user-definable parameters of the equations for heavy and light hole masses in Ishikawa's strain model (see Chapter 33: “Physics”, Section 3.9.10: “Ishikawa's Strain Effects Model”).

**C11, C12, C13** and **C33** specify the elastic stiffness coefficients.

**DEGENERACY** specifies the spin degeneracy.

**DELTA1, DELTA2** and **DELTA3** specify the valence band energy splits.

**DGN.GAMMA** and **DGP.GAMMA** specify the electron and hole tuning parameters for density gradient modeling.

**DINDEXDT** specifies the temperature coefficient of the index of refraction.

**DRHODT** specifies the temperature coefficient of conductor resistivity.

**D1, D2, D3, and D4** specify shear deformation potentials.

**E31, E33 and PSP** specify piezo-electric constants.

**LUTT1, LUTT2 and LUTT3** specify the luttinger parameters.

**M.VTHN and M.VTHP** specify the electron and hole effective masses used for calculation of thermal velocity.

**MC** specifies the conduction band effective mass.

**MINIMA** specifies the number of equavilent minima in the conduction band energy.

**MHH** specifies the heavy hole effective mass.

**ML** specifies the conduction band longitudinal effective mass.

**MLH** specifies the light hole effective mass.

**MSO** specifies the split off (crystal lattice) effective mass.

**MSTAR** specifies the conduction band effective mass dispersion.

**MTT** specifies the transverse effective mass (wurtzite).

**MT1 and MT2** specify the transverse effective masses (zincblende).

**MV** specifies the valence band effective mass.

**MZZ** specifies the effective mass along the crystal axis (wurtzite).

**PSP** specifies the spontanteous polarization.

**RESISTIVITY** specifies the resistivity of conductor regions.

**STABLE** specifies the selected strain table for the Ishikawa strain effects model. See Chapter 33: "Physics", Section 3.9.10: "Ishikawa's Strain Effects Model".

**TE.MODES** specifies whether TE or TM modes will be used for calculation of assymetry factors for the LI model (see Chapter 13: "Quantum: Quantum Effect Simulator", Section 13.6: "Multiple Quantum Well Model").

**USER.DEFAULT** specifies which material the user-defined material should use for its default parameters.

**USER.GROUP** specifies the material group for the user-defined material. `USER.GROUP` can be either `SEMICONDUCTOR`, `INSULATOR`, or `CONDUCTOR`.

**WELL.DELTA** specifies the spin orbital splitting energy in a quantum well.

**WELL.EPS** specifies the high frequency permittivity used in calculating gain and radiative recombination in a quantum well.

**WELL.GAMMA0** specifies the Lorentzian gain broadening factor from Chapter 33: "Physics", Section 3.9.9: "Lorentzian Gain Broadening".

**WELL.TAUIN** specifies the Lorentzian gain broadening factor from Chapter 33: "Physics", Section 3.9.9: "Lorentzian Gain Broadening".

## Conductor Parameters

**DRHODT** specifies the temperature coefficient of resistivity in  $\mu\Omega\text{-cm/K}$ .

**RESISTIVITY** specifies the material resisitvity in  $0\Omega\text{cm}$ .



## Material Coefficient Definition Examples

### Numbered region

This example specifies SRH lifetimes and concentration independent low-field mobilities for region number 2. All other parameters use default values and parameters in other regions are unaffected.

```
MATERIAL TAUN0=5.0E-6 TAUP0=5.0E-6 MUN=3000 MUP=500 REGION=2
```

### All regions

This example defines carrier lifetimes and the refractive index for all semiconductor regions.

```
MATERIAL TAUP0=2.E-6 TAUN0=2.E-6 REAL.INDEX=3.7 \  
IMAG.INDEX=1.0E-2
```

### Named Material

This shows the definition of bandgap for all InGaAs regions in the structure:

```
MATERIAL MATERIAL=InGaAs EG300=2.8
```

All materials are divided into three classes: semiconductors, insulators and conductors. See Appendix B: “Material Systems” for more information about the parameters required for each material class.

---

**Note:** You can use the `MODEL PRINT` command to echo back default material parameters or `MATERIAL` parameter settings to the run-time output.

---

## 18.25: MEASURE

MEASURE extracts selected electrical data from the solution.

**Note:** This statement is almost obsolete. Its functions have been replaced by the EXTRACT , OUTPUT , or PROBE statement.

### Syntax

```
MEASURE <dt> [<boundary>] [OUTFILE=<filename>]
```

| Parameter   | Type      | Default        | Units |
|-------------|-----------|----------------|-------|
| CONTACT     | Integer   |                |       |
| E.CRIT      | Real1E-8  |                |       |
| ELECTRON    | Logical   | False          |       |
| HOLE        | Logical   | False          |       |
| IONIZINT    | Logical   | False          |       |
| LRATIO      | Real      | 1.0            |       |
| METAL.CH    | Logical   | False          |       |
| N.CURRENT   | Logical   | False          |       |
| N.LAYER     | Real      | 15             |       |
| N.LINES     | Integer   | 50             |       |
| N.RESIST    | Logical   | False          |       |
| NET.CARR    | Logical   | False          |       |
| NET.CHAR    | Logical   | False          |       |
| OUTFILE     | Character |                |       |
| P.CURRENT   | Logical   | False          |       |
| P.RESIST    | Logical   | False          |       |
| REGIONS     | Integer   | All regions    |       |
| SUBSTR      | Character |                |       |
| U.AUGER     | Logical   | False          |       |
| U.RADIATIVE | Logical   | False          |       |
| U.SRH       | Logical   | False          |       |
| U.TOTAL     | Logical   | False          |       |
| X.MIN       | Real      | Left of device | μm    |

| Parameter | Type | Default          | Units |
|-----------|------|------------------|-------|
| X.MAX     | Real | Right of device  | μm    |
| Y.MIN     | Real | Top of device    | μm    |
| Y.MAX     | Real | Bottom of device | μm    |

## Description

**dt** is used to specify the type of information to be measured.

**boundary** specifies which nodes will be measured.

**OUTFILE** specifies a filename where simulation results and bias information will be written.

## Data Type Parameters

Net carrier concentration, charge concentration, electron concentration, or hole concentration can be integrated over a section of a device. The charge on part of an electrode can be calculated, just like the current through that part. This is useful for capacitance studies in conjunction with the difference mode of the **LOAD** statement. The resistance of a structure cross-section, such as a diffused line, can also be calculated.

**E.CRIT** specifies the critical electric field used to calculate integration integrals.

**ELECTRON** extracts integrated electron concentration.

**HOLE** extracts integrated hole concentration.

**IONIZINT** enable the calculation of ionization integrals. Other integral ionization parameters will be ignored unless **IONIZINT** is specified.

**LRATIO** specifies the ratio between electric field lines used in ionization integral calculation. The value of this parameter should be set from 0.5 to 1.5.

**METAL.CH** extracts integrated charge on a contact.

**N.CURRENT** extracts n-current through an electrode.

**N.LINES** specifies the number of ionization integrals.

**N.RESIST** extracts n-resistance of a cross-section.

**NET.CARR** extracts integrated carrier concentration.

**NET.CHAR** extracts integrated net charge.

**NLAYERS** controls the distance from the contact where electric field lines start.

**P.CURRENT** extracts p-current through an electrode.

**P.RESIST** extracts p-resistance of a cross-section.

**SUBSTR** selects the substrate electrode for electric field lines. You don't need to specify this parameter if a substrate electrode has been defined in the **ELECTRODE** statement.

**U.AUGER** specifies that the integrated Auger recombination rate is to be extracted.

**U.RADIATIVE** specifies that the integrated radiative recombination rate is to be extracted.

**U.SRH** specifies that the integrated SRH recombination rate is to be extracted.

**U.TOTAL** specifies that the integrated total recombination rate is to be extracted.

## Boundary Parameters

Boundary parameters: **X.MIN**, **X.MAX**, **Y.MIN**, and **Y.MAX** define a bounding box. Only nodes falling within this bounding box are included in the integration. The default bounds are the boundaries of the entire device.

**CONTACT** specifies the contact number. For electrode quantities (current and metal charge), a contact must be selected. Only nodes falling within the bounds and belonging to the contact are included in the integration. When **IONIZINT** is specified, this is the electrode used to start electric field lines.

**REGIONS** specifies a particular set of regions. If **REGIONS** is specified, only nodes within the specified bounds that are part of a particular set of regions will be integrated.

**X.MAX** specifies the x coordinate of the right edge of the bounding box.

**X.MIN** specifies the x coordinate of the left edge of the bounding box.

**Y.MAX** specifies the y coordinate of the top of the bounding box.

**Y.MIN** specifies the y coordinate of the bottom of the bounding box.

## Resistance Example

This example extracts the resistance of a p-type line diffused into a lightly doped n-substrate. Since the p-conductivity of the substrate is negligible, the integration bounds can include the whole device.

```
MEASURE P.RESIST
```

## Gate Charge Example

In this example, the charge on the lower surface of a gate electrode is integrated. There is 0.05  $\mu\text{m}$  of gate oxide on the surface, which is located at  $y=0$ .

```
MEASURE METAL.CH CONT=1 X.MIN=-2.0 X.MAX=2.0 \
Y.MAX=-0.0499 Y.MIN=-0.0501
```

## Ionization Integral Example

This example shows how to extract the maximum ionization integral in the device.

```
MEASURE IONIZINT CONTACT=3 SUSTR=4 N.LINES=200 \
NLAYERS=15 LRATIO=1.1
```

This syntax was the original implementation of ionization integrals in early ATLAS versions. It has been superseded. See Sections 18.40: "SOLVE" and 18.32: "OUTPUT" for the recommended approach to extract ionization integrals.

## 18.26: MESH

MESH generates a mesh or reads a previously generated mesh.

### Syntax

```
MESH <prev>|<new> [<output>]
```

| Parameter   | Type      | Default | Units |
|-------------|-----------|---------|-------|
| ATHENA      | Logical   | False   |       |
| AUTO        | Logical   | False   |       |
| CONDUCTER   | Logical   | False   |       |
| CYLINDRICAL | Logical   | False   |       |
| DIAG.FLIP   | Logical   | True    |       |
| FLIP.Y      | Logical   | False   |       |
| INFILE      | Character |         |       |
| MASTER.IN   | Logical   | True    |       |
| MASTER.OUT  | Logical   | True    |       |
| NX          | Integer   |         |       |
| NY          | Integer   |         |       |
| NZ          | Integer   |         |       |
| OUTFILE     | Character |         |       |
| PISCES.IN   | Logical   | False   |       |
| SCALE.Y     | Integer   | 1       |       |
| SMOOTH.KEY  | Integer   |         |       |
| SPACE.MULT  | Real      | 1.0     |       |
| THREE.D     | Logical   | False   |       |
| WIDTH       | Real      | 1.0     |       |

### Description

**prev** is a set of parameters that allows you to read a previously generated mesh type.

**new** is a set of parameters that allow you to initiate the generation of a rectangular mesh.

**output** is a set of the parameters for saving the mesh.

## Mesh File Parameters

**CONDUCTOR** interprets metal regions loaded in with the **INFILE** parameter as conductors .

**CYLINDRICAL** specifies that the mesh being read in contains cylindrical symmetry. Since this information is not saved in the mesh file, the **CYLINDRICAL** parameter must be specified each time a structure with cylindrical symmetry is loaded.

**FLIP.Y** reverses the sign of the y coordinate.

**INFILE** specifies the name of a previously generated mesh that has been saved to disk.

**MASTER.IN** specifies a filename to read mesh and doping information in the Silvaco Standard Structure File (SSF) Format. This parameter is used to read **ATHENA** or **DEVEDIT** structure files. Typically, these files contain all **REGION**, **ELECTRODE**, and **DOPING** information. Although **ATLAS** allows you to modify the structure using these statements, this parameter is true by default and is the only file format supported by Silvaco.

**PISCES.IN** indicates that the mesh file is in the old **PISCES-II** format. This is not recommended or supported by Silvaco.

**SCALE.Y** specifies a factor by which all x- and y coordinates are multiplied.

**SPACE.MULT** is a scale factor that is applied to all specified grid spacings. This parameter can be used to produce a coarse mesh and thereby reduce the simulation time.

**ATHENA** reads mesh and doping data generated by the **ATHENA PISCES-II** format file. This parameter and file format is obsolete.

## Mesh Parameters

**AUTO** specifies that mesh lines will be generated automatically from **REGION** statements. See Chapter 9: "VCSEL Simulator", Section "Specifying the Mesh" for more information on how to specify mesh lines.

**CYLINDRICAL** specifies that the mesh contains cylindrical symmetry. Since this information is not saved in the mesh file, the **CYLINDRICAL** parameter must be specified each time a grid with cylindrical symmetry is loaded. Structures defined as cylindrical will be rotated 360 degrees about the y-axis. The coordinate, x=0, must be on the leftmost side of the structure.

**DIAG.FLIP** flips the diagonals in a square mesh about the center of the grid. If the parameter is negated, using **^DIAG.FLIP** is specified, all diagonals will be in the same direction.

**NX** specifies the number of nodes in the x direction.

**NY** specifies the number of nodes in the y direction.

**NZ** specifies the number of nodes in the z direction, used in **DEVICE3D** or **BLAZE3D** only.

**RECTANGULAR** initiates the generation of a rectangular mesh.

**THREE.D** starts **ATLAS3D**.

**WIDTH** specifies a scale factor to represent the un-simulated dimension for 2-D simulations. This scale factor is applied to all run time and log file outputs.

## Output Parameters

**OUTFILE** specifies the output filename to which the mesh is written.

**MASTER.OUT** specifies the format of the output file. This parameter is true by default so the output file will conform to the Silvaco Standard Structure File Format and can be plotted in **TONYPLOT**.

**SMOOTH.KEY** specifies a smoothing index. The digits of the index are read in reverse order and interpreted as follows:

- Triangle smoothing. All region boundaries remain fixed.
- Triangle smoothing. Only material boundaries are maintained.
- Node averaging.
- Improved triangle smoothing method. This method uses diagonal flipping to reduce the number of obtuse triangles.
- Triangle smoothing by flipping diagonals according to electric field.

Usually option 1 is sufficient. Option 2 is useful only if a device has several regions of the same material and the border between different regions is unimportant. Option 3 is not recommended when the initial mesh is basically rectangular, such as mesh information usually obtained from SSUPREM4. Option 4 is similar to Option 1 but Option 4 usually creates less obtuse triangles.

### Mesh Definition Example

This example initiates a rectangular mesh and stores the mesh in file, MESH1 .STR.

```
MESH RECTANGULAR NX=40 NY=17 OUTF=MESH1 .STR
```

### ATHENA Interface Example

This syntax reads in a mesh from ATHENA or DEVEDIT:

```
MESH INFILE=NMOS .STR
```

When the **auto-** interface feature is used in DECKBUILD, the program will automatically insert the MESH statement to load the result of previous programs into ATLAS.

---

**Note:** See Chapter 2: "Getting Started with ATLAS", Sections 2.6.1: "Interface From ATHENA" and 2.6.2: "Interface From DevEdit", or the on-line examples for details of the interfaces from ATHENA or DEVEDIT to ATLAS.

---

## 18.27: METHOD

METHOD sets the numerical methods to be used to solve the equations and parameters associated with the these algorithms.

### Syntax

METHOD <gp> <mdp>

| Parameter   | Type    | Default                      | Units            |
|-------------|---------|------------------------------|------------------|
| 2NDORDER    | Logical | True                         |                  |
| ALT.SCHRO   | Logical | False                        |                  |
| ATRAP       | Real    | 0.5                          |                  |
| AUTONR      | Logical | False                        |                  |
| BICGST      | Logical | False                        |                  |
| BLOCK       | Logical | False                        |                  |
| BLOCK.TRAN  | Logical | False                        |                  |
| BQP.ALTEB   | logical | false                        |                  |
| BQP.NOFERMI | logical | false                        |                  |
| BQPX.TOL    | REAL    | 2.5E-7                       |                  |
| BQPR.TOL    | REAL    | 1.0E-26 (2D)<br>1.0E-18 (3D) |                  |
| CARRIERS    | Real    | 2                            |                  |
| C.ITLIMIT   | Integer | 500                          |                  |
| C.STABIL    | Real    | $1.0 \times 10^{-10}$        |                  |
| C.RESID     | Real    | $1.0 \times 10^{-8}$         |                  |
| CLIM.DD     | Real    | $4.5 \times 10^{13}$         | $\text{cm}^{-3}$ |
| CLIM.EB     | Real    | 0                            | $\text{cm}^{-3}$ |
| CLIMIT      | Real    | 10000                        |                  |
| CR.TOL      | Real    | $5.0 \times 10^{-18}$        |                  |
| CUR.PROJ    | Logical | False                        |                  |
| CX.TOLER    | Real    | $1.0 \times 10^{-5}$         |                  |
| DIRECT      | Logical | False                        |                  |
| DG.INIT     | logical | false                        |                  |
| DG.N.INIT   | logical | false                        |                  |
| DG.P.INIT   | logical | false                        |                  |



| Parameter    | Type    | Default               | Units |
|--------------|---------|-----------------------|-------|
| DT.MAX       | Real    | •                     |       |
| DT.MIN       | Real    | $1.0 \times 10^{-25}$ | s     |
| DVLIMIT      | Real    | 0.1                   |       |
| DVMAX        | Real    | 2.5                   | V     |
| EF.TOL       | Real    | $10^{-12}$            |       |
| ELECTRONS    | Logical | True                  |       |
| EXTRAPOLATE  | Logical | False                 |       |
| FIX.QF       | Logical | False                 |       |
| GMRES        | Logical | False                 |       |
| GUM.INIT     | Integer | 15                    |       |
| GUMITS       | Integer | 100                   |       |
| GUMMEL       | Logical | False                 |       |
| HALFIMPLICIT | Logical | False                 |       |
| HCIR.TOL     | Real    | $5.0 \times 10^{-11}$ |       |
| HCIX.TOL     | Real    | $5.0 \times 10^{-4}$  |       |
| HOLES        | Logical | True                  |       |
| ICCG         | Logical | False                 |       |
| IR.TOL       | Real    | $5.0 \times 10^{-15}$ |       |
| ITLIMIT      | Integer | 25                    |       |
| IX.TOL       | Real    | $2.0 \times 10^{-5}$  |       |
| LAS.PROJ     | Logical | False                 |       |
| LU1CRI       | Real    | $3.0 \times 10^{-3}$  |       |
| LU2CRI       | Real    | $3.0 \times 10^{-2}$  |       |
| L2NORM       | Logical | True                  |       |
| MAXTRAPS     | Integer | 4                     |       |
| MAX.TEMP     | Real    | 2000                  | K     |
| MEINR        | Logical | False                 |       |
| MIN.TEMP     | Real    | 120                   | K     |
| NBLOCKIT     | Integer | 15                    |       |
| NEG.CONC     | Logical | False                 |       |
| NEW.EI       | Logical | False                 |       |

| Parameter     | Type    | Default               | Units |
|---------------|---------|-----------------------|-------|
| NEWTON        | Logical | True                  |       |
| NITGUMM       | Integer | 5                     |       |
| NT0           | Integer | 4                     |       |
| NT1           | Integer | 10                    |       |
| NT2           | Integer | 25                    |       |
| NT3           | Integer | 100                   |       |
| NRRCRITER     | Real    | 0.1                   |       |
| NO.POISSON    | Logical | False                 |       |
| PR.TOL        | Real    | $1.0 \times 10^{-26}$ |       |
| PX.TOLER      | Real    | $1.0 \times 10^{-5}$  |       |
| RHSNORM       | Logical | False                 |       |
| RXNORM        | Logical | True                  |       |
| QUASI         | Logical | True                  |       |
| SEMIIMPLICIT  | Logical | False                 |       |
| SINGLEPOISSON | Logical | False                 |       |
| TAUTO         | Logical | True                  |       |
| TCR.TOL       | Real    | 100                   |       |
| TCX.TOL       | Real    |                       |       |
| TLR.TOL       | Real    | 100                   |       |
| TLX.TOL       | Real    |                       |       |
| TMIN.FACT     | Real    | 0.4                   |       |
| TOL.LTEMP     | Real    | 0.001                 |       |
| TOL.RELAX     | Real    | 1                     |       |
| TOL.TIME      | Real    | $5.0 \times 10^{-3}$  |       |
| TRAP          | Logical | True                  |       |
| TSETP.INCR    | Real    | 2.0                   |       |
| V.TOL         | Real    | $1.0 \times 10^{-6}$  |       |
| VSATMOD.INC   | Real    | 0.01                  |       |
| XNORM         | Logical | False                 |       |
| WEAK          | Real    | 200                   |       |

## Description

The `METHOD` statement is used to set the numerical methods for subsequent solutions. All structure and model definitions should precede the `METHOD` statement and all biasing conditions should follow it. Parameters in the `METHOD` statement are used to set the solution technique, specify options for each technique and tolerances for convergence.

## Solution Method Parameters

**ALT.SCHRO** specifies that the alternative Schrodinger solver should be used.

**BLOCK** specifies that the block Newton solution method will be used as a possible solution method in subsequent solve statements until otherwise specified. The Block method only has meaning when either lattice heating or energy balance is included in the simulation. For isothermal drift diffusion simulations, **BLOCK** is equivalent to **NEWTON**.

**BLOCK.TRAN** specifies that the block Newton solution method will be used in subsequent transient solutions.

**BICGST** switches from the default **ILUCGS** iterative solver to the **BICGST** iterative solver for 3-D simulations.

**DIRECT** specifies that a direct linear solver should be used to solve the linear problem during 3-D simulation. By default the **ILUCGS** iterative solver is used for 3-D problems.

**GMRES** switches from the default **LUCGS** iterative solver to the **GMRES** iterative solver for 3-D simulations.

**GUMMEL** specifies the Gummel method will be used as a solution method in subsequent **SOLVE** statements until otherwise specified. If other methods (**BLOCK** or **NEWTON**) are specified in the same `METHOD` statement, each solution method will be applied in succession until convergence is obtained. The order that the solution methods will be applied is **GUMMEL** then **BLOCK** then **NEWTON**. If no solution methods are specified **NEWTON** is applied by default.

**HALFIMPLICIT** specifies that a semi-implicit scheme will be used for transient solutions in 3-D. In most cases this method is significantly less time consuming than the default **TR-BDG** method.

**MEINR** specifies the Meinerzhagens Method, whereby carrier temperature equations will be coupled with the associated carrier continuity equation and used during **GUMMEL** iterations.

**NEWTON** specifies that Newton's method will be used as the solution method in subsequent **SOLVE** statements unless specified otherwise. Certain models and boundary conditions settings require that the Newton's method is used. If no solution methods are specified, **NEWTON** is applied by default.

**NEW.EI** enables an alternative eigenvalue solver that obtains eigenvectors using the reverse iteration method.

---

**Note:** Details on the different solution methods can be found in Chapter 17: "Numerical Techniques".

---

## Equation Solver Parameters

**CARRIERS** specifies the number of carrier continuity equations that will be solved. Valid values are 0, 1 and 2. **CARRIERS=0** implies that only Poisson's Equation will be solved. **CARRIERS=1** implies that only one carrier solution will be obtained. When this is specified, also specify either **HOLES** or **ELECTRONS**. **CARRIERS=2** implies that solutions will be obtained for both electrons and holes.

**ELECTRONS** specifies that only electrons will be simulated for single carrier simulation.

**HOLES** specifies that only holes will be simulated for single carrier simulations.

## Solution Tolerance Parameters

The default convergence criteria used in ATLAS consists of a combination of relative and absolute values. The program will converge if either criterion is met. This is particularly useful when low-carrier concentrations would not converge using just relative criteria.

Current convergence criteria are also used. Terminal currents are monitored at each iteration and overall convergence is allowed if currents converge along with absolute potential error.

**BQPX.TOL** is the convergence criterion for the update vector in the BQP model.

**BQPR.TOL** is the convergence criterion for the Right hand side (residual) in the BQP model.

**CR.TOL** specifies an absolute tolerance for the continuity equation.

**CX.TOL** or **C.TOL** is the relative tolerance for the continuity equation. The **XNORM** parameter uses the **CX.TOL** and **PX.TOL** parameters to calculate convergence criteria.

**EF.TOL** specifies the Schrodinger solver tolerance when **NEW.EI** is specified.

**HCIR.TOL** is the absolute current convergence criteria for energy transport models.

**HCIX.TOL** is the relative current convergence criteria for energy transport models.

**IR.TOL** specifies absolute current convergence criteria.

**IX.TOL** specifies relative current convergence criteria.

**PR.TOL** specifies an absolute tolerance for the Poisson Equation.

**PX.TOL** is the relative tolerance for the potential equation. The **XNORM** parameter uses the **CX.TOL** and **PX.TOL** parameters to calculate convergence criteria.

**RHSNORM** specifies that only absolute errors will be used to determine convergence. If **RHSNORM** is selected Poisson error are measured in  $C/\mu\text{m}$  and the continuity error is measured in  $A/\mu\text{m}$ .

**RXNORM** specifies that both relative and absolute convergence criteria will be used in the solution method. This is the equivalent of specifying both **XNORM** and **RHSNORM**. This is the default and it is not recommended to change this.

**TCR.TOL** specifies the absolute (**RHSNORM**) tolerance for convergence of the carrier temperature equations.

**TCX.TOL** specifies the relative (**XNORM**) tolerance for convergence of the carrier temperature equations.

**TOL.TIME** specifies maximum local truncation error for transient simulations.

**TOL.LTEMP** specifies the temperature convergence tolerance in block iterations using the lattice heat equation.

**TOL.RELAX** specifies a relaxation factor for all six Poisson, continuity, and current convergence parameters (**PX.TOL**, **CX.TOL**, **PR.TOL**, **CR.TOL**, **IX.TOL**, and **IR.TOL**).

**TLR.TOL** specifies the relative (**XNORM**) tolerance for convergence of the lattice temperature equation.

**TLX.TOL** specifies the relative (**XNORM**) tolerance for convergence of the lattice temperature equation.

**WEAK** specifies the multiplication factor for weaker convergence tolerances applied when current convergence is obtained.

**XNORM** specifies that only the relative errors will be used to determine convergence for the drift-diffusion equations. If **XNORM** is used Poisson updates are measured in  $kT/q$ , and carrier updates are measured relative to the local carrier concentration.

---

**Note:** Generally, the solution tolerances should not be changed. Convergence problems should be tackled by improving the mesh or checking the model and method combinations. Chapter 2: “Getting Started with ATLAS” has useful hints.

---

## General Parameters

**ATRAP** specifies the multiplication factor which reduces the electrode bias steps when a solution starts to diverge. This parameter has no effect unless the **TRAP** parameter is specified.

**CLIM.DD** is analogous to **CLIMIT** except it is expressed in a dimensional value representing the minimum carrier concentration that can be resolved.

**CLIM.EB** can be treated as a regularization parameter for the case of very small carrier concentrations for energy balance simulation. It specifies the minimum value of carrier concentration for which the relaxation term in the energy balance equation will still be properly resolved. Carrier temperatures for points where the concentration is much less than **CLIM.EB**, will tend to the lattice temperature.

**CLIMIT** specifies a concentration normalization factor. See Chapter 17: “Numerical Techniques”, the “Carrier Concentrations and **CLIM.DD** (**CLIMIT**)” Section on page 17-8 for a complete description.

**CUR.PROJ** enables the use of projection method for initial guesses with current boundary conditions.

**FIX.QF** fixes the quasi-Fermi potential of each non-solved for carrier to a single value, instead of picking a value based on local bias.

**ITLIMIT** or **GITLIMIT** specifies the maximum number of allowed outer loops (Newton loops or Gummel continuity iterations).

**LAS.PROT** extrapolates that photon rates for the initial guess during bias ramp.

**MAXTRAPS** specifies the number of times the trap procedure will be repeated in case of divergence. The value of **MAXTRAPS** may range from 1 to 10.

**MIN.TEMP** and **MAX.TEMP** are specified to control the absolute range of lattice temperatures allowed during Gummel loop iterations with lattice temperature. These parameters help insure that lattice temperatures converge during the outer loop iterations.

**NBLOCKIT** specifies the maximum number of **BLOCK** iterations. If **METHOD BLOCK NEWTON** is specified, the solver will switch to Newton’s method after **NBLOCKIT** Block-Newton iterations.

**NEG.CONC** flag allows negative carrier concentrations.

**NO.POISSON** flag allows you to omit the solution of the Poisson’s Equation (see Chapter 33: “Physics”, Equation 3-1). This feature doesn’t work with Gummel’s Method (see Chapter 17: “Numerical Techniques”, Section 17.5.2: “Gummel Iteration”).

**TMIN.FACT** specifies the minimum electron or hole temperature allowable during non-linear iteration updates. **TMIN.FACT** is normalized to 300K.

**TRAP** specifies that if a solution process starts to diverge, the electrode bias steps taken from the initial approximation are reduced by the multiplication factor **ATRAP**.

**VSATMOD.INC** specifies that the derivatives of the negative differential mobility (**MODEL FLDMOB EVSATMOD=1**) will not be included into the Jacobian until the norm of Newton update for potential is less than the value specified by **VSATMOD.INC**. This is useful since the negative differential mobility model is highly nonlinear and causes numerical stability problems.

## Gummel Parameters

**DVLIMIT** limits the maximum potential update for a single loop.

**GUM.INIT** specifies the maximum number of Gummel iterations in order to obtain an initial approximation for successive Newton iterations. This parameter is used when METHOD GUMMEL NEWTON is specified

**GUMITS** specifies the maximum number of Gummel iterations.

**LU1CRI**, **LU2CRI** specifies amount of work per Poisson loop. The inner norm is required to either decrease by at least LU1CRI before returning, or reach a factor of LU2CRI below the projected Newton error, whichever is smaller. If the inner norm is exceeds the projected Newton error, the quadratic convergence is lost.

**SINGLEPOISSON** specifies that only a single Poisson iteration is to be performed per Gummel loop. In the default state, the continuity equation is only treated after the Poisson iteration has fully converged. This technique is useful where the carrier concentration and potential are strongly coupled but the initial guess is poor precluding the use of NEWTON.

**NITGUMM**, **NT0**, **NT1**, **NT2**, and **NT3** specify Gummel iteration control parameters described in Chapter 17: "Numerical Techniques", Section 17.5.10: "Detailed Convergence Criteria" Newton Parameters.

**2NDORDER** specifies that second-order discretization will be used when transient simulations are performed.

**AUTONR** implements an automated Newton-Richardson procedure, which attempts to reduce the number of LU decompositions per bias point. We strongly recommend that you use this parameter to increase the speed of NEWTON solutions. Iterations using AUTONR will appear annotated with an A in the run-time output. Often an extra iteration is added when using this parameters since the final iteration of any converged solution cannot be done using AUTONR.

**DT.MAX** specifies the maximum time-step for transient simulation.

**DT.MIN** specifies the minimum time-step for transient simulations.

**DVMAX** sets the maximum allowed potential update per Newton iteration. Large voltage steps are often required when simulating high voltage devices. If any simulation requires voltage steps of 10V or more, set DVMAX to 100,000. Reducing DVMAX may serve to damp oscillations in solutions in some cases leading to more robust behavior. However excessive reduction in DVMAX is not recommended since the maximum voltage step allowed will be limited by  $DVMAX * ITLIMIT$ .

**EXTRAPOLATE** specifies the use of second-order extrapolation to compute initial estimates for successive time-steps for transient simulations.

**L2NORM** specifies the use of L2 error norms rather than infinity norms when calculating time steps for transient simulations.

**NRCRITER** specifies the ratio by which the norm from the previous Newton loop must decrease in order to be able to use the same Jacobian (LU decomposition) for the current Newton loop.

**TAUTO** selects automatic, adaptive timesteps for transient simulations from local truncation error estimates. Automatic time-stepping is the default for second-order discretization, but is not allowed for first-order.

**TSTEP.INCR** specifies the maximum allowable ratio between the time step sizes of successive (increasing) time steps during transient simulation.

**QUASI** specifies a quasistatic approximation for transient simulations. This is useful in simulating transient simulations with long timescales where the device is in equilibrium at each timestep.

## Numerical Method Definition Example

The default numerical method is the equivalent of:

```
METHOD NEWTON CARRIERS=2
```

For more complex problems including those involving floating regions the following is recommended

```
METHOD GUMMEL NEWTON GUM.INIT=5
```

When impact ionization is combined with floating regions as in SOI or guard ring breakdown simulation the above syntax can also be used. Quicker solutions, however, can be obtained using the following SINGLEPOISSON technique:

```
METHOD GUMMEL NEWTON GUM.INIT=5 SINGLE
```

## Quantum Parameters

**BQP.NOFERMI** forces the BQP model to only use its formulation derived using Maxwell Boltzmann statistics. If this is not set, then the BQP formulation used will be the same as the carrier statistics specified for the electrons or holes or both.

**BQP.ALTEB** enables an alternative iteration scheme that can be used when solving the BQP equation and the energy balance equation. This may produce a more robust convergence than for the default scheme. The scheme used with `BQP.ALTEB` set, however, will be slower.

**DG.INIT** enables an algorithm to initialize the Density Gradient method within the `SOLVE INIT` statement. This is not self-consistent with the solution of Poisson's equation, which makes it limited in usefulness. You can specify the carrier type to be initialized using either `DG.N.INIT` or `DG.P.INIT`. `DG.INIT` will enable both `DG.N.INIT` and `DG.P.INIT`.

## TRAP Parameter Example

This example illustrates the trap feature (often used to capture knees of I-V curves for junction breakdown).

The first `SOLVE` statement solves for the initial, zero bias case. In the second `SOLVE` statement, we attempt to solve for `V2=3` volts and `V3=5` volts. If such a large bias change caused the solution algorithms to diverge for this bias point, the bias steps would be multiplied by `ATRAP (0.5)`.

An intermediate point (`V2=1.5` volts, `V3=2.5` volts) would be attempted before trying to obtain `V2=3` volts and `V3=5` volts again. If the intermediate point can not be solved for either case, then the program will continue to reduce the bias step (the next would be `V2=0.75` volts and `V3=1.25` volts) up to `MAXTRAPS` times.

```
METHOD TRAP ATRAP=0.5
SOLVE INIT
SOLVE V2=3 V3=5 OUTFILE=OUTA
```

### Transient Method Example

In this transient simulation example, second-order discretization is used (by default), but the required LTE ( $10^{-3}$ ) is smaller than the default. Since the Jacobian is exact for the second part (BDF-2) of the composite timestep, there should be very few factorizations for the BDF-2 interval when AUTONR is specified.

```
METHOD NEWTON TOL.TIME=1E-3 AUTONR
```

---

**Note:** For recommendations on METHOD parameters for different simulations, see Chapter 2: "Getting Started with ATLAS" or the on-line examples.

---



## 18.28: MOBILITY

MOBILITY allows specification of mobility model parameters.

### Syntax

```
MOBILITY [NUMBER=<n>] [REGION=<n>] [MATERIAL=<name>]
        [NAME=<region_name>] <parameters>
```

| Parameter    | Type    | Default                | Units |
|--------------|---------|------------------------|-------|
| ACCN.SF      | Real    | 0.87                   |       |
| ACCP.SF      | Real    | 0.87                   |       |
| ALBRCT.N     | Logical | False                  |       |
| ALBRCT.P     | Logical | False                  |       |
| AL1N.WATT    | Real    | -0.16                  |       |
| AL1P.WATT    | Real    | -0.296                 |       |
| AL2N.WATT    | Real    | -2.17                  |       |
| AL2P.WATT    | Real    | -1.62                  |       |
| AL3N.WATT    | Real    | 1.07                   |       |
| AL3P.WATT    | Real    | 1.02                   |       |
| ALPHAN.ARORA | Real    | -0.57                  |       |
| ALPHAN.CAUG  | Real    | 0.0                    |       |
| ALPHAP.ARORA | Real    | -0.57                  |       |
| ALPHAP.CAUG  | Real    | 0.0                    |       |
| ALPHAN.FLD   | Real    | $2.4 \times 10^7$      | cm/s  |
| ALPHAP.FLD   | Real    | $2.4 \times 10^7$      | cm/s  |
| ALPHA1N.KLA  | Real    | 0.68                   |       |
| ALPHA1P.KLA  | Real    | 0.719                  |       |
| ALPHAN.TAS   | Real    | 2                      |       |
| ALPHAP.TAS   | Real    | 3.4                    |       |
| ALPHN.CVT    | Real    | 0.680                  |       |
| ALPHP.CVT    | Real    | 0.71                   |       |
| ALN.CVT      | Real    | $6.85 \times 10^{-21}$ |       |
| ALP.CVT      | Real    | $7.82 \times 10^{-21}$ |       |
| AN.PLBRCT    | Real    |                        |       |

| Parameter   | Type    | Default               | Units                                 |
|-------------|---------|-----------------------|---------------------------------------|
| AN.CCS      | Real    | $4.61 \times 10^{17}$ | $\text{cm}^{-3}$                      |
| AN.CVT      | Real    | 2.58                  |                                       |
| ANALYTIC.N  | Logical | False                 |                                       |
| ANALYTIC.P  | Logical | False                 |                                       |
| AP.CCS      | Real    | $1.0 \times 10^{17}$  | $\text{cm}^{-3}$                      |
| AP.CVT      | Real    | 2.18                  |                                       |
| ARORA.N     | Logical | False                 |                                       |
| ARORA.P     | Logical | False                 |                                       |
| ASN.YAMA    | Real    | $1.54 \times 10^{-5}$ | $\text{cm/V}$                         |
| ASP.YAMA    | Real    | $5.35 \times 10^{-5}$ | $\text{cm/V}$                         |
| B1N.TAS     | Real    | 1.75                  |                                       |
| B1P.TAS     | Real    | 1.5                   |                                       |
| B2N.TAS     | Real    | -0.25                 |                                       |
| B2P.TAS     | Real    | -0.3                  |                                       |
| BETAN       | Real    | 2.0                   |                                       |
| BETAP       | Real    | 1.0                   |                                       |
| BETAN.ARORA | Real    | -2.33                 |                                       |
| BETAP.ARORA | Real    | -2.33                 |                                       |
| BETAN.CAUG  | Real    | -2.3                  |                                       |
| BETAP.CAUG  | Real    | -2.2                  |                                       |
| BETAN.CVT   | Real    | 2.00                  |                                       |
| BETAP.CVT   | Real    | 2.00                  |                                       |
| BETAN.TAS   | Real    | 2                     |                                       |
| BETAP.TAS   | Real    | 1                     |                                       |
| BN.CCS      | Real    | $1.52 \times 10^{15}$ | $\text{cm}^{-3}$                      |
| BP.CCS      | Real    | $6.25 \times 10^{14}$ | $\text{cm}^{-3}$                      |
| BN.CVT      | Real    | $4.75 \times 10^7$    | $\text{cm}/(\text{K} \cdot \text{s})$ |
| BP.CVT      | Real    | $9.925 \times 10^6$   | $\text{cm}/(\text{K} \cdot \text{s})$ |
| CA.KLA      | Real    | 0.50                  |                                       |
| CCSMOB.N    | Logical | False                 |                                       |
| CCSMOB.P    | Logical | False                 |                                       |

| Parameter   | Type      | Default                 | Units            |
|-------------|-----------|-------------------------|------------------|
| CD.KLA      | Real      | 0.21                    |                  |
| CONMOB.N    | Logical   | False                   |                  |
| CONMOB.P    | Logical   | False                   |                  |
| CVT.N       | Logical   | False                   |                  |
| CVT.P       | Logical   | False                   |                  |
| CN.CVT      | Real      | $1.74 \times 10^5$      |                  |
| CP.CVT      | Real      | $8.842 \times 10^5$     |                  |
| CRN.CVT     | Real      | $9.68 \times 10^{16}$   | $\text{cm}^{-3}$ |
| CRP.CVT     | Real      | $2.23 \times 10^{17}$   | $\text{cm}^{-3}$ |
| CSN.CVT     | Real      | $3.43 \times 10^{20}$   | $\text{cm}^{-3}$ |
| CSP.CVT     | Real      | $6.10 \times 10^{20}$   | $\text{cm}^{-3}$ |
| DELN.CVT    | Real      | $5.82 \times 10^{14}$   | V/s              |
| DELP.CVT    | Real      | $2.0546 \times 10^{14}$ | V/s              |
| DELTAN.CAUG | Real      | 0.73                    |                  |
| DELTAP.CAUG | Real      | 0.70                    |                  |
| DEVICE      | Character |                         |                  |
| DP.CVT      | Real      | 1/3                     |                  |
| DN.CVT      | Real      | 1/3                     |                  |
| DN.TAS      | Real      | $3.2 \times 10^{-9}$    |                  |
| DP.TAS      | Real      | $2.35 \times 10^{-9}$   |                  |
| E1N.SHI     | Real      | 6.3e3                   | V/cm             |
| E2N.SHI     | Real      | 0.77e6                  | V/cm             |
| E1P.SHI     | Real      | 8.0e3                   | V/cm             |
| E2P.SHI     | Real      | 3.9e5                   | V/cm             |
| ECRITN      | Real      | $4.0 \times 10^3$       | V/cm             |
| ECRITP      | Real      | $4.0 \times 10^3$       | V/cm             |
| EN.CVT      | Real      | 1.0                     |                  |
| EP.CVT      | Real      | 1.0                     |                  |
| ESRN.TAS    | Real      | $2.449 \times 10^7$     |                  |
| ESRP.TAS    | Real      | $1.0 \times 10^9$       |                  |

| Parameter    | Type      | Default | Units |
|--------------|-----------|---------|-------|
| ETAN.CVT     | Real      | 0.0767  |       |
| ETAP.CVT     | Real      | 0.123   |       |
| ETAN         | Real      |         |       |
| ETAN.WATT    | Real      | 0.50    |       |
| ETAP.WATT    | Real      | 0.33    |       |
| EVSATMOD     | Real      | 0       |       |
| EXP.WATT.N   | Logical   | False   |       |
| EXP.WATT.P   | Logical   | False   |       |
| F.COMMUN     | Character |         |       |
| F.CONMUP     | Character |         |       |
| F.ENMUN      | Character |         |       |
| F.ENMUP      | Character |         |       |
| F.MUNSAT     | Character |         |       |
| F.MUPSAT     | Character |         |       |
| F.VSATN      | Character |         |       |
| F.VSATP      | Character |         |       |
| FBH.KLA      | Real      | 3.828   |       |
| FCW.KLA      | Real      | 2.459   |       |
| FLDMOB.N     | Logical   | False   |       |
| FLDMOB.P     | Logical   | False   |       |
| GAMMAN       | Real      | 4.0     |       |
| GAMMAP       | Real      | 1.0     |       |
| GAMMAN.ARORA | Real      | 2.546   |       |
| GAMMAP.ARORA | Real      | 2.546   |       |
| GAMMAN.CAUG  | Real      | -3.8    |       |
| GAMMAP.CAUG  | Real      | -3.7    |       |
| GAMN.CVT     | Real      | 2.5     |       |
| GAMP.CVT     | Real      | 2.2     |       |
| GN.YAMA      | Real      | 8.8     |       |
| GP.YAMA      | Real      | 1.6     |       |
| HVSATMOD     | Real      | 0       |       |
| KLA.N        | Logical   | False   |       |

| Parameter   | Type      | Default | Units                  |
|-------------|-----------|---------|------------------------|
| KLA.P       | Logical   | False   |                        |
| INVN.SF     | Real      | 0.75    |                        |
| INVP.SF     | Real      | 0.75    |                        |
| MATERIAL    | Character |         |                        |
| MOBMOD.N    | Real      | 1       |                        |
| MOBMOD.P    | Real      | 1       |                        |
| MOD.WATT.N  | Logical   | False   |                        |
| MOD.WATT.P  | Logical   | False   |                        |
| MU0N.SHI    | Real      | 1430.0  | cm <sup>2</sup> /(V.s) |
| MU0P.SHI    | Real      | 500.0   | cm <sup>2</sup> /(V.s) |
| MU1N.ARORA  | Real      | 88.0    | cm <sup>2</sup> /(V.s) |
| MU1P.ARORA  | Real      | 54.3    | cm <sup>2</sup> /(V.s) |
| MU2N.ARORA  | Real      | 1252.0  | cm <sup>2</sup> /(V.s) |
| MU2P.ARORA  | Real      | 407.0   | cm <sup>2</sup> /(V.s) |
| MU1N.CAUG   | Real      | 55.24   | cm <sup>2</sup> /(V.s) |
| MU1P.CAUG   | Real      | 49.7    | cm <sup>2</sup> /(V.s) |
| MU2N.CAUG   | Real      | 1429.23 | cm <sup>2</sup> /(V.s) |
| MU2P.CAUG   | Real      | 479.37  | cm <sup>2</sup> /(V.s) |
| MREF1N.WATT | Real      | 481.0   | cm <sup>2</sup> /(V.s) |
| MREF1P.WATT | Real      | 92.8    | cm <sup>2</sup> /(V.s) |
| MREF2N.WATT | Real      | 591.0   | cm <sup>2</sup> /(V.s) |
| MREF2P.WATT | Real      | 124.0   | cm <sup>2</sup> /(V.s) |
| MREF3N.WATT | Real      | 1270.0  | cm <sup>2</sup> /(V.s) |
| MREF3P.WATT | Real      | 534.0   | cm <sup>2</sup> /(V.s) |
| MU0N.CVT    | Real      | 52.2    | cm <sup>2</sup> /(V.s) |
| MU0P.CVT    | Real      | 44.9    | cm <sup>2</sup> /(V.s) |
| MU1N.CVT    | Real      | 43.4    | cm <sup>2</sup> /(V.s) |
| MU1P.CVT    | Real      | 29.0    | cm <sup>2</sup> /(V.s) |
| MUBN.TAS    | Real      | 1150    |                        |

| Parameter    | Type      | Default                | Units                  |
|--------------|-----------|------------------------|------------------------|
| MUBP.TAS     | Real      | 270                    |                        |
| MULN.YAMA    | Real      | 1400.0                 | cm <sup>2</sup> /(V·s) |
| MULP.YAMA    | Real      | 480.0                  | cm <sup>2</sup> /(V·s) |
| MUMAXN.CVT   | Real      | 1417.0                 | cm <sup>2</sup> /(V·s) |
| MUMAXP.CVT   | Real      | 470.5                  | cm <sup>2</sup> /(V·s) |
| N.ANGLE      | Real      | 0.0                    | Degrees                |
| N2N.TAS      | Real      | 1.1×10 <sup>21</sup>   |                        |
| N2P.TAS      | Real      | 1.4×10 <sup>18</sup>   |                        |
| N1N.TAS      | Real      | 2.0×10 <sup>19</sup>   |                        |
| N1P.TAS      | Real      | 8.4×10 <sup>16</sup>   |                        |
| NAME         | Character |                        |                        |
| NCRITN.ARORA | Real      | 1.432×10 <sup>17</sup> | cm <sup>-3</sup>       |
| NCRITP.ARORA | Real      | 2.67×10 <sup>17</sup>  | cm <sup>-3</sup>       |
| NCRITN.CAUG  | Real      | 1.072×10 <sup>17</sup> | cm <sup>-3</sup>       |
| NCRITP.CAUG  | Real      | 1.606×10 <sup>17</sup> | cm <sup>-3</sup>       |
| NEWCVT.N     | Logical   | False                  |                        |
| NEWCVT.P     | Logical   | False                  |                        |
| NREFN.YAMA   | Real      | 3.0×10 <sup>16</sup>   | cm <sup>-3</sup>       |
| NREFP.YAMA   | Real      | 4.0×10 <sup>16</sup>   | cm <sup>-3</sup>       |
| MUDEG.N      | Real      | 1.0                    |                        |
| MUDEG.P      | Real      | 1.0                    |                        |
| MUMAXN.KLA   | Real      | 1417.0                 | cm <sup>2</sup> /(V·s) |
| MUMAXP.KLA   | Real      | 470.5.0                | cm <sup>2</sup> /(V·s) |
| MUMINN.KLA   | Real      | 52.2                   | cm <sup>2</sup> /(V·s) |
| MUMINP.KLA   | Real      | 44.9                   | cm <sup>2</sup> /(V·s) |
| MUN          | Real      | 1.0                    | cm <sup>2</sup> /(V·s) |
| MUP          | Real      | 1.0                    | cm <sup>2</sup> /(V·s) |
| NREF1N.KLA   | Real      | 9.68×16                | cm <sup>-3</sup>       |
| NREF1P.KLA   | Real      | 2.23×17                | cm <sup>-3</sup>       |

| Parameter | Type    | Default               | Units            |
|-----------|---------|-----------------------|------------------|
| NREFD.KLA | Real    | 4.0×20                | cm <sup>-3</sup> |
| NREFA.KLA | Real    | 7.2×20                | cm <sup>-3</sup> |
| OLDSURF.N | Logical | False                 |                  |
| OLDSURF.P | Logical | False                 |                  |
| OXLEFTN   | Real    |                       | microns          |
| OXLEFTP   | Real    |                       | microns          |
| OXRIGHTN  | Real    |                       | microns          |
| OXRIGHTP  | Real    |                       | microns          |
| OXBOTTOMN | Real    |                       | microns          |
| OXBOTTOMP | Real    |                       | microns          |
| P1N.SHI   | Real    | 0.28                  |                  |
| P1P.SHI   | Real    | 0.3                   |                  |
| P2N.SHI   | Real    | 2.9                   |                  |
| P2P.SHI   | Real    | 1.0                   |                  |
| P1N.TAS   | Real    | 0.09                  |                  |
| P1P.TAS   | Real    | 0.334                 |                  |
| P2N.TAS   | Real    | 4.53×10 <sup>-8</sup> |                  |
| P2P.TAS   | Real    | 3.14×10 <sup>-7</sup> |                  |
| P.ANGLE   | Real    | 0.0                   | Degrees          |
| PCN.CVT   | Real    | 0.0                   | cm <sup>-3</sup> |
| PCP.CVT   | Real    | 0.23×10 <sup>16</sup> | cm <sup>-3</sup> |
| R1.KLA    | Real    | 0.7643                |                  |
| R2.KLA    | Real    | 2.2999                |                  |
| R3.KLA    | Real    | 6.5502                |                  |
| R4.KLA    | Real    | 2.3670                |                  |
| R5.KLA    | Real    | -0.8552               |                  |
| R6.KLA    | Real    | 0.6478                |                  |
| RN.TAS    | Real    | 2                     |                  |
| RP.TAS    | Real    | 3                     |                  |
| REGION    | Integer |                       |                  |
| S1.KLA    | Real    | 0.89233               |                  |

| Parameter  | Type    | Default           | Units |
|------------|---------|-------------------|-------|
| S2.KLA     | Real    | 0.41372           |       |
| S3.KLA     | Real    | 0.19778           |       |
| S4.KLA     | Real    | 0.28227           |       |
| S5.KLA     | Real    | 0.005978          |       |
| S6.KLA     | Real    | 1.80618           |       |
| S7.KLA     | Real    | 0.72169           |       |
| SCHWARZ.N  | Logical | False             |       |
| SCHWARZ.P  | Logical | False             |       |
| SHI.N      | Logical | False             |       |
| SHI.P      | Logical | False             |       |
| SN.YAMA    | Real    | 350               |       |
| SP.YAMA    | Real    | 81.0              |       |
| SURFMOB.N  | Logical | False             |       |
| SURFMOB.P  | Logical | False             |       |
| TASCH.N    | Logical | False             |       |
| TASCH.P    | Logical | False             |       |
| TAUN.CVT   | Real    | 0.125             |       |
| TAUP.CVT   | Real    | 0.0317            |       |
| THETAN.FLD | Real    | 0.8               |       |
| THETAP.FLD | Real    | 0.8               |       |
| THETAN.KLA | Real    | 2.285             |       |
| THETAN.SHI | Real    | 2.285             |       |
| THETAP.KLA | Real    | 2.247             |       |
| THETAP.SHI | Real    | 2.247             |       |
| TMUBN.TAS  | Real    | 2.5               |       |
| TMUBP.TAS  | Real    | 1.4               |       |
| TMUN       | Real    | 1.0               |       |
| TMUP       | Real    | 1.0               |       |
| TNOMN.FLD  | Real    | 600.0             | K     |
| TNOMP.FLD  | Real    | 600.0             | K     |
| ULN.YAMA   | Real    | $4.9 \times 10^6$ | cm/s  |



| Parameter   | Type | Default               | Units   |
|-------------|------|-----------------------|---------|
| ULP.YAMA    | Real | $2.928 \times 10^6$   | cm/s    |
| VSATN       | Real |                       | cm/s    |
| VSATP       | Real |                       | cm/s    |
| VSN.YAMA    | Real | $1.036 \times 10^7$   | cm/s    |
| VSP.YAMA    | Real | $1.200 \times 10^7$   | cm/s    |
| XMINN.WATT  | Real | $-1.0 \times 32$      | microns |
| XMAXN.WATT  | Real | $1.0 \times 32$       | microns |
| YMAXN.WATT  | Real | $-1.0 \times 32$      | microns |
| XMINP.WATT  | Real | $-1.0 \times 32$      | microns |
| XMAXP.WATT  | Real | $1.0 \times 32$       | microns |
| YMAXP.WATT  | Real | $-1.0 \times 32$      | microns |
| YCHARN.WATT | Real | $1.0 \times 32$       | microns |
| YCHARP.WATT | Real | $1.0 \times 32$       | microns |
| Z11N.TAS    | Real | 0.0388                |         |
| Z11P.TAS    | Real | 0.039                 |         |
| Z22N.TAS    | Real | $1.73 \times 10^{-5}$ |         |
| Z22P.TAS    | Real | $1.51 \times 10^{-5}$ |         |

## Description

**MATERIAL** specifies which material from Table B-1 in Appendix B: “Material Systems” should be applied to the MOBILITY statement. If a material is specified, then all regions defined as being composed of that material will be affected.

**DEVICE** specifies the device in MIXEDMODE simulation (see Chapter 12: “MixedMode: Mixed Circuit and Device Simulator”) to be applied to the MOBILITY statement.

**NAME** specifies the name of the region to be applied to the MOBILITY statement. Note that the name must match the name specified in the NAME parameter of the REGION statement.

**REGION** specifies the number of the region to be applied to the MOBILITY statement.

## Mobility Model Flags

**ALBRCT.N** and **ALBRECT.P** enable the Albrecht mobility model (see Chapter 33: “Physics”, “The Albrecht Model for Low Field Mobility in GaN” Section on page 3-38).

**N.ANGLE** specifies angle for application of electron mobility parameters in simulation of anisotropic mobility.

**P.ANGLE** specifies angle for application of hole mobility parameters in simulation of anisotropic mobility.

**CVT.N** invokes the Lombardi CVT mobility model for electrons (see Chapter 33: “Physics”, “Lombardi CVT Model” Section on page 3-45 ).

**CVT.P** invokes the Lombardi CVT mobility model for holes (see Chapter 33: “Physics”, “Lombardi CVT Model” Section on page 3-45 ).

**NEWCVT.N** specifies that a new surface mobility degradation calculation is used in the CVT mobility model for electrons in place of the original (see Chapter 33: “Physics”, the “Extended CVT Model” Section on page 3-48).

**NEWCVT.P** specifies that a new surface mobility degradation calculation is used in the CVT mobility model for holes in place of the original (see Chapter 33: “Physics”, the “Extended CVT Model” Section on page 3-48).

**FLDMOB.N** specifies a lateral electric field dependent model for electrons (see Chapter 33: “Physics”, Equation 3-217).

**FLDMOB.P** specifies a lateral electric field dependent model for holes (see Chapter 33: “Physics”, Equation 3-218).

**CONMOB.N** specifies that doping concentration dependent model to be used for electrons.

**CONMOB.P** specifies that a doping concentration dependent model is to be used for holes.

**CCSMOB.N** specifies that carrier-carrier scattering model is to be used for electrons (see Chapter 33: “Physics”, Equations 3-149 - 3-153).

**CCSMOB.P** specifies that carrier-carrier scattering model is to be used for holes (see Chapter 33: “Physics”, Equations 3-149 - 3-153).

**ANALYTIC.N** specifies that the analytic concentration dependent model is to be used for electrons (see Chapter 33: “Physics”, Equation 3-144).

**ANALYTIC.P** specifies that the analytic concentration dependent model is to be used for holes (see Chapter 33: “Physics”, Equation 3-145).

**ARORA.N** specifies that the Arora analytic concentration dependent model is to be used for electrons (see Chapter 33: “Physics”, Equation 3-146).

**ARORA.P** specifies that the Arora analytic concentration dependent model is to be used for electrons (see Chapter 33: “Physics”, Equation 3-147).

**SURFMOB.N** invokes the effective field based surface mobility model for electrons (see Equation 3-217).

**SURFMOB.P** invokes the effective field based surface mobility model for holes (see Equation 3-218).

**SCHWARZ.N** specifies the use of transverse electric field-dependent mobility models for electrons. See `TFLDMB1` or `SCHWARZ` in the `MODELS` statement.

**SCHWARZ.P** specifies the use of transverse electric field-dependent mobility models for holes. See `TFLDMB1` or `SCHWARZ` in the `MODELS` statement.

**TASCH.N** specifies a transverse electric field dependent mobility model for electrons based on Tasch [44,46] (see Chapter 33: “Physics”, Equations 3-198 through 3-216).

**TASCH.P** specifies a transverse electric field dependent mobility model for holes based on Tasch [44,46] (see Chapter 33: “Physics”, Equations 3-198 through 3-216).

**EVSATMOD** specifies which parallel field dependent mobility model (see Chapter 33: “Physics”, Equation 3-225 and Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-50) should be used for electrons as follows:

1. Use the standard saturation model (`EVSATMOD=0`, see also Chapter 33: “Physics”, Equation 3-225).
2. Use the negative differential mobility saturation model (`EVSATMOD=1`, see also Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-50).
3. Use simple field-dependent velocity mode (`EVSATMOD=2`, see also Chapter 33: “Physics”, Equation 3-238).

**MOBMOD.N** specifies transverse field degradation for electrons as follows:

1. No transverse degradation.
2. Use the Watt or Tasch transverse field models depending on the settings of `FIELDMOB1` and `FIELDMOB2`.
3. Use the Yamaguchi transverse field dependent model.
4. Use the CVT transverse field dependent model.

**MOBMOD.P** specifies transverse field degradation for holes as follows:

1. No transverse degradation.
2. Use the Watt or Tasch transverse field models depending on the settings of `FIELDMOB1` and `FIELDMOB2`.
3. Use the Yamaguchi transverse field dependent model.
4. Use the CVT transverse field dependent model.

**KLA.N** turns on Klaassen's mobility model for electrons (see Chapter 33: "Physics", Equations 3-155 through 3-180).

**KLA.P** turns on Klaassen's mobility model for holes (see Chapter 33: "Physics", Equations 3-155 through 3-180).

**MOD.WATT.N** turns on modified Watt mobility model for electrons (see Chapter 33: "Physics", Equation 3-221).

**MOD.WATT.P** turns on modified Watt Mobility Model for holes (see Chapter 33: "Physics", Equation 3-222).

**EXP.WATT.N** turns on exponential modification to Watt's mobility model for electrons (see Chapter 33: "Physics", Equation 3-221).

**EXP.WATT.P** turns on exponential modification to Watt's mobility model for holes (see Chapter 33: "Physics", Equation 3-222).

**SHI.N** turns on Shirahata's Mobility Model for electrons (see Chapter 33: "Physics", Equation 3-223).

**SHI.P** turns on Shirahata's Mobility Model for holes (see Chapter 33: "Physics", Equation 3-224).

## Temperature Dependent Low Field Mobility Parameters

For information about these parameters, see Chapter 33: "Physics", Table 3-3-16.

## Albrecht Model Parameters

For information about these parameters, see Chapter 33: "Physics", "The Albrecht Model for Low Field Mobility in GaN" Section on page 3-38.

## Caughey-Thomas Concentration Dependent Model Parameters

For more information about these parameters, see Chapter 33: "Physics", Table 3-3-18.

## Arora Concentration Dependent Mobility Model Parameters

For more information about these parameters, see Chapter 33: "Physics", Table 3-3-19.

## Carrier-Carrier Scattering Model Parameters

For more information about these parameters, see Chapter 33: "Physics", Table 3-3-20.

### Parallel Field Dependent Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-35 and Chapter 5: “Blaze: Compound Material 2D Simulator”, Tables 5-3 and 5-4.

### Yamaguchi Transverse Field Dependent Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-30.

### CVT Transverse Field Dependent Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-28.

### Extended CVT Transverse Field Dependent Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-29.

### Watt Effective Transverse Field Dependent Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-30.

### Tasch Mobility Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-31.

### Klaassen's Mobility Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Tables 3-3-22 and 3-3-27.

### The Modified Watt Mobility Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-33.

### Shirahata's Mobility Model Parameters

For more information about these parameters, see Chapter 33: “Physics”, Table 3-3-34.

### SCHWARZ and TASCH Transverse Field Dependent Model Parameters

**ACCN.SF** specifies the accumulation saturation factor which describes the ratio of the electron concentration in the accumulation layer before and after bending of conductivity and valence bands for electron mobility.

**ACCN.SF** specifies the accumulation saturation factor which describes the ratio of the hole concentration in the accumulation layer before and after bending of conductivity and valence bands for hole mobility.

**INVN.SF** specifies the inversion saturation factor which describes the ratio of the electron concentration in the inversion layer before and after the bending of conductivity and valence bands for electron mobility.

**INVN.SF** specifies the inversion saturation factor which describes the ratio of the hole concentration in the inversion layer before and after the bending of conductivity and valence bands for hole mobility.

**OXBOTTOMN** specifies the coordinate of the bottom edge of the gate oxide for a MOSFET transistor for electron mobility.

**OXBOTTOMP** specifies the coordinate of the bottom edge of the gate oxide for a MOSFET transistor for hole mobility.

**OXLEFTN** specifies the coordinate of the left edge of the gate oxide for a MOSFET transistor for electron mobility.

**OXLEFTP** specifies the coordinate of the left edge of the gate oxide for a MOSFET transistor for hole mobility.

**OXRIGHTN** specifies the coordinate of the right edge of the gate oxide for a MOSFET transistor for electron mobility.

**OXRIGHTP** specifies the coordinate of the right edge of the gate oxide for a MOSFET transistor for hole mobility.

### Interpreter Functions

**F.CONMUN** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature, composition and doping dependent electron mobility model.

**F.CONMUP** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature, composition and doping dependent hole mobility model.

**F.ENMUN** specifies a C-Interpreter file for the electron mobility as a function of Electron Temperature and perpendicular field as well as other choice variables. The function itself is named `endepmun` and only applies to ATLAS2D.

**F.ENMUP** specifies a C-Interpreter file for the hole mobility as a function of Hole Temperature and perpendicular field as well as other choice variables. The function itself is named `endepmup` and only applies to ATLAS2D.

**F.MUNSAT** specifies the name of a file containing a C-INTERPRETER function for the specification of parallel field dependent electron mobility model for velocity saturation.

**F.MUPSAT** specifies the name of a file containing a C-INTERPRETER function for the specification of parallel field dependent hole mobility model for velocity saturation.

**F.VSATN** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature and composition dependent electron saturation velocity models.

**F.VSATP** specifies the name of a file containing a C-INTERPRETER function for the specification of temperature and composition dependent electron saturation velocity models.

### Modified Watt Model Example

The following example sets the Modified Watt Surface mobility model for MOSFETs. The MOBILITY statement is used to set the models and to specify the value of the depth of action of the Modified Watt model.

```
MODELS CONMOB FLDMOB SRH MIN.SURF PRINT
MOBILITY WATT.N MOD.WATT.N YMAXN.WATT=0.01
```

## 18.29: MODELS

MODELS specifies model flags to indicate the inclusion of various physical mechanisms, models, and other parameters such as the global temperature for the simulation.

### Syntax

```
MODELS <mf> <gp> <mdp>
```

| Parameter   | Type    | Default              | Units  |
|-------------|---------|----------------------|--|
| A.TEMP      | Logical | False                |  |
| ACC.SF      | Real    | 0.87                 |  |
| ALBRCT      | Logical | False                |  |
| ALL         | Logical | True                 |  |
| ALN1        | Real    | -0.160               |  |
| ALN2        | Real    | -2.17                |  |
| ALN3        | Real    | 1.07                 |  |
| ALP1        | Real    | -0.296               |  |
| ALP2        | Real    | -1.62                |  |
| ALP3        | Real    | 1.02                 |  |
| ALT.SCHRO   | Logical | False                |  |
| ANALYTIC    | Logical | False                |  |
| AR.MU1N     | Real    | 88                   |  |
| AR.MU2N     | Real    | 1252                 |  |
| AR.MU1P     | Real    | 54.3                 |  |
| AR.MU2P     | Real    | 407                  |  |
| ARORA       | Logical | False                |  |
| AUGER       | Logical | False                |  |
| AUGGEN      | Logical | False                |  |
| AUTOBBT     | Logical | False                |  |
| B.DORT      | Real    | 1.0                  |  |
| B.ELECTRONS | Real    | 2                    |  |
| B.HOLES     | Real    | 1                    |  |
| BB.A        | Real    | $4.0 \times 10^{14}$ | $\text{cm}^{-1/2} \text{V}^{-5/2} \text{S}^{-1}$ |
| BB.B        | Real    | $1.97 \times 10^7$   | $\text{cm}^{-1/2} \text{V}^{-2} \text{S}^{-1}$   |
| BB.GAMMA    | Real    | 2.5                  | V/cm   |

| Parameter     | Type    | Default               | Units         |
|---------------|---------|-----------------------|---------------|
| BBT.HURKX     | Logical | False                 |               |
| BBT.KL        | Logical | False                 |               |
| BBT.STD       | Logical | False                 |               |
| BBT3          | Logical | False                 |               |
| BC.QUANT      | Logical | False                 |               |
| BGN           | Logical | False                 |               |
| BGN.KLA       | Logical | False                 |               |
| BGN.KLASSEN   | Logical | False                 |               |
| BGN.SLOTBOOM  | Logical | False                 |               |
| BIPOLAR       | Logical | False                 |               |
| BIPOLAR2      | Logical | False                 |               |
| BOLTZMANN     | Logical | True                  |               |
| BOUND.TRAP    | Logical | False                 |               |
| BQP.N         | Logical | False                 |               |
| BQP.P         | Logical | False                 |               |
| BQP.NALPHA    | Real    | 0.5                   |               |
| BQP.NGAMMA    | Real    | 1.2                   |               |
| BQP.NEUMANN   | Logical | true                  |               |
| BQP.PALPHA    | Real    | 0.5                   |               |
| BQP.PGAMMA    | Real    | 1.0                   |               |
| BQP.QDIR      | Integer | 2                     |               |
| C0            | Real    | $2.5 \times 10^{-10}$ |               |
| CALC.FERMI    | Logical | False                 |               |
| CARRIERS      | Real    |                       |               |
| CAVITY.LENGTH | Real    |                       | $\mu\text{m}$ |
| CCS.EA        | Real    | $4.61 \times 10^{17}$ |               |
| CCS.EB        | Real    | $1.52 \times 10^{15}$ |               |
| CCS.HA        | Real    | $1.0 \times 10^{17}$  |               |
| CCS.HB        | Real    | $6.25 \times 10^{14}$ |               |
| CCSMOB        | Logical | False                 |               |
| CCSNEW        | Logical | False                 |               |

| Parameter   | Type      | Default              | Units |
|-------------|-----------|----------------------|-------|
| CCSSURF     | Logical   | False                |       |
| CGATE.N     | Real      | 0.025                |       |
| CGATE.P     | Real      | 150.0                |       |
| CHI.HOLES   | Real      | $4.6 \times 10^4$    |       |
| CHIA        | Real      | 3e5                  |       |
| CHIB        | Real      | $5.0 \times 10^4$    |       |
| CHUANG      | Logical   | False                |       |
| CONMOB      | Logical   | False                |       |
| CONSRH      | Logical   | False                |       |
| CVT         | Logical   | False                |       |
| D.DORT      | Real      | $2.5 \times 10^{-6}$ |       |
| DG.N        | Logical   | False                |       |
| DG.P        | Logical   | False                |       |
| DGN.GAMMA   | Real      | 3.6                  |       |
| DGP.GAMMA   | Real      | 3.6                  |       |
| DEVDEG.E    | Logical   | False                |       |
| DEVDEG.H    | Logical   | False                |       |
| DEVDEG.B    | Logical   | False                |       |
| DEVICE      | Character |                      |       |
| DGLOG       | Logical   | True                 |       |
| DGROOT      | Logical   | False                |       |
| DRIFT.DIFF  | Logical   | True                 |       |
| E.BENDING   | Logical   | False                |       |
| E.TAUR.VAR  | Logical   | False                |       |
| E0_TCOEF    | Real      |                      |       |
| E0.TCOEF    | Real      |                      |       |
| ECRIT       | Real      | 4000.0               | V/cm  |
| EF.TOL      | Real      | $10 \times 10^{-10}$ |       |
| EIGENS      | Integer   | 15                   |       |
| ELECTRONS   | Logical   | True                 |       |
| ENERGY.STEP | Real      | 0.0025               | eV    |



| Parameter        | Type      | Default               | Units                         |
|------------------|-----------|-----------------------|-------------------------------|
| ERASE            | Logical   | False                 |                               |
| ETAN             | Real      | 0.50                  |                               |
| ETAP             | Real      | 0.33                  |                               |
| EVSATMOD         | Integer   | 0                     |                               |
| FERMIDIRAC       | Logical   | False                 |                               |
| FERRO            | Logical   | False                 |                               |
| FIXED.FERMI      | Logical   | False                 |                               |
| FLDMOB           | Logical   | False                 |                               |
| F.AE             | Real      | $1.82 \times 10^{-7}$ | $\text{CV}^{-2}\text{S}^{-1}$ |
| F.BE             | Real      | $1.90 \times 10^8$    | V/cm                          |
| F.AH             | Real      | $1.82 \times 10^{-7}$ | $\text{CV}^{-2}\text{S}^{-1}$ |
| F.BH             | Real      | $1.90 \times 10^8$    | V/cm                          |
| F.EFEMIS         | Character |                       |                               |
| F.HFEMIS         | Character |                       |                               |
| F.KSN            | Character |                       |                               |
| F.KSP            | Character |                       |                               |
| F.TRAP.COULOMBIC | Character |                       |                               |
| F.TRAP.TUNNEL    | Character |                       |                               |
| FAST.EIG         | Logical   | False                 |                               |
| FG.RATIO         | Real      |                       |                               |
| FNHOLES          | Logical   | False                 |                               |
| FNORD            | Logical   | False                 |                               |
| FNPP             | Logical   | False                 |                               |
| G.EMPIRICAL      | Logical   | False                 |                               |
| G.STANDARD       | Logical   | False                 |                               |
| GAINMOD          | Logical   | 0                     |                               |
| GR.HEAT          | Logical   | False                 |                               |
| HANSCHQM         | Logical   | False                 |                               |
| H.BENDING        | Logical   | False                 |                               |
| H.TAUR.VAR       | Logical   | False                 |                               |
| HCTE             | Logical   | False                 |                               |

| Parameter   | Type    | Default               | Units                    |
|-------------|---------|-----------------------|--------------------------|
| HCTE.EL     | Logical | False                 |                          |
| HCTE.HO     | Logical | False                 |                          |
| HEAT.FULL   | Logical | False                 |                          |
| HEAT.PETHOM | Logical | False                 |                          |
| HEI         | Logical | False                 |                          |
| HHI         | Logical | False                 |                          |
| HOLE        | Logical | False                 |                          |
| HVSATMOD    | Integer | 0                     |                          |
| IG.ELINR    | Real    | $6.16 \times 10^{-6}$ | cm                       |
| IG.HLINR    | Real    | $6.16 \times 10^{-6}$ | cm                       |
| IG.ELINF    | Real    | $9.2 \times 10^{-7}$  | cm                       |
| IG.HLINF    | Real    | $9.2 \times 10^{-7}$  | cm                       |
| IG.EBETA    | Real    | $2.59 \times 10^{-4}$ | $(V \cdot cm)^{0.5}$     |
| IG.HBETA    | Real    | $2.59 \times 10^{-4}$ | $(V \cdot cm)^{0.5}$     |
| IG.EETA     | Real    | $2.0 \times 10^{-5}$  | $V^{1/3} \cdot cm^{2/3}$ |
| IG.HETA     | Real    | $2.0 \times 10^{-5}$  | $V^{1/3} \cdot cm^{2/3}$ |
| IG.EEOX     | Real    | $9.0 \times 10^4$     | V/cm                     |
| IG.HEOX     | Real    | $9.0 \times 10^4$     | V/cm                     |
| IG.EB0      | Real    | 3.2                   | V                        |
| IG.HB0      | Real    | 4.0                   | V                        |
| IG.LRELE    | Real    | $3.0 \times 10^{-6}$  | [Q=1] cm                 |
| IG.LRELH    | Real    | $2.0 \times 10^{-6}$  | [Q=1] cm                 |
| IMPACT      | Logical | False                 |                          |
| INCOMPLETE  | Logical | False                 |                          |
| INFINITY    | Real    | 0.001                 |                          |
| IONIZ       | Logical | False                 |                          |
| INV.SF      | Real    | 0.75                  |                          |
| ISHIKAWA    | Logical | False                 |                          |
| JOULE.HEAT  | Logical | True                  |                          |
| K.P         | Logical | False                 |                          |

| Parameter      | Type    | Default               | Units            |
|----------------|---------|-----------------------|------------------|
| KAUGCN         | Real    |                       |                  |
| KAUGCP         | Real    |                       |                  |
| KAUGDN         | Real    |                       |                  |
| KAUGDP         | Real    |                       |                  |
| KSRHCN         | Real    |                       |                  |
| KSRHCP         | Real    |                       |                  |
| KSRHGN         | Real    |                       |                  |
| KSRHGP         | Real    |                       |                  |
| KSRHTN         | Real    |                       |                  |
| KSRHTP         | Real    |                       |                  |
| KSN            | Integer | 0-1                   |                  |
| KSP            | Integer | 0-1                   |                  |
| KLA            | Logical | False                 |                  |
| KLAAUG         | Logical | False                 |                  |
| KLASRH         | Logical | False                 |                  |
| L.TEMP         | Logical | False                 |                  |
| LAS.ABSOR_SAT  | Logical | False                 |                  |
| LAS.ABSORPTION | Logical | False                 |                  |
| LAS.EFINAL     | Real    |                       | eV               |
| LAS.EINIT      | Real    |                       | eV               |
| LAS.ESEP       | Real    |                       | eV               |
| LAS.ETRANS     | Logical | False                 |                  |
| LAS.FCARRIER   | Logical | False                 |                  |
| LAS.GAIN_SAT   | Logical | False                 |                  |
| LAS.ITMAX      | Integer | 30                    |                  |
| LAS.LOSSES     | Real    | 0                     | cm <sup>-1</sup> |
| LAS.MIRROR     | Real    | 90                    | %                |
| LAS.MULTISAVE  | Logical | False                 |                  |
| LAS.NEFF       | Real    | 3.57                  |                  |
| LAS.OMEGA      | Real    | $2.16 \times 10^{15}$ | 1/sec            |
| LAS.NMODE      | Integer | 1                     |                  |

| Parameter        | Type      | Default           | Units                   |
|------------------|-----------|-------------------|-------------------------|
| LAS.NX           | Real      |                   |                         |
| LAS.NY           | Real      |                   |                         |
| LAS.REFLECT      | Logical   | False             |                         |
| LAS.RF           | Real      |                   |                         |
| LAS.RR           | Real      |                   |                         |
| LAS.SIN          | Real      | $1.0 \times 10^4$ | $\text{cm}^{-1}$        |
| LAS.SPECSAVE     | Integer   | 1                 |                         |
| LAS.SPONTANEOUS  | Real      |                   |                         |
| LAS.TAUSS        | Real      | 0.05              |                         |
| LAS.TIMERATE     | Logical   | True              |                         |
| LAS.TOLER        | Real      | 0.01              |                         |
| LAS.TRANS_ENERGY | Real      |                   |                         |
| LAS.XMAX         | Real      |                   |                         |
| LAS.XMIN         | Real      |                   |                         |
| LAS.YMAX         | Real      |                   |                         |
| LAS.YMIN         | Real      |                   |                         |
| LAS_MAXCH        | Real      | 2.5               |                         |
| LASER            | Logical   | False             |                         |
| LAT.TEMP         | Logical   | False             |                         |
| LI               | Logical   | False             |                         |
| LMODE            | Logical   | False             |                         |
| LORENTZ          | Logical   | False             |                         |
| MASS.TUNNEL      | Real      | 0.25              |                         |
| MATERIAL         | Character |                   |                         |
| MIN.SURF         | Logical   | False             |                         |
| MOBMOD           | Integer   |                   |                         |
| MOBTEM.SIMPL     | Logical   | False             |                         |
| MOS              | Logical   | False             |                         |
| MOS2             | Logical   | False             |                         |
| MREFN1           | Real      | 481.0             | $\text{cm}^2/\text{Vs}$ |
| MREFN2           | Real      | 591.0             | $\text{cm}^2/\text{Vs}$ |

| Parameter   | Type      | Default | Units               |
|-------------|-----------|---------|---------------------|
| MREFN3      | Real      | 1270.0  | cm <sup>2</sup> /Vs |
| MREFP1      | Real      | 92.8    | cm <sup>2</sup> /Vs |
| MREFP2      | Real      | 124.    | cm <sup>2</sup> /Vs |
| MREFP3      | Real      | 534.    | cm <sup>2</sup> /Vs |
| N.CONCANNON | Logical   | False   |                     |
| N.DORT      | Logical   | False   |                     |
| N.KSI.VAR   | Logical   | False   |                     |
| N.KSI_VAR   | Logical   | False   |                     |
| N.QUANTUM   | Logical   | False   |                     |
| N.TEMP      | Logical   | False   |                     |
| NAME        | Character |         |                     |
| NEARFLG     | Logical   | False   |                     |
| NEW.EIG     | Logical   | False   |                     |
| NEW.SCHRO   | Logical   | False   |                     |
| NEW.DORT    | Logical   | False   |                     |
| NEWIMPACT   | Logical   | False   |                     |
| NI.FERMI    | Logical   | False   |                     |
| NUM.BAND    | Real      |         |                     |
| NUM.DIRECT  | Real      |         |                     |
| NUMBER      | Integer   | 0       |                     |
| NUMCARR     | Real      |         |                     |
| OLDIMPACT   | Logical   | False   |                     |
| OPTR        | Logical   | False   |                     |
| OX.BOTTOM   | Real      | 0.0     | μm                  |
| OX.LEFT     | Real      |         | mm                  |
| OX.POISSON  | Logical   | False   |                     |
| OX.RIGHT    | Real      |         | μm                  |
| OX.SCHRO    | Logical   | False   |                     |
| P.CONCANNON | Logical   | False   |                     |
| P.DORT      | Logical   | False   |                     |
| P.KSI_VAR   | Logical   | False   |                     |

| Parameter      | Type      | Default               | Units            |
|----------------|-----------|-----------------------|------------------|
| P.KSI.VAR      | Logical   | False                 |                  |
| P.SCHRODING    | Logical   | False                 |                  |
| P.TEMP         | Logical   | False                 |                  |
| PASSLER        | Logical   | False                 |                  |
| PATH.N         | Real      | $3.4 \times 10^7$     | microns          |
| PATH.P         | Real      | $2.38 \times 10^{-7}$ | microns          |
| PEFF.N         | Real      | 3.2                   | eV               |
| PEFF.P         | Real      | 4.8                   | eV               |
| PHOTON.ENERGY  | Real      |                       | eV               |
| POISSON        | Logical   | False                 |                  |
| POST.SCHRO     | Logical   | False                 |                  |
| PRINT          | Logical   | False                 |                  |
| PRINT.REGION   | Integer   |                       |                  |
| PRINT.MATERIAL | Character |                       |                  |
| PRT.BAND       | Logical   | False                 |                  |
| PRT.COMP       | Logical   | False                 |                  |
| PRT.FLAGS      | Logical   | False                 |                  |
| PRT.IMPACT     | Logical   | False                 |                  |
| PRT.RECOM      | Logical   | False                 |                  |
| PRT.THERM      | Logical   | False                 |                  |
| PROGRAM        | Logical   | False                 |                  |
| PRT.BAND       | Logical   | False                 |                  |
| PRT.COMP       | Logical   | False                 |                  |
| PRT.FLAGS      | Logical   | False                 |                  |
| PRT.IMPACT     | Logical   | False                 |                  |
| PRT.RECOM      | Logical   | False                 |                  |
| PRT.THERM      | Logical   | False                 |                  |
| PT.HEAT        | Logical   | False                 |                  |
| QMINCONC       | Real      | $1.0 \times 10^{-10}$ | $\text{cm}^{-3}$ |
| QUANTUM        | Logical   | False                 |                  |
| QX.MIN         | Real      | LHS of device         | $\mu\text{m}$    |

| Parameter      | Type      | Default       | Units   |
|----------------|-----------|---------------|---------|
| QX.MAX         | Real      | RHS of device | μm      |
| REGION         | Integer   | 0             |         |
| SCHRO          | Logical   | False         |         |
| SHI            | Logical   | False         |         |
| SPEC.NAME      | Character |               |         |
| SPONTANEOUS    | Logical   | False         |         |
| SRH            | Logical   | False         |         |
| SURFMOB        | Logical   | False         |         |
| TATUN          | Logical   | False         |         |
| TAUMOB         | Logical   | False         |         |
| TAUTEM         | Logical   | False         |         |
| TAYAMAYA       | Logical   | False         |         |
| TEMPERATURE    | Real      | 300           | K       |
| TFLDMB1        | Logical   | False         |         |
| TFLDMB2        | Logical   | False         |         |
| THETA.N        | Real      | 60.0          | degrees |
| THETA.P        | Real      | 60.0          | degrees |
| TRAP.COULOMBIC | Logical   | False         |         |
| TRAP.TUNNEL    | Logical   | False         |         |
| UNSAT.FERRO    | Logical   | False         |         |
| YAMAGUCHI      | Logical   | False         |         |
| YAN            | Logical   | False         |         |

## Description

**mf** is one or more of the model flags described on the next page.

**gp** is one or more of the general parameters described in the “General Parameters” Section on page 18-144. These parameters are used to specify general information used during the simulation.

**mdp** is one or more of the model dependent parameters described in the “Model Dependent Parameters” Section on page 18-145.

## Mobility Model Flags

**ALBRCT** enables the Albrecht mobility model for electrons and holes (see Chapter 33: “Physics”, Equation 3-146).

**ANALYTIC** specifies an analytic concentration dependent mobility model for silicon which includes temperature dependence (see Chapter 33: “Physics”, Equations 3-144 and 3-145).

**ARORA** specifies an analytic concentration and temperature dependent model according to Arora (see Chapter 33: “Physics”, Equations 3-146 and 3-147).

**CCSMOB** specifies carrier-carrier scattering model according to Dorkel and Leturq (see Chapter 33: “Physics”, Equations 3-149-3-153).

**CONMOB** specifies that a concentration dependent mobility model be used for silicon and gallium arsenide. This model is a doping versus mobility table valid for 300K only.

**CVT** specifies that the CVT transverse field dependent mobility model is used for the simulation.

**FLDMOB** specifies a lateral electric field-dependent model (see Chapter 33: “Physics”, Equations 3-225 and Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-50). The `EVSATMOD` parameter may be used to define which field dependent equation is used.

**KLA** specifies that the Klaassen Mobility Model (see Chapter 33: “Physics”, Equations 3-155 - 3-180) will be used for electrons and holes.

**MIN.SURF** specifies that the `WATT`, `TASCH`, or `SHI` mobility models should only apply to minority carriers.

**MOBMOD** specifies mobility degradation by longitudinal electric field only (`MOBMOD=1`), or by both longitudinal and transverse electric fields (`MOBMOD=2`). When `MOBMOD=2`, the `ACC.SF`, `INV.SF`, `OX.BOTTOM`, `OX.LEFT`, and `OX.RIGHT` parameters should be specified. This parameter is only used with `TFLDMB1` and `TFLDMB2`.

**SHI** specifies that the Shirahata Mobility Model (see Chapter 33: “Physics”, Equation 3-224) will be used for electrons and holes.

**SURFMOB** or **WATT** invokes the effective field based surface mobility model (see Chapter 33: “Physics”, Equations 3-217 and 3-218). `SURFMOB` parameters are used in the calculation of surface mobility according to the Watt Model [19]. Do not specify this parameter unless S-PISCES is installed on your system.

**TFLDMB1** or **SCHWARZ** specifies the use of transverse electric field-dependent mobility models. The electron model is based on the Schwarz and Russe equations [43] and is implemented in [44]. The hole model, which is used only when `MOBMOD=2`, is based on the Watt and Plummer equations [45].

**TFLDMB2** or **TASCH** specifies a transverse electric field dependent mobility model for electrons and holes based on a semi-empirical equation [44, 46].

**YAMAGUCHI** specifies that the Yamaguchi transverse field dependent mobility model is used in the simulation.

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**Note:** See Section 18.28: “MOBILITY” for alternative ways to set mobility models

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## Recombination Model Flags

**AUGER** specifies Auger recombination (see Chapter 33: “Physics”, Equation 3-227)

**AUGGEN** specifies that the Auger recombination model will be used as a generation and a recombination term.

**CONSRH** Specifies Shockley-Read-Hall recombination using concentration dependent lifetimes (see Equations 3-241 and 3-242).

**KLAAUG** enables Klaassen’s model for concentration dependent auger coefficients (see Chapter 33: “Physics”, Equations 3-251, 3-252, and 3-253).

**KAUGCN**, **KAUGCP**, **KAUGDN** and **KAUGDP** specify parameters of Klaassen's Auger recombination model (see Chapter 33: “Physics”, Equations 3-145 and 3-146).



**KLASRH** enables Klaassen's model for concentration dependent lifetimes for Shockley Read Hall recombination (Chapter 33: "Physics", Equations 3-254 and 3-255).

**KSRHCN**, **KSRHCP**, **KSRHGN**, **KSRHGP**, **KSRHTN** and **KSRHTP** specify parameters of Klaassen's SRH recombination model (see Chapter 33: "Physics", Equations 3-237 and 3-238).

**NI.FERMI** includes the effects of Fermi statistics into the calculation of the intrinsic concentration in expressions for SRH recombination.

**OPTR** selects the optical recombination model (see Chapter 33: "Physics", Equation 3-253). When this parameter is specified, the **COPT** parameter of the **MATERIAL** statement should be specified.

**SRH** specifies Shockley-Read-Hall recombination using fixed lifetimes (see Chapter 33: "Physics", Equation 3-240).

**TATUN** enables the Klaassen trap-assisted tunneling model.

**TRAP.COULOMBIC** specifies that the Poole-Frenkel barrier lowering for coulombic wells will be used for traps.

**TRAP.TUNNEL** specifies that the trap-assisted tunneling model will be used for traps.

### Generation Model Flags

**AUTOBBT** causes band-to-band tunneling parameters to be calculated from first principals (see Chapter 33: "Physics", Equations 3-300, 3-301, and 3-302).

**BBT.HURKX** enables the Hurkx model (see Chapter 33: "Physics", Equation 3-300).

**BBT.KL** specifies a band-to-band tunneling model according to Klaassen.

**BBT.STD** specifies a standard band-to-band tunneling model (see Chapter 33: "Physics", Equation 3-302).

**DEVDEG.E** activates the device degradation caused by hot electron injection current. **HEI** should also be specified in this case.

**DEVDEG.H** activates the device degradation caused by hot hole injection current. **HHI** should also be specified in this case.

**DEVDEG.B** activates the device degradation caused by both the hot electron and hot hole injection currents. **HEI** and **HHI** should also be specified in this case.

---

**Note:** The specification of either **DEVDEG.E**, **DEVDEG.H**, or **DEVDEG.B** will initialize the density of electron (hole) like traps on the interface and will clear out the trapped electron (hole) density on the interface if any.

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**E.BENDING** specifies that electron band bending will be taken into account for electron injection (see Chapter 33: "Physics", Equation 3-313).

**FERRO** enables the ferroelectric permittivity model (see Section 3.6.7: "The Ferroelectric Permittivity Model").

**FG.RATIO** for 2D simulation specifies the ratio of the floating gate extent in the Z direction to the channel width in Z direction.

**FNHOLES** enables self-consistent analysis of hole Fowler-Nordheim currents.

**F.TRAP.TUNNEL** specifies the name of a file containing a C-interpreter function to simulate trap assisted tunneling (alias: **F.TRAP.DIRAC**).

**F.TRAP.COULOMBIC** specifies the name of a file containing a C-interpreter function to simulate trap assisted tunneling with Coulombic wells.

**FNORD** selects a self-consistent Fowler-Nordheim tunneling model for electrons (see Chapter 33: “Physics”, Equation 3-307). This is the recommended approach for calculating Fowler-Nordheim current.

**FNPP** selects a post-processing Fowler-Nordheim tunneling model (see Chapter 33: “Physics”, Equation 3-308). Generally the Fowler-Nordheim current does not cause convergence problems so this approach is not required.

**H.BENDING** specifies that hole band bending will be taken into account for hole injection (see Chapter 33: “Physics”, Equation 3-315).

**HEI** specifies the calculation of hot electron injection into oxides. This parameter can be used to simulate MOS gate current or EPROM programming. In transient mode, the oxide current is self-consistently added to the floating gate charge (see Chapter 33: “Physics”, Equation 3-310).

**HHI** specifies the calculation of hot hole current into an oxide in a similar manner to HEI (see Chapter 33: “Physics”, Equation 3-311).

**IMPACT** invokes the empirical impact ionization model with ionization coefficients taken from [48]. More rigorous impact ionization models may be specified with the **IMPACT** statement.

**MASS.TUNNEL** specifies the effective mass for band to band tunneling (see Chapter 33: “Physics”, Equations 3-293 and 3-294).

**N.CONCANNON** enables the Concannon gate current model for electrons.

**NEARFLG** specifies the model used for oxide transport when HEI or HHI are used. The default is false which sets a purely drift based model assigning gate current to the electrodes where the electric field lines through the oxide terminate. Setting **NEARFLG** replaces this model with one assuming the gate current is flowing the electrode physically nearest the point of injection. This assumes a purely diffusion transport mechanism. Setting **NEARFLG** for devices with only one gate or a coarse mesh is advised.

**NEWIMPACT** specifies that impact ionization should use the form described in Chapter 33: “Physics”, Equation 3-256.

**OLDIMPACT** specifies that the impact ionization should use the form described in Chapter 33: “Physics”, Equation 3-255.

**P.CONCANNON** enables the Concannon gate current model for holes.

## Classical Carrier Statistics Model Flags

**BGN** specifies band-gap narrowing (see Chapter 33: “Physics”, Equation 3-40).

**BGN.KLA** specifies that the bandgap narrowing model will use the Klaassen coefficients.

**BGN.KLASSEN** enables the use of Klaassen's parameters for defaults for bandgap narrowing parameters (see Chapter 33: “Physics”, Table 3-3-3).

**BGN.SLOTBOOM** specifies band-gap narrowing using the original Slotboom coefficients (see also Equation 3-40).

**BOLTZMANN** specifies that Boltzmann carrier statistics be used (see Chapter 33: “Physics”, Equations 3-25 and 3-26).

**BQP.N** enables the BQP model for electrons.

**BQP.P** enables the BQP model for holes.

**BQP.NGAMMA** sets the value of BQP  $\gamma$  factor for electrons.

**BQP.NALPHA** sets the value of BQP  $\alpha$  factor for electrons.

**BQP.NEUMANN** uses explicitly enforced Neumann boundary conditions instead of the implicit implementation.

**BQP.PALPHA** sets the value of BQP  $\alpha$  factor for holes.

**BQP.PGAMMA** sets the value of BQP  $\gamma$  factor for holes.

**BQP.QDIR** sets the direction of principal quantization.

**FERMIDIRAC** specifies that Fermi-Dirac carrier statistics be used (see Chapter 33: “Physics”, Equations 3-25 – 3-70).

**INCOMPLETE** accounts for incomplete ionization of impurities in Fermi-Dirac statistics (see Chapter 33: “Physics”, Equations 3-47 and 3-48).

**IONIZ** accounts for complete ionization of heavily doped silicon when using **INCOMPLETE**.

All parameters prefixed **BQP** are specific to the BQP model. Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.3: “Bohm Quantum Potential (BQP)” along with the parameters above describe this in detail.

### Quantum Carrier Statistics Model Flags

**ALT.SCHRO** specifies usage of an alternate Schrodinger solver.

**BC.QUANT** specifies Dirichlet boundary conditions for all insulator interfaces for the quantum transport equation.

**CALC.FERMI** specifies that the Fermi level used in calculation of the quantum carrier concentration in the Schrodinger-Poisson model is calculated from the classic carrier concentrations (Chapter 13: “Quantum: Quantum Effect Simulator”, Table 13-1 ).

**DG.N** is an alias for **QUANTUM** (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.2: “Density Gradient (Quantum Moments Model)”).

**DG.P** is an alias for **P.QUANTUM** (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.2: “Density Gradient (Quantum Moments Model)”).

**DGN.GAMMA** specifies the fit factor for electrons for the electron density gradient model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Equation 13-4).

**DGP.GAMMA** specifies the fit factor for holes for the hole density gradient model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Equation 13-5).

**DGLOG** specifies that the gradient of the log of concentration is to be used in the calculation of the quantum potential in the density gradient model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Equation 13-6).

**DGROOT** specifies that the gradient of the root of the concentration is to be used in the calculation of the quantum potential in the density gradient model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Equation 13-7).

**EIGENS** specifies the number of eigenstates solved for by the Poisson-Schrodinger solver (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”).

**EF.TOL** controls the eigenvector tolerance on numerical accuracy for the alternate eigenvalue solver enabled by the **NEW.EIG** parameter.

**EV.TOL** controls eigenvalue tolerance on numerical accuracy for the alternate eigenvalue solver enabled by the **NEW.EIG** parameter.

**FAST.EIG** enables a computationally efficient version of the eigen-value solver.

**FIXED.FERMI** specifies that a constant Fermi level is used along each individual slice in the Y direction for carrier concentration calculation in the Schrodinger-Poisson Model (Chapter 13: “Quantum: Quantum Effect Simulator”, Table 13-1 ).

**HANSCHQM** turns on the Hansch quantum effects approximation model for N channel MOS devices (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.4.1: “Hansch’s Model”).

**N.DORT** turns on the Van Dort quantum effects approximation model for N channel MOS devices (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.4.2: “Van Dort’s Model”).

**NEW.EIG** enables an alternate eigenvalue solver that obtains eigenvectors using the INVERSE ITERATION method.

**N.QUANTUM** is an alias for QUANTUM (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.2: “Density Gradient (Quantum Moments Model)”).

**NEW.SCHRO** specifies that the new non-rectilinear self-consistent Schrodinger-Poisson solver will be used for an ATLAS mesh (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”). When this is specified, the Schrodinger solver mesh should also be specified using the SX.MESH and SY.MESH statements.

**NUM.BAND** specifies the number of valence bands to retain for Schrodinger Poisson solutions.

**NUM.DIRECT** specifies the number of conduction band directions in the  $k$  space to retain for Schrodinger Poisson solutions.

**OX.POISSON** calculates the quasi-Fermi levels in insulators for Schrodinger Poisson solutions.

**OX.SCHRO** specifies that the band edges of insulators are included in the solution of Schrodinger's Equation in self-consistent solutions of the Schrodinger-Poisson Model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”).

**P.DORT** turns on the Van Dort quantum effects approximation model for P channel MOS devices (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.4.2: “Van Dort’s Model”).

**POST.SCHRO** specifies to calculate the Schrodinger Equation (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”) for quantum effects as a post processing step.

**P.SCHRODING** computes the self consistent Schrodinger Poisson for holes.

**QMINCONC** specifies the minimum carrier concentration considered in the gradient calculations of the density gradient model or in Poisson's Equation in the self-consistent Schrodinger-Poisson Model (see Chapter 13: “Quantum: Quantum Effect Simulator”, Sections 13.1: “Self-Consistent Coupled Schrodinger Poisson Model” and 13.2: “Density Gradient (Quantum Moments Model)”).

**QUANTUM** enables the density gradient (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.2: “Density Gradient (Quantum Moments Model)”).

**QX.MIN**, **QX.MAX** specify the minimum and maximum extent of the Poisson-Schrodinger solver along the x-axis direction (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”).

**SCHRO** enables the Poisson-Schrodinger solver (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”). This can be used for zero carrier solutions only (specified by METHOD CARRIERS=0). This is typically combined with the EIGENS parameter to control the number of eigenstates calculated. This is a 1D solver that is solved within the mesh between limits set by QX.MIN and QX.MAX.

## Energy Balance Simulation Flags

**E.TAUR.VAR** specifies that electron temperature dependent energy relaxation time is used. Use the `TRE.T1`, `TRE.T2`, `TRE.T3`, `TRE.W1`, `TRE.W2`, and `TRE.W3` parameters on the material statement to specifies the energy relaxation time.

**H.TAUR.VAR** specifies that hole temperature dependent energy relaxation time is used. Use `TRH.T1`, `TRH.T2`, `TRH.T3`, `TRH.W1`, `TRH.W2`, and `TRH.W3` parameters on the material statement to specifies the energy relaxation time.

**HCTE** specifies that both electron and hole temperature will be solved.

**HCTE.EL** specifies that electron temperature will be solved.

**HCTE.HO** specifies that hole temperature will be solved.

**F.KSN** specifies the name of a file containing a C-INTERPRETER function specifying the electron Peltier coefficient as a function of electron energy.

**F.KSP** specifies the name of a file containing a C-INTERPRETER function specifying the hole Peltier coefficient as a function of hole energy.

**GR.HEAT** includes generation/recombination heat source terms in the lattice heat flow equation.

**JOULE.HEAT** includes the Joule heat source terms in the lattice heat flow equation.

**KSN** specifies which hot carrier transport model will be used for electrons. `KSN=0` selects the hydrodynamic model and `KSN=-1` selects the energy balance model.

**KSP** specifies which hot carrier transport model will be used for holes. `KSP=0` selects the hydrodynamic model and `KSP=-1` selects the energy balance model.

**TAUMOB** specifies the dependence of relaxation times with carrier temperature in the mobility definition. If **TAUMOB** is specified, the values of MATERIAL statement parameters `TAUMOB.EL` and `TAUMOB.HO` are dependent on the carrier temperature.

**TAUTEM** specifies the dependence of relaxation times with carrier temperature. If **TAUTEM** is specified, the values of MATERIAL statement parameters `TAUREL.EL` and `TAUREL.HO` are dependent on carrier temperature.

**N.TEMP** or **HCTE.EL** specifies that the electron temperature equation will be solved.

**P.TEMP** or **HCTE.HO** specifies that the hole temperature equation will be solved.

**PASSLER** enables Passler's bandgap versus temperature model.

**PT.HEAT** includes Peltier-Thomson heat sources in the lattice heat flow equation.

## Lattice Heating Simulation Flags

**HEAT.FULL** enables all thermal sources and sinks (Joule heat, generation-recombination heat, and Peltier Thomson heat).

**HEAT.PETHOM** can be used to turn off the Peltier-Thomson heat source in the `HEAT.FULL` option.

**LAT.TEMP** or **L.TEMP** specifies that the lattice temperature equation will be solved. For lattice heating simulation there must be at least one thermal contact defined using the `THERMCONTACT` statement.

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**Note:** These parameters should only be specified if `GIGA` or `GIGA3D` is enabled on your system.

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## Model Macros

**BIPOLAR** selects a default set of models which are used when simulating bipolar devices. The bipolar models are CONMOB, FLDMOB, BGN, CONSRH, and AUGER.

**BIPOLAR2** selects an alternative default set of models which are used when simulating bipolar devices. The bipolar models are FERMI, KLA, KLASRH, KLAAUG, FLDMOB, and BGN.

**ERASE** specifies a default set of models which are used to simulate EEPROM erasure. When it's specified, the MOS, FNORD, IMPACT, and BBT.KL models will be used.

**MOS** specifies a default set of models for MOS devices. The MOS models are CVT, SRH and FERMI.

**PROGRAM** specifies a default set of models used when writing to EEPROMS. When PROGRAM is specified, the MOS, HEI, and IMPACT models will be used.

## General Parameters

**ALL** enables solution for both electrons and holes.

**BOUND.TRAP** enables modeling of traps coincident with ohmic boundaries.

**CARRIERS** specifies the number of carriers to simulate, which should be 0, 1 or 2. The alias is NUMCARR.

**CHUANG** enables the Chuang gain/radiative recombination model.

**DEVICE** specifies which device in MIXEDMODE simulation the MODELS statement should apply to.

**DRIFT.DIFF** specifies that the drift-diffusion transport model is to be used. This implies that the electron and hole carrier temperature equations will not be solved.

**ELECTRONS** specifies that the electron continuity equation is included in simulation.

**G.EMPIRICAL** enables the empirical gain model from Chapter 33: "Physics", Section 3.9.4: "The Empirical Gain Model" (GAINMOD=2).

**G.STANDARD** enables the gain model from Chapter 33: "Physics", Section 3.9.3: "The Standard Gain Model" (GAINMOD=1).

**HOLE** specifies that the hole continuity equation is included in simulation.

**ISHIKAWA** enables Ishikawa's strain model for InGaAs/InGaAsP/InGaP (see Chapter 33: "Physics", Section 3.9.10: "Ishikawa's Strain Effects Model").

**K.P** enables using the k\*p model effective masses and band edge energies for drift-diffusion simulation.

**LI** enables the Li gain/radiative recombination model.

**LORENTZ** enables Lorentz gain broadening.

**MATERIAL** specifies which material from Table B-1 in Appendix B: "Material Systems", will apply to the MODELS statement. If a material is specified, then all regions defined as being composed of that material will be affected.

**MOS2** specifies a default set of models for MOS devices. The MOS2 models are CVT, SRH, FERMI and BGN.

**NAME** specifies which region will be applied to the MODELS statement. Note that the name must match the name specified in the NAME parameter of the REGION statement.

**PRT.BAND** enables run-time output of regional band parameter model information.

**PRT.COMP** enables run-time output of regional composition information.

**PRT.FLAGS** enables run-time output of regional model flag information.

**PRT.IMPACT** enables run-time output of regional impact ionization model information.

**PRT.RECOM** enables run-time output of regional recombination model information.

**PRT.THERM** enables run-time output of regional thermal model information.

**PRINT** prints the status of all models, a variety of coefficients, and constants. We recommended that you include this parameter in all ATLAS runs.

**PRINT.REGION** prints the model status and coefficients for the specified region.

**PRINT.MATERIAL** prints the model status and coefficients for the specified material.

**REGION** specifies the region number for this MODELS statement. The alias is NUMBER.

**SPEC.NAME** specifies the name of a file to collect the emission spectrum from the LASER simulator.

**SPONTANEOUS** includes the radiative recombination rates derived from the LI, YAN or CHUANG model into the drift diffusion.

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**Note:** This requires additional computational resources since the radiative rate must be numerically integrated for each grid point.

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**TAYAMAYA** enables the from Chapter 33: “Physics”, Section 3.9.5: “Tayamaya's Gain Model” (GAINMOD=3).

**TEMPERATURE** specifies the temperature in Kelvin.

**UNSAT.FERRO** enables unsaturated loop modeling for ferroelectrics.

**YAN** enables the Li gain/radiative recombination model.

## Model Dependent Parameters

### ARORA Model Parameters

The parameters that can only be used with the ARORA model (see Chapter 33: “Physics”, Equations 3-146 and 3-147) are: AR.MU1N, AR.MU2N, AR.MU1P, and AR.MU2P.

### BBT.KL and BBT.STD Model Parameters

The parameters used with the BBT.KL model are BB.A1 and BB.B. The BB.A2 and BB.B parameters are used with the BBT.STD model. The BB.A1 and BB.A2 parameters are the pre-exponential coefficients in the band-to-band tunneling models. The BB.B parameter is the exponential coefficient used in both models. The default value of BB.B depends on which model is chosen (see Chapter 33: “Physics”, Equation 3-302).

### CCSMOB Model Parameters

The CCS.EA, CCS.EB, CCS.HA, and CCS.HB parameters describe the dependence of mobility on doping, carrier concentration, and temperature (see Chapter 33: “Physics”, Equations 3-149 – 3-153).

### FLDMOB Model Parameters

**B.ELECTRONS** is used in the field-dependent mobility expression for EVSATMOD=0 (see Chapter 33: “Physics”, Equation 3-225).

**B.HOLES** is used in the field-dependent mobility expression for EVSATMOD=0 (see Chapter 33: “Physics”, Equation 3-226).

**E0** is used in the field dependent mobility model for EVSATMOD=1 (see Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-50).

**EVSATMOD** specifies which parallel field dependent mobility model (see Chapter 33: “Physics”, Equation 3-225 and Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-50) should be used for electrons. The value of **EVSATMOD** should be assigned as follows:

1. Use the standard saturation model. You also can apply the option parameter, **MOBTEM.SIMPL** (see Chapter 33: “Physics”, the “Carrier Temperature Dependent Mobility” Section on page 3-59 for more information).
2. Use the negative differential velocity saturation model
3. Use a simple velocity limiting model.

In most cases the default value of 1 should be used.

**HVSATMOD** specifies which parallel field dependent mobility model (see Chapter 33: “Physics”, Equation 3-226 and Chapter 5: “Blaze: Compound Material 2D Simulator”, Equation 5-51) should be used for holes. The value of **HVSATMOD** should be assigned as follows:

1. Use the standard saturation model
2. Use a simple velocity limiting model.

In most cases the default value of 1 should be used.

#### Fowler-Nordheim Tunneling Model Parameters

The parameters used in this model are **F.AE** and **F.BE**. **F.AE** is the pre-exponential factor and **F.BE** is the exponential coefficient (see Chapter 33: “Physics”, Equation 3-307).

#### WATT or SURFMOB Model Parameters

The parameters that can be used with the **WATT** model, include: **ALN1**, **ALN2**, **ALN3**, **ALP1**, **ALP2**, **ALP3**, **ETAN**, **ETAP**, **MREFN1**, **MREFN2**, **MREFN3**, **MREFP1**, **MREFP2**, and **MREFP3** (see Chapter 33: “Physics”, Equations 3-217 and 3-218).

#### TFLDMB1 and TFLDMB2 Model Parameters

**ACC.SF** specifies the accumulation saturation factor which describes the ratio of the majority carrier concentration in the accumulation layer before and after bending of conductivity and valance bands.

**INV.SF** specifies the inversion saturation factor which describes the ratio of the majority carrier concentration in the inversion layer before and after the bending of conductivity and valance bands.

**OX.BOTTOM** specifies the coordinate of the bottom edge of the gate oxide for a MOSFET transistor.

**OX.LEFT** specifies the coordinate of the left edge of the gate oxide for a MOSFET transistor.

**OX.RIGHT** specifies the coordinate of the right edge of the gate oxide for a MOSFET transistor.

#### CONCANNON Model Parameters

**CGATE.N** specifies an empirical tuning factor for electrons in the Concannon gate current model.

**CGATE.P** specifies an empirical tuning factor for holes in the Concannon gate current model.

**PEFF.N** specifies an effective barrier height for electrons in the Concannon gate current model.

**PEFF.P** specifies an effective barrier height for holes in the Concannon gate current model.

**THETA.N** specifies the critical rejection angle for electrons in the Concannon gate current model.

**THETA.P** specifies the critical rejection angle for electrons in the Concannon gate current model.

**C0** specifies the electron distribution weight factor in the Concannon gate current model.

**CHIA** specifies the electron distribution function constant in the Concannon gate current model.

**CHIB** specifies the electron distribution function constant in the Concannon gate current model.

**CHI.HOLES** specifies the hole distribution function constant in the Concannon gate current model.



**ENERGY.STEP** specifies the energy step for numeric integration in the Concannon gate current model.

**INFINITY** specifies the highest energy in numeric integration in the Concannon gate current model.

**PATH.N** specifies the mean free path in the oxide for electrons in the Concannon gate current model.

**PATH.P** specifies the mean free path in the oxide for holes in the Concannon gate current model.

## HEI Model Parameters

The parameters which may be used with the HEI model include: `IG.ELINR`, `IG.HLINR`, `IG.ELINF`, `IG.HLINF`, `IG.EBETA`, `IG.HBETA`, `IG.EETA`, `IG.HETA`, `IG.EEOX`, `IG.HEOX`, `IG.EB0`, `IG.HB0`.

## N.DORT and P.DORT Model Parameters

**B.DORT** user-specifiable model parameter for the Van Dort quantum effects approximation model.

**D.DORT** user-specifiable model parameter for the Van Dort quantum effects approximation model.

## LASER Simulation Parameters

**CAVITY.LENGTH** specifies the cavity length in the longitudinal direction (in  $\mu\text{m}$ ).

**GAINMOD** specifies the local optical gain model to be used. `GAINMOD=0` specifies that no optical gain model will be used. `GAINMOD=1` specifies that the complex frequency-dependent gain model will be used (see Chapter 33: “Physics”, Section 3.9.4: “The Empirical Gain Model”). `GAINMOD=2` specifies that the simple gain model will be used (see Chapter 33: “Physics”, Section 3.9.3: “The Standard Gain Model”).

**LAS.ABSOR\_SAT** enables the non-linear absorption loss saturation model.

**LAS.ABSORPTION** enables the absorption loss model in LASER.

**LAS.EINIT**, **LAS.EFINAL** specify the lower and upper photon energies. LASER will calculate multiple longitudinal photon rates within this range. Using wide ranges can slow down simulation.

**LAS.ESEP** specifies the photon energy separation. If this is not specified, LASER will automatically calculate the number of longitudinal modes based on the cavity length and the energy range.

**LAS.ETRANS** specifies that the Helmholtz solver should use the transverse mode with the eigen-energy closes to the energy specified by the `LAS.TRANS_ENERGY` parameter.

**LAS.FCARRIER** enables the free carrier loss model in LASER.

**LAS.GAIN\_SAT** enables the non-linear gain saturation model.

**LAS.ITMAX** specifies the maximum number of iterations allowed for LASER simulation at each bias point.

**LAS.LOSSES** specifies the total losses in Equation 8-5.

**LAS.MIRROR** specifies the percentage facet reflectivity (both facets are assumed to have this value of reflectivity) for the mirror loss in Laser. 100% reflectivity is equivalent to no mirror loss.

**LAS.NEFF** specifies the effective refractive index in Equation 9-2.

**LAS.NMODE** specifies the number of transverse modes simulated.

**LAS.NX** specifies the number of discrete samples in the laser mesh in the X direction.

**LAS.NY** specifies the number of discrete samples in the laser mesh in the Y direction.

**LAS.OMEGA** specifies the lasing frequency to be used in Chapter 8: “Laser: Edge Emitting Simulator”, Equation 8-1. If model 2 is used for simulation, then this parameter specifies an estimate of the lasing frequency. Instead of using this parameter, `PHOTON.ENERGY` can be used to specify photon energy.

**LAS.REFLECT** specifies that the Helmholtz equation should be solved with the Y axis (X=0) as an axis of symmetry.

**LAS.RF** specifies the front mirror reflectivity in percent.

**LAS.RR** specifies the rear mirror reflectivity in percent.

**LAS.SIN** specifies an initial photon density in the fundamental lasing mode. This value provides an initial guess for subsequent iterations. This parameter is used only when the single frequency model has been selected.

**LAS.SPECSAVE** the spectrum file will be saved after every LAS . SPECSAVE LASER solution steps.

**LAS.SPONTANEOUS** enables the physically based model for spontaneous emission to be used.

**LAS.TAUSS** specifies the iteration parameter to be used for the photon rate equation when solving Equation 9-8.

**LAS.TIMERATE** specifies that the time dependent photon rate equation will be used in a transient laser simulation.

**LAS.TOLER** specifies the desired accuracy in photon areas.

**LAS.TRANS\_ENERGY** specifies the transverse mode energy for mode selection with LAS . ETRANS set.

**LAS.XMAX**, **LAS.XMIN**, **LAS.YMAX** and **LAS.YMIN** specify the maximum and minimum limits on the laser Helmholtz solution mesh.

**LAS\_MAXCH** specifies the maximum allowable relative change in photon densities between iterations. Rapid changes of the photon densities can cause convergence problems.

**LASER** enables the LASER simulation.

**LMODE** specifies that multiple longitudinal models are to be taken into account during the LASER simulation.

**PHOTON.ENERGY** specifies the energy of photons. If model 2 is used for simulation, this parameter specifies only an initial estimate of the photon energy. Instead of using this parameter, LAS . OMEGA can be used to specify the lasing frequency.

**SPEC.NAME** specifies the name of a spectrum file, which LASER will produce for each bias point if the LMODES parameter has been specified.

### Model Selection Example

This example selects concentration and field dependent mobilities, SRH recombination, and Auger recombination. This is a typical model set for bipolar simulation. The simulation temperature is 290K.

```
MODELS CONMOB FLDMOB SRH AUGER TEMP=290
```

### Confirming Model Selection

To echo back model selections, parameters and material constants use

```
MODELS PRINT
```

---

**Note:** For the best model selection for different applications, see the Standard Examples set (see also Chapter 2: "Getting Started with ATLAS", Section 2.4: "Accessing The Examples" for more information about to how to access these examples ).

---

## 18.30: MQW

MQW defines multiple quantum well structures in an existing device structure. This statement should follow all other structure definition statements (i.e., MESH, REGION, ELECTRODE, and DOPING).

**Note:** The method for defining quantum wells using the MQW statement described in this section has been superseded by the method described in Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.6: “Multiple Quantum Well Model”. Therefore, we highly recommended that you use to the newer syntax.

### Syntax

MQW<parameters>

| Parameter | Type      | Default  | Units |
|-----------|-----------|----------|-------|
| ACCEPTORS | Real      | 0.0      | cm-3  |
| ALT.SCHRO | Logical   | False    |       |
| ASTR      | Real      | 0.0      |       |
| BSTR      | Real      | 0.0      |       |
| CSTR      | Real      | 0.0      |       |
| DELTA     | Real      | 0.341    | eV    |
| DONORS    | Real      | 0.0      | cm-3  |
| DSTR      | Real      | 0.0      |       |
| EPSILON   | Real      | 0.0      |       |
| ESTR      | Real      | 0.0      |       |
| FSTR      | Real      | 0.0      |       |
| GAIN0     | Real      | 1.0      |       |
| GAMMA0    | Real      | 2.0×10-3 | eV    |
| GSCALE    | Real      | 1.0      |       |
| ISHIKAWA  | Logical   | False    |       |
| LI        | Logical   | False    |       |
| LORENTZ   | Logical   | False    |       |
| MATERIAL  | Character |          |       |
| MC        | Real      | 0.067    |       |
| MHH       | Real      | 0.62     |       |
| MLH       | Real      | 0.087    |       |
| MSTAR     | Real      | 0.053    |       |

|             |         |                       |         |
|-------------|---------|-----------------------|---------|
| NBS         | Integer | 15                    |         |
| NWELL       | Integer | 1                     |         |
| NX          | Integer | 10                    |         |
| NY          | Integer | 10                    |         |
| RESOLVE     | Logical | True                  |         |
| SPONTANEOUS | Logical | False                 |         |
| STRAIN      | Real    | 0.0                   |         |
| STABLE      | Integer | 0                     |         |
| SY          | Real    |                       | microns |
| TAU.IN      | Real    | $3.3 \times 10^{-13}$ | seconds |
| TE.MODES    | Logical | True                  |         |
| WW          | Real    |                       | microns |
| WB          | Real    |                       | microns |
| XCOMP       | Real    | 0.0                   |         |
| XMAX        | Real    |                       | microns |
| XMIN        | Real    |                       | microns |
| YAN         | Logical | False                 |         |
| YCOMP       | Real    | 0.0                   |         |
| YMAX        | Real    |                       | microns |
| YMIN        | Real    |                       | microns |

## Description

The MQW regions will be added to ATLAS when you specify the MQW statement. This statement is necessary to correctly model the recombination and gain effects of these MQW regions.

The multiple quantum well structure is restricted to place the quantum wells only parallel to the X axis (perpendicular to the Y axis). Also, if more than one well is specified, then each well will have the same width defined by the WW parameter. Each barrier between wells will then have the same width defined by the WB parameter.

The MQW structure is located within the rectangle defined by the XMIN, XMAX, YMIN, and YMAX parameters. In the Y direction, the wells are centered within the span of YMIN to YMAX. Make sure that the difference between YMIN and YMAX is larger than the sum of the well width (WW) and the barrier width (WB) multiplied by the number of wells (NWELL). In the X direction, the wells extend the entire length from XMIN to XMAX.

The quantum well material is specified by the MATERIAL parameter, modified by the composition fractions: XCOMP and YCOMP. The barrier material is given by the material specified in the region, where the wells are defined.

This implementation solves the Schrodinger's equation (see Chapter 13: "Quantum: Quantum Effect Simulator", Equations 13-1 and 13-2) for each quantum well, in order to calculate the quantum well-bound state energies and carrier distributions in the wells. You can specify the number of bound states

to use for this calculation with the NBS parameter. For laser gain calculations, only the lowest bound state energy in the conduction band and the highest bound state energy in the valence band are used. These bound state energies feed directly into the gain model and spontaneous emission models are shown in Chapter 33: “Physics”, Section 3.9: “Optoelectronic Models”

## Parameters

**ACCEPTORS** specifies a uniform density of ionized acceptors in the quantum wells.

**ALT.SCHRO** specifies that the alternative Schrodinger solver should be used in the calculations.

**ASTR, BSTR, CSTR, DSTR, ESTR, and FSTR** specify coefficients to calculate the effective masses in the strained quantum well.

**DELTA** specifies the spin orbital splitting energy in the quantum well.

**DONORS** specifies the uniform density of ionized donors in the quantum wells.

**EPSILON** specifies the high frequency permittivity to used in calculating the gain and radiative recombinations.

**GAIN0** scaling factor for the MQW gain models.

**GAMMA0** specifies the width in eV (Note:  $GAMMA0 = h / TAU \cdot IN$ ).

**GSCALE** specifies a scale factor to be multiplied by the optical gain.

**ISHIKAWA** specifies that the Ishikawa model [133] is used to account for strain effects (see Chapter 33: “Physics”, Section 3.9.10: “Ishikawa's Strain Effects Model” for more information).

**LI** specifies that the Li model [40] be used for spontaneous emission in multiple quantum wells. The **DELTA**, **MSTAR**, **MC** and **MHH** parameters can be used with this model.

**LORENTZ** is the Lorentzian line broadening model for MQW gain. The half width of the Lorentzian shape function is controlled by the **GAMMA0** parameter of the MQW statement. You can also set the **TAU.IN** parameter to specify the intraband relaxation time in seconds. For more information about the Lorentzian line broadening model, see Chapter 33: “Physics”, Section 3.9.9: “Lorentzian Gain Broadening”.

**MATERIAL** specifies the name of the material to be used in the wells. The barrier material is taken from whatever material is already in the structure at the MQW location.

**MC** is the conduction band effective mass.

**MHH** is the heavy hole effective mass.

**MLH** is the light hole effective mass.

**MSTAR** disperses energy in the conduction band. This doesn't necessarily equate to the conduction band effective mass, see [128].

**NBS** defines the number of bound states used in solving the Schrodinger equation.

**NWELL** specifies the number of quantum wells.

**NX, NY** specify the number of mesh points in the X and Y direction for resolving the MQW structure. Make sure that these are specified large enough to resolve the individual quantum wells. **NY** is defined as:

$$NY = \left\lceil \frac{YMAX - YMIN}{\langle YGridSpacing(\mu m) \rangle} \right\rceil + 1 \quad 18-4$$

**RESOLVE** specifies whether the band edge discontinuities at the well edges are resolved by the device equations.

**SPONTANEOUS** specifies whether the quantum well spontaneous recombination is included in the device continuity equations.

**STABLE** specifies the table row to be used for coefficients to calculate the effective masses in strained quantum wells.

**STRAIN** specifies the strain percentage in the quantum well.

**SY** specifies the maximum mesh spacing to be applied in the y direction through the quantum wells.

**TAU.IN** specifies the intraband relaxation time in seconds (Note:  $\text{GAMMA0} = h / \text{TAU.IN}$ ).

**TE.MODES** specifies whether TE or TM modes will be used in calculating the asymmetrical factors in the LI model.

**WB** specifies the individual barrier width between wells in microns.

**WW** specifies the individual quantum well width in microns.

**XCOMP** defines the X composition fraction for the wells for ternary and quaternary materials.

**XMIN, XMAX, YMIN, YMAX** specify a rectangular box where the quantum wells are to be simulated. The units of these parameters are in microns.

**YCOMP** defines the Y composition fraction for the wells for quaternary materials.

**YAN** specifies that the Yan model [128] be used for spontaneous emission in multiple quantum wells. The **DELTA, MSTAR, MC** and **MHH** parameters can be used with this model.

---

**Note:** The MQW gain model is now enabled with **GAINMOD=4**, specified in the **MODELS** statement.

---

## 18.31: OPTIONS

OPTIONS sets options for an entire run.

### Syntax

```
OPTIONS [<rcp>]
```

| Parameter  | Type    | Default | Units |
|------------|---------|---------|-------|
| CINT.DLL   | Logical | False   |       |
| CINT.MODE  | Integer |         |       |
| FAIL.QUIT  | Logical | False   |       |
| NORMAL     | Logical | True    |       |
| QUIET      | Logical | False   |       |
| TRANSITION | Logical | False   |       |
| VERBOSE    | Logical | False   |       |

### Description

**CINT.DLL** specifies that ATLAS should treat subsequent C-Interpreter files with the extension ".so" (on UNIX based machines) or ".dll" (on Windows based machines) as shared object libraries instead of C code files. The shared object libraries will be dynamically loaded at run-time.

**CINT.MODE** specifies the C-Interpreter compilation mode. If CINT.MODE is set to 0, all subsequent C-Interpreter files will be compiled in optimize mode. If CINT.MODE is set to 1, all subsequent C-Interpreter files will be compiled in command-line debug mode. If CINT.MODE is set to 2, all subsequent C-Interpreter files will be compiled in GUI debug mode. The default compilation mode is optimize.

**FAIL.QUIT** if enabled will cause the simulation to quit if the number of cutbacks exceeds the number specified by the MAXTRAP parameter of the METHOD statement and TRAP is enabled.

**rcp** is one or more of the run control parameters described below. These parameters, which are not normally used, specify debugging options.

**NORMAL** is the default specification for run-time output filtering. At this setting ATLAS prints out the most relevant information (e.g., mesh statistics, terminal voltages, currents, warnings, and error messages).

**QUIET** specifies the maximum of filtering of run-time output.

**TRANSITION** specifies that during calculation of bound state energies for optical transitions. The allowable transitions are printed to the run-time output.

**VERBOSE** specifies the minimum filtering of run-time output. You should specify VERBOSE if you want output of residual norms.

### Example

The following syntax can be used to provide extra debugging output.

```
OPTION VERBOSE
```

## 18.32: OUTPUT

OUTPUT allows you to specify the data that will be stored in standard structure format files.

### Syntax

OUTPUT <parameters>

| Parameter   | Type    | Default | Units |
|-------------|---------|---------|-------|
| ANGLE       | Logical | False   |       |
| AREA        | Logical | False   |       |
| BAND.PARAM  | Logical | False   |       |
| BAND.TEMP   | Logical | false   |       |
| CHARGE      | Logical | False   |       |
| CON.BAND    | Logical | False   |       |
| CONTACT     | Integer |         |       |
| DELTAV      | Real    | 0.1     | Volts |
| DEVDEG      | Logical | False   |       |
| E.FIELD     | Logical | True    |       |
| E.LINES     | Logical | False   |       |
| E.MOBILITY  | Logical | False   |       |
| E.TEMP      | Logical | True    |       |
| E.VELOCITY  | Logical | False   |       |
| EFIELD      | Logical | True    |       |
| EIGENS      | Integer | 0       |       |
| EX.FIELD    | Logical | True    |       |
| EX.VELOCITY | Logical | False   |       |
| EY.FIELD    | Logical | True    |       |
| EY.VELOCITY | Logical | False   |       |
| FLOWLINES   | Logical | False   |       |
| H.MOBILITY  | Logical | False   |       |
| H.TEMP      | Logical | True    |       |
| H.VELOCITY  | Logical | False   |       |
| HX.VELOCITY | Logical | False   |       |
| HY.VELOCITY | Logical | False   |       |
| IMPACT      | Logical | True    |       |



| Parameter    | Type      | Default | Units |
|--------------|-----------|---------|-------|
| INV.AREA     | Logical   | False   |       |
| INV.ANGLE    | Logical   | False   |       |
| INAME        | Character |         |       |
| JX.ELECTRON  | Logical   | True    |       |
| J.ELECTRON   | Logical   | True    |       |
| JY.ELECTRON  | Logical   | True    |       |
| J.CONDUC     | Logical   | True    |       |
| J.DISP       | Logical   | False   |       |
| J.HOLE       | Logical   | True    |       |
| J.TOTAL      | Logical   | True    |       |
| JX.CONDUC    | Logical   | False   |       |
| JX.HOLE      | Logical   | True    |       |
| JX.TOTAL     | Logical   | True    |       |
| JY.CONDUC    | Logical   | False   |       |
| JY.HOLE      | Logical   | True    |       |
| JY.TOTAL     | Logical   | True    |       |
| KSN          | Logical   | False   |       |
| KSP          | Logical   | False   |       |
| LRATIO       | Real      | 1.0     |       |
| MINSET       | Logical   | False   |       |
| N.LINES      | Integer   | 20      |       |
| NOISE        | Logical   | False   |       |
| NOISE.IMP    | Logical   | False   |       |
| NOISE.ALL    | Logical   | False   |       |
| OPT.INTENS   | Logical   | False   |       |
| OX.CHARGE    | Logical   | False   |       |
| OLD.AVG      | Logical   | False   |       |
| PERMITTIVITY | Logical   | False   |       |
| PHOTOGEN     | Logical   | True    |       |
| QFN          | Logical   | True    |       |
| QFP          | Logical   | True    |       |
| QSS          | Logical   | False   |       |

| Parameter   | Type    | Default | Units |
|-------------|---------|---------|-------|
| RECOMB      | Logical | True    |       |
| TAURN       | Logical | False   |       |
| TAURP       | Logical | False   |       |
| TOT.DOPING  | Logical | False   |       |
| TRAPS       | Logical | True    |       |
| TRAPS.FT    | Logical | False   |       |
| U.AUGER     | Logical | False   |       |
| U.RADIATIVE | Logical | False   |       |
| U.SRH       | Logical | False   |       |
| VAL.BAND    | Logical | False   |       |
| VECTORS     | Logical | False   |       |
| X.COMP      | Logical | True    |       |
| Y.COMP      | Logical | False   |       |

**Description**

**BAND.PARAM** specifies that the band parameters (e.g., ni, Ne, Nv, and c) are included in the standard structure file.

**BAND.TEMP** outputs the following temperature dependent band parameters.

- $\sqrt{\text{electron concentration} * \text{hole concentration}}$  ( $\text{cm}^{-3}$ )
- Conduction band effective density of states ( $\text{cm}^{-3}$ )
- Valence band effective density of states ( $\text{cm}^{-3}$ )
- Energy band gap (eV)
- Conduction Band Energy (eV)
- Valence Band Energy (eV)

**CHARGE** specifies that the net charge will be included in the standard structure file.

**CON.BAND** specifies that the conduction band edge will be included in the standard structure file.

**DEVDEG** causes the distribution of acceptor/donor like traps on the interface, hot electron/hole current density on the interface, and trapped electron/holes to be written to the structure file.

**E.FIELD** or **EFIELD** specifies that total electric field will be included in the standard structure file.

**E.LINES** specifies the electric field lines will be included in the standard structure file.

**E.MOBILITY** specifies that electron mobility will be included in the standard structure file.

**E.TEMP** specifies that the electron temperature will be included in the standard structure file.

**E.VELOCITY** specifies that the total electron velocity will be included in the standard structure file.

**EIGENS** specifies the maximum number of eigen energies and eigen functions to be written to the structure file from a Poisson- Schrodinger solution.

**EX.FIELD** specifies that the x-component of electric field will be included in the standard structure file.

**EX.VELOCITY** specifies that the x-component of electron velocity will be included in the standard structure file.

**EY.FIELD** specifies that the y-component of electric field will be included in the standard structure file.

**EY.VELOCITY** specifies that the y-component of electron velocity will be included in the standard structure file.

**FLOWLINES** specifies that the current flowlines will be included in the standard structure file.

**H.MOBILITY** specifies that hole mobility will be included in the standard structure file.

**H.TEMP** specifies that the hole temperature will be included in the standard structure file.

**H.VELOCITY** specifies that the total hole velocity will be included in the standard structure file.

**HX.VELOCITY** specifies that the x-component of hole velocity will be included in the standard structure file.

**HY.VELOCITY** specifies that the y-component of hole velocity will be included in the standard structure file.

**IMPACT** specifies that the impact ionization rate will be included in the standard structure file.

**J.CONDUC** specifies that the total conduction current density will be included in the standard structure file.

**J.DISP** specifies that the total displacement current density will be included in the standard structure file.

**J.ELECTRON** specifies that the total electron current density will be included in the standard structure file.

**J.HOLE** specifies that the total hole current density will be included in the standard structure file.

**J.TOTAL** specifies that the total current density will be included in the standard structure file.

**JX.CONDUC** specifies that the x-component of the total conduction current density will be included in the standard structure file.

**JX.ELECTRON** specifies that the x-component of electron current density will be included in the standard structure file.

**JX.HOLE** specifies that the x-component of hole current density will be included in the standard structure file.

**JX.TOTAL** specifies that the x-component of total current density will be included in the standard structure file.

**JY.CONDUC** specifies that the y-component of the total conduction current density will be included in the standard structure file.

**JY.ELECTRON** specifies that the y-component of electron current density will be included in the standard structure file.

**JY.HOLE** specifies that the y-component of hole current density will be included in the standard structure file.

**JY.TOTAL** specifies that the y-component of total current density will be included in the standard structure file.

**KSN** specifies that electron Peltier coefficients are to be written to any saved structure file.

**KSP** specifies that hole Peltier coefficients are to be written to any saved structure file.

**MINSET** that a minimum set of data (potential, carrier concentration, and electric field) will be included in the standard structure file.

**OPT.INTENS** specifies that optical intensity is included in the standard structure file.

**OX.CHARGE** specifies that fixed oxide charge is include in the standard structure file.

**PERMITTIVITY** specifies the dielectric permittivity is saved.

**PHOTOGEN** specifies that the photogeneration rate will be included in the standard structure file.

**QFN** specifies that the electron quasi-fermi level will be included in the standard structure file.

**QFP** specifies that the hole quasi-fermi level will be included in the standard structure file.

**QSS** specifies that the surface charge will be included in the standard structure file.

**RECOMB** specifies that the recombination rate will be included in the standard structure file.

**TAURN** specifies that electron relaxation times are to be written to any saved structure file.

**TAURP** specifies that hole relaxation times are to be written to any saved structure file.

**TOT.DOPING** specifies that total doping will be included in the standard structure file.

**TRAPS** specifies that trap density information will be included in the standard structure file.

**TRAPS.FT** specifies that the trap probability of occupation will be included in the standard structure file.

**U.AUGER** specifies that the Auger component of recombination is to be written to solution files.

**U.RADIATIVE** specifies that the radiative component of recombination is to be written to solution files.

**U.SRH** specifies that the SRH component of recombination is to be written to solution files.

**VAL.BAND** specifies that the valence band edge will be included in the standard structure file.

**VECTORS** specifies that only vector components will be included in the standard structure file.

**X.COMP** specifies that the composition fraction,  $x$ , is to be written to solution files.

**Y.COMP** specifies that the composition fraction,  $y$ , is to be written to solution files.

### Ionization Integral Parameters

**INAME** specifies the name of a contact for which electric field lines are calculated.

**CONTACT** specifies a contact number for which electric field lines are calculated.

**LRATIO** specifies the spacing ratio between adjacent electric field lines. Defaults to 1.0 for uniform spacing.

**N.LINES** specifies the number of electric field lines.

**DELTA V** since the electric field is near zero at the contact, the electric field line calculations begin at a distance from the contact at which the contact voltage has changed by **DELTA V**. Defaults to 0.1 V.

---

**Note:** See Section 18.40: "SOLVE" and the on-line examples for instructions on using ionization integrals.

---

## NOISE Parameters

**NOISE** selects the total local noise source for output.

**NOISE.IMP** selects the impedance fields for output.

**NOISE.ALL** selects everything for output. Currently, the local noise source, the impedance fields, the short-circuit current Green's function, the individual microscopic noise sources, and the individual local noise sources.

## Averaging Parameters for Vector Quantities

**OLD.AVG** specifies that the current and field quantities will be averaged using an older algorithm (from version 3.0.0.R and back). By default the new method is used.

**ANGLE** specifies that averaging of current and fields will be weighted by the size of the angle of triangles intersecting at the node.

**INV.ANGLE** specifies that averaging of current and fields will be weighted by the inverse of the size of the angle of triangles intersecting at the node.

**AREA** specifies that averaging of current and fields will be weighted by the areas of triangles intersecting at the node.

**INV.AREA** specifies that averaging of current and fields will be weighted by the inverse of areas of triangles intersecting at the node.

---

**Note:** Certain quantities that can be output into the structure file and subsequently displayed using TONYPLOT need special mention. These quantities are evaluated within ATLAS along the links between grid points. They are represented in the structure file at the grid points themselves. As such these quantities are subject to averaging. In particular, electric field and currents are averaged so as to take into account the vector nature of these values. Mobility is simply summed up over all the links surrounding the grid point and divided by the total number of links. Carrier velocities are derived by dividing the averaged current by the carrier density at the grid point and the fundamental electron charge,  $q$ .

---

## An Example of Combining OUTPUT with SOLVE and SAVE

The OUTPUT statement is often used in conjunction with the SAVE statement. The following statement lines specify that current flowlines and electron velocity components are saved in all subsequent standard structure solution files.

```
OUTPUT FLOWLINES EX.VELO EY.VELO
SOLVE PREVIOUS V5=2 OUTF=data1.str MASTER
SAVE OUTF=data2.str
```

### 18.33: PROBE

PROBE allows you to output the minimum value, maximum value, or value at a specified location of any of several distributed quantities to the log file. The quantities will be saved at each bias point of timestep in the log file.

**Note:** PROBE is the most accurate way to determine the value of many parameters calculated by ATLAS. Parameters stored on node points in the structure files for TonyPlot are often interpolated and subject to noise.

#### Syntax

PROBE [MIN | MAX | X=<n>Y=<n> [ DIR=<n> ] ] [ POTENTIAL | N. CONC | P. CONC | N. TEMP | P. TEMP | LAT. TEMP | GENERATION | RECOMBINATION | RSRH | RAUGER | RRADIATIVE ]

| Parameter     | Type      | Default         | Units   |
|---------------|-----------|-----------------|---------|
| ACC. TRAP     | Logical   | False           |         |
| ALPHAN        | Logical   | False           |         |
| ALPHAP        | Logical   | False           |         |
| APCURRENT     | Logical   | False           |         |
| AUGER         | Logical   | False           |         |
| BACK          | Real      | maximum z coord | µm      |
| BEAM          | Integer   |                 |         |
| BOTTOM        | Real      | maximum y coord | µm      |
| CHARGE        | Logical   | False           |         |
| COMPLIANCE    | Real      |                 |         |
| CONCACC. TRAP | Logical   | False           |         |
| CONCDON. TRAP | Logical   | False           |         |
| DEVICE        | Character |                 |         |
| DIR           | Real      | 0.0             | degrees |
| DON. TRAP     | Logical   |                 |         |
| EMIN          | Real      |                 | eV      |
| EMAX          | Real      |                 | eV      |
| ENERGY        | Real      |                 | eV      |
| EXCITON       | Logical   | False           |         |
| FIELD         | Logical   | False           |         |
| FRONT         | Real      | minimum z coord | µm      |
| FTACC. TRAP   | Logical   | False           |         |

| Parameter          | Type      | Default         | Units   |
|--------------------|-----------|-----------------|---------|
| FTDON.TRAP         | Logical   | False           |         |
| GENERATION         | Logical   | False           |         |
| H.CONC             | Logical   | False           |         |
| INTEGRATED         | Logical   | False           |         |
| J.PROTON           | Logical   | False           |         |
| LMIN               | Real      |                 | microns |
| LMAX               | Real      |                 | microns |
| LANGEVIN           | Logical   | False           |         |
| LASER.INTENSITY    | Logical   | False           |         |
| LASER.GAIN         | Logical   | False           |         |
| LASER.MODE         | Real      |                 |         |
| LAT.TEMP           | Logical   | False           |         |
| LEFT               | Real      | minimum x coord | μm      |
| LUMINOUS.INTENSITY | Logical   | False           |         |
| MATERIAL           | Character |                 |         |
| MAX                | Logical   | False           |         |
| MIN                | Logical   | False           |         |
| N.CONC             | Logical   | False           |         |
| N.MOB              | Logical   | False           |         |
| N.TEMP             | Logical   | False           |         |
| NAME               | Character |                 |         |
| P.CONC             | Logical   | False           |         |
| P.MOB              | Logical   | False           |         |
| P.TEMP             | Logical   | False           |         |
| PERMITTIVITY       | Logical   | False           |         |
| PHOTOGEN           | Logical   | False           |         |
| POLARIZATION       | Logical   | False           |         |
| POTENTIAL          | Logical   | False           |         |
| QFN                | Logical   | False           |         |
| QFP                | Logical   | False           |         |
| R.TRAP             | Logical   | False           |         |
| R.BBT              | Logical   | False           |         |

| Parameter    | Type    | Default         | Units |
|--------------|---------|-----------------|-------|
| RADIATIVE    | Logical | False           |       |
| RAUGER       | Logical | False           |       |
| RECOMBIN     | Logical | False           |       |
| REGION       | Integer |                 |       |
| RIGHT        | Real    | maximum x coord | µm    |
| SRH          | Logical | False           |       |
| TOP          | Real    | minimum y coord | µm    |
| VEL.ELECTRON | Logical | False           |       |
| VEL.HOLE     | Logical | False           |       |
| WAVELENGTH   | Logical | False           |       |
| X            | Real    |                 | µm    |
| Y            | Real    |                 | µm    |
| Z            | Real    |                 | µm    |

**Description**

**ACC.TRAP** specifies that the ionized acceptor trap density is to be probed. If multiple trap levels are present the **ENERGY** parameter should be set to the desired energy level that is to be probed.

**ALPHAN** specifies that the electron impact ionization coefficient is to be probed. The **DIR** parameter should also be specified as this is a vector quantity.

**ALPHAN**, **ALPHAP** specify that the electron or hole impact ionization constant alpha is to be probed.

**ALPHAP** specifies that the hole impact ionization coefficient is to be probed. The **DIR** parameter should also be specified as this is a vector quantity.

**APCURRENT** specifies that the available photocurrent is probed.

**AUGER** specifies that Auger recombination rate is probed.

**BEAM** specifies a beam number to focus the application of the probe to that specific beam.

**CHARGE** specifies that the net charge is to be probed.

**COMPLIANCE** specifies the probed quantity compliance value. When the probed quantity reaches the specifies value, the **SOLVE** statement will terminate and will execute the next statement.

**CONCACC.TRAP** specifies that the acceptor trap concentration is to be probed. You can use the **ENERGY** parameter to specify the trap energy level to be probed. If **ENERGY** is not specified, then the total value of all acceptor energy levels will be probed.

**CONCDON.TRAP** specifies that the donor trap concentration is to be probed. You can use the **ENERGY** parameter to specify the trap energy level to be probed. If **ENERGY** is not specified, then the total value of all donor energy levels will be probed.

**DEVICE** specifies which device in mixed mode simulation the probe statement should apply to.

**DIR** specifies the direction relative to the x axis in degrees associated with certain directed quantities. These quantities include **FIELD**, **N.MOB**, **P.MOB**, and **POLARIZATION**.



**EMIN, EMAX** specifies the range of energies to search for peak emission wavelength when the **WAVELENGTH** parameter is set on the **PROBE** statement.

**DON.TRAP** specifies that the ionized donor trap density is to be probed. If multiple trap levels are present the **ENERGY** parameter should be set to the desired energy level that is to be probed.

---

**Note:** The algorithm used finds the triangle in the mesh containing the specified X and Y values. Then the value of the **DIR** parameter is used to find which edge of the triangle lies in the direction nearest that value.

---

**EXCITON** specifies that the exciton density is probed.

**FIELD** specifies that a value of electric field is probed. The **DIR** parameter should also be specified if **FIELD** is used.

**FTACC.TRAP** specifies that the acceptor trap probability of occupation is to be probed. You can use the **ENERGY** parameter to specify the trap energy level to be probed. If **ENERGY** is not specified, then the total value of all acceptor energy levels will be probed.

**FTDON.TRAP** specifies that the donor trap probability of occupation is to be probed. You can use the **ENERGY** parameter to specify the trap energy level to be probed. If **ENERGY** is not specified, then the total value of all donor energy levels will be probed.

**GENERATION** specifies that the generation rate due to impact ionization is probed.

**H.CONC** specifies that proton concentration is probed.

**INTEGRATED** specifies that the probed value is to be integrated over all mesh points inside a box defined with the parameters **FRONT**, **BACK**, **LEFT**, **RIGHT**, **TOP** and **BOTTOM**.

**J.PROTON** specifies that the proton current density is probed.

**LANGEVIN** specifies that the Langevin recombination rate is probed.

**LASER.GAIN** specifies that the probe will operate on the **LASER** optical gain. For more about information **LASER**, see Chapter 8: "Laser: Edge Emitting Simulator".

**LASER.INTENSITY** specifies that the probe will operate on the **LASER** optical intensity. For more about information **LASER**, see Chapter 8: "Laser: Edge Emitting Simulator".

**LASER.MODE** specifies the optical mode for **LASER . INTENSITY** and **LASER . GAIN**.

**LAT.TEMP** specifies that the probe will operate on lattice temperature.

**LMIN, LMAX** specifies the range of wavelengths to search for peak emission wavelength when the **WAVELENGTH** parameter is set on the **PROBE** statement.

**LUMINOUS.INTENSITY** specifies that the probe will operate on the **LUMINOUS** optical intensity. For more information about **LUMINOUS**, see Chapter 10: "Luminous: Optoelectronic Simulator".

**MATERIAL** is assigned to a specific material name that will act to direct the probe to only address regions composed of the specified material.

**MAX** specifies that the probe will find the maximum value on the mesh.

**MIN** specifies that the probe will find the minimum value on the mesh.

**NAME** sets a character string that allows you to specify the description displayed by **TONYPLOT**.

**N.CONC** specifies that the probe will operate on electron concentration.

**N.MOB** specifies that the probe will operate on the electron mobility. The **DIR** parameter should also be specified if **N.MOB** is used.

**N.TEMP** specifies that the probe will operate on electron temperature.

**P.CONC** specifies that the probe will operate on hole concentration.

**P.MOB** specifies that the probe will operate on the hole mobility. The **DIR** parameters should also be specified if **P.MOB** is used.

**P.TEMP** specifies that the probe will operate on hole temperature.

**PERMITTIVITY** specifies that material permittivity is probed.

**PHOTOGEN** specifies that photogeneration rate is probed.

**POLARIZATION** specifies that the probe will operate on ferroelectric polarization. The **DIR** parameter should also be specified if **POLARIZATION** is used.

**POTENTIAL** specifies that the probe will operate on electrostatic potential.

**QFN** specifies that the probe will operate on the electron quasi-Fermi level.

**QFP** specifies that the probe will operate on the hole quasi-Fermi level.

**R.TRAP** specifies that the trap recombination is to be probed.

**R.BBT** specifies that the band-to-band tunneling rate is to be probed.

**RADIATIVE** specifies that the probe will operate on radiative recombination rate.

**RECOMBIN** specifies that the probe will operate on net recombination rate.

**REGION** specifies a region number that is used to confine the action of the probe to a specific region.

**SRH** specifies that the probe will operate on SRH recombination rate.

**VEL.ELECTRON** specifies that the probe will operate on electron velocity.

**VEL.HOLE** specifies that the probe will operate on hole velocity.

**WAVELENGTH** specifies that the radiative emission wavelength is probed.

## Region Parameters

**BOTTOM** specifies the maximum y coordinate for the integrated probe region or probing of a minimum or maximum value.

**TOP** specifies the minimum y coordinate for the integrated probe region or the region for probing of a minimum or maximum value.

**LEFT** specifies the minimum x coordinate for the integrated probe region or the region for probing of a minimum or maximum value.

**RIGHT** specifies the maximum x coordinate for the integrated probe region or the region for probing of a minimum or maximum value.

**FRONT** specifies the minimum z coordinate for the integrated probe region or the region for probing of a minimum or maximum value.

**BACK** specifies the maximum z coordinate for the integrated probe region or the region for probing of a minimum or maximum value.

**X,Y,Z** describe the location of the probe in microns.

## Example of Probing the Maximum Value

The following line will cause the maximum electron concentration on the grid to be output to the log file:

```
PROBE NAME=peak_electrons MAX N.CONC
```

**Probing at a location Example**

This syntax will cause the potential at the location X=0.5 Y=0.1 to be output to the log file.

```
PROBE NAME=mypotential X=0.5 Y=0.1 POTENTIAL
```

**Vector Quantity Example**

For vector quantities, the direction parameter, DIR, must be specified. These two lines allow a lateral mobility and vertical field in a MOSFET.

```
PROBE NAME=channel_mobility x=1 y=0.001 N.MOB DIR=0
```

```
PROBE NAME=channel_field x=1 y=0.001 FIELD DIR=90
```

## 18.34: QUIT

QUIT stops execution of ATLAS.

### Syntax

QUIT

### Synonyms

END

EXIT

### Description

The QUIT statement may be placed anywhere in an input file. ATLAS will stop execution upon encountering the QUIT statement. All input lines after the occurrence of the QUIT statement will be ignored for that execution of ATLAS.

---

**Note:** To quit and immediately restart ATLAS inside of DECKBUILD, use the GO ATLAS statement. Full details on the GO syntax statement are found in the VWF INTERACTIVE TOOLS MANUAL, VOLUME 1.

---

## 18.35: REGION

REGION specifies the location of materials in a previously defined mesh. Every triangle must be defined as a material.

### Syntax

```
REGION NUMBER=<n> <material> [<position>]
```

| Parameter    | Type      | Default             | Units            |
|--------------|-----------|---------------------|------------------|
| ACCEPTORS    | Real      | 0.0                 | cm <sup>-3</sup> |
| BOTTOM       | Logical   | False               |                  |
| CALC.STRAIN  | Logical   | False               |                  |
| COMPX.BOTTOM | Real      | 0.0                 |                  |
| COMPY.BOTTOM | Real      | 0.0                 |                  |
| COMPX.TOP    | Real      | 0.0                 |                  |
| COMPY.TOP    | Real      | 0.0                 |                  |
| CONDUCTOR    | Logical   | False               |                  |
| DONORS       | Real      | 0.0                 | cm <sup>-3</sup> |
| FIXED.FERMI  | Logical   | False               |                  |
| GRAD.12      | Real      |                     | μm               |
| GRAD.23      | Real      |                     | mm               |
| GRAD.34      | Real      |                     | μm               |
| GRAD.41      | Real      |                     | μm               |
| GRADED       | Logical   | False               |                  |
| IX.LOW       | Integer   | left of structure   |                  |
| IX.HIGH      | Integer   | right of structure  |                  |
| IY.LOW       | Integer   | top of structure    |                  |
| IY.HIGH      | Integer   | bottom of structure |                  |
| IZ.HIGH      | Real      |                     |                  |
| IZ.LOW       | Real      |                     |                  |
| LED          | Logical   | False               |                  |
| MATERIAL     | Character |                     |                  |
| MODIFY       | Logical   | False               |                  |
| NAME         | Character |                     |                  |
| NA.TOP       | Real      | 0.0                 | cm <sup>-3</sup> |

| Parameter     | Type      | Default            | Units            |
|---------------|-----------|--------------------|------------------|
| ND.TOP        | Real      | 0.0                | cm <sup>-3</sup> |
| NA.BOTTOM     | Real      | 0.0                | cm <sup>-3</sup> |
| ND.BOTTOM     | Real      | 0.0                | cm <sup>-3</sup> |
| NUMBER        | Integer   |                    |                  |
| NX            | Real      | 2                  |                  |
| NY            | Real      | 2                  |                  |
| POLAR.SCALE   | Real      | 1.0                |                  |
| POLARIZATION  | Logical   | False              |                  |
| QWELL         | Logical   | False              |                  |
| SELF          | Logical   | False              |                  |
| STAY          | Logical   | False              |                  |
| STRAIN        | Real      | 0.0                |                  |
| SX            | Real      | 0.0                |                  |
| SY            | Real      | 0.0                |                  |
| THICKNESS     | Real      | 0.0                | microns          |
| TOP           | Logical   | False              |                  |
| USER.MATERIAL | Character |                    |                  |
| WELL.CNBS     | Integer   | 1                  |                  |
| WELL.DEBUG    | Logical   | False              |                  |
| WELL.FIELD    | Logical   | True               |                  |
| WELL.GAIN     | Real      | 1.0                |                  |
| WELL.NX       | Integer   | 10                 |                  |
| WELL.NY       | Integer   | 10                 |                  |
| WELL.OVERLAP  | Real      | 1.0                |                  |
| WELL.VNBS     | Integer   | 1                  |                  |
| X.COMP        | Real      | 0.0                |                  |
| X.MAX         | Real      | right of structure | μm               |
| X.MIN         | Real      | left of structure  | μm               |
| Y.COMP        | Real      | 0.0                |                  |
| Y.MIN         | Real      | top of structure   | μm               |

| Parameter | Type | Default             | Units |
|-----------|------|---------------------|-------|
| Y.MAX     | Real | bottom of structure | μm    |
| Z.MAX     | Real |                     |       |
| Z.MIN     | Real |                     |       |

## Description

**n** specifies a region number from 1 to 200.

**material** is one or more of the material names described below.

**position** is one or more of the position parameters described below.

## Material Parameters

**ACCEPTORS** specifies a uniform density of ionized acceptors in the region.

**CALC.STRAIN** specifies that the strain in the region is calculated from the lattice mismatch with adjacent regions.

**COMPX.BOTTOM**, **COMPY.BOTTOM**, **COMPX.TOP** and **COMPY.TOP** specify the composition fractions at the top and bottom of a region when linearly graded. Linear grading is specified by the **GRADED** parameter. See Chapter 2: “Getting Started with ATLAS”, Section 2.6.4: “Automatic Meshing (Auto-meshing) Using The Command Language”.

**CONDUCTOR** specifies that the region is to be simulated as a conductor. This means that the conduction equation is solved for the region.

**DONORS** specifies a uniform density of ionized donors in the region.

**GRAD.<n>** specifies the compositional gradings for heterojunctions along each side of the region rectangle or quadrilateral. The value of the **GRAD** parameters specifies the distance at which the composition fraction reduces to zero. A value of 0.0 specifies that the heterojunction is abrupt. The value of <n> can be the numbers: 12, 23, 34, and 41. The meanings of these numbers is down below.

- 12 = top surface
- 23 = right hand side
- 34 = bottom surface
- 41 = left hand side

These correspond to the point indices around the rectangular region working clockwise from top left.

**GRADED** specifies that the region has linear compositional or doping variation or both. See also **COMPX.BOTTOM**, **COMPY.BOTTOM**, **COMPX.TOP**, **COMPY.TOP**, **ND.BOTTOM**, **ND.TOP**, **NA.BOTTOM** and **NA.TOP**.

**LED** specifies that the region is to be treated as a light emitting region and included in postprocessing for LED analysis. See Chapter 11: “LED: Light Emitting Diode Simulator”.

**MATERIAL** specifies the material used for the region. Valid material names are listed in Appendix B: “Material Systems”, Table B-1. All materials are divided into three classes: semiconductors, insulators and conductors. Also see Appendix B for important information about requirements for each material class.

**MODIFY** is used to modify the characteristics of regions imported into the simulator. See Chapter 2: “Getting Started with ATLAS”, Section 2.6.5: “Modifying Imported Regions”.

**NAME** specifies the name of the region. The name can be used in the `MODELS`, `MATERIAL`, and `IMPACT` statements to provide regionally dependent models. This name is just a label. It doesn't imply any material parameter settings.

**ND.BOTTOM**, **ND.TOP**, **NA.BOTTOM** and **NA.TOP** specify the doping concentrations at the top and bottom of a region when linearly graded. Linear grading is specified by the `GRADED` parameter. See Chapter 2: "Getting Started with ATLAS", Section 2.6.4: "Automatic Meshing (Auto-meshing) Using The Command Language".

**NUMBER** assigns a region number. Multiple `REGION` lines with the same number can be used to define region shapes made from several rectangles.

**POLARIZATION** enables the automatic calculation of added interface charge due to spontaneous and piezoelectric polarization. See Chapter 33: "Physics", Section 3.6.8: "Polarization in Wurtzite Materials".

**POLAR.SCALE** specifies a constant scale factor multiplied by the calculated spontaneous and piezoelectric polarization charges when you enable polarization by setting the `POLARIZATION` parameter of the `REGION` statement. See Chapter 33: "Physics", Section 3.6.8: "Polarization in Wurtzite Materials".

**QWELL** specifies that the region is treated as a quantum well for calculation of radiative recombination or gain or both for certain optoelectronic models.

**STRAIN** specifies the strain in the region.

**USER.MATERIAL** specifies a user-defined material name. The specified material name can be any name except that of a default material, such as Silicon. You should define each material with an accompanying definition in the `MATERIAL` statement. You can define up to 50 user-defined materials.

**WELL.CNBS** and **WELL.VNBS** specify the number of bound states retained for calculation of radiative recombination or gain if the region is treated as a quantum well as specified by the `QWELL` parameter.

**WELL.FIELD** specifies that the calculations of bound state energies should include the effects of the local field.

**WELL.GAIN** specifies a constant scale factor multiplied by the calculated gain to give the net gain used for certain optoelectronic calculations.

**WELL.NX** and **WELL.NY** specify the number of slices (`WELL.NX`) and the number of samples per slice (`WELL.NY`) are used in the solution of Schrodinger's equation to obtain the local bound state energies for calculation of radiative recombination or gain or both for certain optoelectronic models.

---

**Note:** The highest region number takes precedence if `REGION` definitions overlap.

---

## Position Parameters

You can use grid indices to define a region only when the mesh is rectangular. To define a region with a rectangular mesh, use the `X.MESH` and `Y.MESH` statements to specify grid indices.

You can also use the `IX.HIGH`, `IX.LOW`, `IY.HIGH`, and `IY.LOW` parameters to specify x and y mesh line number values.

---

**Note:** To add regions to irregular meshes, such as those from `ATHENA`, specify the boundaries with the `X.MAX`, `X.MIN`, `Y.MAX`, and `Y.MIN` parameters.

---



**BOTTOM** specifies that the region is to be added at the bottom (starting at the maximum previously specified Y coordinate and extending in the positive Y direction) of the structure.

**IX.HIGH** specifies the maximum x value of the grid index.

**IX.LOW** specifies the minimum x value of the grid index.

**IY.HIGH** specifies the maximum y value of the grid index.

**IY.LOW** specifies the minimum y value of the grid index.

**IZ.HIGH** specifies the maximum z value of the grid index.

**IZ.LOW** specifies the minimum z value of the grid index.

**NX** specifies the number of uniformly spaced mesh lines to be added to resolve the region in the X direction.

**NY** specifies the number of uniformly spaced mesh lines to be added to resolve the region in the Y direction.

**STAY** is used in automeshing to create material variations in the x-direction. See Chapter 2: “Getting Started with ATLAS”, Section 2.6.4: “Automatic Meshing (Auto-meshing) Using The Command Language”.

**SX** specifies the spacing between mesh lines to be applied at the edges of the region in the X direction.

**SY** specifies the spacing between mesh lines to be applied at the edges of the region in the Y direction.

**THICKNESS** specifies the thickness of the region in the Y direction. This parameter must accompany the specification of the TOP or BOTTOM parameters.

**TOP** specifies that the region is to be added at the top (starting at the minimum previously specified Y coordinate and extending in the negative Y direction) of the structure.

**X.COMP** is the composition fraction (X) for a region with a composition dependent cations (e.g., AlGaAs).

**X.MAX** specifies the maximum x-boundary.

**X.MIN** specifies the minimum x-boundary.

**Y.COMP** is the composition fraction (Y) for a region with a composition dependent anions (e.g., InGaAsP).

**Y.MAX** specifies the maximum y-boundary.

**Y.MIN** specifies the minimum x-boundary.

**Z.MIN** specifies the minimum z-boundary.

**Z.MAX** specifies the maximum z-boundary.

### Grid Indices Example

Define a silicon region extending from nodes 1 to 25 in the x direction and from nodes 1 to 20 in the y direction.

```
REGION NUM=1 IX.LO=1 IX.HI=25 IY.LO= 1 IY.HI=20 MATERIAL=SILICON
```

### Non-Rectangular Region Example

Define a region that's composed of two separate rectangular areas. Note that REGION statements are cumulative.

```
REGION NUM=1 IX.LO=4 IX.HI=5 IY.LO=1 IY.HI=20 MATERIAL=OXIDE
REGION NUM=1 IX.LO=1 IX.HI=30 IY.LO=1 IY.HI=37 MATERIAL=OXIDE
```

## Typical MOS Example

Define regions for a typical MOS structure.

```
REGION NUM=1 Y.MAX=0 MATERIAL=OXIDE
REGION NUM=2 Y.MIN=0 MATERIAL=SILICON
```

## 3D Region Definition Example

Define a cube of oxide within a region silicon in 3D.

```
REGION NUM=1 MATERIAL=SILICON
REGION NUM=2 Y.MAX=0.5 X.MIN=0.5 \
X.MAX=1.0 Z.MIN=0.5 Z.MAX=1.0 MATERIAL = OXIDE
```

## Graded Heterojunction Definition Example

Define a graded heterojunction of AlGaAs/GaAs.

```
REGION NUM=1 MATERIAL=GaAs Y.MIN=1
REGION NUM=2 MATERIAL=AlGaAs Y.MAX=0.9 X.COMP=0.2 GRAD.34=0.1
```

In this case, the area between  $y=0.9$  and  $1.0$  is graded in composition from  $0.2$  to  $0.0$ . The  $Y.MAX$  parameter refers to the bottom of the uniform composition region. The actual bottom of the AlGaAs region is  $Y.MAX+GRAD.34$

## 18.36: REGRID

REGRID allows you to refine a crude mesh. A triangle is refined when the chosen variable changes by more than one specified criteria.

### Syntax

```
REGRID RATIO=<n> <var> [<lp>] [<cp>] [<io>]
```

| Parameter  | Type      | Default                  | Units            |
|------------|-----------|--------------------------|------------------|
| ABSOLUTE   | Logical   | False                    |                  |
| ASCII      | Logical   | False                    |                  |
| CHANGE     | Logical   | True                     |                  |
| COS.ANG    | Real      | 2.0                      |                  |
| DOPFILE    | Character |                          |                  |
| DOPING     | Logical   |                          | cm <sup>-3</sup> |
| E.TEMP     | Logical   | False                    |                  |
| EL.FIELD   | Logical   |                          | V/cm             |
| ELECTRON   | Logical   |                          | cm <sup>-3</sup> |
| H.TEMP     | Logical   | False                    |                  |
| HOLE       | Logical   |                          | cm <sup>-3</sup> |
| IGNORE     | Integer   |                          |                  |
| IN.GREEN   | Character |                          |                  |
| LOCALDOP   | Logical   | False                    |                  |
| LOGARITHM  | Logical   | True                     |                  |
| MAX.LEVEL  | Integer   | 1+ maximum level of grid |                  |
| MIN.CARR   | Logical   |                          | cm <sup>-3</sup> |
| NET.CARR   | Logical   |                          | cm <sup>-3</sup> |
| NET.CHRG   | Logical   |                          | cm <sup>-3</sup> |
| PISCES.OUT | Logical   | False                    |                  |
| OUT.GREEN  | Character | value of OUTFILE + tt    |                  |
| OUTFILE    | Character |                          |                  |
| POTENTIAL  | Logical   |                          | V                |
| QFN        | Logical   |                          | V                |
| QFP        | Logical   |                          | V                |

| Parameter | Type    | Default | Units         |
|-----------|---------|---------|---------------|
| REGION    | Integer |         | All           |
| SMOOTH.K  | Integer |         |               |
| STEP      | Real    |         |               |
| X.MAX     | Real    | Right   | $\mu\text{m}$ |
| X.MIN     | Real    | Left    | $\mu\text{m}$ |
| Y.MAX     | Real    | Bottom  | $\mu\text{m}$ |
| Y.MIN     | Real    | Top     | $\mu\text{m}$ |

## Description

**RATIO** or **STEP** specifies the maximum allowed variance across one element.

**var** is one of the variable parameters described below. The selected parameter is used as the basis for regridding.

**lp** is one of more of the location parameters described below. These parameters are used to select the areas which are to be refined.

**cp** is one or more of the control parameters. These parameters are used to control the plotted output.

**io** is one or more of the File I/O parameters.

## Variable Parameters

**DOPING** selects net doping.

**E.TEMP** select electron temperature.

**EL.FIELD** selects electric field.

**ELECTRON** selects electron concentration.

**H.TEMP** selects hole temperature.

**HOLE** selects hole concentration.

**MIN.CARR** selects minority carrier concentration.

**NET.CARR** selects net carrier concentration.

**NET.CHRG** selects net charge.

**POTENTIAL** selects mid-gap potential.

**QFN** selects the electron quasi-Fermi level.

**QFP** selects the hole quasi-Fermi level.

## Location Parameters

If no location parameters are specified, refinement will include:

- All regions for potential and electric field regrids
- All semiconductor regions for regrids which depend on the other variables

**IGNORE** specifies regions that are not to be refined.

**REGION** specifies regions which are refined according to the specified criterion. Other regions may be refined to maintain well-shaped triangles.

**X.MAX** uses device coordinates to specify the maximum x-value for refinement.

**X.MIN** uses device coordinates to specify the minimum x-value for refinement.

**Y.MAX** uses device coordinates to specify the maximum y-value for refinement.

**Y.MIN** uses device coordinates to specify the minimum y-value for refinement.

### Control Parameters

**ABSOLUTE** specifies that the absolute value of the variable be used.

**CHANGE** determines whether to use the magnitude or the difference of a triangle variable as the refinement criterion. This parameter defaults to “difference”.

**COS.ANGLE** limits the creation of obtuse angles in the mesh by specifying obtuse criterion. If this parameter is used, nodes are added to the mesh so that the number of obtuse triangles is reduced.

---

**Note:** Be careful when using the **COS . ANGLE** parameter. Recommended values are from 0.8 to 0.95. Smaller values may dramatically increase the number of nodes.

---

**LOCALDOP** specifies that if minority carrier concentration exceeds local doping, the grid will be refined. This parameter is used in conjunction with minority carrier regrid.

**LOGARITHM** specifies a logarithmic refinement scale. Since many of the quantities may become negative, numerical problems are avoided by using  $\log(x)=\text{sign}(x)\cdot\log_{10}(1+|x|)$ . If you wish to obtain the true logarithm of a quantity, the **ABSOLUTE** parameter must be specified before the **LOGARITHM** parameter is specified. The absolute value of a quantity is computed first, thereby eliminating negative arguments.

**MAX.LEVEL** specifies the maximum level of any triangle relative to the original mesh. This parameter defaults to one more than the maximum level of the grid, but can be set to a smaller value to limit refinement. Values less than or equal to zero are interpreted relative to the current maximum grid level.

**SMOOTH.KEY** specifies a smoothing index. The digits of the index are read in reverse order and interpreted as follows:

1. Triangle smoothing: All region boundaries remain fixed.
2. Triangle smoothing: Only material boundaries are maintained.
3. Node averaging.
4. Improved triangle smoothing method: This method uses diagonal flipping to reduce the number of obtuse triangles.
5. Aligns triangles with electric field gradient.

Usually option 1 is sufficient. Option 2 is useful only if a device has several regions of the same material and the border between different regions is unimportant. Option 3 is not recommended when the initial mesh is basically rectangular, such as mesh information usually obtained from **SSUPREM4**. Option 4 is similar to option 1, but option 4 usually creates less obtuse triangles.

### File I/O Parameters

**ASCII** specifies that mesh files and triangle trees will be written in an ASCII rather than a binary format. This parameter has no effect on the device doping file (see the **DOPFILE** parameter).

**DOPFILE** specifies the name of a file, which contains device doping information. This file is created on the **DOPING** statement. Specifying **DOPFILE** avoids linear interpolation of doping values at newly created grid points by using the initial doping specification to apply doping to the new grid points.

**IN.GREEN** specifies a triangle tree for the mesh which will be used in this regrid. If this parameter is not specified, the program will look for a file with the same name as the current mesh plus, *tt*, at the end. If no such file exists, the program will not use a triangle tree for the previous mesh.

**MASTER.OUT** saves mesh and doping information in a standard structure file format.

**OUTFILE** specifies the name of a standard structure output file where mesh information will be stored. This parameter must be specified if the mesh is to be used for subsequent runs.

**OUT.GREEN** specifies the name of the file that holds the history of the triangle tree. This history is used in further regrid steps.

**PISCES.OUT** saves mesh and doping information in a binary PISCES-II format. Files in this format cannot be displayed in TONYPLOT

## Doping Regrid Examples

Starting with an initial grid, we refine twice so that all triangles with large doping steps are refined.

```
REGRID LOG DOPING RATIO=6 OUTF=grid1 DOPF=dopxx SMOOTH=4
REGRID LOG DOPING RATIO=6 OUTF=grid2 DOPF=dopxx SMOOTH=4
```

A similar effect could be obtained with just one regrid statement.

```
REGRID LOG DOPING RATIO=6 OUTF=grid2 DOPF=dopxx MAX.LEVEL=2
```

In both cases, two levels of refinement are performed. The first example is recommended because new doping information is introduced at each level of refinement. This produces better refinement criterion and fewer triangles.

## Potential Regrid Example

Next, an initial solution is produced and triangles which exhibit large potential steps are refined.

```
SOLVE INIT
REGRID POTENTIAL RATIO=0.2 OUTF=grid3.str SMOOTH=4
```

## Re-initializing after Regrid example

Often you need to re-solve the same bias point after a REGRID using the following style of syntax.

```
SOLVE VDRAIN=3.0
REGRID POTENTIAL RATIO=0.25 SMOOTH=4 OUTF=mygrid.str
SOLVE PREV
```

Occasionally, you need to quit and restart ATLAS with the new mesh. To do this, type syntax such as:

```
SOLVE VDRAIN=3.0
REGRID POTENTIAL RATIO=0.25 SMOOTH=4 OUTF=mygrid.str
go atlas
MESH INF=mygrid.str
```

After this MESH statement all models, material parameters and numerical methods have to be re-specified before any SOLVE statement.

## 18.37: SAVE

SAVE saves all node point information into an output file.

**Note:** In all cases the region boundaries, electrodes, mesh and doping are saved. If a SOLVE statement has preceded the SAVE statement all electrical data from the last solution is stored.

### Syntax

```
SAVE OUTFILE=<filename> [MASTER]
```

| Parameter  | Type      | Default | Units   |
|------------|-----------|---------|---------|
| ABSORB     | Logical   | False   |         |
| ANGPOWER   | Character |         |         |
| COMPARE    | Logical   | False   |         |
| COUPLING3D | Logical   | False   |         |
| DIPOLE     | Logical   | False   |         |
| EMIN       | Real      |         | eV      |
| EMAX       | Real      |         | eV      |
| INTERFERE  | Logical   | False   |         |
| L.WAVE     | Real      | 0.8     | microns |
| LMAX       | Real      |         | microns |
| LMIN       | Real      |         | microns |
| MASTER     | Character | True    |         |
| MIN.POWER  | Real      | 1E-4    |         |
| MIR.BOTTOM | Logical   | False   |         |
| MIR.TOP    | Logical   | False   |         |
| NSAMP      | Integer   | 100     |         |
| NUMRAYS    | Integer   | 180     |         |
| OUTFILE    | Character |         |         |
| PATTERNS   | Character |         |         |
| PISCES     | Logical   | False   |         |
| POLAR      | Real      | 45.0    |         |
| RAYPLOT    | Character |         |         |
| REFLECTS   | Integer   | 0       |         |
| SIDE       | Logical   | False   |         |

| Parameter | Type      | Default | Units   |
|-----------|-----------|---------|---------|
| SPECTRUM  | Character |         |         |
| STRUCTURE | Character | False   |         |
| TEMPER    | Real      | 300.0   |         |
| X         | Real      | 0.0     | microns |
| XMAX      | Real      | 0.0     | microns |
| XMIN      | Real      | 0.0     | microns |
| XNUM      | Integer   | 0       |         |

## Description

**ABSORB** takes absorption into account in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). The absorption is assumed to be constant specified for each material by the imaginary part of the refractive index.

**ANGPOWER** enables the reverse ray-tracing algorithm (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”) for analysis of output coupling of light from the structure of a Light Emitting Diode. **ANGPOWER** specifies the name of the output file for the angular power density vs. output angle dependence.

**COUPLING3D** calculates an output coupling coefficient, assuming a cylindrically symmetric light output with the light source located on the axis of symmetry (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). Takes into account the 3D nature of the problem with output coupling calculation.

**DIPOLE** specifies a particular angular distribution of the internal radiating field that corresponds to a preferred in-plane orientation of dipoles often relevant to OLED devices (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**EMAX**, **EMIN** specify the energy range for saving a spectrum file.

**INTERFERE** specifies that rays originating in the same point are fully coherent in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). In this case, the phase information upon propagation is preserved. Phase change upon reflection is also considered. Thus, interference of rays exiting the device at the same angle are taken into account.

**LMAX**, **LMIN** specify the range of wavelength for saving spectrum files.

**L.WAVE** specifies the wavelength for reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**MASTER** specifies that the output file will be written in a standard structure format. Files in this format can be plotted in **TONYPLOT**.

**MIN.POWER** specifies the minimum relative power of a ray (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). The ray is not traced after its power falls below **MIN.POWER** value. This is useful to limit the number of rays traced. The default value is **MIN.POWER=1e-4**.

**MIR.TOP** specifies that the top surface of the device be treated as an ideal mirror in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**MIR.BOTTOM** specifies that the bottom surface of the device be treated as an ideal mirror in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**NSAMP** specifies the number of samples to use for a spectrum plot.



**NUMRAYS** specifies the number of rays starting from the origin in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). The default is 180. Acceptable range is 36-3600.

**OUTFILE** specifies the name of an output file name.

**PISCES** specifies that the output file will be written in the original PISCES-II format.

**PATTERNS** specifies a character string representing the root of the file names where near and far field patterns are written for LASER. The near field pattern file is appended with the string *.nfp* and the far field pattern file is appended with the string *.ffp*.

**POLAR** specifies polarization of the emitted photons in degrees while linearly polarized light is assumed (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). Parallel (TM-mode,  $POLAR=0.0$ ) and perpendicular (TE-mode,  $POLAR=90.0$ ) polarizations result in significantly different output coupling values. Use the default value ( $POLAR=45.0$ ) if there is no preferred direction of polarization of emitted photons (unpolarized light emission).

**RAYPLOT** specifies the name of the output file containing the information on each ray exiting the device in single origin reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). This file is only created when the single origin for all rays is assumed. The information includes ray output angle, relative ray power (TE and TM-polarization and total), and initial internal angle at the origin (only if INTERFERE parameter is unspecified).  $0^\circ$  angle corresponds to the rays in the X axis direction.  $90^\circ$  angle corresponds to the rays in the Y axis direction.

**REFLECTS** specifies a number of reflections to be traced for each ray in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”). The default value is  $REFLECTS=0$ . The maximum allowed value is  $REFLECTS=10$ . Setting the number of reflections to 3 or 4 is often a good choice.

**SIDE** specifies that the rays reaching the sides of the device are terminated there and do not contribute to the total light output (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**SPECTRUM** specifies the name of a file for saving spectrum plots.

**STRUCTURE** is a synonym for SAVE.

**TEMPER** is the temperature (needed for using appropriate refractive indexes of the materials in reverse ray-tracing). The default setting of 300 K will be used if TEMPER is unspecified.

**X** is the x-coordinate of light origin for a single point reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**XMAX** is the maximum x-coordinate of a rectangular area containing multiple origin points in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**XMIN** is the minimum x-coordinate of a rectangular area containing multiple origin points in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**XNUM** specifies the number of points along x-axis within a rectangular area in multiple origin reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**Y** is the y-coordinate of light origin for a single point reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**YMAX** is the maximum y-coordinate of a rectangular area containing multiple origin points in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**YMIN** is the minimum y-coordinate of a rectangular area containing multiple origin points in reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

**YNUM** specifies the number of points along y-axis within a rectangular area in multiple origin reverse ray-tracing (see Chapter 11: “LED Simulation”, Section 11.5: “Reverse Ray-Tracing”).

## Basic Save Example

```
SOLVE V1=5
SAVE OUTF=data1.str
```

is equivalent to

```
SOLVE V1=5 OUTF=data1.str MASTER
```

## Save Example with User-Defined Output

In the second example, the `SAVE` and `OUTPUT` commands are used to produce two output files for the same bias. The `OUTPUT` statement selects which data will be stored in each file. The first file (*data1.str*) contains the default contents, total electric field, and components of electron velocity. The second file (*data2.str*) contains components of hole velocity and band edge potentials. Note that the `^EX.VELO` and `^EY.VELO` parameters are used to prevent electron velocity components from being stored in file *data2*.

```
OUTPUT E.FIELD EX.VELO EY.VELO
SAVE OUTF=data1.str
OUTPUT HX.VELO HY.VELO CON.BAND VAL.BAND ^EX.VELO ^EY.VELO
SAVE OUTF=data2.str
```

---

**Note:** You can customize the contents of the saved file by using the `OUTPUT` statement.

---

---

## 18.38: SET

The SET statement is used to define variables for substitution into ATLAS syntax. SET commands are executed by DECKBUILD.

---

**Note:** Full documentation of the SET statement is found in the VWF INTERACTIVE TOOLS MANUAL VOLUME 1.

---

### Numeric Variable Example

Define a numerical variable. Use it in a calculation and substitute it into the ATLAS syntax for REGION definition

```
SET MYLENGTH=0.1
SET HALFLENGTH= $"MYLENGTH"*0.5
...
REGION NUM=1 MATERIAL=SILICON X.MIN=$"HALFLENGTH" X.MAX=$"MYLENGTH"
```

### String Variable Example

Define a string variable to use as part of a filename

```
SET LABEL=testcase1
..
LOG OUTF=$"LABEL".log
..
SAVE OUTF=bias_"$LABEL"_25.str
```

This will produce files called `testcase1.log` and `bias_testcase1_25.str`

## 18.39: SINGLEEVENTUPSET

SINGLEEVENTUPSET specifies the values of parameters used in Single Event Upset modeling in DEVICE3D or BLAZE3D.

### Syntax

```
SINGLEEVENTUPSET <parameters>
```

| Parameter   | Type    | Default | Units            |
|-------------|---------|---------|------------------|
| A1          | Real    |         |                  |
| A2          | Real    |         |                  |
| A3          | Real    |         |                  |
| A4          | Real    |         |                  |
| B1          | Real    |         |                  |
| B2          | Real    |         |                  |
| B3          | Real    |         |                  |
| B4          | Real    |         |                  |
| B.DENSITY   | Real    | 0       | cm <sup>-3</sup> |
| BEAM.RADIUS | Real    | 0       | μm               |
| DENSITY     | Real    |         | cm <sup>-3</sup> |
| ENTRYPOINT  | Real    | vector  | μm               |
| EXITPOINT   | Real    | vector  | μm               |
| PCUNITS     | Logical | False   |                  |
| RADIALGAUSS | Logical | False   |                  |
| RADIUS      | Real    |         | μm               |
| RESCALE     | Logical | False   |                  |
| TFINAL.SEU  | Real    |         |                  |
| T0          | Real    |         | c                |
| TC          | Real    |         | c                |
| TF          | Real    |         | sec              |
| UNIFORM     | Logical | False   |                  |

### Description

**A1, A2, A3** and **A4** are the first set of parameters for the length dependence of the charge generation pulse.

**B1, B2, B3** and **B4** are the second set of parameters for the length dependence of the charge generation pulse.

**B.DENSITY** specifies the number of electron-hole pairs per unit volume or generated charge in pico Coulombs per micron if the PCUNITS parameter is specified.

**BEAM.RADIUS** is the radius of the beam where the generation rate is maintained constant. Beyond this point the generation will decay by either an exponential or by a Gaussian function.

**DENSITY** specifies the number of electron-hole pairs per unit volume generated along the alpha particle track.

**ENTRYPOINT** specifies the x, y, and z coordinates of the beginning of the alpha particle track. The specified point should belong to the semiconductor region.

**EXITPOINT** specifies the x, y, and z coordinates of the end of the alpha particle track. The specified point should belong to the semiconductor region.

**PCUNITS** sets the units of B.DENSITY to be pC per micron.

**RADIALGAUSS** specifies the Gaussian radial dependence of the charge generation pulse. By default the exponential dependence is used.

**RADIUS** specifies the radius of the alpha particle track.

**RESCALE** causes nodal generation rates to be scaled by the ratio of the integral of the analytic generation rate divided by the numerically integrated value.

---

**Note:** This may cause problems when the track radius approaches device dimensions.

---

**TFINAL.SEU** specifies the finish time for the track, this defaults to the finish time of the transient simulation if TFINAL.SEU is not specified.

**T0** specifies the peak in time of the charge generation pulse.

**TC** specifies the width of the charge generation pulse.

**UNIFORM** specifies that a uniform generation rate corresponding to that specified by the DENSITY parameter is applied.

### SEU Example

This statement specifies a track path, radius and density:

```
SINGLEEVENTUPSET ENTRYPOINT="1.5,2.0,0.0"\  
EXITPOINT="1.0,1.0,4.0 RADIUS=0.05" \  
DENSITY=1E18
```

---

**Note:** For user-defined Single Event Generation profiles, the C-INTERPRETER function, F3.RADIATE, on the BEAM statement can be used.

---

## 18.40: SOLVE

SOLVE instructs ATLAS to perform a solution for one or more specified bias points.

### Syntax

```
SOLVE [<ion>] <dc> [<fp>][<ep>][<tp>][<ac>][<photo>] [<thermal>]
```

| Parameter    | Type      | Default              | Units             |
|--------------|-----------|----------------------|-------------------|
| AC.ANALYSIS  | Logical   | False                |                   |
| ANAME        | Character |                      |                   |
| AR.INDEX     | Real      | 1.0                  |                   |
| AR.THICKNESS | Real      | 0.0                  | microns           |
| ASCII        | Logical   | False                |                   |
| AUTO         | Logical   | True                 |                   |
| B<n>         | Real      | 0.0                  | W/cm <sup>2</sup> |
| BRANIN       | Logical   | True                 |                   |
| CNAME        | Character |                      |                   |
| COMPLIANCE   | Real      |                      |                   |
| CURVETRACE   | Logical   | False                |                   |
| CYCLES       | Integer   | 1                    |                   |
| CYCLIC.BIAS  | Logical   | False                |                   |
| CYCLIC.RELAX | Real      | 0.2                  |                   |
| CYCLIC.TOL   | Real      | 1.0x10 <sup>-5</sup> |                   |
| DECAY        | Real      |                      | s                 |
| DELTA V      | Real      | 0.1                  | V                 |
| DIRECT       | Logical   | False                |                   |
| DT           | Real      | 0                    | s                 |
| E.COMPL      | Real      |                      |                   |
| E.CRIT       | Real      | 1.0x10 <sup>-8</sup> |                   |
| ELECTRODE    | Integer   |                      |                   |
| EMAX         | Real      | 0.0                  | eV                |
| EMIN         | Real      | 0.0                  | eV                |
| ENDRAMP      | Real      |                      | s                 |
| FREQUENCY    | Real      |                      | Hz                |

| Parameter   | Type      | Default         | Units             |
|-------------|-----------|-----------------|-------------------|
| FSTEP       | Real      | 0               | Hz                |
| GRAD        | Logical   | False           |                   |
| I<n>        | Real      |                 | A/ $\mu\text{m}$  |
| IFINAL      | Real      |                 | A/ $\mu\text{m}$  |
| IMULT       | Logical   | False           |                   |
| INAME       | Character |                 |                   |
| INDEX.CHECK | Logical   | False           |                   |
| INITIAL     | Logical   | False           |                   |
| ION.CRIT    | Real      | 1.0             |                   |
| ION.ELEC    | Integer   | see Description |                   |
| IONIZINT    | Logical   | False           |                   |
| IONLINES    | Integer   | 50              | none              |
| IONSTOP     | Logical   | True            |                   |
| ISTEP       | Real      | 0.0             | A/ $\mu\text{m}$  |
| LAMBDA1     | Real      |                 | $\mu\text{m}$     |
| LIT.STEP    | Real      |                 | W/cm <sup>2</sup> |
| LMAX        | Real      | 0.0             | $\mu\text{m}$     |
| LMIN        | Real      | 0.0             | $\mu\text{m}$     |
| LOCAL       | Logical   | False           |                   |
| LRATIO      | Real      | 1.0             |                   |
| L.WAVE      | Real      |                 | $\mu\text{m}$     |
| MASTER      | Logical   | False           |                   |
| MAX.INNER   | Integer   | 25              |                   |
| MLOCAL      | Logical   | False           |                   |
| MULT.FREQ   | Logical   | False           |                   |
| N.BIAS      | Real      |                 | V                 |
| NAME        | Character |                 |                   |
| NB1         | Real      |                 | V                 |
| NB2         | Real      |                 | V                 |
| NB3         | Real      |                 | V                 |
| NB4         | Real      |                 | V                 |

| Parameter   | Type      | Default               | Units      |
|-------------|-----------|-----------------------|------------|
| NB5         | Real      |                       | V          |
| NB6         | Real      |                       | V          |
| NB7         | Real      |                       | V<B>       |
| NB8         | Real      |                       | V          |
| NFSTEPS     | Integer   | 0                     |            |
| NLAYERS     | Real      | 15                    |            |
| NOCONTACT   | Logical   | False                 |            |
| NOCURRENT   | Logical   | false                 |            |
| NOINTERFACE | Logical   | False                 |            |
| NOISE.SS    | Logical   | False                 |            |
| NSAMP       | Integer   | 100                   |            |
| NSTEPS      | Integer   | 0                     |            |
| ONEFILEONLY | Logical   | See Description       |            |
| OUTFILE     | Character |                       |            |
| P.BIAS      | Real      |                       |            |
| PB1         | Real      |                       | V          |
| PB2         | Real      |                       | V          |
| PB3         | Real      |                       | V          |
| PB4         | Real      |                       | V          |
| PB5         | Real      |                       | V          |
| PB6         | Real      |                       | V          |
| PB7         | Real      |                       | V          |
| PB8         | Real      |                       | V          |
| PIEZSCALE   | Real      | 1.0                   |            |
| POWER<n>    | Real      |                       | $\Omega$   |
| POWERFINAL  | Real      |                       | $\Omega$   |
| PREVIOUS    | Logical   | False                 |            |
| PROJECT     | Logical   | False                 |            |
| PULSE.WIDTH | Real      |                       | s          |
| Q<n>        | Real      |                       | C/ $\mu$ m |
| QFACTOR     | Real      | 1.0 or previous value |            |



| Parameter    | Type      | Default              | Units             |
|--------------|-----------|----------------------|-------------------|
| QFINAL       | Real      |                      | C/ $\mu\text{m}$  |
| QSCV         | Logical   | false                |                   |
| QSTEP        | Real      |                      | C/ $\mu\text{m}$  |
| RAMPTIME     | Real      |                      | s                 |
| RAMP.LIT     | Logical   | False                |                   |
| RELATIVE     | Logical   | False                |                   |
| SCAN.SPOT    | Real      |                      |                   |
| S.OMEGA      | Real      | 1.0                  |                   |
| SINUAMP.COMP | Real      | 0.0                  |                   |
| SINUVAR.COMP | Real      | 0.0                  |                   |
| SOR          | Logical   | False                |                   |
| SPECTRUM     | Character |                      |                   |
| SQPULSE      | Logical   | False                |                   |
| SS.LIGHT     | Real      | 0.001                | W/cm <sup>2</sup> |
| SS.PHOT      | Logical   | False                |                   |
| T <n>        | Real      |                      | K                 |
| T.COMP       | Real      | 0                    | K                 |
| T.SAVE       | Real      | 0.0                  | s                 |
| TABLE        | Character |                      |                   |
| TDELAY       | Real      | 0.0                  | s                 |
| TFALL        | Real      | 0.0                  | s                 |
| TRISE        | Real      | 0.0                  | s                 |
| TSAVE.MULT   | Real      | 1.0                  |                   |
| TERMFINAL    | Real      |                      | K                 |
| TERMINAL     | Integer   | all contacts         |                   |
| TOLERANCE    | Real      | 1.0x10 <sup>-5</sup> |                   |
| TRANS.ANALY  | Logical   | False                |                   |
| TSTOP        | Real      |                      |                   |
| TWOFILESONLY | Logical   | False                |                   |
| V<n>         | Real      |                      | V                 |

| Parameter | Type | Default | Units |
|-----------|------|---------|-------|
| VFINAL    | Real |         | V     |
| VSTEP     | Real | 0.0     | V     |
| VSS       | Real | 0.1     | V     |

## Description

Each SOLVE statement must specify an initial bias condition. Once any DC condition has been solved, either a transient or AC analysis may be performed. You may also solve for carrier generation due to incident light under DC, or AC analysis transient conditions.

**dc** is one or more of the DC bias parameters

**fp** is one or more of the file parameters

**ep** is one or more of the initial guess or estimate parameters. Estimate parameters are used to specify how the initial approximation for the solution is to be obtained.

**tp** is one or more of the transient parameters. These parameters are used to specify data for transient analysis.

**ac** is one or more of the AC parameters. AC parameters are used to specify data for AC analysis.

**ion** is a set of the ionization integral parameters.

**photo** is one or more of the photogeneration parameters. Photogeneration parameters are used to specify illumination data.

**therm** is one or more of the thermal parameters. Thermal parameters are used for obtaining solutions in THERMAL3D.

## DC Parameters

**CURVETRACE** initiates curve tracing. See also the CURVETRACE statement.

**ELECTRODE** specifies electrodes that you wish to add voltage and current increments (VSTEP and ISTEP) to. If n electrodes are to be stepped, ELECTRODE should be an n-digit integer, where each of the digits is a separate electrode number. See also the NAME parameter.

**I<name>** specifies the applied current for a named electrode. One of several commonly used terminal names should be specified. These names are as follows: gate, gg, drain, dd, source, bulk, substrate, emitter, ee, collector, cc, base, bb, anode, cathode, fgate, cgate, ngate, pgate, well, nwell, pwell, channel, and ground. No other user-defined names are allowed. This parameter is used when current boundary conditions are selected (see Section 18.4: "CONTACT")

**I<n>** specifies the terminal current for electrode, n. This parameter is used when current boundary conditions are selected (see Section 18.4: "CONTACT"). Normally, I defaults to the current from the previous bias point. It is more usual to use electrode names rather than numbers. This parameter is superseded by I<name>.

**IFINAL** specifies the final current value for a set of bias increments. If IFINAL is specified, either ISTEP or NSTEPS must be specified.

**IMULT** specifies that the current (for current boundary conditions) be multiplied by ISTEP rather than incremented.

**ISTEP** specifies a current increment to be added to one or more electrodes, as specified by the electrode name applied to the NAME parameter. If ISTEP is specified, either IFINAL or NSTEPS must also be specified.

**N.BIAS** specifies fixed electron quasi-Fermi potentials if electron continuity is not being solved. If **N.BIAS** is not specified, then local quasi-Fermi potentials based on bias and doping are used. But if **FIX.QF** is set in the **METHOD** statement, the quasi-Fermi levels will be set to the maximum bias.

**NB<n>** allows region by region specification of **N.BIAS**. The **n** index corresponds to the region index for which the specified value of electron quasi-fermi level applies.

**NAME** specifies that the named electrode is to be ramped. Custom electrode names are supported by name. See also the **V<name>** parameter.

**NSTEPS** specifies the number of DC bias increments.

**P.BIAS** specifies fixed hole quasi-Fermi potentials if hole continuity is not being solved. If **P.BIAS** is not specified, then local quasi-Fermi potentials based on bias and doping are used. But if **FIX.QF** is set in the **METHOD** statement, the quasi-Fermi levels will be set to the minimum bias.

**PB<n>** allows region by region specification of **P.BIAS**. The **n** index corresponds to the region index for which the specified value of hole quasi-fermi level applies.

**Q<name>** specifies the charge on a named electrode. These names are as follows: *gate*, *gg*, *fgate*, *cgate*, *ngate*, and *pgate*. No other user-defined names are allowed. This parameter is used when floating or charge boundary conditions are selected (see Section 18.4: “CONTACT”).

**Q<n>** specifies the charge on electrode number, **n**. It is more usual to use electrode names rather than numbers. This parameter is superseded by **Q<name>**.

**QFINAL** specifies the final charge for a set of bias increments. If **QFINAL** is specified, either **QSTEP** or **NSTEPS** must also be specified.

**QSCV** specifies the Quasi-static Capacitance calculation. This only has meaning when the **SOLVE** statement is ramping a bias. This requires a small voltage increment between solutions for best results.

**QSTEP** specifies a charge increment to be added to one or more electrodes, as specified by the electrode name applied to the **NAME** parameter. If **QSTEP** is specified, either **QFINAL** or **NSTEPS** must also be specified.

**V<name>** specifies the bias voltage for a named electrode. One of several commonly used terminal names should be specified. These names are as follows: *gate*, *gg*, *drain*, *dd*, *source*, *bulk*, *substrate*, *emitter*, *ee*, *collector*, *cc*, *base*, *bb*, *anode*, *cathode*, *fgate*, *cgate*, *ngate*, *pgate*, *well*, *nwell*, *pwell*, *channel*, and *ground*. No other user-defined names are allowed.

**V<n>** specifies the bias voltage for electrode, **n**. Normally, **V<sub>n</sub>**, defaults to the potential from the previous bias point. It is more usual to use electrode names rather than numbers. This parameter is superseded by **V<name>**.

**VFINAL** specifies the final voltage for a set of bias increments. If **VFINAL** is specified, either **VSTEP** or **NSTEPS** must also be specified.

**VSTEP** specifies a voltage increment to be added to one or more electrodes, as specified by the electrode name applied to the **NAME** parameter. If **VSTEP** is specified, you must either specify **VFINAL** or **NSTEPS**.

## File Output Parameters

**EMIN**, **EMAX** specify the energy range for output of spectral data in the file named by the **SPECTRUM** parameter.

**LMIN**, **LMAX** specify the wavelength range for spectral output in the file named by the **SPECTRUM** parameter.

**MASTER** specifies that the output file selected by the **OUTFILE** parameter will be written in a standard structure file rather than in the older **PISCES-II** binary format.

**ONEFILEONLY** specifies that only one filename will be used to save solutions during a bias ramp. If this parameter is specified, filename incrementing described under **OUTFILE** is not applied. This parameter is true by default unless the **NAME** or **ELECTRODE** parameters or transient simulations specified. When **CURVETRACE** is used, you need to explicitly set this parameter to *false* using **^ONEFILEONLY** to save a different filename at each bias point.

**OUTFILE** specifies the name of the output file where bias point solution information will be stored. If an electrode is stepped so that more than one solution is generated by the **SOLVE** statement, the ASCII code of the last non-blank character of the supplied file name will be incremented by one for each bias point in succession, resulting in a unique file per bias point.

**SPECTRUM** specifies the name of an output file where LED spectral data are stored after each step.

---

**Note:** The output file specified by **OUTFILE** has a limit of 132 characters on a UNIX system and eight characters on a PC system.

---

## Initial Guess Parameters

**INITIAL** sets all voltages to zero. If this parameter is not specified for the first bias point in a given structure a **SOLVE INIT** statement is automatically inserted. The **SOLVE INIT** statement is always solved in zero carrier mode with no external elements attached. It is used to provide a good initial guess to subsequent solutions.

**LOCAL** specifies that the initial approximation should use local values of quasi-Fermi levels. See Chapter 17: “Numerical Techniques”, Section 17.6: “Initial Guess Strategies” for more detailed information.

**MLOCAL** specifies the modified local initial guess. This parameter is used when solved for carrier temperatures in the energy balance models. If any energy balance model is specified, **MLOCAL** defaults to true.

**NOCURRENT** specifies an initial guess strategy that solves the non-linear Poisson equation and uses this solution as the initial guess. This will typically give good results for situations where the quasi-fermi levels are almost flat and the current is consequently low. Under these conditions, you can solve almost any desired bias point directly.

**PREVIOUS** specifies that the previous solution as the initial approximation.

**PROJ** specifies that an extrapolation from the last two solutions will be used as an initial approximation. This parameter may be used if there are two or more existing solutions and equivalent bias steps are taken on any electrodes that are changed.

---

**Note:** If no initial guess parameters are specified, **ATLAS** will use **PROJ** wherever possible.

---

**QFACTOR** specifies as scaling factor to improve initial guesses when the **QUANTUM** model is used. This parameter should be ramped slowly from zero to unity at the start of quantum effect simulations.

## Compliance Parameters

Compliance parameters define a current limit for a DC bias ramp or transient simulation. You can terminate the simulation by monitoring the current and checking against a user-defined limit.

**COMPLIANCE** sets a limit on the current from the electrode which has been specified by the **CNAME** or **E.COMPLIANCE** parameter. When the **COMPLIANCE** value is reached, any bias ramp is stopped and the program continues with the next line of the input file. The **COMPLIANCE** parameter is normally specified in A. If the **GRAD** parameter is specified, **COMPLIANCE** is specified in A/V.

**E.COMPLIANCE** specifies the electrode number to be used by the **COMPLIANCE** parameter. See also **CNAME**.

**CNAME** specifies the name of the electrode used by the **COMPLIANCE**.

**GRAD** specifies that the compliance value is a current/voltage gradient, and not a current value.

## Transient Parameters

**CYCLES** specifies the number of periods to be simulated (both **FREQUENCY** and **TRANS.ANALY** must be specified when this parameter is used). The synonym for this parameter is **PERIODS**.

**CYCLIC.BIAS** specifies that a cyclic bias [127] simulation is being performed. Cyclic biasing allows the effects of repeated trapezoidal/square transient pulses (see **SQPULSE**) on the output characteristics to be determined, without having to do the extremely large numbers of cycles. When **CYCLIC.BIAS** is specified, **ATLAS** will calculate a series of trapezoidal/square pulses using the **SQPULSE** parameters. At the end of the third cycle (and at all subsequent cycles) the values of the potential (V), electron concentration (n), hole concentration (p) and trap probability of occupation ( $f_T$ ) will be modified according to the equation:

$$x(k+1) = x(k) - \mathbf{CYCLIC.RELAX} * ((x(k) - x(k-1)) * dx(k)) / (dx(k) - dx(k-1)) \quad 18-5$$

where  $x$  is a parameter such as V, n, p or  $f_T$  at every node point,  $x(k)$  is the updated value calculated from the equation,  $k$  is the cycle number (with  $k+1$  being the new update for parameter  $x$ ), **CYCLIC.RELAX** is the relaxation factor,  $\delta x(k)$  is the difference between the simulated values of  $x$  at the start and beginning of the current cycle, while  $\delta x(k-1)$  is the equivalent for the previous cycle.

Steady state cyclic convergence is determined by comparing the normalizing sum of the updated values of V, n, p, and  $f_T$  with a tolerance value (**CYCLIC.TOL**).

**CYCLIC.RELAX** specifies the **CYCLIC.BIAS** relaxation factor (the recommended range for this parameter to ensure stable convergence is between 0.2 and 1).

**CYCLIC.TOL** specifies the **CYCLIC.BIAS** tolerance factor.

**DECAY** specifies the time constant used for defining an exponential change in bias for transient simulation.

**ENDRAMP** applies any bias changes as linear ramps. **ENDRAMP** specifies the exact end of the ramp in running time (i.e., the ramp will start at  $t=t_0$  and end at  $t=\text{ENDRAMP}$ ).

**NSTEPS** can be used to signal the end of the run (i.e., the final time would be  $t = t + \text{NSTEPS} * \text{DT}$ ). You can use this parameter instead of the **TSTOP** parameter.

**PULSE.WIDTH** specifies the time constant used for sinusoidal non-linear time domain simulation. If **SQPULSE** is specified, **PULSE.WIDTH** is the width of the trapezoidal/square pulse not including the rise and fall times.

**RAMPTIME** applies any bias changes as linear ramps. **RAMPTIME** specifies a ramp interval in seconds (i.e., the ramp will begin at  $t=t_0$  and ends at  $t=t_0 + \text{RAMPTIME}$ ).

**RELATIVE** specifies that the **TSTOP** value is relative to the current time value.

**SINUAMP.COMP** specifies that sinusoidal amplitude compliance will be used. The transient simulation will stop if the amplitude of a sinusoidal waveform is less than the value of **SINUAMP.COMP**.

**SINUVAR.COMP** specifies that sinusoidal variance compliance will be used. The transient simulation will stop if the change in amplitude of a sinusoidal waveform is less than **SINUVAR.COMP**.

**SQPULSE** specifies that multiple trapezoidal/square transient pulses will be applied. The pulse is controlled by the **TDELAY**, **TRISE**, **PULSE.WIDTH**, **TFALL**, and **FREQUENCY** parameters.

**T.COMP** specifies a temperature for temperature compliance. Once the specified temperature is obtained at some location on the mesh the solution process is discontinued.

**T.SAVE** specifies a time increment at which the device structure files are saved. Note: Actual time steps may not correspond to the user-specified increment.

**TABLE** specifies the filename of a table of time and bias values for the specified electrode. The following format must be used for the **TABLE** file.

```
time1 bias1
time2 bias2
time3 bias3
....
end
```

The time value should be in seconds. The value of the bias should be in the same units as displayed in ATLAS (i.e., Volts for a voltage controlled electrode, A/um for a current controlled electrode, and A for a current controlled electrode in **DEVICE3D** or **ATLAS** with the **WIDTH** parameter specified on the **MESH** statement). There's no limit to the number of time/bias pairs that can be defined in the table file. The keyword, **END**, must be placed after the last time/bias pair. Linear interpolation will be used to determine the bias for time points that aren't specified in the table file.

---

**Note:** An electrode must also be specified when using the **TABLE** parameter. The electrode can be specified either by name (e.g., **NAME=anode**) or by number (e.g., **ELECTRODE=1**).

---

**TDELAY** specifies the time delay before the first cycle of multiple trapezoidal/square transient pulses (**SQPULSE**) will be applied.

**TFALL** specifies the fall time for trapezoidal/square transient pulses (**SQPULSE**).

**TRISE** specifies the rise time for trapezoidal/square transient pulses (**SQPULSE**).

**TRANS.ANALY** specifies that transient analysis is being performed and that a sinusoid with a frequency, specified by the **FREQUENCY** parameter, should be applied.

**TSAVE.MULT** specifies a multiplier the save time increment, **T.SAVE**, is multiplied by after each time a structure is saved.

**TSTEP** or **DT** specifies the time-step to be used. For automatic time-step runs, **DT** is used to select only the first time step (see Section 18.27: "METHOD").

**TSTOP** specifies the end of the time interval. If simulation begins at  $t=t_0$  and **RELATIVE** is specified, it will end at  $t=TSTOP+t_0$ .

## AC Parameters

**AC.ANALYSIS** specifies that AC sinusoidal small-signal analysis should be performed after solving for the DC condition. The full Newton method must be used for this analysis. This is typically specified with the statement:

```
METHOD NEWTON CARRIERS=2
```

**ANAME** specifies the name of the electrode to which the AC bias will be applied. See also **TERMINAL**. If no **ANAME** is specified, all electrodes have AC bias applied in turn.

**AUTO** selects an automatic AC analysis method. This method initially uses **SOR**. The **DIRECT** method will be used if convergence problems occur. We strongly recommend the use of the **AUTO** parameter.

**DIRECT** selects the direct AC solution method. This method is robust at all frequencies, but slow.

**FREQUENCY** specifies the AC analysis frequency. Analysis may be repeated at a number of different frequencies (without solving for the DC condition again) by specifying **FSTEP**. **FREQUENCY** can also be used to specify a sinusoidal or square pulse frequency for transient simulations.

**FSTEP** specifies a frequency increment which is added to the previous frequency. If **MULT.FREQ** is specified, the frequency will be multiplied by **FSTEP**.

**MAX.INNER** specifies the maximum number of SOR iterations.

**MULT.FREQ** specifies that the frequency will be multiplied by **FSTEP**, instead of added to **FSTEP**.

**NFSTEPS** specifies the number of times that the frequency is to be incremented by **FSTEP**.

**S.OMEGA** specifies the SOR parameter. This parameter is not the AC frequency.

**SOR** selects the SOR AC solution method. Although SOR is fast, it should only be used when you are performing simulations at low frequencies. Low frequency can be defined here as at least an order of magnitude below the cutoff frequency.

**TERMINAL** specifies the electrode number to which the AC bias will be applied. Although more than one contact number may be specified (via concatenation), each will be solved separately. Each contact that is specified generates a column of the admittance matrix. If no **TERMINAL** is specified, all electrodes have AC bias applied in turn. See also **ANAME**.

**TOLERANCE** specifies SOR convergence criterion.

**VSS** specifies the magnitude of the applied small-signal bias. The approach used for small-signal analysis constructs a linear problem based on derivatives calculated during Newton iterations, so adjusting **VSS** will generally not affect the results.

## NOISE Parameters

**BRANIN** specifies that Branin's method should be used in the calculation of the impedance field. The direct method (which is the alternative to Branin's method) is very slow. Therefore, we recommend that **BRANIN** is never set to `False`.

**NOINTERFACE** specifies that any element which is adjacent to an interface should be ignored in the noise calculation.

**NOCONTACT** specifies that any element which is adjacent to a contact should be ignored in the noise calculation.

**NOISE.SS** specifies that a small-signal noise simulation should be performed.

## Ionization Integral Parameters

Ionization parameters are used to calculate ionization integrals. No calculation will take place unless the **IONIZINT** parameter is specified.

**DELTAV** since the electric field can be near zero at electrodes, the electric field line calculations begin at a distance from the electrode. A potential contour is drawn around the electrode at a distance where the potential is **DELTAV** less than the applied bias on the contact. Defaults to 0.1 V, but will typically need to be increased especially for power devices and heavily doped contact regions.

**E.CRIT** specifies the minimum electric field used to calculate integration integrals. Field lines will terminate when the field drops below **E.CRIT**.

**INAME** specifies the electrode name from which the electric field lines are calculated. The default is to use the same as electrode as specified in **NAME**.

**ION.CRIT** specifies the critical value of the ionization integral used by IONSTOP to terminate the simulation. When the critical value is reached, any bias ramp will be terminated and the next line of the input file will be executed.

**ION.ELEC** specifies the electrode from which the electric field lines are calculated. This parameter defaults to the electrode which is being ramped (if any).

**IONIZINT** enables the calculation of ionization integrals along electric field lines.

**IONLINES** specifies the number of electric field lines to be calculated. Ionization integrals are calculated along each line.

**IONSTOP** stops the bias ramp if integral is greater than 1.0

**LRATIO** specifies the ratio between the starting points of the electric field lines. An LRATIO value of between 0.5 and 1.5 is recommended. LRATIO=1 means that the spacing between the starting points of the electric field lines is equal. LRATIO < 1 means more lines start towards the left hand side of the structure. LRATIO > 1 means more lines start towards the right hand side.

## Photogeneration Parameters

All these parameters require LUMINOUS to be licensed for correct operation.

**AR.INDEX** specifies the index of refraction for an anti-reflective coating.

**AR.THICKNESS** specifies the thickness in microns of an anti-reflective coating.

**B<n>** specifies the optical spot power associated with optical beam number, n. The beam number must be an integer from 1 to 10.

**BEAM** specifies the beam number of the optical beam when AC photogeneration analysis is performed. Unlike the ELECTRODE parameter, this parameter can only be used to specify a single beam.

**INDEX.CHECK** specifies that the real and imaginary refractive indices used in the ray tracing of each beam will be printed to the run-time output. This parameter can be used as confirmation of the input of user-defined refractive indices or to check the default parameters.

**L.WAVE** specifies the luminous wavelength to use to calculate the luminous power estimate for radiative recombination. If a positive value of L.WAVE is specified the luminous power will be saved in any log file specified for that solution.

**LAMBDA1** specifies the wavelength of the optical source (beam) number 1 for this solution. This parameter can be used to perform analysis of spectral response as a function of wavelength.

**LIT.STEP** selects the light intensity increment of all optical beams which have been specified. This parameter is used when light intensity varies by stepping (similar to the VSTEP parameter). If LIT.STEP is specified, the NSTEP parameter should be used to select the number of steps.

**RAMP.LIT** specifies that the light intensity is to be ramped when transient simulations are performed. If RAMP.LIT is specified, transient mode parameters such as RAMPTIME, TSTEP, and TSTOP must also be specified. The RAMP.LIT parameter affects all specified optical beams (i.e., all beams are ramped).

**SCAN.SPOT** specifies a beam number for spot scanning. Spot scanning requires you to specify the RAYS parameter of the BEAM statement. With this specification, the incident light is split into the user-specified number of rays. During the spot scan, solutions are obtained with the beam energy applied to each of the rays in sequence.

**SS.LIGHT** specifies the intensity in the small signal part of the optical beam when small signal AC photogeneration analysis is performed.



**SS.PHOT** specifies that small signal AC analysis will be performed on the optical beam selected by the **BEAM** parameter. When **SS.PHOT** is specified, other AC parameters (e.g., **FREQUENCY**, **FSTEP**, **MAX.INNER**, **MULT.FREQ**, **NFSTEPS**, **S.OMEGA**, and **TOLERANCE**) should also be specified. You don't need to specify the **AC.ANALYSIS** parameter when performing small signal AC analysis on optical beams.

### Thermal3D Parameters

**POWER<n>** specifies the power in watts on the n-th heat source.

**POWERFINAL** specifies the final power for a linearly ramped heat source.

**T<n>** specifies the temperature in K on the n-th heat sink.

**TEMPFINAL** specifies the final temperature for a linearly ramped heat sink.

For more information about these parameters, see also Chapter 16: "Thermal 3D: Thermal Packaging Simulator", Section 16.4: "Obtaining Solutions In THERMAL3D".

### DC Conditions Example

The following statement solves for a defined bias point and saves the solution to output file, *OutA*. The voltages on electrodes other than the gate will keep the value from the previous **SOLVE** statement.

```
SOLVE VGATE=0.1 OUTFILE=OutA
```

### Bias Stepping Example

In the next example, the bias stepping is illustrated. The two **SOLVE** statements produce the following bias conditions:

| Bias Point | Vgate | Vdrain | Vsub |
|------------|-------|--------|------|
| 1          | 0.0   | 0.5    | -0.5 |
| 2          | 1.0   | 0.5    | -0.5 |
| 3          | 2.0   | 0.5    | -0.5 |
| 4          | 3.0   | 0.5    | -0.5 |
| 5          | 4.0   | 0.5    | -0.5 |
| 6          | 5.0   | 0.5    | -0.5 |

The solutions for these bias points will be saved to the files: *OUT1*, *OUTA*, *OUTB*, *OUTC*, *OUTD*, and *OUTE*. The initial approximation for each bias point is obtained directly from the preceding solution.

For bias points 4, 5, and 6, the program will use a **PROJ** to obtain an initial approximation. Since, starting with bias point 4, both of its preceding solutions (bias points 2 and 3) only had the same electrode bias (number 1) altered.

```
SOLVE Vdrain=.5 Vsub=-.5 OUTF=OUT1
```

```
SOLVE Vgate=1 VSTEP=1 VFINAL=5 NAME=gate OUTF=OUTA
```

## Transient Simulation Example

The following sequence is an example of a time dependent solution. The `METHOD` statement specifies second-order discretization, automatic time-step selection, and an automated Newton-Richardson procedure.

The first `SOLVE` statement then computes the solution for a device with 1V on the base electrode and 2V on the collector in steady-state. The second `SOLVE` statement specifies that the base electrode is to be ramped to 2V over a period of 10 ns and is left on until 25 ns. Each solution is written to a file. The name of the file is incremented in a manner similar to that described for a DC simulation (`UP1`, `UP2`, and so on). Note that an initial time step had to be specified in this statement.

The third `SOLVE` statement ramps the base down from 2V to -0.5V in 20 ns (end of ramp is at 45 ns). The device is then solved at this bias for another 55 ns (out to 100 ns). Each solution is again saved in a separate file (`DOWN1`, `DOWN2`, and so on).

No initial timestep was required since one had been estimated from the last transient solution from the previous `SOLVE` statement.

Finally, the fourth `SOLVE` statement performs the steady-state solution at  $V_{be} = -0.5V$  and  $V_{ce} = 2V$ .

```
METHOD 2ND TAUTO AUTONR
SOLVE Vbase=1 Vcollector=2
SOLVE Vbase=2 DT=1E-12 TSTOP=25E-9 RAMPTIME=10E-9 OUTF=UP1
SOLVE Vbase= -0.5 TSTOP=100E-9 RAMPTIME=20E-9 OUTF=DOWN1
SOLVE Vbase= -0.5 Vcollector=2
```

## AC Analysis Example

The following example illustrates an application of the `SOLVE` statement for AC analysis. It is assumed that the device has three electrodes. This analysis is being performed after DC conditions are solved at  $V_1 = 0V$ ,  $0.5V$ ,  $1.0V$ ,  $1.5V$ , and  $2.0V$ . A series of 10mV AC signals with frequencies of 1 MHz, 10 MHz, 100 MHz, 1 GHz, 10 GHz, and 100 GHz are applied to each electrode in the device.

Ninety AC solutions will be performed ( $5 \times 6 \times 3 = 90$ ).

```
SOLVE V1=0 V2=0 V3=0 VSTEP=0.5 NSTEPS=4 ELECT=1 \
AC FREQ=1E6 FSTEP=10 MULT.F NFSTEP=5 VSS=0.01
```

## Photogeneration Examples

The following statement simulates two DC optical beams incident on the device with optical spot powers of 15 and 25  $W/cm^2$ .

```
SOLVE B1=15 B3=25
```

The next example shows how DC spot power of the two optical beams can be stepped simultaneously. Beam #1 will increase to 35  $W/cm^2$  and beam #3 will increase to 45  $W/cm^2$ .

```
SOLVE LIT.STEP=5.0 NSTEP=4
```

In the next example, the beams are ramped in the time domain. Beam #1 is ramped down to 0  $W/cm^2$  and beam #3 is ramped up to 100  $W/cm^2$ . The duration of the ramp is 1 ns. After the ramp, simulation will continue for 4 ns.

```
SOLVE B1=0 B3=100 RAMP.LIT TSTEP=2E-11 RAMPTIME=1E-9 TSTOP=5E-9
```

Next, the small signal response of a single beam is analyzed. First, `ATLAS` will solve the DC characteristics at the specified optical spot powers. Then, the AC response of beam #1 will be calculated at a frequency of 10 MHz.

```
SOLVE B1=10 B3=20 BEAM=1 FREQUENCY=1e7 SS.PHOT SS.LIGHT=0.01
```

Finally, frequency stepping is used to look at the small signal AC frequency response of one of the beams. AC response is calculated at frequencies from 1kHz to 100MHz at each decade. The `MULT.F` parameter is used to geometrically increase the frequency.

```
SOLVE B1=10 B3=5 BEAM=1 SS.PHOT SS.LIGHT=0.01 \  
MULT.F FREQUENCY=1E3 FSTEP=10 NFSTEP=6
```

### Ionization Integral Example

Ionization integrals are used to estimate the breakdown voltage from analysis of the electric field. They can be used in zero carrier mode providing much faster simulation than conventional breakdown analysis. The ionization syntax uses the parameter `IONIZ` to enable the ionization integral calculation. An equipotential contour is calculated at a potential `DELTAV` from the contact `NAME` (or `INAME`). Electric field lines are started at distances along this potential contour. `IONLINES` sets the number of lines and `LRATIO` is the ratio of the distance between the starting points of the lines. The following syntax is for a PMOS transistor. See the on-line examples for other cases using ionization integrals.

```
IMPACT SELB  
METHOD CARR=0  
SOLVE VDRAIN=-1 VSTEP=-1 VFINAL=-20.0 NAME=DRAIN \  
IONIZ IONLINES=50 LRATIO=0.9 DELTAV=1.2
```

---

**Note:** There are over 300 on-line examples supplied with `ATLAS` to provide examples of sequences of `SOLVE` statements applied to practical problems for a variety of device technologies.

---

## 18.41: SPX.MESH, SPY.MESH

S<n>.MESH specifies the location of grid lines along the <n>-axis in a rectangular mesh used in self-consistent Schrodinger-Poisson Model simulation (see Chapter 13: “Quantum: Quantum Effect Simulator”, Section 13.1: “Self-Consistent Coupled Schrodinger Poisson Model”). The syntax is equivalent for x and y directions.

### Syntax

```
SPX.MESH NODE=<n> LOCATION=<n>
SPX.MESH SPACING=<n> LOCATION=<n>
SPY.MESH NODE=<n> LOCATION=<n>
SPY.MESH SPACING=<n> LOCATION=<n>
```

| Parameter | Type    | Default | Units |
|-----------|---------|---------|-------|
| LOCATION  | Real    |         | μm    |
| NODE      | Integer |         |       |
| SPACING   | Real    |         | μm    |

### Description

**NODE** specifies the mesh line index. These mesh lines are assigned consecutively.

**LOCATION** specifies the location of the grid line.

**SPACING** specifies the mesh spacing at the mesh locations specified by the LOCATION parameter. If the SPACING parameter is specified, then the NODE parameter should not be specified.

---

**Note:** The mesh defined in these statements for the Self-Consistent Schrodinger-Poisson Model is entirely separate from the electrical device simulation mesh defined on the MESH statement.

---

### Setting Locally Fine Grids Example

This example shows how to space grid lines closely around a topological feature such as a junction at  $y=0.85$  microns.

```
SPY.MESH LOC=0.0 SPAC=0.2
SPY.MESH LOC=0.85 SPAC=0.01
SPY.MESH LOC=2 SPAC=0.35
```

## 18.42: SYMBOLIC

---

**Note:** In versions 3.0 and greater, the `SYMBOLIC` statement is no longer needed. All functions have been moved to the `METHOD` statement.

---

## 18.43: SPREAD

SPREAD distorts rectangular grids defined by ATLAS in the vertical direction to follow surface and junction contours.

---

**Note:** The use of this parameter is not recommended by SILVACO.

---

### Syntax

```
SPREAD LEFT|RIGHT WIDTH=<r> UPPER=<i> LOWER=<i>
Y.LOWER|THICKNESS [<options>]
```

| Parameter | Type    | Default                         | Units |
|-----------|---------|---------------------------------|-------|
| ENCROACH  | Real    | 1.0                             |       |
| GRADING   | Real    | 1.0                             |       |
| GR1       | Real    | 1.0                             |       |
| GR2       | Real    | 1.0                             |       |
| LEFT      | Logical | False                           |       |
| LOWER     | Integer |                                 |       |
| MIDDLE    | Integer | Halfway between UPPER and LOWER |       |
| RIGHT     | Logical | False                           |       |
| THICKNESS | Real    |                                 | μm    |
| UPPER     | Integer |                                 |       |
| VOL.RATIO | Real    | 0.44                            |       |
| WIDTH     | Real    |                                 | μm    |
| Y.LOWER   | Real    |                                 | μm    |
| Y.MIDDLE  | Real    | 0.50                            | μm    |

### Description

SPREAD can reduce the grid complexity of specific simulations. Since the SPREAD statement is somewhat complicated, we suggest that you follow the supplied examples carefully until you're confident to understand the workings of this statement.

### Mandatory Parameters

**LEFT** distorts the left side of the grid. If LEFT is specified, RIGHT must not be specified.

**LOWER** specifies the lower y-grid line above which distortion will take place.

**RIGHT** distorts the right side of the grid. If RIGHT is specified, LEFT must not be specified.

**THICKNESS** specifies the thickness of the distorted region. Unless VOL.RATIO is set to 0 or 1, THICKNESS will usually move the positions of both the UPPER and LOWER grid lines. The Y.LOWER and

**THICKNESS** parameters define the distorted grid region. Only one of these parameters should be specified.

**UPPER** specifies the upper y-grid line under which distortion will take place.

**WIDTH** specifies the width from the left or right edge (depending on whether **LEFT** or **RIGHT** is selected) of the distorted area. The actual x coordinate specified by **WIDTH** ( $\min[x] + \text{WIDTH}$  for **LEFT**,  $\max[x] + \text{WIDTH}$  for **RIGHT**) will lie in the middle of the transition region between distorted and undistorted grid regions.

**Y.LOWER** specifies the physical location in the distorted region to which the line specified by **LOWER** will be moved. The line specified by **UPPER** is not moved. The **Y.LOWER** and **THICKNESS** parameters define the distorted grid region. Only one of these parameters should be specified.

## Optional Parameters

**ENCROACH** defines the abruptness of the transition between a distorted and non-distorted grid. The transition region becomes more abrupt with smaller **ENCROACH** factors (the minimum is 0.1).

---

**Note:** Depending on the characteristics of the undistorted grid, long, thin, or obtuse triangles may result if too low an **ENCROACH** value is used.

---

**GRADING** specifies a grid ratio which produces a non-uniform grid in the distorted region. This parameter is identical to the **RATIO** parameter in the **X.MESH** and **Y.MESH** statements.

**GR1** and **GR2** may be used instead of the **GRADING** parameter. **GR1** and **GR2** may be specified in conjunction with **MIDDLE** (y grid line) and **Y.MIDDLE** (location) so that **GR1** specifies grading in the spread region from **UPPER** to **MIDDLE**, and **GR2** specifies grading from **MIDDLE** to **LOWER**.

**MIDDLE** specifies the y-grid line that serves as a boundary between the grading specified by **GR1** and the grading specified by **GR2**.

**VOL.RATIO** specifies the ratio of the downward displacement of the lower grid line to the net increase in thickness. The default (0.44) should be used for oxide-silicon interfaces. **VOL.RATIO** is ignored if **Y.LOWER** is specified.

**Y.MIDDLE** specifies the physical location in the distorted grid to which the line specified by **MIDDLE** will be moved.

## Examples

This example spreads a uniform 400 Å of oxide to 1000 Å on the left side of the device. This increases oxide thickness by 600 Å. Because **VOL.RATIO** is not specified, the default (0.44) is used. Therefore,  $0.44 \times 600 = 264$  Å of the net increase will lie below the original 400 Å and  $0.56 \times 600 = 336$  Å of the net increase will lie above the original 400 Å. The width of the spread region is 0.5 μm, and the oxide taper is quite gradual because of the high encroachment factor. The grid is left uniform in the spread region.

```

# *** Mesh definition ***
MESH NX=30 NY=20 RECT
X.M N=1 L=0
X.M N=30 L=5
Y.M N=1 L=-.04
Y.M N=5 L=0
Y.M N=20 L=1 R=1.4

```

```
# *** Thin oxide ***
REGION IY.H=5 OXIDE NUM=1
# *** Silicon substrate ***
REGION IY.L=5 SILICON NUM=2
# *** Spread ***
SPREAD LEFT W=0.7 UP=1 LO=4 THICK=0.1 MID=2 Y.MID=0.05
```

In the second example, the right side of the grid is distorted in order to follow a junction contour. The initial grid is assumed to be above. Y.LOWER is used so that there is no increase in the size of the device, just grid redistribution. When Y.LOWER is set to the junction, choose the ENCROACH parameter so that the lower grid line (LOWER=10) follows the junction as closely as possible. The grid is graded so that grid lines are spaced closer together as they approach the junction. Because the point specified by WIDTH lies in the middle of the transition region, it should be chosen to be slightly larger than the width of the doping box.

```
# *** Doping ***
DOPING UNIFORM N.TYPE CONC=1E15
DOPING GAUSS P.TYPE X.LEFT=1.5 X.RIGHT=2 \
PEAK= CONC=1.e19 RATIO=.75 JUNC=0.3
# *** Spread ***
SPREAD RIGHT W=0.7 UP=1 LO=4 THICK=0.3 MID=2 Y.MID=0.10
```



---

## 18.44: SYSTEM

SYSTEM allows execution of any UNIX command within an input file

---

**Note:** The SYSTEM statement is executed by DECKBUILD and is fully documented in the VWF INTERACTIVE TOOLS MANUAL VOLUME 1. To enable SYSTEM command, select **Category: Options** in the DeckBuild Main Control menu.

---

### Examples

The following command will remove all files test\*.str before a SOLVE statement where the OUTF parameter is used.

```
system \rm -rf test*.str
SOLVE .... OUTF=test0
```

The system command and the UNIX commands are case sensitive.

UNIX commands may be concatenated on a single line using the semicolon (;) operator. For example to run a third party program that reads and writes Silvaco format files with fixed names input.str and output.str.

```
SAVE OUTF=mysave.str
system mv mysave.str input.str; source myprog.exe; mv output.str
myrestart.str
EXTRACT INIT INF=myrestart.str
```

The UNIX re-direct symbol > is not supported by the system command. The UNIX echo and sed syntax can be used instead to output values or variables to a given filename. For example to save the extracted value of variable \$myvariable to the file myfile.

```
system echo "$myvariable" | sed -n " w myfile"
```

## 18.45: THERMCONTACT

THERMCONTACT specifies the position and properties of thermal contacts. This statement must be used when lattice heating solutions are specified using GIGA or GIGA3D.

### Syntax

```
THERMCONTACT NUMBER=<n> <position> [EXT.TEMPER=<n>] [ALPHA=<n>]
```

| Parameter   | Type      | Default                 | Units                     |
|-------------|-----------|-------------------------|---------------------------|
| ALPHA       | Real      | .                       | W / (cm <sup>2</sup> · K) |
| BOUNDARY    | Logical   | true                    |                           |
| DEVICE      | Character |                         |                           |
| ELEC.NUMBER | Integer   |                         |                           |
| EXT.TEMPER  | Real      | 300                     | K                         |
| F.CONTEMP   | Character |                         |                           |
| NAME        | Character |                         |                           |
| NUMBER      | Integer   | 1                       |                           |
| X.MAX       | Real      | Right side of structure | μm                        |
| X.MIN       | Real      | Left side of structure  | μm                        |
| Y.MAX       | Real      | Bottom of structure     | mμ                        |
| Y.MIN       | Real      | Top of structure        | μm                        |
| Z.MIN       | Real      | Front                   | microns                   |
| Z.MAX       | Real      | Back                    | microns                   |

### Description

At least one THERMCONTACT statement must be specified when simulating lattice heating effects (MODELS LAT.TEMP). The THERMCONTACT statement must appear in the input deck before any METHOD statement.

**position** is a set of the position parameters described below. Use either the X.MIN, X.MAX, Y.MIN, and Y.MAX parameters to specify the exact position of the contact or the ELEC.NUMBER parameter to specify an electrode number that coincides with the thermal contact.

**NUMBER** specifies a thermal contact number from 1 to 20. Contact numbers should be specified in increasing order. This parameters must be specified on all THERMCONTACT statements.

**ALPHA** specifies the reverse value of thermal resistance ( $\alpha=1/R_{TH}$ ). This parameter may not be used if ELEC.NUMBER parameter has been specified.

**EXT.TEMPER** specifies the external temperature. The synonym for this parameter is TEMPERATURE.

**F.CONTEMP** specifies the name of a file containing a C-Interpreter function describing the contact temperature as a function of time.

## Position Parameters

**BOUNDARY** specifies which parts of the thermal contact the thermal boundary conditions are applied at. See Chapter 7: “Giga: Self-Heating Simulator”, Section 7.2.4: “Thermal Boundary Conditions” for a full description.

**NAME** specifies which region the THERMCONTACT statement applies to. Note that the name must match the name specified in the NAME parameter of the REGION statement.

**DEVICE** specifies which device in MIXEDMODE simulation the THERMCONTACT statement applies to.

**ELEC.NUMBER** specifies an electrode number that the thermal contact is coincident with.

**X.MIN** specifies the left edge of the contact.

**X.MAX** specifies the right edge of the contact.

**Y.MIN** specifies the top edge of the contact.

**Y.MAX** specifies the bottom edge of the contact.

**Z.MIN** specifies the location of the front edge of the thermal contact.

**Z.MAX** specifies the location of the rear edge of the thermal contact.

## Coordinate Definition Example

A thermal contact is located where y coordinate values range from 10  $\mu\text{m}$  to the bottom side of the structure and x coordinate values range from the left edge of the structure to the right edge of the structure (be default). The external temperature is set to 300K and a thermal resistance of 1 is added. Thus, the temperature at  $y = 10 \mu\text{m}$  will be greater than 300K once lattice heating effects occur.

```
THERMCONTACT NUM=1 Y.MIN=10 EXT.TEMP=300 ALPHA=1
```

## Setting Thermal and Electrical Contacts Coincident Example

The next statement line creates a thermal contact at the location of electrode #4. An external temperature of 400K is specified.

```
THERMCONTACT NUM=2 ELEC.NUM=4 EXT.TEMP=400
```

---

**Note:** Location and Parameters of thermal contacts are not stored in the ATLAS solution files. Therefore, THERMCONTACT statements must be defined in each ATLAS run involving lattice heating.

---

## 18.46: TITLE

TITLE specifies the title (up to 29 characters) that will appear in the standard output. If used, the TITLE command should be the first statement in the ATLAS input file.

### Syntax

```
TITLE <string>
```

### Example

This example causes the text, `*** CMOS p-channel device ***`, to be printed at the top of all ATLAS printouts and screen displays.

```
TITLE *** CMOS p-channel device ***
```

---

**Note:** TITLE cannot be used with the automatic ATHENA to ATLAS interface feature of DECKBUILD

---

## 18.47: TONYPLOT

TONYPLOT starts the graphical post-processor TONYPLOT

---

**Note:** The TONYPLOT statement is executed by DECKBUILD and is fully described in the VWF INTERACTIVE TOOLS MANUAL, VOLUME 1.

---

### Examples

All graphics in ATLAS is performed by saving a file and loading the file into TONYPLOT. The TONYPLOT command causes ATLAS to automatically save a structure file and plot it in TONYPLOT. The TonyPlot window will appear displaying the material boundaries. Use the **Plot:Display** menu to see more graphics options.

This command will display the file, *myfile.str*.

```
tonyplot -st myfile.str
```

This command will overlay the results of *myfile1.str* and *myfile2.str*.

```
tonyplot -overlay myfile1.str myfile2.str
```

---

**Note:** For documentation of the extensive features of TONYPLOT for graphical display and analysis, see the TONYPLOT chapter of the VWF INTERACTIVE TOOLS MANUAL, VOLUME 1.

---

## 18.48: TRAP

TRAP activates bulk traps at discrete energy levels within the bandgap of the semiconductor and sets their parameter values.

### Syntax

```
TRAP DONOR|ACCEPTOR E.LEVEL=<r> DENSITY=<r> DEGEN=<v>
<capture parameters> REGION|NUMBER
```

| Parameter | Type      | Default   | Units            |
|-----------|-----------|-----------|------------------|
| ACCEPTOR  | Logical   | False     |                  |
| DEVICE    | Character |           |                  |
| DEGEN.FAC | Real      | undefined |                  |
| DENSITY   | Real      |           | cm <sup>-3</sup> |
| DONOR     | Logical   | False     |                  |
| E.LEVEL   | Real      |           | eV               |
| FAST      | Logical   | False     |                  |
| MATERIAL  | Character |           |                  |
| NUMBER    | Integer   | 0         |                  |
| REGION    | Integer   | 0         |                  |
| SIGN      | Real      |           | cm <sup>2</sup>  |
| SIGP      | Real      |           | cm <sup>2</sup>  |
| TAUN      | Real      |           | s                |
| TAUP      | Real      |           | s                |

### Description

**ACCEPTOR** specifies an acceptor-type trap level.

**DEGEN.FAC** specifies the degeneracy factor of the trap level used to calculate the density.

**DENSITY** sets the maximum density of states of the trap level.

**DEVICE** specifies which device the statement applies to in MIXEDMODE simulation.

**DONOR** specifies a donor-type trap level.

**E.LEVEL** sets the energy of the discrete trap level. For acceptors, E.LEVEL is relative to the conduction band edge. For donors, it depends on the valence band edge.

**FAST** specifies that the trap densities are static even during transient simulation (i.e., they reach equilibrium instantaneously).

**MATERIAL** specifies which material from the table in Appendix B: “Material Systems” will apply to the TRAP statement. If a material is specified, then all regions defined as being composed of that material will be affected.

**NUMBER** is the synonym for **REGION**.

**REGION** specifies which region the traps apply to. If unspecified, the traps apply to all regions.

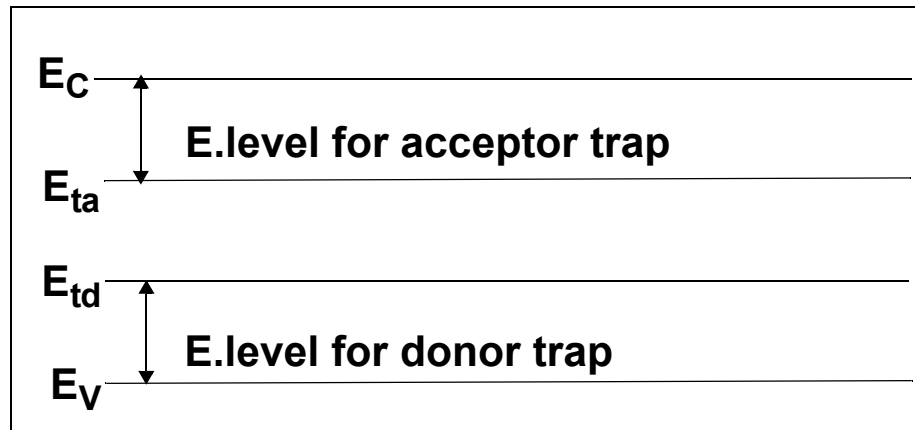


Figure 18-8: Acceptor and Donor Trap Energy Levels

### Capture Parameters

Either the cross section or lifetime parameters should be used to define the capture parameters.

**SIGN** specifies the capture cross section of the trap for electrons.

**SIGP** specifies the capture cross section of the trap for holes.

**TAUN** specifies the lifetime of electrons in the trap level.

**TAUP** specifies the lifetime of holes in the trap level.

### Multiple Trap Level Definition Example

The following example sets three discrete trap levels within the silicon bandgap. These trap levels will capture carriers, slowing the switching speed of any device. In this example the capture cross sections are used to define the properties of each trap.

```
trap e.level=0.49 acceptor density=2.e15 degen=12 \
sign=2.84e-15 sigp=2.84e-14
trap e.level=0.41 acceptor density=1.e15 degen=12 \
sign=7.24e-16 sigp=7.24e-15
trap e.level=0.32 donor density=1.e15 degen=1 \
sign=1.00e-16 sigp=1.00e-17
```

**Note:** For distributed trap levels, see Section 18.7: “DEFECTS”. For interface traps, see Section 18.19: “INTTRAP”. Also, spatial **TRAP** distributions in x, y or z directions must be defined in the **DOPING** statement.

## 18.49: UTMOST

UTMOST converts data from a ATLAS logfile format into an UTMOST logfile format.

**Note:** UTMOST 12.3.4 or later can read ATLAS format logfiles directly in batch mode. This statement is obsolete and its use is not recommended.

### Syntax

```
UTMOST BIP|DIODE|MOS <input> OUTFILE=<fn> WIDTH=<n>
[<elec>] <cntrl>
[TRANSLATE INFILE1=<filename>][<analysis>] [<parasites>]
```

| Parameter | Type      | Default    | Units |
|-----------|-----------|------------|-------|
| AC        | Logical   | False      |       |
| ANODE     | Integer   | 1          |       |
| APPEND    | Logical   | False      |       |
| BASE      | Integer   |            |       |
| BIP       | Logical   | False      |       |
| BULK      | Integer   |            |       |
| CATHODE   | Integer   |            |       |
| COLLECTOR | Integer   |            |       |
| DEVICE    | Integer   | 1          |       |
| DIODE     | Logical   | False      |       |
| DRAIN     | Integer   |            |       |
| EMITTER   | Integer   |            |       |
| GATE      | Integer   |            |       |
| INFILE    | Character |            |       |
| INTERNAL  | Logical   | False      |       |
| LENGTH    | Real      | 1.0        | μm    |
| MESFET    | Logical   | False      |       |
| MINSTEP   | Real      | 0.01       | V     |
| MOS       | Logical   | False      |       |
| OUTFILE   | Character |            |       |
| POLARITY  | Integer   | 1 (n-type) |       |
| ROUTINE   | Integer   | 1          |       |



| Parameter   | Type    | Default | Units |
|-------------|---------|---------|-------|
| SOURCE      | Integer |         |       |
| TEMPERATURE | Real    | 300     | K     |
| WELL        | Integer |         |       |
| WIDTH       | Real    | 1.0     | μm    |

## Description

Specify a technology parameter (BIP, DIODE, or MOS), an input file (INFILE1=), and an output file (OUTFILE=). You can also specify one or more of the optional electrode parameters.

**INFILE** is used to convert up to nine ATLAS logfiles into a single UTMOST logfile. The ATLAS logfiles must be specified in the form:

```
INFILE1=<fn> INFILE2=<fn> INFILE3=<fn> . . .
```

where *fn* is the name of the logfile that you wish to convert.

**OUTFILE** specifies the name of a file where I-V data will be stored in an UTMOST file format.

**APPEND** specifies that I-V data should be appended to the output file specified by **OUTFILE2**.

**WIDTH** is used to specify the width of the device. Electrode current is multiplied by the value of **WIDTH** before being saved in the logfile.

## Technology Parameters

**BIP** creates an UTMOST bipolar transistor log file.

**DIODE** creates an UTMOST diode log file.

**MOS** creates an UTMOST MOSFET log file.

**MESFET** creates an UTMOST MESFET log file.

## Electrode Parameters

Different electrode parameters may be specified with different technologies.

**BIP** Technology

**BASE** specifies the base electrode number.

**COLLECTOR** specifies the collector electrode numb.

**EMITTER** specifies the emitter electrode numb.

**POLARITY** indicates the device type. Polarity=1 specifies npn. Polarity=-1 specifies pnp.

**MOS** And **MESFET** Technologies

---

**Note:** If you have used the **NAME** parameter of the **ELECTRODE** statement to assign standard electrode names (bulk, drain, gate, and source), you don't need to re-specify these names in the **UTMOST** statement.

---

**BULK** or **SUBSTRATE** specifies the bulk electrode number.

**DRAIN** specifies the drain electrode number.

**GATE** specifies the gate electrode number.

**POLARITY** indicates the device type. **POLARITY=1** specifies nmos. **POLARITY=-1** specifies pmos.

**SOURCE** specifies the source electrode number.

### Control Parameters

The optional control parameters are used to specify what type of information will be converted to an UTMOST logfile.

**AC** specifies that input logfiles contain AC parameters and that the UTMOST routine numbers refer to the UTMOST capacitance routines.

**DEVICE** specifies the device (or row) number used to identify different devices in UTMOST. The synonym for this parameter is **ROW**.

**INTERNAL** specifies that internal contact voltage will be used instead of applied bias.

**LENGTH** specifies the length of the device.

**MINSTEP** specifies the minimum voltage step between data points.

**TEMPERATURE** specifies the simulation temperature.

**ROUTINE** specifies which UTMOST routine number data will be saved for. The following routines are supported.

### BIP Technology

**ROUTINE=1** specifies  $I_C$  vs.  $V_{CE}$  curves. Each input file holds I-V data for a solution with a fixed base current and  $V_{CE}$  stepped. (UTMOST IC/VCE routine).

**ROUTINE=9** specifies a  $B_F$  vs.  $V_{BE}$  plot. Each input file holds I-V data for a solution with constants  $V_{CE}$  and  $V_{BE}$  stepped. (UTMOST BF vs. IC routine)

**ROUTINE=10** specifies a  $B_F$  vs.  $V_{BC}$  plot. Each input file holds I-V data for a solution with constants  $V_{CE}$  and  $V_{BC}$  stepped. (UTMOST BR routine)

**ROUTINE=14** specifies a  $I_C, I_B$  vs.  $V_{BE}$  (Gummel) plot. Each input file holds I-V data for a solution with constant  $V_{CE}$  and  $V_{BE}$  stepped. (UTMOST gummel routine)

**ROUTINE=15** specifies a  $I_E, I_B$  vs.  $V_{BC}$  (Reverse Gummel) plot. Each input file holds I-V data for a solution with constants  $V_{EC}$  and  $V_{BC}$  stepped. (UTMOST rgummel routine)

**ROUTINE=29** specifies  $I_E$  vs.  $V_{EC}$  plot. Each input file holds I-V data for a solution with a fixed base current and  $V_{EC}$  stepped. (UTMOST IE/VEC routine)

### MOS Technology

**ROUTINE=1** specifies a  $I_D$  vs.  $V_{DS}$  plot.  $V_B$  is constant and  $V_G$  is stepped. (UTMOST ID/VD-VG routine)

**ROUTINE=2** specifies a  $I_D$  vs.  $V_{GS}$  plot.  $V_D$  is constant and  $V_B$  is stepped. (UTMOST ID/VG-VB routine)

**ROUTINE=3** specifies the  $L_{EFF}, R_{SD}$  routine. Two devices of different lengths are needed. The  $I_D/V_{GS}$  data should be used.

**ROUTINE=5** specifies a  $I_D$  vs.  $V_{GS}$  plot.  $V_D$  is constant and  $V_B=0$ . (UTMOST VTH routine)

**ROUTINE=9** specifies a  $I_D$  vs.  $V_{GS}$  plot.  $V_D$  is constant and  $V_B$  is stepped. (UTMOST NSUB routine).

**ROUTINE=10** specifies the IS routine. The forward diode characteristics of the drain to bulk junction are required.

**ROUTINE=11** specifies the LAMBDA routine. An  $I_D/V_D$  curve is required.

**ROUTINE=12** specifies the ETA routine. A set of  $I_D/V_{GS}$  data for different  $V_{DS}$  is required.

**ROUTINE=13** specifies the VMAX routine. A set of  $I_D/V_{GS}$  curves for small changes in  $V_{DS}$  are required.

**ROUTINE=14** specifies the U0 routine. A set of  $I_D/V_{GS}$  data is required.

**ROUTINE=26** specifies a  $I_D$  vs.  $V_{GS}$  plot.  $V_B$  is constant and  $V_D$  is stepped. (UTMOST ID/VG-VD routine).

### MOS Capacitances

The following routines may be specified if both MOS and AC parameters are selected.

**ROUTINE=1** specifies the CGSO routine.  $C_{GS}$  vs.  $V_{GS}$  data is required.

**ROUTINE=2** specifies the CGDO routine.  $C_{GD}$  vs.  $V_{GS}$  data is required.

**ROUTINE=5** specifies the CJ routine.  $C_{BD}$  vs.  $V_{DS}$  data is required.

**ROUTINE=6** specifies the CJSW routine.  $C_{BD}$  vs.  $V_{DS}$  data is required.

**ROUTINE=12** specifies the CJ/CJSW routine.  $C_{GD}$  vs.  $V_{GS}$  data is required for two different size drain areas.

### Diode Technology

**ROUTINE=1** specifies an I vs. V plot. V is stepped. (UTMOST ID vs. VD routine).

## 18.50: VCSEL

The VCSEL statement specifies certain VCSEL simulation parameters.

### Syntax

VCSEL <parameters>

| Parameter       | Type    | Default | Units |
|-----------------|---------|---------|-------|
| ABSORPTION      | Logical | False   |       |
| CHECK           | Logical | False   |       |
| EFINAL          | Real    |         | eV    |
| EINIT           | Real    |         | eV    |
| FCARRIER        | Logical |         |       |
| INDEX.BOTTOM    | Real    | 1.0     |       |
| INDEX.TOP       | Real    | 1.0     |       |
| ITMAX           | Integer |         |       |
| MAXCH           | Real    |         |       |
| LOSSES          | Real    |         |       |
| NEFF            | Real    |         |       |
| NMODE           | Integer | 1       |       |
| NSPEC           | Integer | 100     |       |
| OMEGA           | Real    |         |       |
| PERTURB         | Logical | False   |       |
| PHOTON.ENERGY   | Real    |         | eV    |
| PHOJ            | Logical | False   |       |
| TAUSS           | Real    |         | s     |
| TOLER           | Real    |         |       |
| VCSEL.CHECK     | Logical | False   |       |
| VCSEL.INCIDENCE | Integer | 1       |       |

### Description

**ABSORPTION** enables the absorption loss model in VCSEL.

**CHECK** enables reflectivity test simulation of the VCSEL structure

**EINIT**, **EFINAL** specify the lower and upper photon energies in reflectivity test. The default values are **EINIT=0.8 PHOTON.ENERGY** and **EFINAL=1.2 PHOTON.ENERGY**.

**INDEX.BOTTOM** specifies the refractive index of the medium below the structure. The default value is 1.0.

**INDEX.TOP** specifies the refractive index of the medium above the structure. The default value is 1.0.

**ITMAX** sets maximum number of external VCSEL iterations during photon density calculation. The default value is 30.

**MAXCH** specifies the maximum allowed relative change in photon densities between iterations. Rapid changes of the photon densities can cause convergence problems.

**LOSSES** specifies additional losses in Chapter 9: “VCSEL Simulator”, Equation 9-16.

**NEFF** specifies the effective refractive index in Chapter 9: “VCSEL Simulator”, Equation 9-11.

**NMODE** specifies the number of transverse modes of interest. The default value is `NMODE=1`.

**NSPEC** specifies the number of sampling points between `EINIT` and `EFINAL` in reflectivity test. The default value is `NSPEC=100`.

**OMEGA** specifies the reference frequency (see Equation 9-2 in Chapter 9: “VCSEL Simulator”). The reference frequency can change after the reflectivity test to correspond to the resonant frequency of the structure.

**PERTURB** enables faster solution of the Helmholtz equation. When it is specified, the program solves the longitudinal wave equation only once. The perturbational approach is used to account for the refractive index changes.

**PHOTON.ENERGY** specifies the reference photon energy. The reference photon energy can change after reflectivity test to correspond to the resonant photon energy of the structure. This parameter is related to `OMEGA` parameter.

**PROJ** enables faster solution of the photon rate equations below threshold. You should disable this solution scheme when the bias reaches lasing threshold. To do this, specify `^PROJ` in a VCSEL statement.

**TAUSS** is an iteration parameter used in the calculation of photon densities. Using a larger value of this parameter can speed up the calculation but may cause convergence problems.

**TOLER** sets the desired relative tolerance of the photon density calculation. The default value is 0.01. Setting this parameter to a lower value may slow down the calculation significantly. Using a larger value will result in a faster but less accurate calculations.

**VCSEL.CHECK** same as `CHECK`.

**VCSEL.INCIDENT** specifies the direction of light incident on the structure. `VCSEL.INCIDENT=1` is the light incident from the top. `VCSEL.INCIDENT=0` is the light incident from the bottom. `VCSEL.INCIDENT=2` or `>2` means both directions of light incidence are considered. By default, light is incident from the top of the structure.

## 18.51: X.MESH, Y.MESH, Z.MESH

<n>.MESH specifies the location of grid lines along the <n>-axis in a rectangular mesh for 2-D or 3-D simulation.

---

**Note:** The commands are equivalent in the x, y or z directions.

---

### Syntax

X.MESH LOCATION=<l> (NODE=<n> [RATIO=<r>]) | SPACING=<v>

| Parameter | Type    | Default | Units |
|-----------|---------|---------|-------|
| LOCATION  | Real    |         | μm    |
| NODE      | Integer |         |       |
| RATIO     | Real    | 1       |       |
| SPACING   | Real    |         | μm    |

### Description

**LOCATION** specifies the location of the grid line.

**NODE** specifies mesh line index. There is a limit of 120 mesh lines. These mesh lines must be assigned in increasing order.

**RATIO** specifies the ratio to use when interpolating grid lines between given locations. Spacing between adjacent grid lines will increase or decrease by the factor assigned to the RATIO parameter. A RATIO value of between 0.667 and 1.5 is recommended. RATIO should not be used if SPACING is specified.

**SPACING** specifies the mesh spacing at the mesh locations specified by the LOCATION parameter. If the SPACING parameter is specified, the NODE and RATIO parameters should not be specified. If the SPACING parameter is used to specify mesh spacings, the NX, NY, and NZ parameters of the MESH statement should not be specified. When the mesh spacings are specified using the SPACING parameter, the mesh size will be calculated.

### Setting Fine Grid at A Junction Example

This example shows how to space grid lines closely around a junction at y=0.85 microns.

```

Y.MESH LOC=0.0 SPAC=0.2
Y.MESH LOC=0.85 SPAC=0.01
Y.MESH LOC=2 SPAC=0.35
    
```

## A.1: Overview

ATLAS has a built-in C language interpreter that allows many of the models contained in ATLAS to be modified. In order to use the SILVACO C-INTERPRETER, (SCI) you must write C language functions containing analytic descriptions of the model. The C-INTERPRETER uses the ANSI standard definition of C. If you are not familiar with the C language, we suggest that you refer to any of the popular C language references such as the one written by Kernighan and Ritchie [91]. Additional information about the C-INTERPRETER can be found in the SILVACO C-INTERPRETER MANUAL.

The function arguments of the C-INTERPRETER functions and return values are fixed in ATLAS. Make sure that the arguments and the return values for the functions match those expected by ATLAS. To help you, this release of ATLAS includes a set of templates for the available functions. The C-INTERPRETER function template can be obtained by typing:

```
atlas -T filename
```

where `filename` is the name of a file where you want the template to be copied. You can also get the C-INTERPRETER function template by accessing the template file through DECKBUILD.

This template file should be copied and edited when implementing user-defined C-INTERPRETER functions. In order to use the C-INTERPRETER function, the file name containing this function must be specified in the appropriate ATLAS statement. The relevant statement names and parameters are listed in the template file.

The following example shows how the C-INTERPRETER function `munsat` can be used to describe velocity saturation for electrons.

First, examine the template file and find the template for `munsat`. The template should look something like this:

```
/*
 * Electron velocity saturation model.
 * Statement: MATERIAL
 * Parameter: F.MUNSAT
 */
/* e      electric field (V/cm) */
/* v      saturation velocity (cm/s) */
/* mu0    low field mobility (cm^2/Vs) */
/* *mu    return: field dependent mobility (cm^2/Vs) */
/* *dmde  return: derivative of mu with e */

int munsat(double e, double v, double mu0, double *mu, double *dmde)
{
    return(0);          /* 0 - ok */
}
```

Here, we see that the function is passed the electric field, the saturation velocity and the low field mobility. The function returns the field dependent mobility and the derivative of mobility with respect to electric field.

---

**Note:** It is important to properly calculate and return derivative values when specified, since the convergence algorithms in ATLAS require these derivatives.

---

The return value is an error flag. In this case, it is set to zero indicating that the function was successful (0=OK, 1=fail).

In this example, the electron saturation velocity characteristic is changed to one which is akin to that used for holes in silicon. You can specify this model by setting the B.ELE parameter to 1 but for example purposes, use the C-INTERPRETER function `munsat` instead. This will enable comparison between the built-in model and the C-INTERPRETER model.

To implement the model, two lines additional lines of C code in the body of the function are specified as follows:

```

/*
 * Electron velocity saturation model.
 * Statement: MATERIAL
 * Parameter: F.MUNSAT
 */
/* e      electric field (V/cm) */
/* v      saturation velocity (cm/s) */
/* mu0    low field mobility (cm^2/Vs) */
/* *mu    return: field dependent mobility (cm^2/Vs) */
/* *dmde  return: derivative of mu with e */

int munsat(double e, double v, double mu0, double *mu, double *dmde)
{
    *mu = mu0/(1.0+mu0*e/v);
    *dmde = (*mu)*(*mu)/v;
    return(0);          /* 0 - ok */
}

```

The function will then need to be stored in a file. For example, the function can be stored in the file: `test.lib`. The function is then introduced into a specific example by specifying the file name on the F.MUNSAT parameter in the MATERIAL statement as follows:

```
MATERIAL F.MUNSAT="test.lib"
```

When the input deck is executed, your C-INTERPRETER functions will be used in place of the built in function. When trying this example, place PRINT statements (using the `printf` C command) in the function to check that the function is working correctly.

A complete list of all the interpreter functions available in ATLAS is shown in Table A-1.



| <b>Table A-1. Complete list of available C-Interpreter functions in ATLAS</b> |                  |                     |   |
|---|------------------|---------------------|---|
| <b>Statement</b>  | <b>Parameter</b> | <b>Template</b>     | <b>Description</b>  |
| BEAM  | F.RADIATE        | radiate ()          | Generation rate as a function of position.                                |
| BEAM  | F3.RADIATE       | radiate3 ()         | Generation rate as a function of position (3D).                           |
| BEAM  | F.REFLECT        | reflect ()          | Reflection coefficient.   |
| DEFECT  | F.TFTACC         | tftacc ()           | TFT acceptor trap density as a function of energy.                        |
| DEFECT  | F.TFTDON         | tftdon ()           | TFT donor trap density as a function of energy.                           |
| DEGREDAT  | F.NTA            | devdeg_nta ()       | Interface acceptor trap density as a function of location.                |
| DEGREDAT  | F.NTD            | devdeg_ntd ()       | Interface donor trap density as a function of location.                   |
| DEGREDAT  | F.SIGMAE         | devdeg_sigmae ()    | Interface electron capture cross-section.                                 |
| DEGREDAT  | F.SIGMAH         | devdeg_sigmah ()    | Interface hole capture cross-section.                                     |
| DOPING  | F.COMPOSIT       | composition ()      | Position dependent composition fractions.                                 |
| DOPING  | F.DOPING         | doping ()           | Position dependent net doping.  |
| DOPING  | F3.DOPING        | doping3()           | Position dependent net doping.  |
| INTERFACE   | F.QF             | int_fixed_charge () | Interface fixed charge as a function of position.                         |
| INTTRAP   | F.DENSITY        | inte_acc_trap ()    | Interface (acceptor/donor) trap density as a function of location.        |
| IMPACT  | F.EDIIN          | ediin ()            | Electron temperature coefficients for impact ionization.                  |
| IMPACT  | F.EDIIP          | ediip ()            | Hole temperature coefficients for impact ionization.                      |
| INTTRAP   | F.INTACCEPTO     | intacceptor ()      | Initial interface acceptor trap density, etc., as a function of position. |

| <b>Table A-1. Complete list of available C-Interpreter functions in ATLAS</b> |                  |                  |   |
|---|------------------|------------------|---|
| <b>Statement</b>  | <b>Parameter</b> | <b>Template</b>  | <b>Description</b>  |
| INTTRAP   | F.INTDONOR       | intdonor ()      | Initial interface donor trap density, etc., as a function of position.      |
| INTTRAP   | F.INTPASSIVA     | intpassivated () | Initial passivated trap density, tec., as a function of position.           |
| LASER   | F.MIRROR         | mirror           | Mirror facet reflectivities on a function of wavelength.                    |
| MATERIAL  | F.BANDCOMP       | bandcomp ()      | Temperature and composition dependent band parameters.                      |
| MATERIAL  | F.BGN            | bgn ()           | Composition, temperature, and doping dependent band gap narrowing.          |
| MATERIAL  | F.CBDOSFN        | cbdosfn          | Electron temperature dependent effective conduction band density of states. |
| MATERIAL  | F.CONMUN         | conmun ()        | Composition, temperature, and doping dependent electron mobility.           |
| MATERIAL  | F.CONMUP         | conmup ()        | Composition, temperature, and doping dependent hole mobility.               |
| MATERIAL  | F.COPT           | copt ()          | Radiative recombination rate as a function of composition and temperature.  |
| MATERIAL  | F.EPSILON        | epsilon ()       | Composition and temperature dependent permittivity.                         |
| MATERIAL  | F.FERRO          | ferro ()         | Position and field dependent permittivity.                                  |
| MATERIAL  | F.GAUN           | gaun ()          | Electron Auger rate as a function of composition and temperature.           |
| MATERIAL  | F.GAUP           | gaup ()          | Hole Auger rate as a function of composition and temperature.               |
| MATERIAL  | F.INDEX          | index ()         | Wavelength dependent complex index of refraction.                           |
| MATERIAL  | F.MNSNDIFF       | mnsndiff ()      | Microscopic noise source for electron diffusion noise.                      |

| <b>Table A-1. Complete list of available C-Interpreter functions in ATLAS</b> |                  |                 |  |
|---|------------------|-----------------|--|
| <b>Statement</b>  | <b>Parameter</b> | <b>Template</b> | <b>Description</b>   |
| MATERIAL  | F.MNSPDIFF       | mnspsdiff ( )   | Microscopic noise source for hole diffusion noise.   |
| MATERIAL  | F.MNSNFLICKER    | mnsnflicker ( ) | Microscopic noise source for electron flicker noise.   |
| MATERIAL  | F.MNSPFlicker    | mnspflicker ( ) | Microscopic noise source for hole flicker noise.   |
| MATERIAL  | F.MUNSAT         | munsat ( )      | Electron velocity saturation model.  |
| MATERIAL  | F.MUPSAT         | mupsat ( )      | Hole velocity saturation model.  |
| MATERIAL  | F.RECOMB         | recomb ( )      | Position, temperature, and concentration dependent recombination.  |
| MATERIAL  | F.TARUP          | taurp ( )       | Energy dependent hole relaxation time.   |
| MATERIAL  | F.TAUN           | taun ( )        | Electron SRH lifetime as a function of position.   |
| MATERIAL  | F.TAUP           | taup ( )        | Hole SRH lifetime as a function of position.   |
| MATERIAL  | F.TAURN          | taurn ( )       | Energy dependent electron relaxation time.   |
| MATERIAL  | F.TCAP           | TCAP( )         | Lattice Thermal Capacity as a function of lattice temperature, position, doping, and fraction composition.     |
| MATERIAL  | F.TCOND          | TCOND( )        | Lattice Thermal Conductivity as a function of lattice temperature, position, doping, and fraction composition. |
| MATERIAL  | F.VSATN          | vsatn ( )       | Composition and temperature dependent electron saturation velocity.  |
| MATERIAL  | F.VSATP          | vsatp ( )       | Composition and temperature dependent hole saturation velocity.  |
| MATERIAL  | F.VBDOFSN        | vbdosfn         | Hole temperature dependent effective valence band density of states.   |
| MATERIAL/<br>MOBILITY   | F.ENMUN          | endepmun        | Electron mobility as a function of electron temperature and a few other choice variables.                      |

| <b>Table A-1. Complete list of available C-Interpreter functions in ATLAS</b> |                  |                 |   |
|---|------------------|-----------------|---|
| <b>Statement</b>  | <b>Parameter</b> | <b>Template</b> | <b>Description</b>  |
| MATERIAL/<br>MOBILITY   | F.ENMUP          | endepmup        | Hole mobility as a function of hole temperature and a few other choice variables. |
| MODELS  | F.ALPHAA         | bulk_absorb ()  | Bulk absorption coefficient versus carrier density and photon energy.             |
| MODELS  | F.KSN            | fksp ()         | Energy dependent electron Peltier coefficient.                                    |
| MODELS  | F.KSP            | fksp ()         | Energy dependent hole Peltier coefficient.  |

## B.1: Overview

ATLAS understands a library of materials for reference to material properties and models of various regions in the semiconductor device. These materials are chosen to represent those most commonly used by semiconductor physicists today. BLAZE or BLAZE3D users will have access to all of these materials. S-PISCES or DEVICE3D users will have only access to Silicon and Polysilicon.

S-PISCES is designed to maintain backward compatibility with the standalone program, SPISCES2 Version 5.2. In the SPISCES2 syntax, certain materials can be used in the REGION statement just by using their name as logical parameters. This syntax is still supported.

## B.2: Semiconductors, Insulators, and Conductors

All materials in ATLAS are strictly defined into three classes: semiconductor materials, insulator materials, or conductors. Each class of materials has particular properties that you should be aware of.

### B.2.1: Semiconductors

All equations specified by your choice of models are solved in semiconductor regions. All semiconductor regions must have a band structure defined in terms of bandgap, density of states, affinity, and so on. The parameters used for any simulation can be echoed to the run-time output using `MODELS PRINT`. For complex cases with mole fraction dependent models, these quantities can be seen in `TONYPLOT` by specifying `OUTPUT BAND.PARAM` and saving a solution file.

Any semiconductor region that is defined as an electrode is then considered to be a conductor region. This is typical for polysilicon gate electrodes.

### B.2.2: Insulators

In insulator materials, only the Poisson and lattice heat equations are solved. Therefore for isothermal simulations, the only parameter required for an insulator is dielectric permittivity defined using `MATERIAL PERM=<n>`.

Materials usually considered as insulators (e.g.,  $\text{SiO}_2$ ) can be treated as semiconductors using `BLAZE`, however all semiconductor parameters are then required.

### B.2.3: Conductors

All conductor materials must be defined as electrodes, and all electrode regions are defined as conductor material regions. If a file containing regions of a material known to be a conductor are read in, these regions will automatically become un-named electrodes. As noted below, if the file contains unknown materials, these regions will become insulators.

During electrical simulation only the electrode boundary nodes are used. Nodes that are entirely within an electrode region are not solved. Any quantities seen inside a conductor region in `TONYPLOT` are spurious. Only optical ray tracing and absorption for `LUMINOUS` and lattice heating are solved inside of conductor/electrode regions.

### B.2.4: Unknown Materials

If a mesh file is read containing materials not in Table B-1, these will automatically become insulator regions with a relative permittivity of 3.9. All user-defined materials from `ATHENA`, regardless of the material name chosen, will also become such insulator materials.

## B.3: ATLAS Materials

This section lists the materials in ATLAS. The superscripted numbers (e.g., Silicon<sup>(1)</sup>) on these tables refer to the notes on the next page.

| <b>Table B-1. The ATLAS Materials</b>     |                     |           |                                |
|---|---------------------|-----------|--------------------------------|
| <b>Single Element Semiconductors</b>      |                     |           |                                |
| Silicon <sup>(1)</sup>                    | Poly <sup>(2)</sup> | Germanium | Diamond                        |
| <b>Binary Compound Semiconductors</b>     |                     |           |                                |
| GaAs <sup>(3)</sup>                       | GaP                 | CdSe      | SnTe                           |
| SiGe                                      | InP                 | CdTe      | ScN                            |
| a-SiC                                     | InSb                | HgS       | GaN                            |
| b-SiC                                     | InAs                | HgSe      | AlN                            |
| AlP                                       | ZnS                 | HgTe      | InN                            |
| AlAs                                      | ZnSe                | PbS       | BeTe                           |
| AlSb                                      | ZnTe                | PbSe      |                                |
| GaSb                                      | CdS                 | PbTe      |                                |
| <b>Ternary Compound Semiconductors</b>    |                     |           |                                |
| AlGaAs                                    | GaSbP               | InAlAs    | GaAsP                          |
| InGaAs                                    | GaSbAs              | InAsP     | HgCdTe                         |
| InGaP                                     | InGaN               | AlGaN     |                                |
| <b>Quaternary Compound Semiconductors</b> |                     |           |                                |
| InGaAsP                                   | AlGaAsP             | AlGaAsSb  | InAlGaN                        |
| InGaNAs                                   | InGaN               | AlGaNAs   | AlGaN                          |
| AlInNAs                                   | AlInNP              | InAlGaAs  | InAlGaP                        |
| InAlAsP                                   |                     |           |                                |
| <b>Insulators</b>                         |                     |           |                                |
| Vacuum                                    | Oxide               | Nitride   | Si <sub>3</sub> N <sub>4</sub> |
| Air                                       | SiO <sub>2</sub>    | SiN       | Sapphire                       |
| Ambient                                   |                     |           |                                |
| <b>Conductors<sup>(4)</sup></b>           |                     |           |                                |
| Polysilicon <sup>(2)</sup>                | Palladium           | TiW       | TaSi                           |
| Aluminum                                  | Cobalt              | Copper    | PaSi                           |
| Gold                                      | Molybdenum          | Tin       | PtSi                           |

|          |          |        |           |
|----------|----------|--------|-----------|
| Silver   | Lead     | Nickel | MoSi      |
| AlSi     | Iron     | WSi    | ZrSi      |
| Tungsten | Tantalum | TiSi   | AlSi      |
| Titanium | AlSiTi   | NiSi   | Conductor |
| Platinum | AlSiCu   | CoSi   | Contact   |

**Notes**

1. The material models and parameters of Silicon are identical to those of S-PISCES2 Version 5.2. Be aware that although these band parameters may be physically inaccurate compared to bulk silicon measurements, most other material parameters and models are empirically tuned using these band parameters.
2. Polysilicon is treated differently depending on how it is used. In cases where it's defined as an electrode, it's treated as a conductor. It can also be used as a semiconductor such as in a polysilicon emitter bipolars.
3. The composition of SiGe is the only binary compound that can be varied to simulate the effects of band gap variations.
4. Conductor names are only associated with electrodes. They are used for the specification of thermal conductivities and complex index of refraction and for display in TONYPLOT.

**B.3.1: Specifying Compound Semiconductors Rules**

The rules for specifying the order of elements for compound semiconductors are derived from the rules used by the International Union of Pure and Applied Chemistry [94]. These rules are:

1. Cations appear before anions.
2. When more than one cation is present the order progresses from the element with the largest atomic number to the element with the smallest atomic number.
3. The order of anions should be the in order of the following list: B, Si, C, Sb, As, P, N, H, Te, Se, S, At, I, Br, Cl, O, and F.
4. The composition fraction x is applied to the cation listed first.
5. The composition y is applied to the anion listed first.

To accommodate popular conventions, there are several exceptions to these rules (see Table B-2).

| <b>Material</b> | <b>Description</b>  |
|-----------------|---|
| <b>SiGe</b>     | The composition fraction x applies to the Ge component. SiGe is then specified as $Si_{(1-x)}Ge_{(x)}$ , an exception to rule #4. |
| <b>AlGaAs</b>   | This is specified as $Al_{(x)}Ga_{(1-x)}As$ . This is an exception to rule #2.  |
| <b>InGaAsP</b>  | The convention $In_{(1-x)}Ga_{(x)}As_{(y)}P_{(1-y)}$ as set forth by Adachi is used. This is an exception to rule #4.             |



## B.4: Silicon and Polysilicon

The material parameters defaults for Polysilicon are identical to those for Silicon. The following paragraphs describe some of the material parameter defaults for Silicon and Polysilicon.

**Note:** A complete description is given of each model Chapter 3: “Physics”. The parameter defaults listed in that chapter are all Silicon material defaults.

| Material | Eg300<br>eV | $\alpha$              | $\beta$ | Nc300<br>per cc      | Nv300<br>per cc       | $\chi$<br>eV |
|----------|-------------|-----------------------|---------|----------------------|-----------------------|--------------|
| Silicon  | 1.08        | $4.73 \times 10^{-4}$ | 636.0   | $2.8 \times 10^{19}$ | $1.04 \times 10^{19}$ | 4.17         |
| Poly     | 1.08        | $4.73 \times 10^{-4}$ | 636.0   | $2.8 \times 10^{19}$ | $1.04 \times 10^{19}$ | 4.17         |

| Material | Dielectric Constant |
|----------|---------------------|
| Silicon  | 11.8                |
| Poly     | 11.8                |

The default mobility parameters for Silicon and Poly are identical in all cases. The defaults used depend on the particular mobility models in question. A full description of each mobility model and their coefficients are given in Chapter 3: “Physics”, Section 3.6.1: “Mobility Modeling”.

Table B-5 contains the silicon and polysilicon default values for the low field constant mobility model.

| Material | MUN<br>cm <sup>2</sup> /Vs | MUP<br>cm <sup>2</sup> /Vs | TMUN | TMUP |
|----------|----------------------------|----------------------------|------|------|
| Silicon  | 1000.0                     | 500.0                      | 1.5  | 1.5  |
| Poly     | 1000.0                     | 500.0                      | 1.5  | 1.5  |

Table B-6 contains the silicon and polysilicon default values for the field dependent mobility model.

| <b>Table B-6. Parallel Field Dependent Mobility Model Parameters for Silicon and Poly</b> |              |              |
|---|--------------|--------------|
| <b>Material</b>   | <b>BETAN</b> | <b>BETAP</b> |
| Silicon   | 2            | 1            |
| Poly  | 2            | 1            |

The default values used in the bandgap narrowing model for Silicon and Polysilicon are defined in Table B-7.

| <b>Table B-7. Bandgap Narrowing Parameters for Silicon and Poly</b> |                  |                       |                  |
|---|------------------|-----------------------|------------------|
| <b>Statement</b>  | <b>Parameter</b> | <b>Defaults</b>       | <b>Units</b>     |
| MATERIAL  | BGN.E            | $6.92 \times 10^{-3}$ | V                |
| MATERIAL  | BGN.N            | $1.3 \times 10^{17}$  | $\text{cm}^{-3}$ |
| MATERIAL  | BGN.C            | 0.5                   | —                |

The default parameters for Shockley-Read-Hall (SRH) recombination are given in Table B-8.

| <b>Table B-8. SRH Lifetime Parameter Defaults for Silicon and Poly</b> |                      |                      |  |  |
|--|----------------------|----------------------|--|--|
| <b>Material</b>  | <b>TAUN0 (s)</b>     | <b>TAUP0 (s)</b>     | <b>NSRHN (<math>\text{cm}^{-3}</math>)</b> | <b>NSRHP (<math>\text{cm}^{-3}</math>)</b> |
| Silicon  | $1.0 \times 10^{-7}$ | $1.0 \times 10^{-7}$ | $5.0 \times 10^{16}$                       | $5.0 \times 10^{16}$                       |
| Poly   | $1.0 \times 10^{-7}$ | $1.0 \times 10^{-7}$ | $5.0 \times 10^{16}$                       | $5.0 \times 10^{16}$                       |

The default parameters for Auger recombination are given in Table B-9.

| <b>Table B-9. Auger Coefficient Defaults for Silicon and Poly</b> |                       |                       |
|---|-----------------------|-----------------------|
| <b>Material</b>   | <b>AUGN</b>           | <b>AUGP</b>           |
| Silicon   | $8.3 \times 10^{-32}$ | $1.8 \times 10^{-31}$ |
| Poly  | $8.3 \times 10^{-32}$ | $1.8 \times 10^{-31}$ |

The default values for the SELB impact ionization coefficients are given in Table B-10.

| <b>Table B-10. Impact Ionization Coefficients for Silicon and Poly</b> |                     |
|--|---------------------|
| <b>Parameter</b>   | <b>Value</b>        |
| EGRAN  | $4.0 \times 10^5$   |
| BETAN  | 1.0                 |
| BETAP  | 1.0                 |
| AN1  | $7.03 \times 10^5$  |
| AN2  | $7.03 \times 10^5$  |
| BN1  | $1.231 \times 10^6$ |
| BN2  | $1.231 \times 10^6$ |
| AP1  | $6.71 \times 10^5$  |
| AP2  | $1.582 \times 10^6$ |
| BP1  | $1.693 \times 10^6$ |
| BP2  | $2.036 \times 10^6$ |

The default values used for thermal conductivity and capacity are given in Table B-11.

| <b>Table B-11. Thermal Parameters for Silicon and Poly</b> |            |                       |                       |            |                      |            |                    |
|--|------------|-----------------------|-----------------------|------------|----------------------|------------|--------------------|
| <b>Material</b>  | <b>TCA</b> | <b>TCB</b>            | <b>TCC</b>            | <b>HCA</b> | <b>HCB</b>           | <b>HCC</b> | <b>HCD</b>         |
| Silicon  | 0.03       | $1.56 \times 10^{-3}$ | $1.65 \times 10^{-6}$ | 1.97       | $3.6 \times 10^{-4}$ | 0.0        | $-3.7 \times 10^4$ |
| Poly   | 0.03       | $1.56 \times 10^{-3}$ | $1.65 \times 10^{-6}$ | 1.97       | $3.6 \times 10^{-4}$ | 0.0        | $-3.7 \times 10^4$ |

| <b>Table B-12. Effective Richardson Coefficients for Silicon and Poly</b> |   |   |
|---|---|---|
| <b>Material</b>   | <b>ARICHN (<math>A/cm^2/K^2</math>)</b> | <b>ARICHP (<math>A/cm^2/K^2</math>)</b> |
| Silicon   | 110.0                                   | 30.0                                    |
| Poly  | 110.0                                   | 30.0                                    |

## B.5: The Al<sub>(x)</sub>Ga<sub>(1-x)</sub>As Material System

The default recombination parameters for AlGaAs are given in Table B-13.

| Table B-13. Default Recombination Parameters for AlGaAs |                       |          |
|---|-----------------------|----------|
| Parameter   | Value                 | Equation |
| TAUN0   | $1.0 \times 10^{-9}$  | 3-213    |
| TAUP0   | $1.0 \times 10^{-8}$  | 3-213    |
| COPT  | $1.5 \times 10^{-10}$ | 3-226    |
| AUGN  | $5.0 \times 10^{-30}$ | 3-227    |
| AUGP  | $1.0 \times 10^{-31}$ | 3-227    |

The default values for the SELB impact ionization coefficients used for GaAs are given in Table B-14. AlGaAs uses the same values as GaAs.

| Table B-14. Impact Ionization Coefficients for GaAs |                     |
|---|---------------------|
| Parameter   | Value               |
| EGRAN   | 0.0                 |
| BETAN   | 1.82                |
| BETAP   | 1.75                |
| EGRAN   | 0.0                 |
| AN1   | $1.889 \times 10^5$ |
| AN2   | $1.889 \times 10^5$ |
| BN1   | $5.75 \times 10^5$  |
| BN2   | $5.75 \times 10^5$  |
| AP1   | $2.215 \times 10^5$ |
| AP2   | $2.215 \times 10^5$ |
| BP1   | $6.57 \times 10^5$  |
| BP2   | $6.57 \times 10^5$  |

The default thermal parameters used for AlGaAs are given in Table B-15.

| <b>Parameter</b> | <b>Value</b> |
|------------------|--------------|
| TCA              | 2.27         |
| HCA              | 1.738        |

The default values for the effective Richardson coefficients for GaAs are  $6.2875 \text{ A/cm}^2/\text{K}^2$  for electrons and  $105.2 \text{ A/cm}^2/\text{K}^2$  for holes.

## B.6: The $\text{In}_{(1-x)}\text{Ga}_{(x)}\text{As}_{(y)}\text{P}_{(1-y)}$ System

The default material thermal models for InGaAsP assumes lattice-matching to InP. The material density is then given by;

$$\rho = 4.791 + 0.575y.\text{composition} + 0.138y.\text{composition}$$

The specific heat for InGaAsP is given by;

$$C_p = 0.322 + 0.026y.\text{composition} - 0.008y.\text{composition}$$

The thermal resistivities of InGaAsP are linearly interpolated from Table B-16.

| Table B-16. Thermal Resistivities for InGaAsP Lattice-Matched to InP |                                |
|--|--------------------------------|
| Composition Fraction y   | Thermal Resistivity (deg/cm/w) |
| 0.0  | 1.47                           |
| 0.1  | 7.05                           |
| 0.2  | 11.84                          |
| 0.3  | 15.83                          |
| 0.4  | 19.02                          |
| 0.5  | 21.40                          |
| 0.6  | 22.96                          |
| 0.7  | 23.71                          |
| 0.8  | 23.63                          |
| 0.9  | 22.71                          |
| 1.0  | 20.95                          |

The default thermal properties of the binary compounds in the InGaAsP system are given in Table B-17.

| Table B-17. Default Thermal Properties of InP InAs GaP and GaAs |                          |                                |
|---|--------------------------|--------------------------------|
| Material  | Thermal Capacity (J/cm3) | Thermal Resistivity (deg/cm/W) |
| InP   | 1.543                    | 1.47                           |
| InAs  | 1.994                    | 3.70                           |
| GaP   | 1.292                    | 1.30                           |
| GaAs  | 1.738                    | 2.27                           |

The default thermal properties for the ternary compounds in the InGaAsP system:  $\text{In}_{(1-x)}\text{Ga}_{(x)}\text{As}$ ,  $\text{In}_{(1-x)}\text{Ga}_{(x)}\text{P}$ ,  $\text{InAs}_{(y)}\text{P}_{(1-y)}$ , and  $\text{GaAs}_{(y)}\text{P}_{(1-y)}$  are given, as a function of composition fraction, by linear interpolations from these binary compounds.

## B.7: Silicon Carbide (SiC)

The default values for the SELB impact ionization coefficients used for SiC are given in Table B-18.

| <b>Parameter</b> | <b>Value</b>        |
|------------------|---------------------|
| EGRAN            | 0.0                 |
| BETAN            | 1.0                 |
| BETAP            | 1.0                 |
| AN1              | $1.66 \times 10^6$  |
| AN2              | $1.66 \times 10^6$  |
| BN1              | $1.273 \times 10^7$ |
| BN2              | $1.273 \times 10^7$ |
| AP1              | $5.18 \times 10^6$  |
| AP2              | $5.18 \times 10^6$  |
| BP1              | $1.4 \times 10^7$   |
| BP2              | $1.4 \times 10^7$   |

The default thermal parameters used for both 6H-SiC and 3C-SiC are shown in Table B-19.

| <b>Parameter</b> | <b>Value</b>  |               |
|------------------|---------------|---------------|
|                  | <b>3C-SiC</b> | <b>6H-SiC</b> |
| TCA              | 0.204         | 0.385         |

## B.8: Material Defaults for GaN/InN/AlN System

Table B-20 shows the default values for the band structure parameters for InN, GaN and AlN.

| Table B-20. Electronic Band-Structure Parameters for InN, GaN and AlN |          |          |       |       |       |        |
|---|----------|----------|-------|-------|-------|--------|
| Parameter   | Symbol   | Syntax   | Units | InN   | GaN   | AlN    |
| Electron eff. mass (z)  | $m_{cz}$ | MZZ      | $m_0$ | 0.11  | 0.20  | 0.33   |
| Electron eff. mass (t)  | $t_{ct}$ | MTT      | $m_0$ | 0.11  | 0.18  | 0.25   |
| Hole eff. mass param.   | A1       | A1       |       | -9.24 | -7.24 | -3.95  |
| Hole eff. mass param.   | A2       | A2       |       | -0.60 | -0.51 | -0.27  |
| Hole eff. mass param.   | A3       | A3       |       | 8.68  | 6.73  | 3.68   |
| Hole eff. mass param.   | A4       | A4       |       | -4.34 | -3.36 | -1.84  |
| Hole eff. mass param.   | A5       | A5       |       | -4.32 | -3.35 | -1.92  |
| Hole eff. mass param.   | A6       | A6       |       | -6.08 | -4.72 | -2.91  |
| Valence band reference  | Ev0      |          | eV    | -1.59 | -2.64 | -3.44  |
| Direct band gap (300K)  | Eg(300)  |          | eV    | 1.89  | 3.42  | 6.28   |
| Spin-orbit split energy   | D1       | DELTA1   | eV    | 0.001 | 0.014 | 0.019  |
| Crystal-field split energy  | D2       | DELTA2   | eV    | 0.041 | 0.019 | -0.164 |
| Lattice constant  | $a_0$    | ALATTICE | Å     | 3.548 | 3.189 | 3.112  |
| Elastic constant  | C33      | C33      | GPa   | 200   | 392   | 382    |
| Elastic constant  | C13      | C13      | GPa   | 94    | 100   | 127    |
| Hydrostatic deformation potential                                     | ac       | AC       | eV    | -4.08 | -4.08 | -4.08  |
| Shear deform. potential   | D1       | D1       | eV    | -0.89 | -0.89 | -0.89  |



| Table B-20. Electronic Band-Structure Parameters for InN, GaN and AlN |    |    |    |       |       |       |
|---|----|----|----|-------|-------|-------|
| Shear deform. potential   | D2 | D2 | eV | 4.27  | 4.27  | 4.27  |
| Shear deform. potential   | D3 | D3 | eV | 5.18  | 5.18  | 5.18  |
| Shear deform. potential   | D4 | D4 | eV | -2.59 | -2.59 | -5.29 |

Table B-21 shows the default polarization parameters for InN, GaN and AlN.

| Table B-21. Polarization Parameters for InN, GaN and AlN |          |          |                  |        |        |       |
|--|----------|----------|------------------|--------|--------|-------|
| Parameter  | Symbol   | Syntax   | Units            | InN    | GaN    | AlN   |
| Lattice constant   | $a_0$    | ALATTICE | Å                | 3.548  | 3.189  | 3.112 |
| Spontaneous polarization                                 | $P_{sp}$ | PSP      | C/m <sup>2</sup> | -0.042 | -0.034 | -0.09 |
| Piezoelectric const. (z)                                 | $e_{33}$ | E33      | C/m <sup>2</sup> | 0.81   | 0.67   | 1.5   |
| Piezoelectric const. (x,y)                               | $e_{31}$ | E31      | C/m <sup>2</sup> | -0.41  | -0.34  | -0.53 |

## B.9: Material Defaults for Compound Semiconductors

Tables B-22a and B-22b, and B-23 show the material defaults for binary compound semiconductors. Table B-24 shows Material defaults for ternary compound semiconductors.

**Note:**  $x_{comp}$  is set to 0.3. See Chapter 5: "Blaze: Compound Material 2D Simulator", Section 5.3: "Material Dependent Physical Models" for more information.

**Table B-22a. Materials Defaults for binary compound semiconductors**

| Material                  | GaAs     | GaP      | CdSe     | SnTe     | InP      | CdTe     | ScN      |
|---------------------------|----------|----------|----------|----------|----------|----------|----------|
| Epsilon                   | 13.2     | 11.1     | 10.6     | 0        | 12.5     | 10.9     | 0        |
| Eg (eV)                   | 1.42     | 2.26     | 1.74     | 0.18     | 1.35     | 1.5      | 2.15     |
| Chi (eV)                  | 4.07     | 4.4      | 0        | 0        | 4.4      | 4.28     | 0        |
| Nc (per cc)               | 4.35E+17 | 1.76E+18 | 1.18E+18 | 1        | 5.68E+17 | 1        | 1        |
| Nv (per cc)               | 8.16E+18 | 8.87E+18 | 7.57E+18 | 1        | 8.87E+18 | 1        | 1        |
| ni (per cc)               | 2.12E+06 | 0.409    | 7.22E+03 | 0.0308   | 1.03E+07 | 2.51E-13 | 8.70E-19 |
| Gc                        | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
| Gv                        | 4        | 4        | 4        | 4        | 4        | 4        | 4        |
| Ed (eV)                   | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    |
| Ea (eV)                   | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    |
| Lifetime (el)             | 1.00E-09 | 1        | 1        | 1        | 1        | 1        | 1        |
| Lifetime (ho)             | 2.00E-08 | 1        | 1        | 1        | 1        | 1        | 1        |
| Auger cn                  | 5.00E-30 | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger cp                  | 1.00E-31 | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kn                  | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kp                  | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Copt                      | 1.50E-10 | 0        | 0        | 0        | 0        | 0        | 0        |
| An**                      | 6.29     | 20.4     | 15.6     | 1.40E-11 | 9.61     | 1.40E-11 | 1.40E-11 |
| Ap**                      | 105      | 60.1     | 54.1     | 1.40E-11 | 60.1     | 1.40E-11 | 1.40E-11 |
| betan                     | 1.82     | 1        | 1        | 1        | 1        | 1        | 1        |
| betap                     | 1.75     | 1        | 1        | 1        | 1        | 1        | 1        |
| egran                     | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| an1                       | 1.90E+05 | 7.30E+04 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.03E+05 |
| bn1                       | 5.75E+05 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| an2                       | 1.90E+05 | 7.30E+04 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.03E+05 |
| an2                       | 5.75E+05 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| ap1                       | 2.22E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 |
| bp1                       | 6.57E+05 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 |
| ap2                       | 2.22E+05 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 |
| bp2                       | 6.57E+05 | 2.40E+05 | 2.40E+05 | 2.04E+06 | 2.40E+05 | 2.04E+06 | 2.04E+06 |
| Vsatn (cm/s) :            | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |
| Vsatp (cm/s) :            | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |
| mun (cm <sup>2</sup> /Vs) | 8000     | 300      | 800      |          | 4600     | 1050     |          |
| tmun                      | 1        | 1.5      | 1.5      |          | 1.5      | 1.5      |          |
| mup (cm <sup>2</sup> /Vs) | 400      | 100      |          |          | 150      | 100      |          |
| tmup                      | 2.1      | 1.5      |          |          | 1.5      | 1.5      |          |

Table B-22b. Materials Defaults for binary compound semiconductors

| Material                  | 6H-SiC   | 4H-SiC   | 3C-SiC   | InSb     | HgS      | GaN      | InAs     | HgSe     | AlN      | AlP      |
|---------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Epsilon                   | 9.66     | 9.7      | 9.72     | 18       | 0        | 10.4     | 14.6     | 25       | 10.1     | 9.8      |
| Eg (eV)                   | 2.9      | 3.26     | 2.2      | 0.17     | 2.5      | 3.42     | 0.35     | 0        | 6.13     | 2.43     |
| Chi (eV)                  | 0        |          | 0        | 4.59     | 0        | 4.31     | 4.13     | 0        | 2.41     | 0        |
| Nc (per cc)               | 7.68E+18 | 1.60E+19 | 6.59E+18 | 4.16E+16 | 1        | 2.73E+18 | 9.33E+16 | 1        | 4.42E+18 | 1        |
| Nv (per cc)               | 4.76E+18 | 3.30E+19 | 1.68E+18 | 6.35E+18 | 1        | 3.31E+18 | 8.12E+18 | 1        | 6.76E+18 | 1        |
| ni (per cc)               | 2.63E-06 | 1.03E-08 | 1.1      | 1.92E+16 | 9.99E-22 | 5.61E-11 | 9.99E+14 | 1        | 1.75E-33 | 3.87E-21 |
| Gc                        | 2        |          | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
| Gv                        | 4        |          | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        |
| Ed (eV)                   | 0.044    |          | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    |
| Ea (eV)                   | 0.045    |          | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    |
| Lifetime (el)             | 1        |          | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Lifetime (ho)             | 1        |          | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Auger cn                  | 2.80E-31 | 5.00E-29 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger cp                  | 9.90E-31 | 9.90E-32 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kn                  | 0        |          | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kp                  | 0        |          | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Copt                      | 0        |          | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| An**                      | 54.6     |          | 49.3     | 1.68     | 1.40E-11 | 27.4     | 2.88     | 1.40E-11 | 37.7     | 1.40E-11 |
| Ap**                      | 39.7     |          | 19.8     | 48.1     | 1.40E-11 | 31.1     | 56.6     | 1.40E-11 | 50.1     | 1.40E-11 |
| betan                     | 1        |          | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| betap                     | 1        |          | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| egran                     | 0        |          | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| an1                       | 1.66E+06 |          | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 |
| bn1                       | 1.27E+07 |          | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| an2                       | 1.66E+06 |          | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 |
| an2                       | 1.27E+07 |          | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| ap1                       | 5.18E+06 |          | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 |
| bp1                       | 1.40E+07 |          | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 |
| ap2                       | 5.18E+06 |          | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 |
| bp2                       | 1.40E+07 |          | 2.04E+06 | 2.40E+05 | 2.04E+06 | 2.40E+05 | 2.40E+05 | 2.04E+06 | 2.40E+05 | 2.04E+06 |
| Vsatn (cm/s) :            | 2.00E+07 | 1.25E+07 | 2.00E+07 | 1.00E+06 | 1.00E+06 | 2.00E+07 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 |
| Vsatp (cm/s) :            | 1.00E+06 | 1.00E+07 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 |
| mun (cm <sup>2</sup> /Vs) | 330      | 460      | 1000     | 78000    |          | 400      | 33000    | 5500     |          | 80       |
| tmun                      | 1.5      | 1        | 1.5      | 1.5      |          | 1.5      | 1.5      | 1.5      |          | 1.5      |
| mup (cm <sup>2</sup> /Vs) | 60       | 124      | 50       | 750      |          | 8        | 460      |          | 14       |          |
| tmup                      | 1.5      | 1        | 1.5      | 1.5      |          | 1.5      | 1.5      |          | 1.5      |          |

**Table B-23. Material Defaults for binary compound semiconductors**

| Material                  | ZnS      | HgTe     | InN      | AlAs     | ZnSe     | PbS      | BeTe     | AlSb     | ZnTe     | PbSe     | GaSb     | CdS      | PbTe     | SiGe     |
|---------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Epsilon                   | 8.3      | 20       | 19.6     | 12       | 8.1      | 170      | 0        | 11       | 9.7      | 250      | 15.7     | 8.9      | 412      | 11.8     |
| Eg (eV)                   | 3.8      | 0        | 1.89     | 2.16     | 2.58     | 0.37     | 2.57     | 1.52     | 2.28     | 0.26     | 0.72     | 2.53     | 0.29     | 0.78     |
| Chi (eV)                  | 0        | 0        | 0        | 3.5      | 4.09     | 0        | 0        | 3.65     | 3.5      | 0        | 4.06     | 4.5      | 4.6      | 4.17     |
| Nc (per cc)               | 6.35E+18 | 1        | 9.15E+17 | 4.35E+17 | 1        | 3.14E+18 | 1        | 6.79E+18 | 1        | 1        | 5.68E+18 | 2.41E+18 | 1.76E+18 | 1.92E+19 |
| Nv (per cc)               | 1        | 1        | 1.76E+18 | 8.16E+18 | 1        | 3.14E+18 | 1        | 6.35E+18 | 1        | 1        | 2.95E+18 | 1.80E+19 | 2.24E+18 | 8.20E+18 |
| ni (per cc)               | 3.02E-23 | 1        | 169      | 1.35     | 2.13E-22 | 2.45E+15 | 2.58E-22 | 1.12E+06 | 7.04E-20 | 0.00655  | 3.66E+12 | 0.00368  | 7.28E+15 | 3.52E+12 |
| Gc                        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
| Gv                        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        |
| Ed (eV)                   | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    |
| Ea (eV)                   | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    |
| Recombination P           |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Lifetime (el)             | 1        | 1        | 1        | 1.00E-09 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 3.00E-05 |
| Lifetime (ho)             | 1        | 1        | 1        | 2.00E-08 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1.00E-05 |
| Auger cn                  | 0        | 0        | 0        | 5.00E-30 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 8.30E-32 |
| Auger cp                  | 0        | 0        | 0        | 1.00E-31 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 1.80E-31 |
| Auger kn                  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kp                  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Copt                      | 0        | 0        | 0        | 1.50E-10 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| An**                      | 48.1     | 1.40E-11 | 13.2     | 8.05     | 1.40E-11 | 30       | 1.40E-11 | 50.3     | 1.40E-11 | 1.40E-11 | 44.6     | 25.2     | 20.4     | 110      |
| Ap**                      | 1.40E-11 | 1.40E-11 | 20.4     | 56.8     | 1.40E-11 | 30       | 1.40E-11 | 48.1     | 1.40E-11 | 1.40E-11 | 28.8     | 96.1     | 24       | 30       |
| Impact Ionizati           |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| betan                     | 1        | 1        | 1        | 1.82     | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| betap                     | 1        | 1        | 1        | 1.75     | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| egran                     | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 4.00E+05 |
| an1                       | 7.03E+05 | 7.03E+05 | 7.03E+05 | 1.90E+05 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 |
| bn1                       | 1.23E+06 | 1.23E+06 | 1.23E+06 | 5.75E+05 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| an2                       | 7.03E+05 | 7.03E+05 | 7.03E+05 | 1.90E+05 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.03E+05 | 7.30E+04 | 7.03E+05 | 7.30E+04 | 7.03E+05 |
| ap1                       | 1.23E+06 | 1.23E+06 | 1.23E+06 | 5.75E+05 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| bp1                       | 6.71E+05 | 6.71E+05 | 6.71E+05 | 2.22E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 |
| ap2                       | 1.69E+06 | 1.69E+06 | 1.69E+06 | 6.57E+05 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 |
| bp2                       | 1.58E+06 | 1.58E+06 | 1.58E+06 | 2.22E+05 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 |
| satp                      | 2.04E+06 | 2.04E+06 | 2.04E+06 | 6.57E+05 | 2.04E+06 | 2.40E+05 | 2.04E+06 | 2.40E+05 | 2.04E+06 | 2.04E+06 | 2.40E+05 | 2.04E+06 | 2.40E+05 | 2.04E+06 |
| Saturation Velo           |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Vsath (cm/s)              | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+07 |
| Vsathp (cm/s)             | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.98E+06 |
| Mobility Parameters       |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| mun (cm <sup>2</sup> /Vs) | 165      | 22000    | 3000     | 1000     | 100      | 600      |          | 200      | 7        | 1020     | 4000     | 340      | 6000     | 1430     |
| tmun                      | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      |          | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      |
| mup (cm <sup>2</sup> /Vs) | 5        | 100      |          | 100      |          | 700      |          | 550      |          | 930      | 1400     | 50       | 4000     | 480      |
| tmup                      | 1.5      | 1.5      |          | 1.5      |          | 1.5      |          | 1.5      |          | 1.5      | 1.5      | 1.5      | 1.5      | 1.5      |

**Note:** `x.comp` is set to 0.3. See Chapter 5: "Blaze: Compound Material 2D Simulator", Section 5.3: "Material Dependent Physical Models" for more information.

Table B-24. Material Default for ternary compound semiconductors

| Material  | AlGaAs   | GaSbP    | InAlAs   | GaAsP    | InGaAs   | GaSbAs   | InAsP    | HgCdTe   | InGaP    | InGaN    | AlGaIn   |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Epsilon   | 12.3     | 0        | 0        | 11.7     | 14.2     | 0        | 13.1     | 16.4     | 12.1     | 0        | 10.3     |
| Band Parameters                                       |          |          |          |          |          |          |          |          |          |          |          |
| Eg (eV)   | 1.8      | 2.01     | 2.1      | 2.31     | 0.571    | 0.665    | 1.03     | 0.291    | 1.61     | 0        | 4.02     |
| Chi (eV)  | 3.75     | 0        | 0        | 4.32     | 4.13     | 4.06     | 4.32     | 2.54     | 4.4      | 0        | 3.89     |
| Nc (per cc)   | 4.35E+17 | 1        | 1        | 1.04E+18 | 1.15E+17 | 1        | 2.86E+17 | 7.58E+16 | 7.18E+17 | 1        | 3.21E+18 |
| Nv (per cc)   | 8.16E+18 | 1        | 1        | 8.54E+18 | 8.12E+18 | 1        | 8.54E+18 | 1.02E+19 | 8.87E+18 | 1        | 4.26E+18 |
| ni (per cc)   | 1.37E+03 | 1.24E-17 | 2.29E-18 | 0.125    | 1.56E+13 | 2.61E-06 | 3.56E+09 | 3.18E+15 | 7.43E+04 | 1        | 5.94E-16 |
| Gc :  | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
| Gv :  | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        |
| Ed (eV)   | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    |
| Ea (eV)   | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    |
| Recombination Parameters                              |          |          |          |          |          |          |          |          |          |          |          |
| Lifetime (e)  | 1.00E-09 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Lifetime (h)  | 2.00E-08 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Auger cn  | 5.00E-30 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger cp  | 1.00E-31 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kn  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kp  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Copt  | 1.50E-10 | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| An**  | 8.05     | 1.40E-11 | 1.40E-11 | 14.4     | 3.32     | 1.40E-11 | 6.08     | 2.51     | 11.2     | 1.40E-11 | 30.5     |
| Ap**  | 56.8     | 1.40E-11 | 1.40E-11 | 58.6     | 56.6     | 1.40E-11 | 58.6     | 66.1     | 60.1     | 1.40E-11 | 36.8     |
| Impact Ionization Model Parameters (Selberherr model) |          |          |          |          |          |          |          |          |          |          |          |
| betan   | 1.82     | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| betap   | 1.75     | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| egran   | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| an1   | 1.90E+05 | 7.03E+05 | 8.60E+06 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 |
| bn1   | 5.75E+05 | 1.23E+06 | 3.50E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| an2   | 1.90E+05 | 7.03E+05 | 8.60E+06 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 |
| bn2   | 5.75E+05 | 1.23E+06 | 3.50E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| ap1   | 2.22E+05 | 6.71E+05 | 2.30E+07 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 |
| bp1   | 6.57E+05 | 1.69E+06 | 4.50E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 |
| ap2   | 2.22E+05 | 1.58E+06 | 2.30E+07 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 |
| bp2   | 6.57E+05 | 2.04E+06 | 4.50E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 |
| Saturation Densities                                  |          |          |          |          |          |          |          |          |          |          |          |
| Vsatsn (cm)   | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |
| Vsatsp (cm)   | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 7.70E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |

**Note:** `x.comp` is set to 0.3. See Chapter 5: “Blaze: Compound Material 2D Simulator”, Section 5.3: “Material Dependent Physical Models” for more information.

Table B-25 shows material defaults for quaternary compound semiconductors.

**Table B-25. Material Defaults for quaternary compound semiconductors**

| Material  | InGaAsP  | AlGaAsP  | AlGaAsSb | InAlGaN  | InGaNaS  | InGaNP   | AlGaNaS  | AlGaNP   | AlInNaS  | AlInNP   | InAlGaAs | InAlGaP  | InAlAsP  |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Epsilon   | 12.7     | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Band Parameters                                       |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Eg (eV)   | 1.27     | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 1.34     | 0        | 0        |
| Chi (eV)  | 4.32     | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 1.46     | 0        | 0        |
| Nc (per cc)   | 3.61E+17 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Nv (per cc)   | 8.54E+18 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| ni (per cc)   | 3.72E+07 | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 5.04E-12 | 1        | 1        |
| Gc  | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
| Gv  | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        | 4        |
| Ed (eV)   | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    | 0.044    |
| Ea (eV)   | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    | 0.045    |
| Recombination Parameters                              |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Lifetime (e)  | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Lifetime (h)  | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| Auger cn  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger cp  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kn  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Auger kp  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| Copt  | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| An**  | 7.11     | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 |
| Ap**  | 58.6     | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 | 1.40E-11 |
| Impact Ionization Model Parameters (Selberherr model) |          |          |          |          |          |          |          |          |          |          |          |          |          |
| betan   | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| betap   | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| egran   | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| an1   | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 |
| bn1   | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| an2   | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 | 7.03E+05 |
| an2   | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 | 1.23E+06 |
| ap1   | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 | 6.71E+05 |
| bp1   | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 | 1.69E+06 |
| ap2   | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 | 1.58E+06 |
| bp2   | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 | 2.04E+06 |
| Saturation densities                                  |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Vsath (cm)  | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |
| Vsath (cm)  | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |

**Note:**  $x_{comp}$  and  $y_{comp}$  are both set to 0.3. See Chapter 5: "Blaze: Compound Material 2D Simulator", Section 5.3: "Material Dependent Physical Models" for more information.

## B.10: Miscellaneous Semiconductors

The remainder of the semiconductors available have defined default parameter values to various degrees of completeness [92]. The following tables describe those parameter defaults as they exist. Since many of the material parameters are not available at this time, we recommended that you should be careful when using these materials. Make sure that the proper values are used

**Note:** You can use the MODEL PRINT statement to echo the parameters used to the run-time output.

| Material    | Eg(0)eV | Eg(300)eV | $\alpha$               | $\beta$  | $m_c$  | $m_v$  | $\chi$ eV |
|-------------|---------|-----------|------------------------|----------|--------|--------|-----------|
| Silicon     |         |           |                        |          |        |        |           |
| Polysilicon |         |           |                        |          |        |        |           |
| Ge          | 0.7437  |           | $4.77 \times 10^{-4}$  | 235.0    | 0.2225 | 0.2915 | 4.0       |
| Diamond     |         | 5.45      | $4.77 \times 10^{-4}$  | 0.0      | (a)    | (b)    | 7.2       |
| 6H-SiC      | 2.9     | 2.9       | 0.0                    | 0.0      | 0.454  | 0.33   |           |
| 4H-SiC      | 3.26    | 3.26      | 0.0                    | 0.0      | 0.76   | 1.20   |           |
| 3C-SiC      | 2.2     | 2.2       | 0.0                    | 0.0      | 0.41   | 0.165  |           |
| AlP         | 2.43    | 2.43      | 0.0                    | 0.0      |        |        |           |
| AlAs        | 2.16    | 2.16      | 0.0                    | 0.0      |        |        | 3.5       |
| AlSb        | 1.6     |           | $2.69 \times 10^{-4}$  | 2.788    | (c)    | 0.4    |           |
| GaSb        | 0.81    |           | $3.329 \times 10^{-4}$ | -27.6622 | (c)    | 0.24   | 3.65      |
| InSb        | 0.235   |           | $2.817 \times 10^{-4}$ | 90.0003  | 0.014  | 0.4    | 4.06      |
| ZnS         | 3.8     | 3.8       | 0.0                    | 0.0      | 0.4    |        | 4.59      |
| ZnSe        | 2.58    | 2.58      | 0.0                    | 0.0      | 0.1    | 0.6    |           |
| ZnTe        | 2.28    |           | 0.0                    | 0.0      | 0.1    | 0.6    | 4.09      |
| Cds         | 2.53    | 2.53      | 0.0                    | 0.0      | 0.21   | 0.8    | 3.5       |
| CdSe        | 1.74    | 1.74      | 0.0                    | 0.0      | 0.13   | 0.45   | 4.5       |
| CdTe        | 1.5     | 1.5       | 0.0                    | 0.0      | 0.14   | 0.37   |           |
| HgS         | 2.5     | 2.5       | 0.0                    | 0.0      |        |        | 4.28      |
| HgSe        |         |           |                        |          |        |        |           |
| HgTe        |         |           |                        |          |        |        |           |
| PbS         | 0.37    | 0.37      | 0.0                    | 0.0      | 0.25   | 0.25   |           |

| Material | Eg(0)eV | Eg(300)eV | $\alpha$ | $\beta$ | $m_c$ | $m_v$ | $\chi eV$ |
|----------|---------|-----------|----------|---------|-------|-------|-----------|
| PbSe     | 0.26    | 0.26      | 0.0      | 0.0     | 0.33  | 0.34  |           |
| PbTe     | 0.29    | 0.29      | 0.0      | 0.0     | 0.17  | 0.20  | 4.6       |
| SnTe     | 0.18    | 0.18      | 0.0      | 0.0     |       |       |           |
| ScN      | 2.15    | 2.15      | 0.0      | 0.0     |       |       |           |
| GaN      | 3.42    | 3.42      | 0.0      | 0.0     | 0.228 | 0.259 |           |
| AlN      | 6.13    | 6.13      | 0.0      | 0.0     | 0.314 | 0.417 |           |
| InN      | 1.89    | 1.89      | 0.0      | 0.0     | 0.11  | 0.17  |           |
| BeTe     | 2.57    | 2.57      | 0.0      | 0.0     |       |       |           |

**Notes**

(a).  $N_{c300} = 5.0 \times 10^{18}$

(b).  $N_{v300} = 1.8 \times 10^{19}$

(c).  $m_c(X) = 0.39$

$m_c(G) = 0.09$

$N_c = N_c(X) + N_c(G)$

(d).  $m_c(G) = 0.047$

$m_c(L) = 0.36$

$N_c = N_c(G) + N_c(L)$

| Material | Dielectric Constant |
|----------|---------------------|
| Ge       | 16.0                |
| Diamond  | 5.5                 |
| 6H-SiC   | 9.66                |
| 4H-SiC   | 9.7                 |
| 3C-SiC   | 9.72                |
| AlP      | 9.8                 |
| AlAs     | 12.0                |
| AlSb     | 11.0                |
| GaSb     | 15.7                |
| InSb     | 18.0                |



| <b>Material</b> | <b>Dielectric Constant</b> |
|-----------------|----------------------------|
| ZnS             | 8.3                        |
| ZnSe            | 8.1                        |
| CdS             | 8.9                        |
| CdSe            | 10.6                       |
| CdTe            | 10.9                       |
| HgS             |                            |
| HgSe            | 25.0                       |
| HgTe            | 20.                        |
| PbS             | 170.0                      |
| PbSe            | 250.0                      |
| PbTe            | 412.0                      |
| SnTe            |                            |
| ScN             |                            |
| GaN             | 10.4                       |
| AlN             | 10.1                       |
| InN             | 19.6                       |
| BeTe            |                            |

| <b>Material</b> | <b>MUNO (cm<sup>2</sup>/Vs)</b> | <b>MUPO (cm<sup>2</sup>/Vs)</b> | <b>VSATN(cm/s)</b> | <b>VSAT(cmcm/s)</b> |
|-----------------|---------------------------------|---------------------------------|--------------------|---------------------|
| Ge              | 3900.0(a)                       | 1900.0(b)                       |                    |                     |
| Diamond         | 500.0                           | 300.0                           | $2.0 \times 10^7$  |                     |
| 6H-SiC          | 330.0                           | 300.0                           | $2.0 \times 10^7$  | $1 \times 10^7$     |
| 4H-SiC          | 460                             | 124                             |                    |                     |
| 3C-SiC          | 1000.0                          | 50.0                            | $2.0 \times 10^7$  | $1 \times 10^7$     |
| AlP             | 80.0                            |                                 |                    |                     |
| AlAs            | 1000.0                          | 100.0                           |                    |                     |
| AlSb            | 200.0                           | 550.0                           |                    |                     |
| GaSb            | 4000.0                          | 1400.0                          |                    |                     |
| InSb            | 7800.0                          | 750.0                           |                    |                     |

| <b>Table B-28. Mobility Parameters for Miscellaneous Semiconductors</b> |                                 |                                 |                     |                     |
|---|---------------------------------|---------------------------------|---------------------|---------------------|
| <b>Material</b>   | <b>MUNO (cm<sup>2</sup>/Vs)</b> | <b>MUPO (cm<sup>2</sup>/Vs)</b> | <b>VSATN(cm/s)</b>  | <b>VSAT(cmcm/s)</b> |
| ZnS   | 165.0                           | 5.0                             |                     |                     |
| ZnSe  | 100.0                           | 16                              |                     |                     |
| CdS   | 340.0                           | 50.0                            |                     |                     |
| CdSe  | 800.0                           |                                 |                     |                     |
| CdTe  | 1050.0                          | 100.0                           |                     |                     |
| HgS   |                                 |                                 |                     |                     |
| HgSe  | 5500.0                          |                                 |                     |                     |
| HgTe  | 22000.0                         | 100.0                           |                     |                     |
| PbS   | 600.0                           | 700.0                           |                     |                     |
| PbSe  | 1020.0                          | 930.0                           |                     |                     |
| PbTe  | 6000.0                          | 4000.0                          |                     |                     |
| SnTe  |                                 |                                 |                     |                     |
| ScN   |                                 |                                 |                     |                     |
| GaN   | 400.0                           | 8.0                             | 2.0x10 <sup>7</sup> |                     |
| AlN   |                                 | 14.0                            |                     |                     |
| InN   | 3000.0                          |                                 |                     |                     |
| BeTe  |                                 |                                 |                     |                     |

**Notes**

- (a) Uses Equation B-4 with TMUN=1.66.
- (b) Uses Equation B-4 with TMUP = 2.33.

## B.11: Insulators

The default material parameters for insulator materials are given in the following tables. As noted in the Section B.2: “Semiconductors, Insulators, and Conductors”, the only parameter required for electrical simulation in insulator materials is the dielectric constant. Thermal and optical properties are required in GIGA and LUMINOUS respectively.

| <b>Material</b>                | <b>Dielectric Constant</b> |
|--------------------------------|----------------------------|
| Vacuum                         | 1.0                        |
| Air                            | 1.0                        |
| Ambient                        | 1.0                        |
| Oxide                          | 3.9                        |
| SiO <sub>2</sub>               | 3.9                        |
| Nitride                        | 7.5                        |
| SiN                            | 7.5                        |
| Si <sub>3</sub> N <sub>4</sub> | 7.55                       |
| Sapphire                       | 12.0                       |

| <b>Material</b>                | <b>Thermal Capacity (J/cm<sup>3</sup>)</b> | <b>Thermal Conductivity (deg(cm/W))</b> | <b>Reference</b> |
|--------------------------------|--|---|------------------|
| Vacuum                         | 0.0  | 0.0                                     |                  |
| Air                            | 1.0  | $0.026 \times 10^{-2}$                  | 7                |
| Ambient                        | 1.0  | $0.026 \times 10^{-2}$                  | 7                |
| Oxide                          | 3.066                                      | 0.014                                   | 4                |
| SiO <sub>2</sub>               | 3.066                                      | 0.014                                   | 4                |
| Nitride                        | 0.585                                      | 0.185                                   | 4                |
| SiN                            | 0.585                                      | 0.185                                   | 4                |
| Si <sub>3</sub> N <sub>4</sub> | 0.585                                      | 0.185                                   | 4                |
| Sapphire                       |  |   |                  |

## B.12: Metals/Conductors

Table B-31 shows the default values for resistivities of metals and the temperature coefficients of resistivity [see also 157].

| <b>Table B-31. Resistivity and Temperature Coefficient of Metals</b> |   |  |
|--|---|--|
| <b>Material</b>  | <b>Resistivity<br/>(<math>\mu\Omega\cdot\text{cm}</math>)</b> | <b>Temperature Coefficient<br/>(<math>\mu\Omega\cdot\text{cm}/\text{K}</math>)</b> |
| Aluminum   | 2.6540  | 0.00429  |
| Gold   | 2.35  | 0.004  |
| Silver   | 1.59  | 0.0041   |
| Tungsten   | 5.65  |  |
| Titanium   | 42.0  |  |
| Platinum   | 10.6  | 0.003927   |
| Palladium  | 10.8  | 0.00377  |
| Cobalt   | 6.24  | 0.00604  |
| Molibdinum   | 5.2   |  |
| Lead   | 20.648  | 0.00336  |
| Iron   | 9.71  | 0.00651  |
| Tantalum   | 12.45   | 0.00383  |
| Copper   | 6.24  | 0.00604  |
| Tin  | 11.0  | 0.0047   |
| Nickel   | 6.84  | 0.0069   |

## B.13: Optical Properties

The default values for complex index of refraction in LUMINOUS are interpolated from the tables in [53, 106]. Rather than print the tables here, the ranges of optical wavelengths for each material are listed in Table B-32.

| Table B-32. Wavelength Ranges for Default Complex Index of Refraction |                 |                      |                       |
|---|-----------------|----------------------|-----------------------|
| Material  | Temperature (K) | Composition Fraction | Wavelengths (microns) |
| Silicon   | 300             | NA                   | 0.0103-2.0            |
| AlAs  | 300             | NA                   | 0.2213 - 50.0         |
| GaAs  | 300             | NA                   | 0.0 - 0.9814          |
| InSb  | 300             | NA                   | 0.2296 - 6.5          |
| InP   | 300             | NA                   | 0.1689 - 0.975        |
| Poly  | 300             | NA                   | 0.1181 - 18.33        |
| SiO <sub>2</sub>  | 300             | NA                   | 0.1145 - 1.7614       |

**Note:** You can add the `INDEX.CHECK` parameter to the `SOLVE` statement to list the values of real and imaginary index being used in each solution.

## B.14: User Defined Materials

The current version of ATLAS doesn't directly support user-defined materials. A simple workaround can be done using the already existing user specifications. This workaround is based on the use of an already existing material name and modifying the material parameters as appropriate.

In ATLAS, material names are defined to give you a reasonable set of default material parameters. You can override any of these defaults using the `MATERIAL`, `IMPACT`, `MODEL`, and `MOBILITY` statements.

The key to defining new materials is choosing a material name that is defined in ATLAS, then modifying the material parameters of that material to match the user material. Here, you should choose a material that has default parameter values that might best match the user material, while being sure to choose a material that is not already in the user device. Then, associate this material name with the device regions where the new material is present. This is done by either specifying the chosen material name on the appropriate `REGION` statements (when the device is defined in the ATLAS syntax) or choosing the material name from the materials menu when defining the region in `DEVEDIT`. Next, modify the material statements using `MATERIAL`, `IMPACT`, `MOBILITY`, and `MODEL` statements. When doing this the `MATERIAL` parameter of the given statement should be assigned to the chosen material name.

For materials with variations in composition fraction, choose a defined material with X and/or Y composition fractions (i.e., a ternary or quaternary material). You may also find it convenient to use C interpreter functions to define the material parameters as a function of composition.

The C interpreter functions that are useful for this approach are: `F.MUNSAT`, `F.MUPSAT`, `F.BANDCOMP`, `F.VSATN`, `F.VSATP`, `F.RECOMB`, `F.INDEX`, `F.BGN`, `F.CONMUN`, `F.CONMUP`, `F.COPT`, `F.TAUN`, `F.TAUP`, `F.GAUN`, and `F.GAUP`.

When defining new materials, there is a minimum set of parameters that should be defined. This set includes bandgap (`EG300`), electron and hole density of states (`NC300` and `NV300`), dielectric permittivity (`PERMITIVITY`), and electron and hole mobilities (`MUN` and `MUP`). For bipolar devices, certain recombination parameters should also be defined such as: lifetimes (`TAUN` and `TAUP`), radiative recombination rates (`COPT`), and Auger coefficients (`AUGN` and `AUGP`).

For devices with variations in material composition certain band-edge alignment parameters should also be defined: either electron affinity (`AFFINITY`) or edge alignment (`ALIGN`). If impact ionization is considered the impact ionization coefficients should also be defined.

As an example, consider the case where a device is simulating with an `AlInGaP` region. In Table B-1, we see that this material system is not defined in ATLAS. We then choose a material that's defined in ATLAS which has default material parameters that best approximate the material parameters of the new material. In this case, we choose `InGaAsP` since, at least for example purposes, we feel that this material is closest to the `AlInGaP`. Next, we must specify `InGaAsP` as the material of the region(s) that is/are composed of `AlInGaP`. This can be done either on the `REGION` statement if the structure is defined in ATLAS syntax or from the material menu when the region is defined in `DEVEDIT`.

Supposing that we're satisfied with the default values of the parameters from the minimum set discussed above and that we're principally concerned with the recombination and heat flow parameters defaults, the following section of the input deck illustrates how these parameter defaults can be modified:

```
# new material AlInGaP
MATERIAL MATERIAL=InGaAsP
# SRH
MATERIAL MATERIAL=InGaAsP TAUN0=1.1e-9 TAUP0=2.3e-8
# Auger
MATERIAL MATERIAL=InGaAsP AUGN=5.8e-30 AUGP=1.1e-31
# Optical
material material=InGaAsP COPT=1.7e-30
```

```
# Thermoconductivity  
MATERIAL MATERIAL=InGaAsP TC.A=2.49  
# Heat capacity  
MATERIAL MATERIAL=InGaAsP HC.A=1.9
```

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## Appendix C: Hints and Tips

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This appendix is a collection of answers to commonly asked questions about the operation of ATLAS. This information has been previously published in articles in The Simulation Standard<sup>TM</sup>, Silvaco's trade publication. The original articles can be viewed at Silvaco's home page at <http://www.silvaco.com>.

### **Question:**

Can ATLAS handle photogeneration from non-normally incident light? What syntax is used to determine the correct photogeneration rate?

---

### **Answer:**

The models with LUMINOUS allow simulation of photogeneration within ATLAS. Arbitrary light sources are available within Luminous using the BEAM statement. The program uses geometric ray tracing to determine the path of a light beam including refraction and reflection of non-normally incident light. It then applies models for the absorption of the light to determine the photogeneration rate.

To use luminous the user should first define a light source using the BEAM statement and then choose the light intensity using a SOLVE statement. The BEAM statement can be explained by a simple example. The following syntax generates the ray trace in Figure C-1.

```
BEAM NUM=1 X.ORIGIN=3.0 Y.ORIGIN=-5.0 ANGLE=60.0 \  
MIN.W=-1 MAX.W=1 WAVEL=0.6 REFLECT=2
```

The parameter NUM sets the beam number. LUMINOUS can applications up to 10 independent beams. X.ORIGIN and Y.ORIGIN define the initial starting point for the light beam. This must be outside the device coordinates and for non-normal beams it is important to keep this point well away from the device. The ANGLE parameter determines the direction of the light beam relative to the x-axis. ANGLE=90 gives normal incidence from the top of the device. The light is defined as coming from a line perpendicular to the direction set by ANGLE and passing through (X.ORIGIN, Y.ORIGIN). MAX.W and MIN.W set a window along this line through which the light passes. The default for these parameters is +/- infinity.

The wavelength of the light beam is defined in microns using the WAVEL parameter. It is also possible to specify spectral sources of light by replacing WAVEL with POWER.FILE={filename}, where the {file} is a UNIX text file defining the spectrum in terms of an XY list of wavelength vs intensity.

LUMINOUS automatically chooses the number of rays needed to resolve the geometry. In the case of Figure C-1, only one initial ray is needed. The number of rays used by LUMINOUS is purely a function of the geometry and is not related to optical intensity, photogeneration rate, or MIN.W and MAX.W. The REFLECT parameter is used to limit the number of reflections the light beam is allowed. In ATLAS Version 3.0.0.R an alternative parameter MIN.POWER is used to set a relative intensity below which no more rays are traced.

The user has a choice in LUMINOUS as to whether the rays should reflect from the sidewalls and bottom of the device structure. If the simulation is of a partial wafer (such as is typical for CCD simulation) the light should not reflect. This is the default shown in Figure C-1. If the simulation is of a complete device, such as is typical for solar cells, the light should reflect. The parameter BACK.REFL is used to enable back and side reflection. The result of adding this to the previous syntax is shown in Figure C-2. In this figure the limit set by REFLECT=2 is also clear as each ray reflects only two times.

The ray trace is only done once a SOLVE statement is used to turn on the light beam. For example, the syntax SOLVE B1=0.5 sets the power of beam #1 to 0.5W/cm<sup>2</sup>. DC and transient ramps of light intensity can also be performed.

The refraction and reflection are determined by the real portion of the refractive index for each material. The imaginary portion on the refractive index controls the absorption of the light. Wavelength dependent defaults exist in ATLAS for common materials, but can be defined by the user as follows:

```
MATERIAL MATERIAL=Silicon REAL.INDEX={value} IMAG.INDEX={value}
```

From the ray trace information and the imaginary refractive indices, the photogeneration rate is calculated at each node in the structure. An integration method is used to ensure the charge generated is independent of the mesh density. The photogeneration rate from the ray trace in Figure C-2 is shown in Figure C-3. The electrons and holes generated are included in electrical simulations in ATLAS to determine collection efficiency, spectral response and other device parameters.

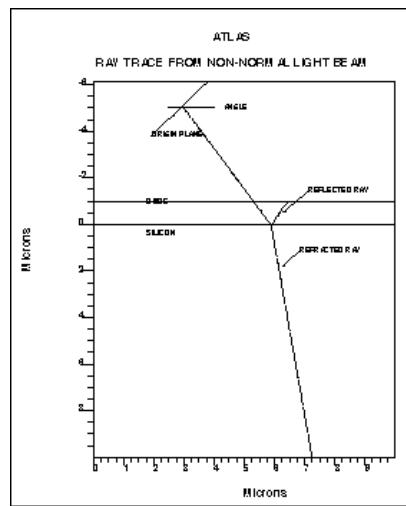


Figure C-1: Simple ray trace in LUMINOUS

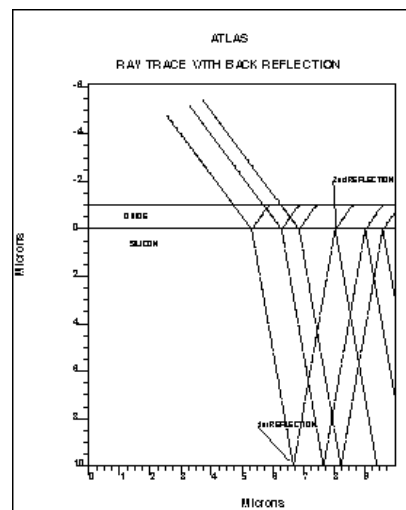


Figure C-2: Addition of back and sidewall reflection to Figure C-1

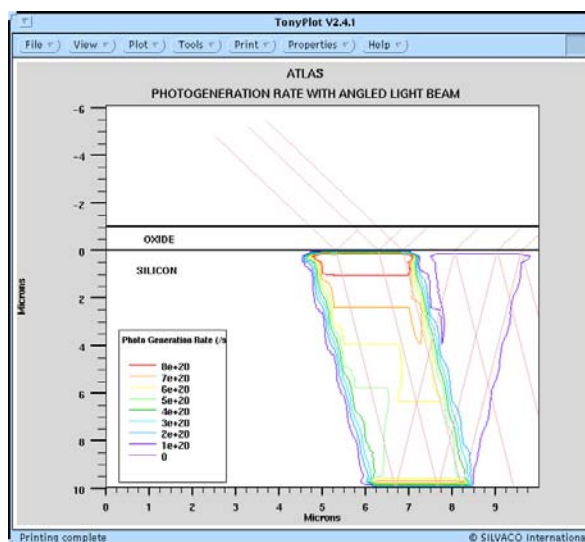


Figure C-3: Photogeneration contours based on ray trace in Figure C-2

### Question:

What choices of numerical methods are available in ATLAS? When should each type of method be used?

### Answer:

The latest release of ATLAS features more choices of numerical methods for users. It also has a new more logical syntax that clears up some of the previously confusing issues with the choice of numerical method for ATLAS solutions.

ATLAS has the ability to solve up to six equations on the simulation mesh. These are the Poisson equation, two carrier continuity equations, two carrier energy balance equations, and the lattice heat flow equation. The choice of numerical technique in solving these equations can strongly affect both the convergence and CPU time required to complete a simulation run.

In general equations can either be solved in a coupled manner with all equations solved at once or a decoupled manner with a subset of the equation solved whilst others are held constant. The coupled solutions are best when the interactions between the equations is strong (i.e., high current producing significant local heating). However they require a good initial guess to the solution variables for reliable convergence. Unless special techniques, such as projection, are used for calculating initial guesses this would mean that the voltage step size during a bias ramp might have to be rather small.

Decoupled methods can have advantages when the interaction between the equations is small (typically low current and voltage levels). They do not require such good initial guesses for convergence. They tend to either not converge or take excessive CPU time once the interactions become stronger.

ATLAS uses the `METHOD` statement to define numerical methods. The older `SYMBOLIC` statement is no longer required, although existing input files will run as before. To select the decoupled method for two carriers use:

```
method gummel carriers=2
```

To select the coupled method for two carriers use:

```
method newton carriers=2
```

This is the default. In fact users do not need to specify a METHOD statement at all for this case. For the majority of isothermal drift-diffusion simulations this choice of numerics is the recommended one.

ATLAS has the ability to switch automatically between different numerical methods. The syntax

```
method gummel newton
```

would start each bias point using a decoupled method and then switch to a coupled solution. This technique is extremely useful when the initial guess is not good. Typically this happens for devices with floating body effects (i.e., SOI).

For more complex simulation with energy balance or lattice heating other techniques are also available in ATLAS. A mixed technique where the poisson and continuity equations are solved coupled, and then the other equations are decoupled can be applied.

The syntax for this is:

```
method block
```

Typically this mixed technique is quicker and more robust at low lattice and carrier temperatures, whereas the fully coupled technique is better for high lattice and carrier temperatures. The mixed method can be combined very effectively with the fully coupled technique to provide improved speed and convergence for all ranges using:

```
method block newton
```

As an example of this Figure C-4 shows the CPU time taken for individual biasing points for a non-isothermal energy balance simulation of second breakdown of a sub-micron MOSFET. The device was constructed using ATHENA and the mesh contains a low number of obtuse triangles (not zero). The graph clearly shows that at initially the coupled method takes much longer to converge. This is because the initial guess is not good until two bias points are solved so that projection can be used. As the voltage is increased the block method has increasing convergence difficulty whereas the time taken for the newton method is flat. The time for the mixed method has the advantages of block at lower currents, but without the severe increases of block.

The ideal solution for most problems is the use of the mixed "block newton" method initially switching to the fully coupled "newton" method as the simulation proceeds. Of course the cross-over point, which is at  $x=2.5$  in Figure C-4, varies from case to case. To avoid excessive user-interaction the "block newton" could be used throughout the simulation without a very excessive hit in terms of CPU time.

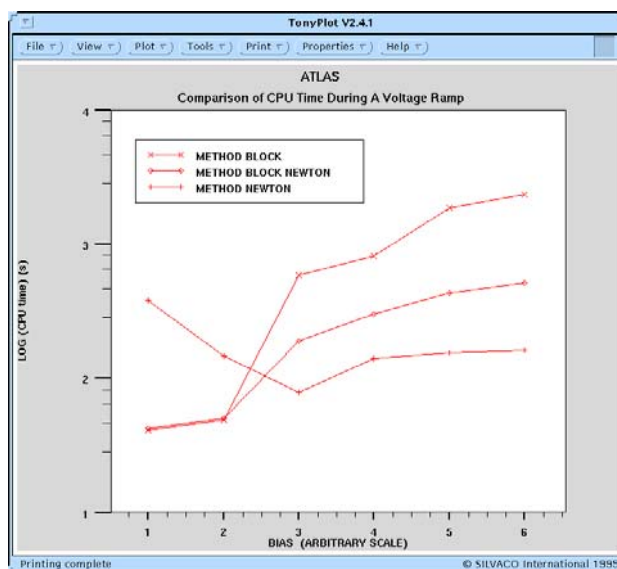


Figure C-4: Comparison of CPU time showing advantages of decoupled methods at low current and coupled method at high currents

### Question:

Can the workfunction of the MOS polysilicon gate contact be calculated by ATLAS based on the doping? Can poly depletion effects be simulated in ATLAS?

### Answer:

The polysilicon gate contact in MOS devices can be simulated in two distinct ways using ATLAS. These correspond to treating the polysilicon region as:

- A metal-like equipotential region with a specified workfunction.
- A semiconductor region with a potential defined by the doping level.

Most commonly the former approach is adopted. The polysilicon region acting as the gate is defined as an electrode in ATHENA.

The `electrode` statement is used with the X and Y parameters acting as crosshairs to target a particular region of the structure. The whole region, irrespective of shape, is then defined as an electrode.

```
ELECTRODE NAME=gate X={x value} Y={y value}
```

A region defined this way is now treated as equipotential in ATLAS. The potential of this region will be defined by the `VGATE` parameter of the `SOLVE` statement. Hence poly depletion cannot be modeled in gate contacts defined this way. The workfunction of this region must be set by the user. For example, a heavily n doped polysilicon contact can be defined by either of the two following statements:

```
CONTACT NAME=gate N.POLY
CONTACT NAME=gate WORK=4.17
```

The second approach of treating the polysilicon gate region as a semiconductor is achieved by placing a contact on the top of the gate. In ATHENA this is done by depositing a metal (or silicide) layer on top of the polysilicon. The `ELECTRODE` statement is then used to define this metal region as the gate electrode. In ATLAS a workfunction for the gate should not be specified on the `CONTACT` statement as this would give an undesirable workfunction difference between the metal and polysilicon. the potential on the metal region is defined by the `VGATE` parameter of the `SOLVE` statement. The potential

within the polysilicon gate region will depend on the doping level of the polysilicon. In non-degenerately doped polysilicon a voltage drop is seen across this region from top to bottom. The workfunction difference between the gate and the substrate can be derived from a potential profile through the channel region.

It is also possible for the polysilicon to be depleted starting at the gate oxide interface. Figure C-5 shows a comparison of high frequency CV curves between a MOS device with a uniform degenerately doped poly gate typical when tube doping is used and a lighter, non-uniformly doped gate typical when source/drain implants are used to dope the polysilicon. In the accumulation region the poly begins to deplete leading to an effectively thicker gate dielectric. This effect is illustrated in Figure C-6. The amount of poly depletion observed is dependent on the doping level. Accurate polysilicon diffusion models are available in ATHENA to simulate the doping. In addition the SILICIDE module allows simulation of the dopant redistribution during gate silicidation. Silicides can typically reduce the effective gate doping making poly depletion more likely.

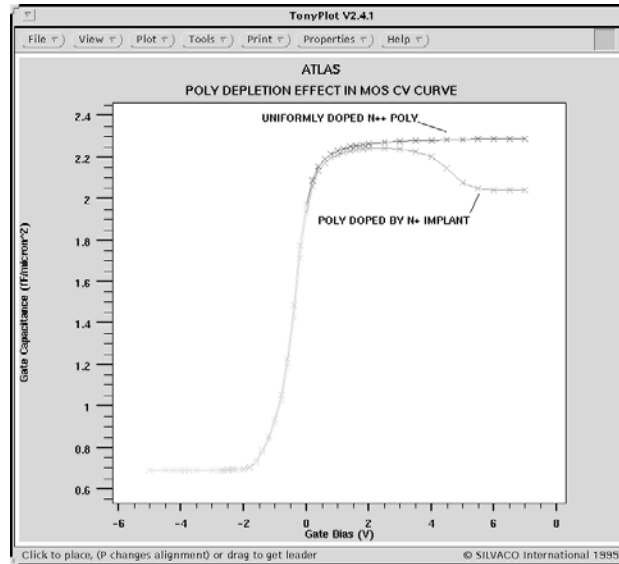


Figure C-5: High frequency CV curve showing poly depletion effects at positive Vgs.

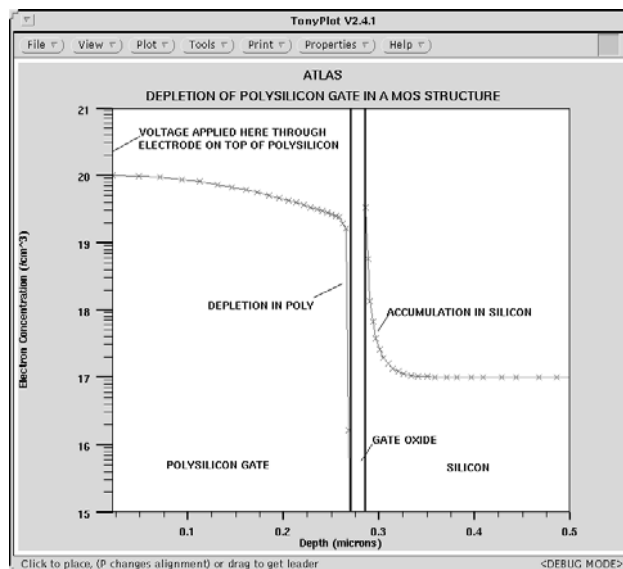


Figure C-6: Figure 2 Electron concentration profile of an NMOS transistor poly depletion occurs at the poly/gate oxide interface.

### Question:

How can I remesh my process simulation result for device simulation?

### Answer:

The structure editing and gridding tool DEVEDIT provides an effective way to remesh structures between process and device simulation.

DEVEDIT is able to read and write files to both ATHENA and ATLAS. In addition to the graphical user interface, DEVEDIT can operate in batch mode under DECKBUILD. The batch mode DEVEDIT features a powerful syntax that can be applied to remesh structures read directly from ATHENA. DEVEDIT employs a hierarchical method for remeshing existing structures. Users specify mesh parameters at each stage. Initially a base mesh is applied with the command:

```
BASE.MESH HEIGHT=<h1> WIDTH=<w1>
```

This mesh of h1 by w1 microns provides the coarsest mesh in the structure. On top of this base level mesh DEVEDIT determines which points must be added to ensure the geometry of all regions is preserved. Optional boundary conditioning to smooth region boundaries can be applied using the BOUND.COND statement.

Mesh constraints can be applied to arbitrary boxes with the device using the syntax:

```
constr.mesh x1=<n> x2=<n> y1=<n> y2=<n>\
max.height=<h2> max.width=<w2>
```

This sets the maximum mesh size to h2 by w2 microns the box with diagonal from (x1,y1) to (x2,y2). Using the constraint boxes in critical areas of the device is the most effective way to use DEVEDIT. In MOSFETS the constraint boxes can be applied to the silicon region under the gate. Typically vertical grid spacings of 5 are required for accurate simulation of channel conduction in sub-micron MOSFETs.

Use of multiple constraint boxes can be applied. For MOSFET breakdown constraint boxes can be applied to the drain/gate overlap area.

In addition to constraint boxes, DEVEDIT can refine on quantities such as individual doping species, net doping, potential. The `IMP.REFINE` statement allows users to select the critical value of a quantity for refinement and an associated minimum grid spacing.

This type of refinement is useful when key effects are located very close to junctions. For example the emitter-base junction in bipolar transistors.

The final level of grid refinement are "manual refine boxes" defined using:

```
Refine Mode={Both|x|y} P1=x1,y1 P2=x2,y2
```

These are boxes with a diagonal from (x1,y1) to (x2,y2), inside which the grid spacing is halved in the given direction. These can be used as a final customization to the mesh. In general, however, the constraint boxes described above are easier to use.

As a demonstration of the effectiveness of regriding using DEVEDIT Figures C-7 and C-8 show meshes created from the same process simulation structure. Figures C-9 and C-10 show the  $I_d/V_d$ s and breakdown characteristics respectively of the device for each mesh. The mesh at the silicon surface is identical in both cases to a depth of 100Å. However the mesh below this is much coarser in Figure C-8.

However the device results show no significant change despite the reduction in the node count by a factor of two.

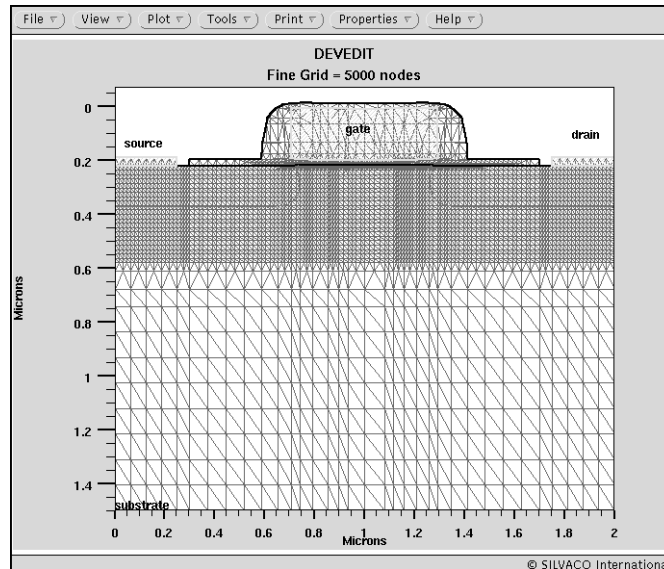


Figure C-7: Fine Grid - 5000 nodes



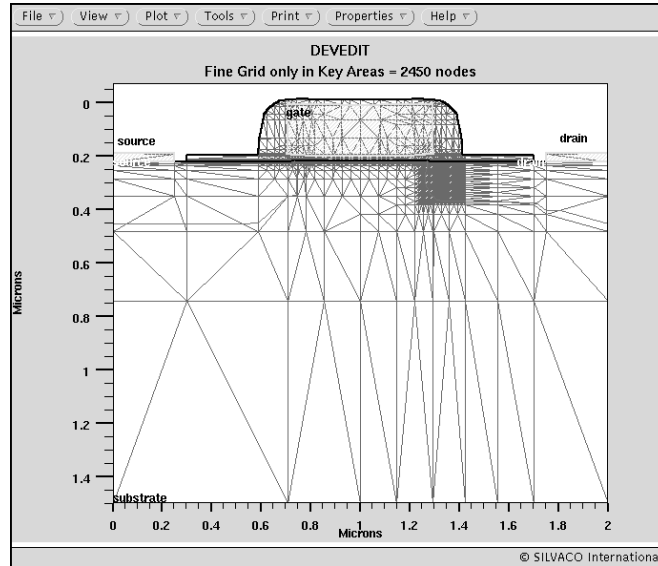


Figure C-8: Fine Grid only in Key Areas - 2450 nodes

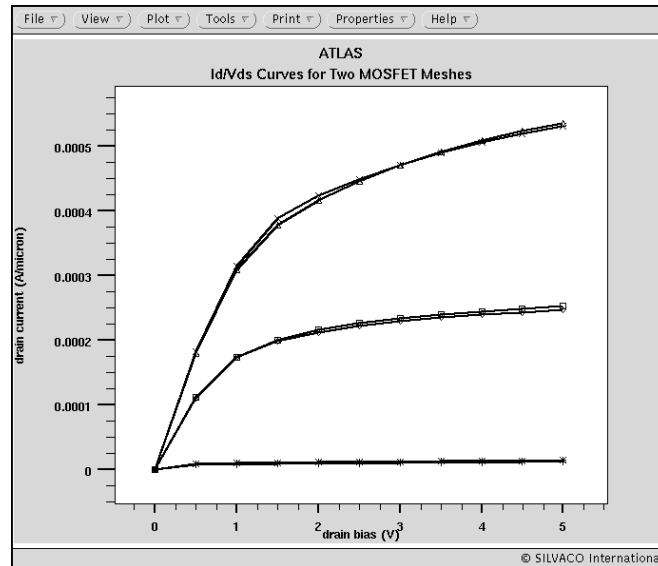


Figure C-9: Id-Vds Curves for two MOSFET Meshes

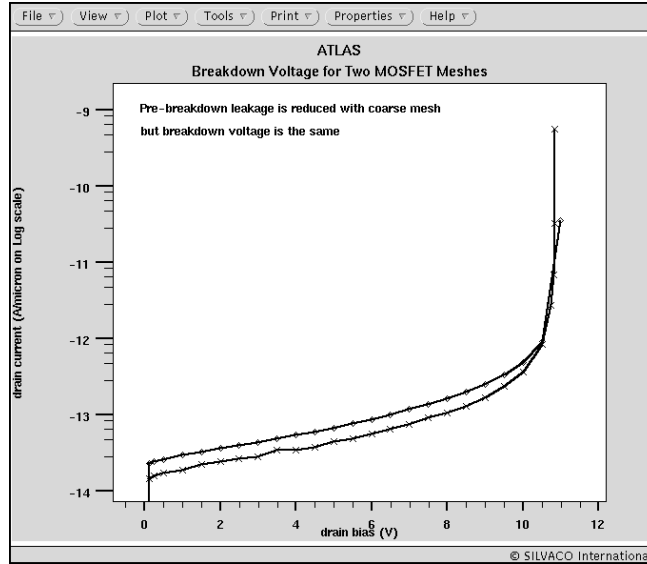


Figure C-10: Break-down Voltage for Two MOSFET Meshes

Demonstration of optimized gridding using constraint boxes in DEVEDIT. Both very fine and optimized mesh produces equivalent results.

**Question:**

How can solution quantities such as Electric Field be saved for plotting against applied bias?

**Answer:**

There are two types of output files saved by ATLAS:

- Solution files contain physical quantities mapped to the simulation grid. One solution file is saved per bias point.
- Log files which traditionally have saved the terminal characteristics for all bias points.

A new feature of ATLAS 4.0 is the addition of a capability to save physical quantities at user-specified locations within the device grid to the log files. A new statement PROBE is used to specify the quantity to be saved and the location. For example, to save the electron concentration rate at a location [1,0.1] the syntax is:

```
PROBE NAME=my_e_conc N.CONC X=1.0 Y=0.5
```

The label specified by the NAME parameter is used to label the saved quantity in TONYPLOT and subsequent EXTRACT statements.

For vector quantities the PROBE statement also requires a direction to be given using the DIR parameter. This is specified as an angle in degrees with the X axis as DIR=0. To find the electric field across an oxide layer the syntax is:

```
PROBE X=1.2 Y=0.2 FIELD DIR=90 \ NAME=oxide_field
```

Figure C-11 shows the resultant plot of electric field in a MOSFET gate oxide during a transient ESD pulse. This result shows the probability of oxide breakdown during the ESD stress, without the need to examine many separate solution files.

Another advantage of the probe for vector quantities is that it reads the values directly from the simulator at the closest location to the specified XY coordinates. This avoids many issues of interpolation and averaging of vector quantities onto the simulation grid.

If two physical quantities are probed at the same location it is possible to plot them against each other to examine model settings. For example, impact ionization rate or mobility versus electric field. Figure C-12 shows a plot of channel electron mobility in a submicron NMOS transistor versus the transverse electric field from the gate.

All of the primary solution quantities can be probed. A full list is given in the manual under the PROBE statement. In addition to values at point locations the PROBE statement also supports MIN and MAX parameters to find the minimum and maximum of a given quantity.

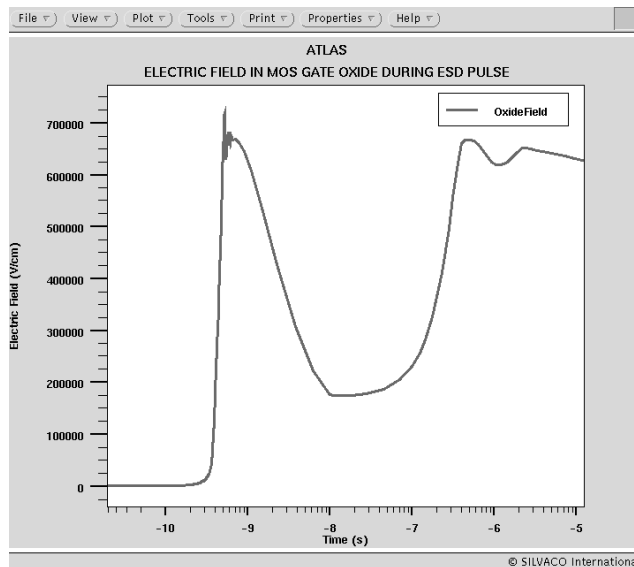


Figure C-11: Electric field in MOS gate oxide during a high current pulse on the drain.

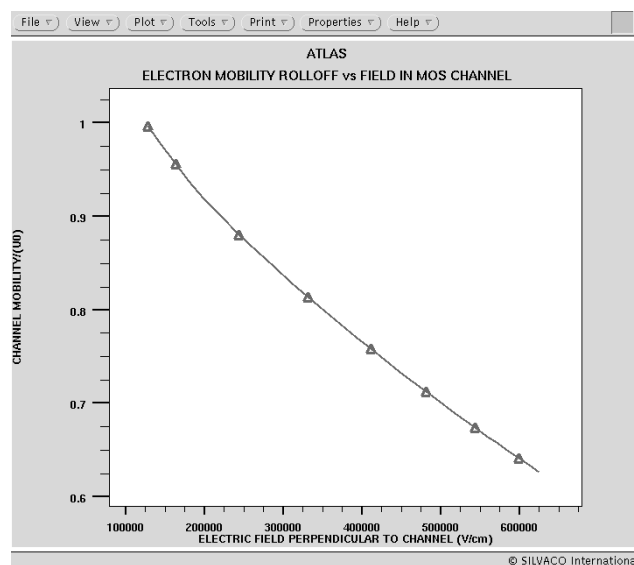


Figure C-12: Mobility (normalized) rolls off as a high gate electric field is applied

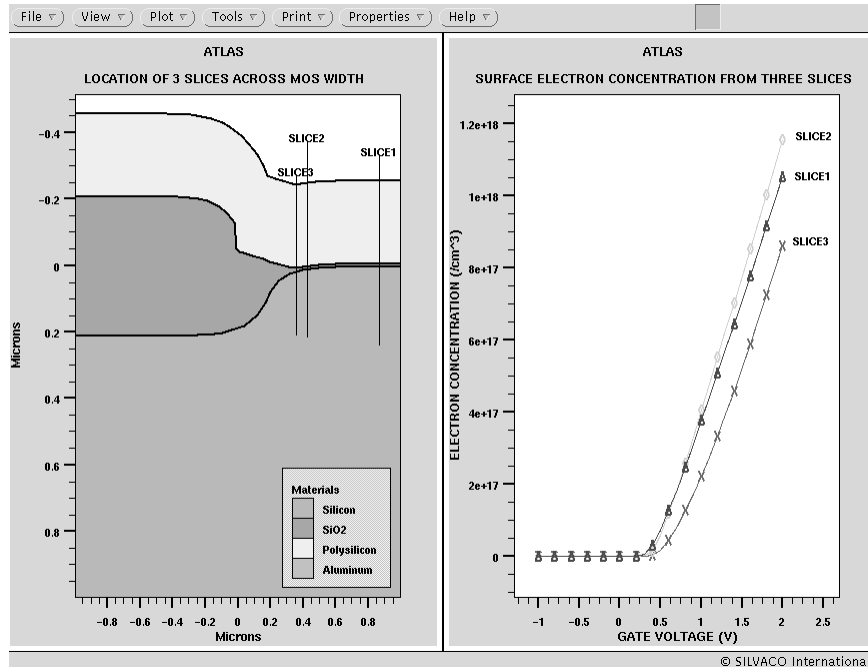


Figure C-13: Using a PROBE of electron concentration allows a study of MOS width effect using 2D simulation. An enhanced electron concentration is seen along slice 2.

### Question:

What are the options for generating 3D structures for ATLAS device simulation?

### Answer:

Currently there are three options for generating 3D device structures. In all cases the prismatic meshing of ATLAS/DEVICE3D permits arbitrary shaped device regions in 2 dimensions (typically X and Y) and rectangular regions in the other dimension (typically Z).

- Definition through the ATLAS syntax.

This limits the user to defining box shaped regions. Region definition is through statements such as:

```
region num=1 silicon x.min=0 \
x.max=1 y.min=0 y.max=1 z.min=0
\ z.max=1
```

Mesh generation is handled through the Z.MESH statement which is analogous to the X.MESH and Y.MESH statement used in 2D ATLAS simulations. Electrodes and doping can be defined using the same syntax as 2D ATLAS but with Z.MIN and Z.MAX parameters to control the Z extent. Doping profiles can be read from the formats supported in 2D ATLAS: `ssuprem3`, `Athena`, `ascii`.

- Use DEVEDIT to create a 3D mesh structure.

DEVEDIT3D is a 3D structure generation and meshing tool used to generate the mesh, regions, electrodes and doping used in ATLAS/DEVEDIT. It allows users to draw regions by hand in 2D and project them into the third direction.

DEVEDIT3D contains all the sophisticated meshing options available to 2D DEVEDIT. These include: mesh constraints by region, mesh constraints by a user defined box, refinement on doping and other

quantities, mouse controlled refine and unrefine boxes. DEVEDIT3D has both interactive and batch mode operation. This is the recommended approach for 3D power device simulation.

- Use ATHENA and DEVEDIT3D to extend a 2D process simulation to 3D.

A 2D process simulation from ATHENA can be extruded to form a 3D structure using DEVEDIT3D. In this mode DEVEDIT3D can be used to add extra regions and doping if required. This mode is commonly used for modeling MOS width effects in 3D (see Figure C-14). An ATHENA simulation of the isolation bird's beak and field stop implant is performed.

The 2D structure is loaded into DEVEDIT3D and extended in Z direction. The polysilicon gate is truncated in Z and aluminum source/drain contacts are added. The source/drain doping profiles can be read from analytical functions or other process simulation results. A worked example, named mos2ex04.in, is supplied with the Fall 96 release CDROM.

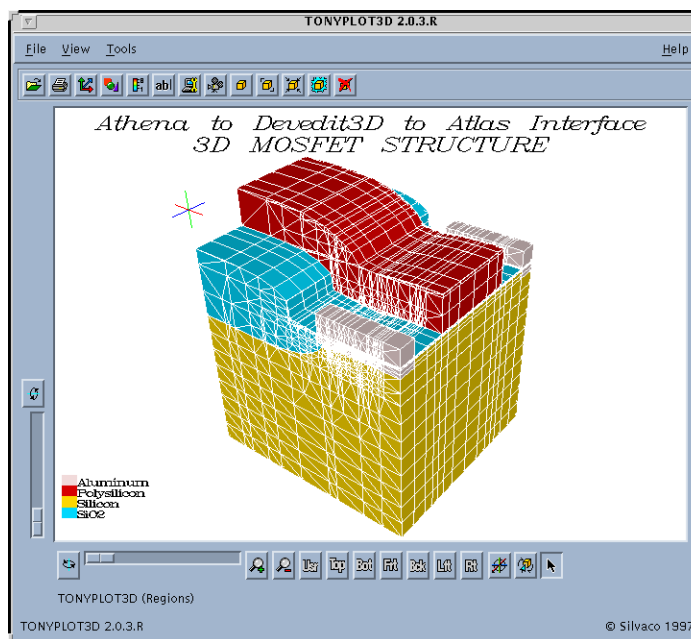


Figure C-14: 3D device simulation of MOS width effect can be performed on structures created Athena.

For devices with non-rectangular regions in the XZ plane such as pillar MOSFETs or cylindrically designed power structures DEVEDIT3D can also be used by drawing in the XZ plane and projecting into the Y direction.

The future release of Silvaco's 3D process/device simulator ODIN will provide a fourth option for 3D simulation problems. ODIN is based on tetrahedral mesh elements and will overcome the mesh restrictions described above.

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**Note:** ODIN is now called Clever.

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### D.1: Version History

#### D.1.1: Version 5.8.0.R

##### 1. Introduced LED

- LED provides new capabilities specifically tailored for the simulation of light emitting diodes.
- Models DC and time dependent responses.
- Uses accurate electronic band structure models based on the k\*p method to predict spectral radiative rates.
- Simulates bulk and quantum well devices in all material systems.
- Predicts luminous intensity, peak emission wavelength, spectral output, and efficiency.
- Estimates output coupling and angular output light distribution.

##### 2. Introduced NOISE

- Calculates equivalent external noise voltage sources for small-signal random behavior of electrons and holes.
- Accounts for random behavior of carrier density and velocity.

##### 3. New Features of BLAZE

- Added models based on the k\*p method to predict band structure and density of states effective masses for Wurtzite InGaN/AlGaN material systems.
- Added models based on the k\*p method to predict gain and radiative recombination rates for Wurtzite InGaN/AlGaN material systems.
- Added models to account for piezoelectric effects in the Wurtzite InGaN/AlGaN material systems.
- Added/updated material parameter defaults for numerous material systems.
- Added 3D-SiC as a recognized material.

##### 4. New Quantum Features

- Added new model/syntax for defining quantum wells. New model is based on the REGION statement and is easier to use and gives greater flexibility in defining quantum wells. The new model also accounts for field effects in spectral characteristics of gain and radiative recombination.
- Added new Bohm quantum potential models in 2D and 3D that allows quantum effects to be included in semi-classical transport modeling.
- Developed Schrodinger-Poisson solver compatible with non-planar and imported structures.
- Added a new eigenvalue solver using the inverse iteration method for Schodinger-Poisson.

##### 5. New LUMINOUS Features

- Added capability to probe photogeneration in LUMINOUS3D.
- Added capability to output the beam power spectrum.
- Added capability to simulate multi-layer anti-reflective coatings using the transfer matrix formalism.
- Modified calculation of reflection and transmission of light at material interfaces to properly account for imaginary part of refractive index using complex transfer matrix methods.

- Implemented two new types of lenslets for LUMINOUS3D, one ellipsoidal and one a composite of planar front face with cylindrical edges.
- Added capability to model integrated waveguide photodetectors.
- Moved the complex index of refraction versus wavelength tables into user-modifiable ascii files in the common directory.
- Added capability to simulate diffraction of light and coherent effects using beam propagation method.

## 6. New Probe Features

- Added capability to probe a specific region or material for minimum, maximum or integrated value.
- Added capability to probe available photocurrent.
- Added the capability to use raw power spectrum data rather than the default method of integrated averaging.
- Added the capability to probe photogeneration rate.
- Added the capability to probe trap recombination rate.
- Added a compliance capability to the probe.
- Implemented a new initial guess strategy for low/zero current applications in MOS devices.
- Added capability to probe peak emission wavelength for LED.
- Added capability to probe electron and hole velocities.

## 7. New VCSEL Features

- Introduced a procedure to check whether a specified VCSEL structure corresponds to general requirements for a VCSEL.
- Added capability to calculate reflectivity of a cold VCSEL cavity as a function of wavelength using transfer matrix method.
- Added capability to find resonance frequency of a cold VCSEL cavity.
- Implemented a new optical solver for VCSEL based on effective frequency method. The new method allows to simulate oxide aperture VCSELs.
- Added a perturbational method to solve for longitudinal modes of a VCSEL cavity. This method allows to speed up the solution of Helmholtz equation.
- Enabled self-consistent solution for modeling of electrical and optical behavior of VCSELs based on effective frequency method.

## 8. New C Interpreter Functions

- Added C-interpreter functions for carrier temperature dependent mobility.
- Added C-interpreter functions for carrier temperature dependent density of states.
- Added carrier concentration to the C interpreter functions for thermionic field emission (tunneling) in Schottkys.
- Added a C-interpreter function for thermal electrode temperature as a function of time for GIGA and GIGA3D.
- Added a C-interpreter function for LASER mirror facet reflectivities as a function of wavelength.



## 9. New MIXEDMODE Features

- Enabled unlimited circuit nodes and elements in MIXEDMODE and MIXEDMODE3D.
- Implemented BLOCK method in MIXEDMODE.
- Enabled use of modified 2-level Newton scheme in MIXEDMODE.

## 10. General Features

- Enabled energy balance/hydrodynamic simulation in 3D.
- Added the capability to modify characteristics of regions in loaded structures.
- Added the capability to load 2D ASCII doping profiles.
- Added quasi-static capacitance calculation in 2D and 3D.
- Implemented curve-tracer in 3D.
- Added capability to print model parameters on a region basis.
- Added random distribution to doping.
- Enabled the use of BLOCK method in transient simulations.
- Reimplemented the Schottky boundary condition with thermionic emission and thermionic field emission.
- Improved the heterojunction thermionic field emission model to work for interfaces in arbitrary directions.
- Enabled region specific specification of the MOBILITY statement.
- Enabled transient load and save.
- Added the capability to specify the electron and hole tunneling effective masses to the Schottky boundary model.
- Added the capability to simulate metals as conductors solving a simple conduction equation.
- Implemented new capabilities for user definable materials.
- Made improvements to the Hurkx band-to-band tunneling model.
- Added a new temperature dependent band-gap model.

## D.1.2: Version 5.6.0.R

### 11. Introduced VCSELS

- VCSELS provides new capabilities that are used in conjunction with BLAZE to simulate cylindrically symmetric vertical cavity surface emitting lasers. This implementation includes numerous new syntactical features, which greatly simplify the specification of complex multilayered epitaxial devices such as VCSELS.

### 12. New Features of LUMINOUS and LUMINOUS3D

- Added periodic optical sources to LUMINOUS.
- Added capability to simulate Gaussian sources in LUMINOUS.
- Added capability to simulate Gaussian sources in LUMINOUS3D.
- Added capability to simulate elliptical sources in LUMINOUS3D.
- Added capability to simulate AC response in LUMINOUS3D.

### 13. New Features of LASER

- Added capability to probe laser optical intensity and optical gain.
- Incorporated fully coupled rate equations with device Jacobian.
- Can specify separate front and rear mirror reflectivities.
- Moved all laser models to a new LASER statement.

- Made it so you can specify non-uniform LASER meshes and choose the device mesh for the LASER mesh.
- Added wavelength to the log file.
- Enabled the simulation of symmetric laser structures with half structures.
- Added stimulated recombination to the structure files.

#### **14. New Features Related to Traps**

- Implemented INTDEFECT for interface defects.
- Implemented a bounding box to limit the extent of interface traps or defects.
- Added the capability to probe ionized trap densities.
- Modified continuous and discrete traps to work for both insulators and semiconductors.
- Implemented interface continuous AC traps for ATLAS and ATLAS3D.

#### **15. New Material System Default Parameters**

- Updated material default parameters for the AlGaN system.
- Updated material default parameters for the HgCtTe system.

#### **16. Miscellaneous Improvements**

- Implemented new impact ionization model suggested by Valdinoci et.al.[27].
- Added thermal resistor boundary conditions for energy-balance.
- Added capability to probe impact ionization rates.
- Added capability to probe integrated charge.
- Added capability to specify angled doping profiles in DEVICE3D.
- Added capability to enable "old" Pisces impact ionization model.
- Implemented new discretization scheme suggested by Patil [140]. The scheme promises to avoid the difficulties with obtuse angles inherent in the standard scheme.
- Implemented small signal AC in DEVICE3D.
- Implemented BLOCK method in DEVICE3D.
- Added region and material specific MODELS PRINT capability.
- Implemented CGS, BICGST, and direct solvers in DEVICE3D AC analysis.
- Implemented a new mobility model combining the Klaassen and CVT models.
- Added concentration dependence of surface contributions of mobility.

### **D.1.3: Version 5.2.0.R**

#### **1. Introduced LUMINOUS3D**

- LUMINOUS3D provides a similar functionality to 2D LUMINOUS. This allows simulation of interaction between arbitrary optical sources and semiconductor devices in three dimensions.

#### **2. Smartlib**

- Implemented the SmartSpice Compact Device Model Library (Smartlib). These models replaces the old MIXEDMODE Diode, MOSFET and BJT Models. Additional device models such as TFT and SOI can now be used. Also, additional devices such as JFETS and MESFETs can now be used.

#### **3. Implemented a New and Improved C-Interpreter**

- Implemented a new C-Interpreter. This completely replaces the old version of the C-Interpreter. The new C-Interpreter is faster than the old version and supports more C functions. The new C-Interpreter conforms more to the ANSI standard.

#### 4. Heterojunction Thermionic Emission and Field Emission

- Introduced a new implementation of thermionic emission models for hetero-interfaces. This implementation supercedes the previous one, which is no longer supported.
- Also introduced a new heterojunction tunneling (thermionic field emission) model that is compatible with the new thermionic emission model.

#### 5. Cyclic Biasing

- Implemented cyclic biasing model to simplify prediction of steady state conditions in cyclically biased devices exhibiting long time constants.

#### 6. Miscellaneous Improvements

- Added the following new material names: InGaN, AlGaN, InAlGaN, InGaNAs, InGaNp, AlGaNAs, AlGaNp, AlInNAs, AlInNP, InAlGaAs, InAlGaP and InAlAsP.
- Added the following new gain output parameters. ATLAS will now output the maximum available gain (Bma) as well as the maximum stable gain (Gms).
- Added capability to add sheet charge along region interfaces for simulation of piezoelectric strain effects.
- Added temperature dependence to the Shirahata mobility model.
- Added capability for multiple trapazodial/square transient pulses.
- Added a more general parameterized temperature-dependent model for saturation velocity for field-dependent mobility.
- Changed the calculation of effective mass used in calculation of thermal velocity for traps in non-silicon materials. The new approach calculates mass, based on the material density of states.

### D.1.4: Version 5.0.0.R

#### 1. Introduced several new 3D products

##### a. Giga3D.

- GIGA3D contains most of the functionality of the 2D Giga, but works with 3D products. This allows modeling of heatflow and self-heating effects in 3D devices. The only functionality not supported in this version of GIGA3D that is supported in 2D is the BLOCK method.

##### b. Blaze3D

- This version accounts for spatial variations in band gap due to spatial variations in material composition in 3D. This version supports all the same models that are supported in Blaze 2D with the exception of thermionic emission at heterojunctions and energy transport. This version also does not support compositional variation in the z direction.

##### c. MixedMode3D

- This improvement allows simulation of 3D devices embedded in lumped element circuits. MIXEDMODE3D contains all the functionality of 2D MixedMode simulator.

##### d. TFT3D

- This model allows modeling of poly and amorphous semiconductor devices such as TFTs in 3D. This model has all the functionality of the 2D TFT simulator.

##### e. Quantum3D

- This allows modeling of the effects of quantum confinement using the quantum moment approach. This model has all the functionality of the 2D Quantum model.

#### 2. Orchid

- ORCHID is a new product used in conjunction with S-PISCES to model the effects of total radiation dosage on MOS device reliability. Key to this capability is the ability to model the gate

oxide as a semiconductor. The user may then define carrier pair generation in the oxide as a function of position, time, and electric fields, using a new C interpreter function. Another C interpreter function can be used to calculate the cumulative fixed charge density as a function of position and electron and hole current densities in the oxide. The deduced fixed oxide charge density directly effects the threshold degradation of the device.

### 3. Introduced SiC

- SiC is a new simulation capability for simulating anisotropic materials such as silicon carbide. The basis of this model is the incorporation of a new anisotropic mobility model that allows users to define separate mobilities along normal directions.
- Also added a new default value for thermal conductivity and electron saturation velocity of silicon carbide.

### 4. Modifications to Laser

Included additional functionality into Laser. The new features are:

- transient mode (time-dependent photon rate equation)
- far field patterns
- additional loss mechanisms including:
  - mirror loss
  - free carrier loss
  - absorption loss (including C interpreter function for bulk absorption)

### 5. New Large Signal and Simulation Capabilities

- Added specifications of sinusoidal waveforms to the SOLVE statement.
- Implemented post processing Fourier analysis. This performs a Fast Fourier Transform (FFT) on data within a log file to convert time domain data into frequency domain data.
- Added solution compliance based on sinusoidal analysis. In this mode, transient simulation will stop if the amplitude of a sinusoidal waveform is less than the user-specified value.

### 6. Modifications to Luminous

- Added capability to print the complex indices of refraction as they are calculated for the various materials during the ray trace in Luminous.
- Added functionality to simulate single-layer antireflective coatings in LUMINOUS. This capability calculates the reflection coefficient for a single layer coating under conditions of normal incidence.

### 7. Modifications to MixedMode

- Added the capability to specify multiple .TRAN statements in a single input deck.

Added the extraction of network parameters ( $S$ ,  $Z$ ,  $Y$ ,  $H$ ,  $ABCD$ ), stability factor, unilateral power gain, and maximum unilateral transducer power gain in MIXEDMODE.

- Added the capability to use the PROBE in MIXEDMODE.

### 8. Modification to GIGA

- Enabled simulations of floating gate structures with heat flow in GIGA.

### 9. New Physical models

- Added Klaassen's concentration and temperature-dependent SRH lifetime and Auger rate models.
- Implemented new continuous trap level model in TFT.
- Added new carrier concentration dependent Auger coefficient model.
- Added the capability to calculate the band-to-band tunneling coefficients from principles.
- Added the capability to model thermionic field emission tunneling in Schottky contacts.

- Added two new parameters to the single-event upset model. The generated electron/holes pairs (or charge) will not be calculated after `tf` seconds if this parameter is specified in the input deck. The width of the beam can now be specified as a constant value, followed by an exponential or Gaussian function by using the `beam.radius` parameter. For radii greater than `beam.radius`, either the Gaussian or exponential functions is used (if they are specified).

## 10. New Numerical Techniques

- Two sparse matrix reordering techniques are now available: Minimum Degree (MD) and Reverse Cuthill McKee (RCM). They are used in the 2D linear solver. MD is the default. Choosing RCM instead of MD sometimes solves the problem of having a zero on the diagonal, which is indicated by the error message:

```
Internal error in linear solver: Z-#.
```

If this happens, the user should switch from MD to RCM or vice-versa.

- For Parallel ATLAS, two new mesh partitioning techniques are now available:
  - Natural Ordering (NO) and
  - Multi-level Graph Partitioning (MGP)

These are used to assign sub-meshes to different processor. MGP is the default and should always outperform NO. On the other hand, NO requires less preprocessing time and might perform as well as MGP in the case of meshes generated by the ATLAS statement.

- Made it possible to use projection for initial guesses in conjunction with current boundaries.

## 11. Structures and Log File Improvements

- Added the capability to write X and G (rhs) errors in a standard structure file for subsequent visualization using TONYPLOT.
- Added the capability to save electron, hole relaxation times, and Peltier coefficients to structure files.
- Added the capability to save electron, hole, and displacement currents to log files.

## 12. New Quantum models

- Implemented a new self-consistent Schrodinger-Poisson solver. This model interactively solves Poisson's and Schrodinger's equations to calculate the potential and carrier concentration, including the effects of quantum confinement. These solutions also produce eigen energies and eigen functions.
- Added Hansch's model for quantum mechanical correction for carrier distributions in N channel MOSFETs inversion layers.
- Added van Dort's model for quantum mechanical correction for carrier distributions in N and P channel MOSFETs in inversion and accumulation layers.

## 13. Miscellaneous ATLAS Improvements

- Reconfigured small signal AC post processing to include the effects of parasitics in gain calculations.
- Changed functionality of C interpreter functions, `F.CONMUN` and `F.CONMUP`, to account for donor and acceptor concentrations separately.
- Added trap concentrations to concentration-dependent mobility models and band gap narrowing models.
- Added new C interpreter functions for energy-dependent relaxation times for electrons and holes.
- Added new C interpreter functions for energy-dependent Peltier coefficients for electrons and holes.

- Added a new C interpreter function to specify doping in 3D as a function of position.
- Added extra checking to the AC memory allocation. If there is insufficient memory for the factorization, more will be allocated. A warning message will also be printed.
- Enabled multiple contacts with the same name to have the same work function and other parameters.
- Modified the DOPING statement so that ATHENA master files can now be used in 2D. ATHENA doping is interpolated onto the ATLAS mesh.

## **D.1.5: Version 4.3.0.R**

### **1. Introduced Quantum Transport Model**

This model accounts for redistribution of carriers near abrupt material transitions due to the effects of quantum confinement. It is also useful when simulating heterojunction devices such as HBTs and HEMTs, as well as short channel thin gate oxide MOS devices.

### **2. Introduced Improvements to the Ferroelectric Model**

This release includes modifications which allow better modeling of unsaturated loop simulation of ferroelectric materials. It also includes the capability to characterize the AC ferroelectric permitibility affected by the polarization as a fraction of the DC case.

### **3. Log File Improvements have been Made for Capturing Data**

- PROBE has been enhanced to add the capability of probing minimums and maximums of the directional quantities; electric field, electron mobility, hole mobility and polarization.
- PROBE has been enhanced to allow the measurement of dielectric permitivity and the band-to-band tunneling rate.
- Added the capability to capture simulation time in the log file.

### **4. Structure File Improvements**

The default method of averaging for capture of impact ionization rate, the electron and hole mobilities to the structure file has been changed. The new averaging techniques provide smoother plots in **TonyPlot**.

### **5. Improved Parameterization of Band-to-Band Tunneling Models**

This release allows user accessibility to the gamma parameter of the standard band-to-band tunneling model.

## **D.1.6: Version 4.0.0.R**

### **1. Introduced a ferroelectric permitivity model**

This model accounts for ferroelectric polarization and hysteresis. This release includes a new model to model ferroelectric materials. It is useful for simulating ferroelectric devices such as ferroelectric capacitors and FETs.

### **2. Introduced Klaassen's mobility model**

This release includes a new model for low field electron and hole mobilities in silicon. This model accounts for lattice, impurity, and carrier scattering and screening as a function of temperature, doping and carrier concentrations. This model has been calibrated over a wide range of conditions and should be used as the default low field model for silicon simulations.

### **3. Introduced Concannon's gate and substrate current models**

This release includes a new model for EPROM simulation. This model estimates the gate current in EPROM devices as a function of carrier temperature by integrating a non-maxwellian distribution function. The model also uses a impact ionization model that uses the same distribution function to ensure a direct relationship between gate and substrate currents.

### **4. Introduced Shirahata's mobility model**

This release includes a new surface mobility model which accounts for carrier screening effects in the channel. This is done largely by using Klaassen's model for the low field mobility. The model also accounts for parallel and perpendicular fields in the channel.

### **5. Introduced a "Probe" capability**

A new statement has been implemented which allows users to write local scalar quantities (e.g. potential, electron concentration, hole concentration, etc.) and vectors (e.g. field etc.) to the log file as a function of bias, time etc. The user may specify the probe by location, minimum or maximum, and type.

### **6. Modifications to the Watt mobility model**

Several modifications were made to the Watt mobility model. First, the user may now apply the model to grid nodes below the interface down to a user specified depth. Also the user can use an exponential scaling on the effective field. Finally, the user can make the models only apply to minority carriers.

### **7. Improved vector averaging**

Certain quantities used in ATLAS are not defined on grid points but between points (e.g. electric fields). To write these quantities into the structure files they must be averaged. In this implementation an improved averaging scheme was introduced which produces smoother results. The user also has control over various weighting schemes for the averaging.

## 8. Traps in MIXEDMODE

New parameters were introduced to the TRAP, INTTRAP, DEFECT, and INTERFACE statements to enable proper handling of these physical models in MIXEDMODE.

## 9. Modified run time output

The ATLAS run time output was modified to be more concise and informative.

## 10. Misalignment and delta CD in INTERCONNECT3D

INTERCONNECT3D now allows users to specify misalignment and variations in critical dimensions with interconnects specified by mask sets from MASKVIEWS.

## 11. Lumped elements and current boundary conditions in DEVICE3D

DEVICE3D now supports lumped element and current boundary conditions.

## 12. GaAs in DEVICE3D

DEVICE3D now supports GaAs material models.

## 13. Electric field lines.

Electric field lines can now be plotted in TONYPLOT. The specification of where to elines lines are calculated was improved for both plotting and for evaluation of ionization integrals.

## 14. Energy dependent impact ionization coefficients.

Two new C interpreter functions were introduced to enable user specification of impact ionization coefficients as a function of carrier temperature for Selberherr's model.

## 15. Removed obsolete syntax

The FIT, COLOR, CONTOUR, LABEL, LOOP, L.END, PLOT.1D, PLOT.2D, and PLOT.3d statements are no longer supported by ATLAS. Equivalent functionalities are available through DECKBUILD and TONYPLOT.

## 16. DEVICE3D improvements for SEU simulation

Introduced a new C interpreter function, F3.RADIATE. This function allows users to specify arbitrary generation rate versus spatial position and time. The SINGLEEVENTUPSET statement was changed to allow users to control whether the generation rate is scaled by the ratio of the numerical and analytic integrals of the analytic generation function. This permits conservation of total generation rate in a device. By default the rescaling is now turned off.

## 17. MIXEDMODE Improvements

The .DC statement now allows linear and logarithmic stepping of sources and nested sweeps.

## D.1.7: Version 3.0.0.R

### 1. First release of “six equation solver” version of ATLAS.

In this release an advanced Non-Isothermal Energy Balance Model was implemented. The model allows self-consistent solution of a set of up to 6 partial differential equations for electrostatic potential, electron and hole concentrations, electron and hole carrier temperatures, and lattice temperature. All the important combinations of equations are supported.

### 2. DEVICE3D introduced.

DEVICE3D is introduced as the first truly 3D simulator in the ATLAS framework. It is a virtual analogy to S-PISCES. With it three dimensional steady-state silicon device simulation can be performed to calculate electrical behavior of bipolar and MOS transistors, as well as EPROM devices.

- Syntactically and behaviorally like ATLAS S-PISCES.
- Poisson, one carrier or two carrier analysis can be performed.
- Uses Gummel, Newton or combined Gummel/Newton algorithms.
- Supports semi-implicit scheme for transient simulation. Significantly faster than TR-BDF.



- Supports the essential set of physical models for silicon modeling including: SRH recombination,

Auger recombination and radiative recombination; concentration dependent mobility models (Conmob, Arora, Analytical); longitudinal and transverse electric field dependent mobility models (Caughey-Thomas, CVT, Yamaguchi); Band Gap Narrowing (BGN), Boltzman statistics, Fermi-Dirac statistics, and incomplete ionization; Fowler-Nordheim current calculation, Lucky electron model for hot carrier injection and transient programming and erasing of EPROM devices.

- The three dimensional simulated structure can be specified using DEVEDIT3D.
- Uses TONYPLOT3D for postprocessing.
- Single Event Upset simulation is feasible with DEVICE3D. The capability of single event upset/ photogeneration transient simulation has been introduced. It allows specification of multiple tracks and radial, length and time dependence specification of generated charge along tracks.

### **3. THERMAL3D introduced.**

THERMAL3D is introduced as a new capability for three dimensional simulation using ATLAS. The Poisson equation for temperature is solved in three dimensional regions of specified heat conductivity with defined temperatures on thermal contacts (which are ideal heat conductors). The user may specify the thermal properties of regions heat sources, and heat sinks.

- Four models of temperature dependent thermal conductivity.
- User may specify independent temperatures on all thermal sinks (thermal electrodes).
- User may specify multiple independent heat sources.
- Completely compatible with ATLAS.
- The simulated structure is specified using DEVEDIT3D (including thermal electrodes).
- Temperature distributions can be examined using TONYPLOT3D.

### **4. INTERCONNECT3D introduced**

INTERCONNECT3D has been introduced as another 3D capability in the ATLAS framework. This simulator is used to extract parasitics from arbitrary 3D interconnect structures.

- Can extract parasitic capacitance and conductance for arbitrary 3D interconnect structures.
- Provides an interface to MASKVIEWS for simple mask layer definition of interconnect structure.
- Completely compatible with ATLAS.

### **5. Curve tracer introduced**

Allows automatic tracing of complex IV behavior (including functions that are multivalued) without user intervention. Automatically varies an external resistance on a given contact to ensure optimal steps are chosen.

### **6. Enhancements for Energy Balance Model**

Aside from the introduction of the “Six Equation Solver”, several other improvements were made with respect to the Energy Balance Model (EBM).

- Fermi statistics can be used with the EBM.
- The “GaAs” like mobility model can be used with the EBM.
- The energy relaxation length can be specified for impact ionization in the EBM.
- Carrier temperature projection for initial guesses is supported.

### **7. New solution methods**

## 8. GIGA improvements

Aside from the introduction of the “Six Equation Solver”, several other enhancements were made to GIGA.

- GIGA now allows self consistent 5 and 6 equation solutions of lattice temperature with electron and hole temperatures.
- GIGA now supports static projection for initial guesses for lattice temperature.

## 9. LUMINOUS improvements

In this release many improvements were made to LUMINOUS.

- LUMINOUS now supports extraction of spatial response to optical sources.
- A MIN.POWER parameter of the BEAM statement can now be used to limit the number of rays traced in LUMINOUS.
- LUMINOUS now recognizes metals (electrodes) as bulk regions.
- Optical properties of bulk metal (electrodes) region can now be defined.
- The C Interpreter function RADIATE for user definable photogeneration was enhanced to include time dependence.

## 10. TFT improvements

Several enhancements were made in this release for TFT.

- Parameters were introduced to allow control of the number of mid-gap states used for TFT simulations.
- TFT now supports output of donor and acceptor trap state densities and energies to user specifiable files for examination by TONYPLOT.
- TFT now provides two new Interpreter functions for specifying the donor and acceptor densities as a function of energy.

## 11. Miscellaneous new features

A host of new features were introduced into ATLAS in general.

ATLAS now properly handles touching electrodes and electrodes with the same name.

Incorporated the trap assisted tunneling model given in Hurkx, G.A.M., Klassen, D.B.M. and Knuvers, M.P.G., “A New Recombination Model for Device Simulation Including Tunneling”, IEEE Transactions on Electron Devices, V. 39, No. 2. Feb., 1992, pp. 331-338. This model accounts for tunneling via trap transitions using an analytic approximation that modifies the lifetimes in the standard Shockley-Read-Hall recombination model.

Modified the models for hot electrons, and holes and Fowler Nordheim tunneling currents. The new models account for the flow of the electrons/holes in the insulating layers to arbitrary electrodes based on one of two primitive models. The first, is the default model and tries to force the currents to follow the maximum potential gradients to find the proper electrode. In the second model insulator, currents go to the nearest electrode. With these modifications the electrode current run time outputs are modified to better reflect the new models.

Enabled correct small signal simulation when simulating with bulk and interface traps.

Distinction made between active and chemical dopant densities.

Small signal analysis with interface traps now works properly.

Moved the C Interpreter function F.COMPOSIT from the MATERIAL statement to the DOPING statement. In previous releases this function did not work as advertised, since material composition needed to be defined at structure creation. In order to make the function work properly it had to be moved to the DOPING statement.

In addition to CLIMIT parameter which existed earlier, new parameters CLIM.DD and CLIM.EB were added in METHOD statement. CLIM.DD is exact analog of CLIMIT parameter, but in comparison with CLIMIT it specifies dimensional value of minimal concentration which can be resolved using

ATLAS. By default CLIM.DD is not specified and ATLAS uses default value of CLIMIT, as in previous versions. Parameter CLIM.EB can be treated as regularization parameter for the case of very small electron (hole) concentration for energy balance model. It specifies the minimal value of concentration for which relaxation term in energy balance equation will be still properly resolved, otherwise temperature for the points where concentration is much less than CLIM.EB, will tend to lattice temperature.

## 12. New syntax

With this release, the ATLAS syntax was augmented to simplify and somewhat rationalize some of the more confusing problems.

- The SYMBOLIC statement is no longer needed.
- The numerical method can now be specified on the MODEL statement. The user may choose from Gummel, Block and Newton methods. More than one method can be chosen; and ATLAS provides automatic switching between the methods.
- ATLAS now supports a new syntax for specifying which equations are simulated. The syntax is now supported on either the MODEL or METHOD statement and is the preferred syntax for future compatibility. The new syntax provides a more rational, intuitive way of choosing which equations are solved.
- ATLAS still supports syntax from previous versions.

## 13. Improved run-time output

Many improvements have been made to the run-time outputs of ATLAS.

- Added multiple levels of verbosity.
- Improved printing of mesh statistics, region and electrode summaries and models.
- Printing of error messages was made more consistent and informative in many places in ATLAS.
- Removed spurious printout from S parameter extraction with the UTMOST statement.

## 14. New platforms

ATLAS has now been ported to DEC Alpha and SGI workstations.

## 15. Miscellaneous bug fixes

In this release many bugs were removed that existed in the previous version.

- Fixed bug that caused setting the value of the MODEL statement parameter CCS.EA to also set the value of the MATERIAL statement parameter COPTR.
- Fixed bug causing improper association of nodes with regions on BLAZE structures read in from DEVEDIT. In some instances nodes j would be assigned a region at the interface then the composition fraction (e.g.) from the opposing region, thus causing distortions in the band diagram at the interface.
- Fixed bug in static projection. Bug caused by two consecutive bias steps of opposite polarity.
- Fixed bug in TFT. Caused the midgap Gaussian donor defects to have the same distribution as the midgap acceptor defects.
- Fixed bug in UTMOST interface. Bug caused ATLAS not to recognize routines 2, 3, 5, 12, 13, 14, and 26.
- The calculations for the electron and hole mobilities in the InGaAsP system were found to be in error both in the manual as well as the code. Referring to the ATLAS Users manual, Edition 2, in the Equations B-36 and B-37, the “y”s should be replaced by (1-y). This fix was introduced into the code for this release.
- Fixed a bug in the calculation of electric fields for output to structure files for examination in TONYPLOT. This bug caused the estimates of the X and Y components of the electric field to be calculated based on the dielectric constant of silicon for all semiconductors. Although, the

calculation properly handled insulators it used the dielectric constant of silicon for all semiconductors regardless of composition. This has been fixed in this version.

Fixed bug causing extra space in UTMOST format output log files.

## 16. New examples

In this release the standard examples were completely reworked and improved. The ATLAS examples are now divided into 21 application specific areas. There are now 117 ATLAS examples in all which illustrate virtually all the functionality of ATLAS.

## 17. Improved quality control

In this version, new quality control tools and procedures for automated testing were implemented and used that greatly simplify and expanded ATLAS testing. This version of ATLAS represents the most thoroughly tested version to date. Continued application of the improved quality control procedures will ensure that future versions will continue to be of the highest quality.

### D.1.8: Version 2.0.0.R

1. **Improved Standard Structure Output** – The standard structure output format has been improved to account for multiple values at region interfaces (e.g., contours projecting into regions where they did not apply).
2. **Reliable Metal Regions** – Fixed bug that caused metal regions on standard structure format structures that are read into ATLAS to be lost following modification in ATLAS by either addition of electrodes or regriding.
3. **MEASURE Statement** – Because of conflicts with the DECKBUILD extract compatibility syntax, the ATLAS EXTRACT statement has been changed to MEASURE.
4. **Error Messages** – Fixed bug that caused infinite loop of error messages during write of structures containing isolated triangles.
5. **Larger Allocation** – Fixed bug for “large” version (altas-E) for dynamic allocation to allow up to 6,000 nodes.
6. **Ramping** – Fixed bug for case where frequency is ramped in AC analysis during a static ramp. The frequency is now properly reset to its base value after each static solution.
7. **Maximum Time Step** – Added DT.MAX parameter to the METHOD statement to limit the maximum time step size during transient solutions.
8. **Electron Current Vectors** – Fixed bug that caused electron current vectors to point in the wrong direction in TONYPLOT.
9. **Ionization Printout** – Removed spurious printout during ionization integral calculation.
10. **Incomplete Ionization** – Fixed bug in incomplete ionization. Bug caused lack of convergence.
11. **Interpreter** – Fixed bug in F.DOPING Interpreter function for specifying doping.
12. **Material** – Fixed bug to allow Interpreter functions in material statement to be defined for a given material.
13. **Region Interface** – Fixed bug to resolve ambiguities in definition of region membership of nodes at interface between two regions.
14. **Holes** – Fixed bug that caused holes in regions or embedded regions to be improperly displayed in TonyPlot.
15. **Trap Recombination** – Fixed bug in recombination calculation for regionally specified traps.
16. **Transient Projection Algorithm** – Installed transient projection algorithm.
17. **Improved Interpreter Function for Complex Index of Refraction** – The C Interpreter

function for complex index of refraction was changed to account for material composition and temperature.

18. **New Built-in Index Data** – Added built-in complex index of refraction data for: AlAs, GaAs, InSb, InP, Polysilicon, and SiO<sub>2</sub>.
19. **Light Intensity Contours** – Added interface to TONYPLOT for optical intensity. To enable, set the OPT.INTENS parameter of the OUTPUT statement.
20. **New C Interpreter Function** – Added C Interpreter function for general generation rate as a function of position.
21. **Cylindrical Coordinates** – LUMINOUS now supports cylindrical coordinates. Specify CYL on the MESH statement.
22. **Energy Balance Modeling** – LUMINOUS is now supported in energy balance simulations.
23. **Loading and Saving Optical Sources** – LOAD and SAVE statements act to save and restore optical sources.

### BLAZE Version 2.0.0.R

24. **Improved DevEdit Composition:** Fixed bug that caused DEVEDIT composition fraction information to be lost when the DEVEDIT structure is loaded in MESH statement followed by any ELECTRODE statement.
25. **Composition Fraction Modification:** Fixed bug to allow composition fraction modification on loaded structures.
26. **Thermionic Emission:** Added capability to specify thermionic emission for heterojunctions in loaded structures.

### GIGA Version 2.0.0.R

27. **Quasi-Fermi Level:** Fixed bug that caused improper display of the hole quasi-fermi level in GIGA generated structure files.
28. **Outer Block Iteration:** Fixed bug in GIGA that caused premature exit from the outer block iteration when the maximum temperature update exceeded the starting temperature during the initial solution.
29. **Material Thermal Parameters:** The ability to specify the GIGA thermal parameters dependently for different materials/regions was added in this version.
30. **Improved Thermal Dependencies:** The temperature dependencies of many models were improved.

### LASER Version 2.0.0.R (Initial Release of LASER Under The ATLAS Framework)

31. This version supports simulation of various types of Fabry-Perot semiconductor diode lasers.

### BLAZE Version 2.0.0.R

32. Now supports running MIXEDMODE decks under DECKBUILD.
33. Implemented small-signal AC simulation in MIXEDMODE.
34. **Energy Balance for Heterojunctions:** Modifications to the ATLAS energy balance formulas were introduced to account for positionally dependent band structures.
35. **Improved Material Defaults:** Some material model parameter defaults were changed to reflect better models in literature. In particular, these improvements affect InGaAsP and related compounds, AlGaAs, and SiGe.
36. **Improved DevEdit Interface:** Donor and acceptor impurities were added to the DEVEDIT interface for doping specification in DEVEDIT.

### MIXEDMODE Version 2.0.0.R

- 37. User-definition of how often solutions are saved during transient simulation
- 38. The cylindrical coordinate system may now be used with MIXEDMODE.
- 39. Schottky contacts are now supported in MIXEDMODE.
- 40. Tabulated time-dependent voltage and current sources may be specified.
- 41. Previously calculated device solutions can be loaded into MIXEDMODE.
- 42. Circuits may include lossless transmission lines.
- 43. User-defined two-terminal elements may be specified.

#### **TFT Version 2.0.0.R**

- 44. User Specifiable Thermal Conductivities of Metals: GIGA now recognizes metals (electrodes) as different materials from semiconductors and insulators. Users can now specify metal thermal conductivity.
- 45. Regional DOS Specification: Added REGION parameter to the DEFECT statement to allow DOS to be defined differently in different regions.

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