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ON-WAFER PHOTODIODE MEASUREMENTS WITH A LIGHTWAVE COMPONENT ANALYZER SYSTEM

Presented at the International Optoelectronics Exhibition '91
Tokyo, Japan

by
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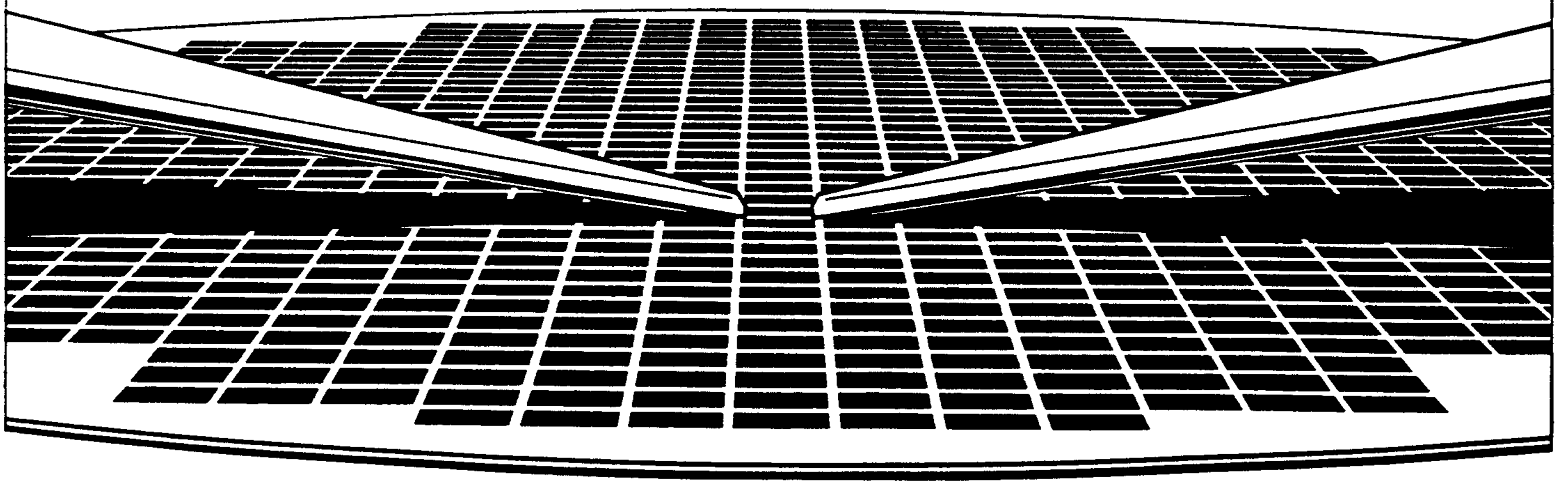

ON-WAFER PHOTODIODE MEASUREMENTS WITH A LIGHTWAVE COMPONENT ANALYZER SYSTEM

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While commercial microwave on-wafer measurements are available for frequencies as high as 75 GHz, optoelectronic on-wafer characterization has to this point remained a research opportunity. This paper introduces the first commercially available on-wafer optoelectronic (O/E) measurement system.

OUTLINE

First we will discuss the benefits of on-wafer testing at microwave frequencies. Since most of the issues which will be presented pertain to microwave issues, a general understanding of S-Parameters and microwave measurements is needed. Therefore, a brief review of these concepts will be presented. After a discussion of the tools necessary for on-wafer optical and microwave measurements, an example of photodiode measurements will be presented.

Why probe at microwave frequencies?

- **Eliminate need to dice and bond devices.**
- **More accurate data.**
- **On-wafer mapping of key parameters.**
- **A practical means to gather statistically significant quantity of data.**
- **Immediate measurements on just completed wafers.**
- **Further processing after microwave measurements.**

The benefits of on-wafer microwave testing are well demonstrated in the GaAs MMIC community. The key advantages are much lower measurement costs, greater accuracy, and faster test time.

Probing saves time and money by eliminating the need to bond and package devices before testing. Probing also screens out bad devices which would otherwise be packaged and permits performance binning.

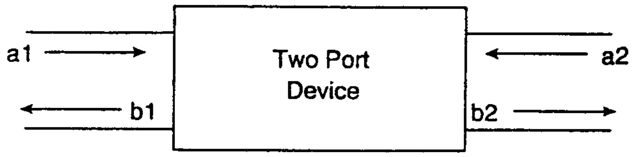
On-wafer measurements are much more accurate since there are no bond wire or package parasitics to obscure the intrinsic device data. The non-repeatability of bondwire parasitics also degrades measurement accuracy.

Probing with an automatic probe station allows wafer mapping of key performance parameters which can reveal material or process variations. Also, the autoprober permits easy measurement of a large number of devices. This, in combination with the high quality measurement can be used to collect statistically significant data which can be used to build highly accurate device models.

Immediate measurement can the shorten time for process optimization by quickly providing feedback of the results of process experiments. Also, process or material problems are revealed as soon as possible so that processing can be stopped before investing in the fabrication of more bad wafers.

In some cases, it is advantageous to perform further wafer processing after the active devices have been characterized, so that a passive circuit can be chosen to match to the active device.

S-Parameters

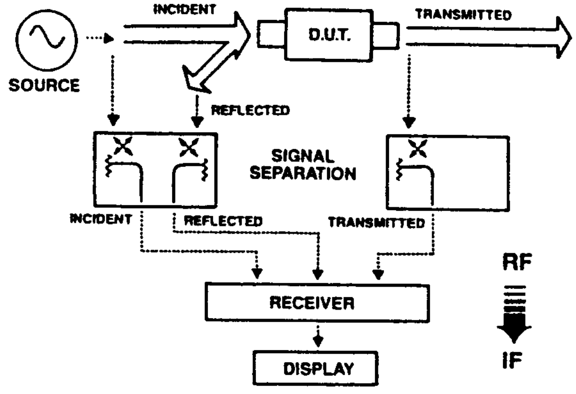


$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

S-parameters are defined as the ratios of incident, reflected, and transmitted waves (power and phase). S-parameters are used to characterize microwave devices because of the practical difficulties in measuring voltages and currents at these frequencies. Two reflection and two transmission S-parameters completely characterize any linear two port device. S-parameters can be converted to other parameter sets such as impedance.

THE MEASUREMENT SYSTEM



The test equipment configuration required to measure the reflection and transmission properties of a two-port test device generally consists of four components:

1. A signal source provides the energy to produce incident signal. By sweeping the source over the desired frequency range, the frequency response of the device can be measured.

2. A signal separation network, or a test set, to sample the incident, reflected, and transmitted signals. This is accomplished using directional couplers and bridges and power splitters.

3. A receiver to convert the microwave signals to a lower intermediate frequency (IF) where the signal levels and phase differences can be measured directly.

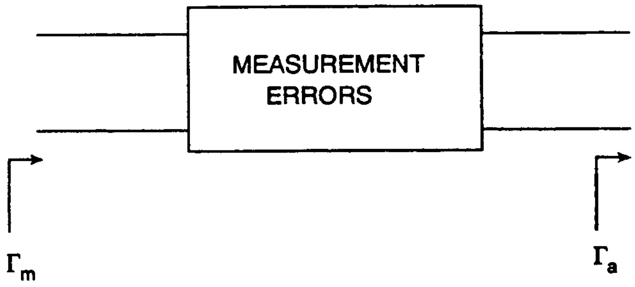
4. A display on which to present the measured results in the desired format, or units of measure.

CHARACTERISTICS OF PERFECT SYSTEM

- **Infinite Isolation.**
  Crosstalk
  Directivity
- **No Impedance Mismatches.**
- **Flat Frequency Response.**

Any practical microwave measurement system induces systematic errors because of imperfections in the connectors, non-ideal impedance in the system, loss, and physical length of the cable connecting the test equipment to the device-under-test. These will obscure the data with reflections and power loss.

SYSTEM ERRORS



$$\Gamma_m = S_{11} + \frac{S_{12}S_{21}\Gamma_a}{1 - S_{22}\Gamma_a}$$

The system errors can be characterized completely with S-parameters. Once the errors are characterized, the actual measurement can be accurately determined.

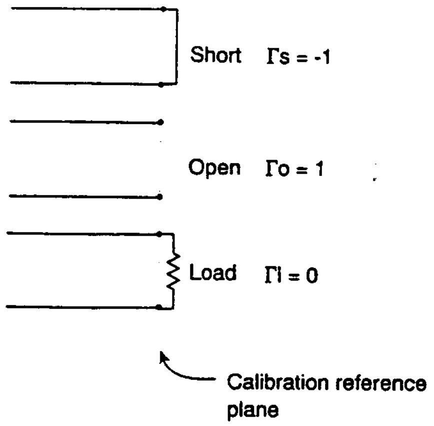
CHARACTERIZING THE ERRORS

- **ERRORS ARE VECTOR QUANTITIES**
  System Can Measure Them
  Vary with Frequency
- **MEASURE THREE DEVICES (STANDARDS)**
  Must Have Known Characteristics
  Called Measurement Calibration
  Yields Three Equations with Three Unknowns
- **ESTABLISHES MEASUREMENT REFERENCE PLANE**

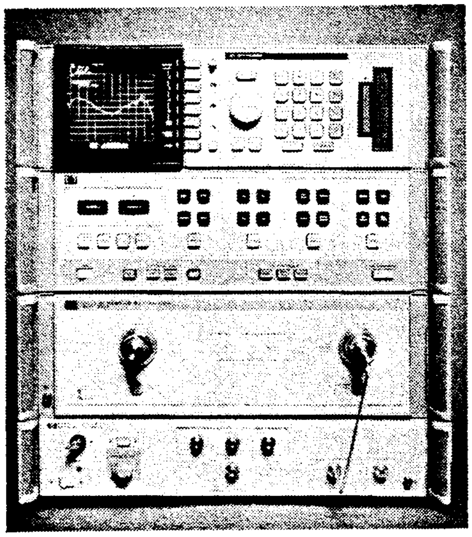
Measurement calibration is the process of characterizing the error terms. Because the errors are vector quantities that can be measured by the system, they can be used in accuracy enhancement equations to reduce or eliminated their effects. The value of each error changes with frequency and must be determined at each measurement frequency over the entire frequency range of interest.

The degree to which the uncertainty of a measurement can be improved is largely dependent on the quality of the standards used to calibrated the system. The value of each error is determined by measuring the response of at least three independent standards whose characteristics are known. The three equation, three unknown solution set is then solved to find the values for each error term at each measurement frequency. This calibration establishes a calibration reference plane at the measurement port by removing, or de-embedding, the systematic effects.

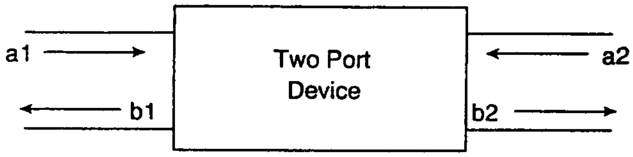
SOL Calibration



The most common one-port calibration procedure is the short-open-load (SOL) method. A short and an open at the end of a transmission line will cause all of the incident power to reflect back to the source, but the reflected phase will differ by 180 degrees. A load which matches the characteristic impedance of the transmission line will reflect no energy. Using these assumptions, the calibration equations are used to solve for error correction terms which establish the measurement reference plane. Any device placed here can now be accurately measured. Cascade Microtech and HP have worked on other calibration routines which provide greater measurement accuracy than the SOL calibration, but will not be discussed here. In addition to the SOL standards, a through is used for a full two-port calibration (SOLT). However most optoelectronic device measurements will require one electrical port calibration at most.



S-Parameters



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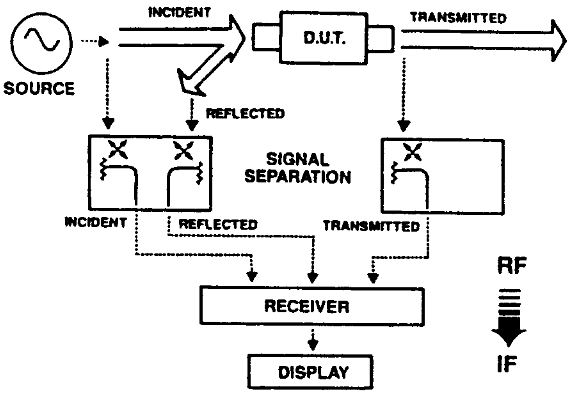

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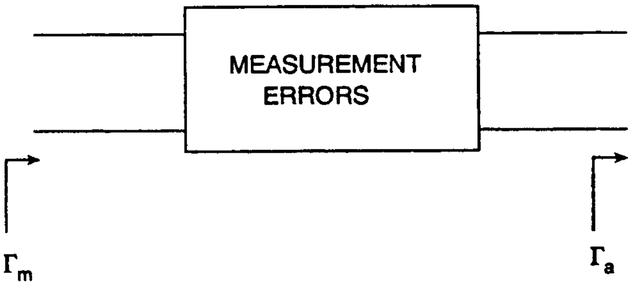
SYSTEM ERRORS



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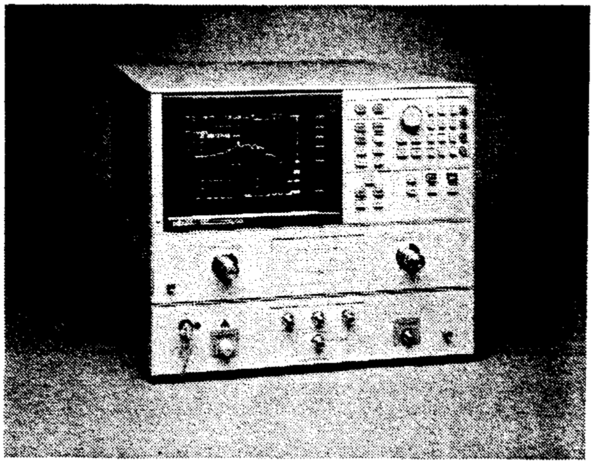
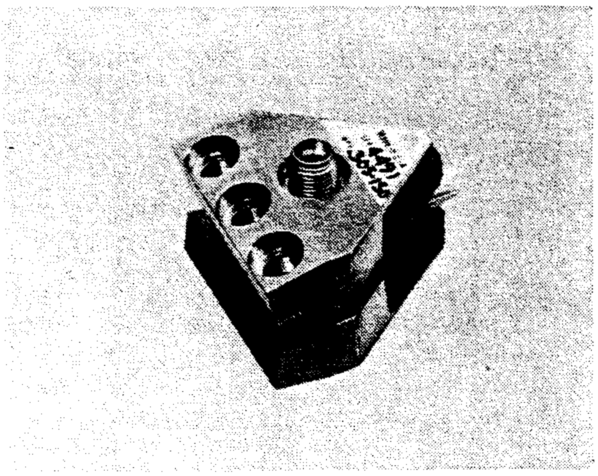
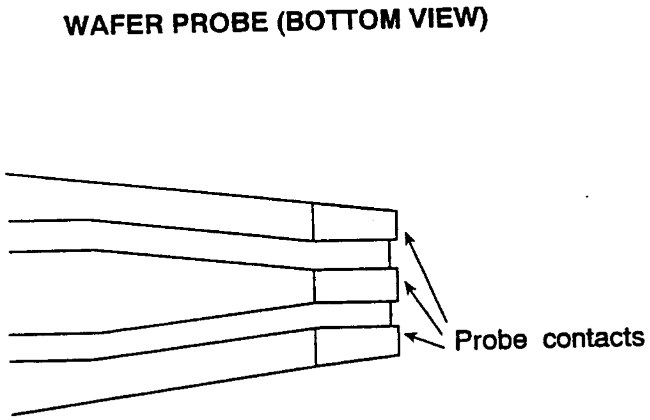
Automatic network analyzers (ANAs), such as the HP 8510, have calibration procedures built-in and display corrected measurements. Here, the system is shown with an HP 83420 which provides full lightwave measurement capability.



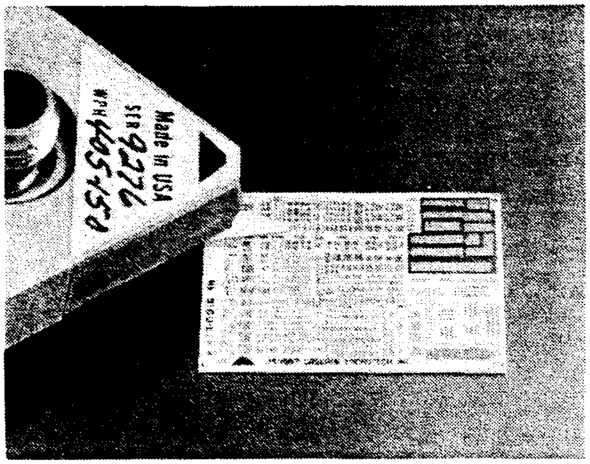
The HP 8703A is a fully integrated microwave and optical test system.



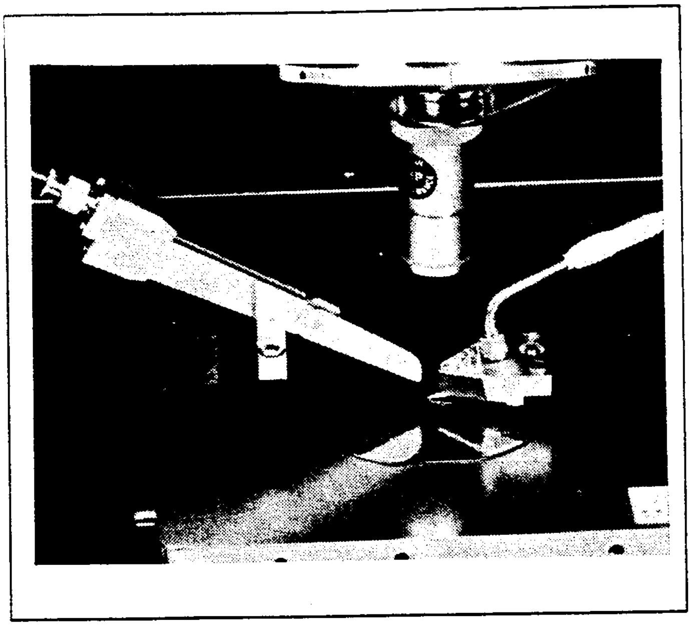
Conventional needle probes cannot be used at microwave frequencies because of their series inductance. A microwave wafer probe maintains a 50 ohm transition from the coaxial cable to the device-under-test. The Cascade Microtech WPH series probes consist of a 50 ohm coaxial connector which launches onto a thin film ceramic substrate containing a coplanar waveguide (CPW) transmission line.



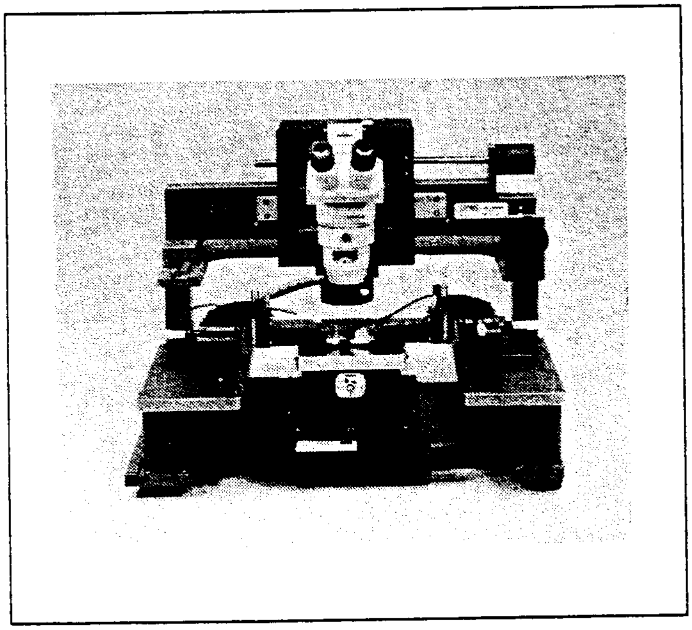
The CPW transmission line maintains a constant 50 ohm impedance as it tapers from the connector to the probe tip. The connection to the device-under-test is accomplished with plated nickel contacts. The contacts are typically arranged in a ground-signal-ground configuration, although other configurations are available. Due to the nature of a high-speed connection, each signal contact must have at least one associated ground contact.



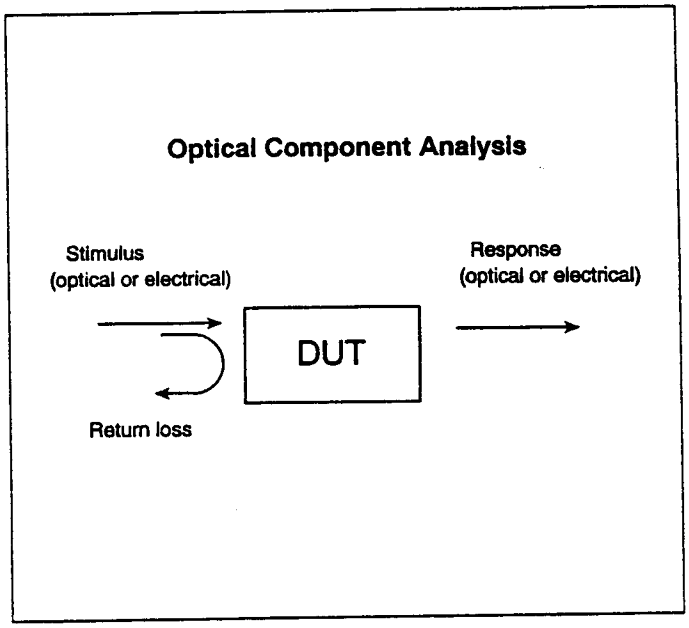
System calibration to the probe tip is accomplished using an impedance standard substrate (ISS).



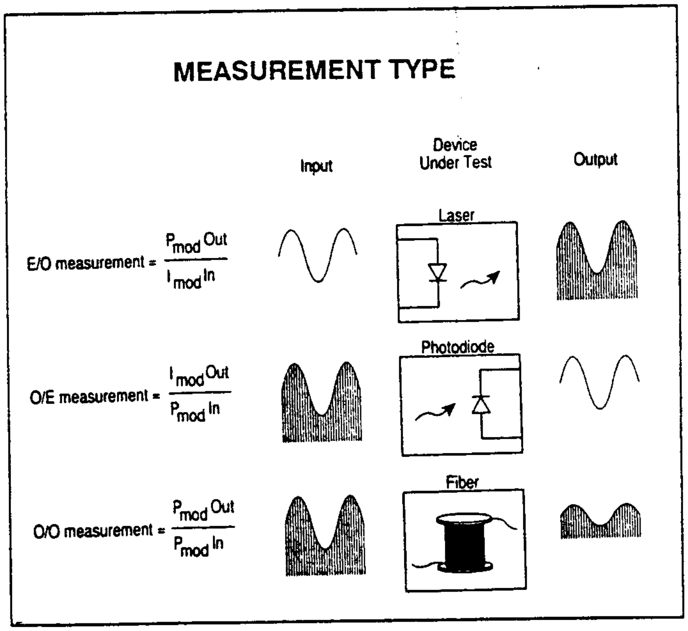
The Cascade LWP series lightwave probe provides non-contacting topside illumination capability for stimulus of O/E devices such as photodiodes or optical receivers. The LWP provides illumination as small as 5 micron diameter using lensed fiber; A cleaved end is also available for illumination of areas 25 micron in diameter and larger. The LWP can be used for optical collection, for testing devices such as lasers or LEDs, but the optical coupling efficiency is unpredictable.



The mechanical task of positioning a multiple contact probe is somewhat more complex than the typical needle probe. The probe station must establish and maintain planarity between the DUT and the microwave probe in the presence of the forces and moments applied by large coaxial cables. Probe placement must repeat from device to device; shifts as small as 5 microns produce noticeable shifts in microwave parameters. Probe vertical overtravel must also be controlled for maximum probe life. The Cascade Summit series probe stations achieve these requirements.



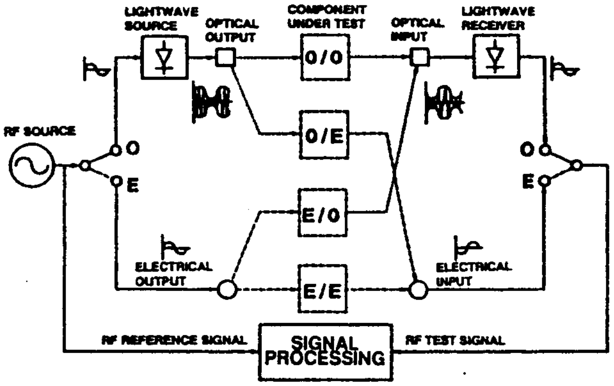
The concept of optical component analysis is to characterize optical devices in terms of its reflection and transmission properties. This is a direct analog to microwave device characterization, however, the stimulus and the response may be either modulated optical, or modulated electrical signals. The modulation frequency of the stimulus is usually swept over a specific bandwidth.



The type of device dictates whether the stimulus and response signals are optical, electrical, or a combination of both. For instance, the modulation bandwidth of a laser is an example of an E/O measurement and is defined as change in optical power output over change in electrical current. Photodiode characterization is an example of an O/E measurement, and is defined as change in electrical current to change in optical power. An example of an O/O measurement is the optical transmission of a passive optical waveguide. The result is expressed as the ratio of the power of the modulated optical input to the modulation power of the output.

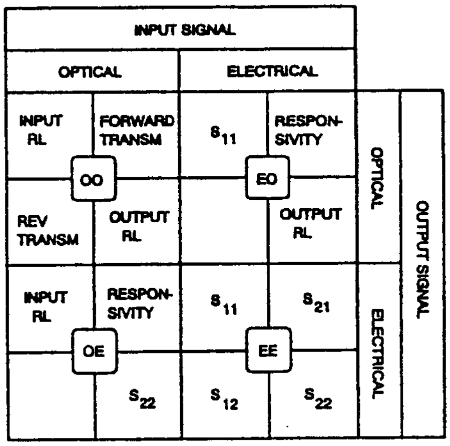
In all cases, the key for accurate measurements is a well characterized signal amplitude and phase delivered to the DUT (optical or electrical) and a calibrated signal receiver (optical or electrical). The HP Lightwave Component Analyzer provides the capability to make these types of measurements.

LIGHTWAVE COMPONENT ANALYZER CONCEPT



The Lightwave Component Analyzer measures the ratio of response to stimulus of the device under test (DUT). The stimulus may be a sinusoidal electrical signal or a sinusoidal intensity modulated lightwave. Built-in calibration allows the instrument to display the measurement result in proper nomenclature and scale.

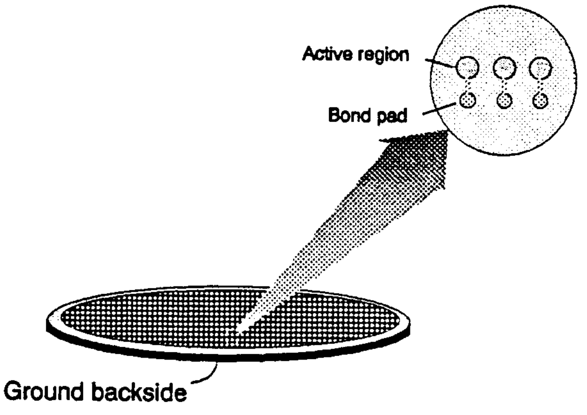
MEASUREMENT CAPABILITY



OUTPUT SIGNAL		INPUT SIGNAL			
		OPTICAL		ELECTRICAL	
OPTICAL		INPUT RL	FORWARD TRANSM	S_{11}	RESPONSIVITY
		OO		EO	
		REV TRANSM	OUTPUT RL		OUTPUT RL
ELECTRICAL		INPUT RL	RESPONSIVITY	S_{11}	S_{21}
		OE		EE	
			S_{22}	S_{12}	S_{22}

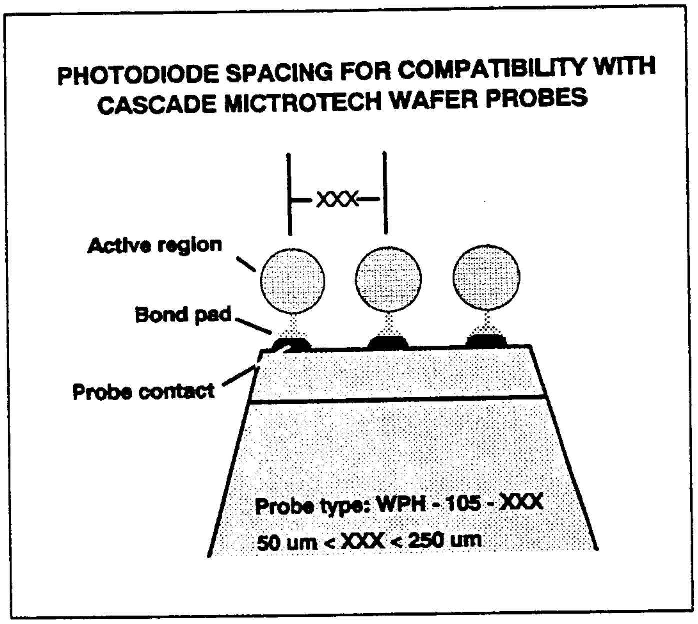
This matrix summarizes the fundamental measurement capabilities of the Lightwave Component Analyzer by type of input and output signal. All measurements are calibrated. For example, responsivity of a photodetector is presented as the ratio of electrical current change to optical input power change. All measurements make use of the modulation phase response of the DUT. This information allows the data to be presented in the time domain format for all of the measurement modes shown. Group delay is calculated automatically from the phase response.

BACKSIDE GROUND PHOTODIODES



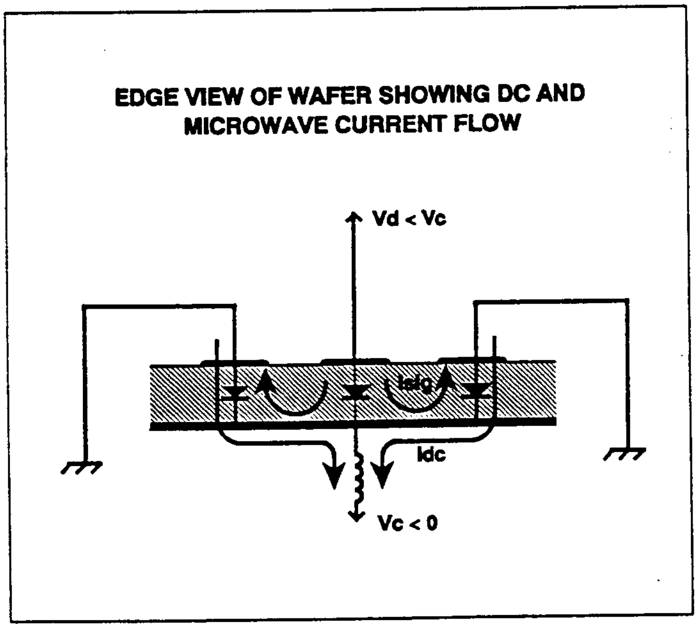
Ground and signal cotacts are not on the same side of the wafer

As an example of on-wafer lightwave component analysis, we will now describe a technique for testing the bandwidth of a photodiode with a ground backside. These type of photodiodes pose a difficulty for on-wafer testing because a standard coplanar waveguide microwave probe cannot make direct contact to the ground plane on the back of the wafer. In addition to these difficulties, the calibration reference plane of the Lightwave Component Analyzer must be extended from the electrical and optical cable ports to the device-under-test.



PHOTODIODE SPACING FOR COMPATIBILITY WITH CASCADE MICTROTECH WAFER PROBES

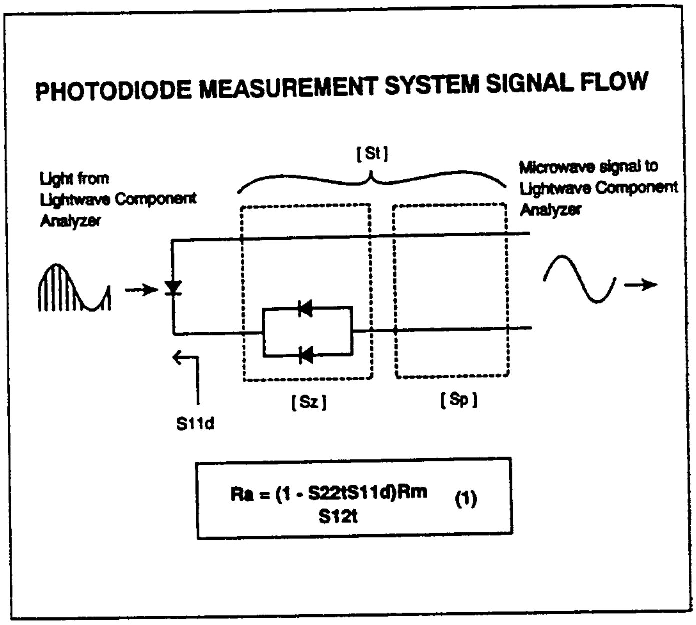
However, if the diodes are fabricated with the center to center spacing of the bond pads between 50 and 250 microns, standard Cascade Microtech high frequency wafer probes can be used to measure their response.



EDGE VIEW OF WAFER SHOWING DC AND MICROWAVE CURRENT FLOW

A Cascade Microtech WPH series probe with a pitch that is equal to the center-to-center spacing of the photodiodes is placed on three adjacent photodiode bond pads. The probe station chuck is biased to a voltage, Vc, which forward biases the outer two photodiodes. This provides a low inductive path from the ground back plane to the ground contacts of the probe.

The central photodiode is the device-under-test (DUT) and can be reverse biased through the bias port of the lightwave component analyzer. I_{DC} is the forward bias current of the outer photodiodes. I_{sig} is the microwave modulated signal of the DUT.



PHOTODIODE MEASUREMENT SYSTEM SIGNAL FLOW

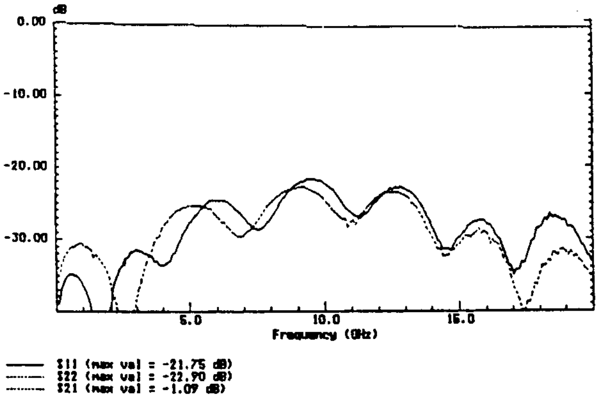
In order to make accurate measurements of the photodiode response at microwave frequencies, the effects of the probe and the ground path diodes must be characterized. The microwave signal flow diagram is shown here. [Sp] and [Sz] are the S-parameters of the wafer probe and the parallel combination of the ground path photodiodes. S11d is the microwave reflection coefficient of the DUT.

Equation (1) gives the magnitude and phase response of the photodiode. Rm is the measured response with the normal calibration of the lightwave component analyzer. Ra is the actual response of the DUT into a 50 ohm load. To solve this equation, we must first determine [Sp], [Sz], and S11d.

Calculating [Sp]

- **Full one-port calibration in coax**
- **Attach probe and measure S11 of three impedance standards**
- **Use standard de-embedding techniques to calculate [Sp]**

[Sp] is calculated using standard microwave de-embedding techniques. First, full one-port calibration is done in coax. Then the probe is attached and three known impedance standards are measured, such as the Cascade Microtech impedance standard substrate (ISS). [Sp] is then calculated using the calibration equations presented earlier. The two tiered calibration technique is necessary since [Sp] is required to correct the lightwave measurement. A single tiered method could be used if a probeable calibration standard were used.



This plot shows the magnitude of the S-parameters for a typical WPH series probe from DC to 20 GHz. Note that the probe has about 1 dB of loss at 20 GHz, and the return loss is typically down 20 dB.

Calculating [Sz]

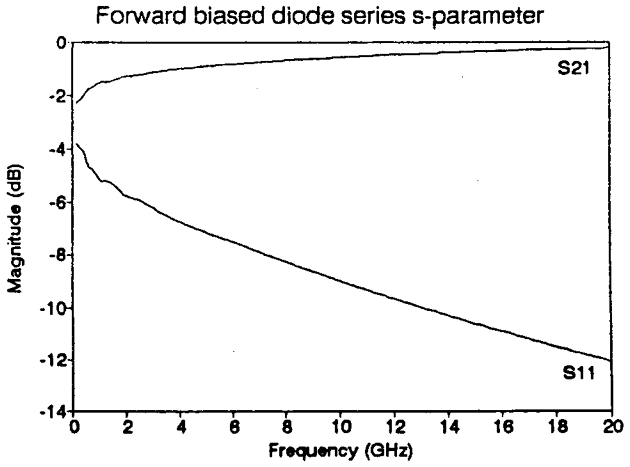
- **Full one-port calibration at probe tip**
- **Forward bias all three diodes**
- **Measure S_{11}**

$$Z = \frac{Zo\,(1 + S11)}{3\,(1 - S_{11})} \quad (2)$$

$$S_{11z} = S_{22z} = \frac{Z/Z_o}{Z/Z_o + 2} \quad (3)$$

$$S_{21z} = S_{12z} = \frac{Z}{Z/Z_o + 2} \quad (4)$$

[Sz] is calculated by measuring the impedance of the forward biased photodiodes. First, the lightwave component analyzer is calibrated at the microwave probe tip using a full one-port calibration. Next, all three photodiodes are forward biased through the probe by grounding the signal line, and S11 is measured. Assuming that the forward biased impedance of the three photodiodes are approximately equal (which is reasonable for adjacent devices of identical geometry), the impedance of each device is given by equation (2). Using this data, the series s-parameters of the parallel combination of the ground path are given by equations (3) and (4).



This plot shows the magnitude of the series S-parameters of a typical 80 um forward biased photodiode as calculated above. This shows the characteristics of a series resistance shunted by a capacitance.

CALCULATING [St]

The total S-parameter matrix for cascaded elements is determined using a T-parameter transformation

$$T_{11} = 1/S_{21} \qquad S_{11} = T_{21}/T_{11}$$

$$T_{12} = -S_{22}/S_{21} \qquad S_{21} = 1/T_{11}$$

$$T_{21} = S_{11}/S_{21} \qquad S_{12} = T_{22} - T_{21}T_{12}/T_{11}$$

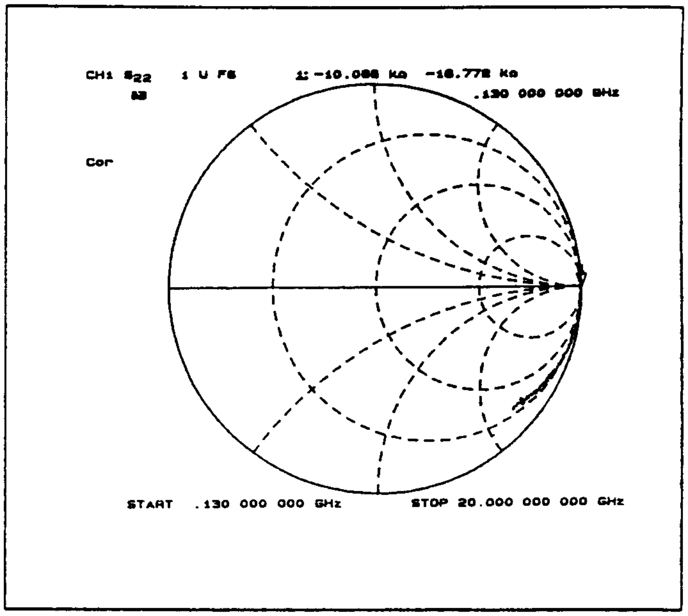
$$T_{22} = S_{12} - S_{11}S_{22}/S_{21} \qquad S_{22} = -\,T_{12}/T_{11}$$

[St] is the ensemble S-parameter matrix of the cascaded elements [Sp], and [Sz]. It is calculated using T-parameter transformation. First [Sp] and [Sz] are transformed into T-parameters and then multiplied using standard matrix multiplication. The inverse transformation is then done on the resultant matrix to give [St]. Alternatively, an ABCD transformation could be used.

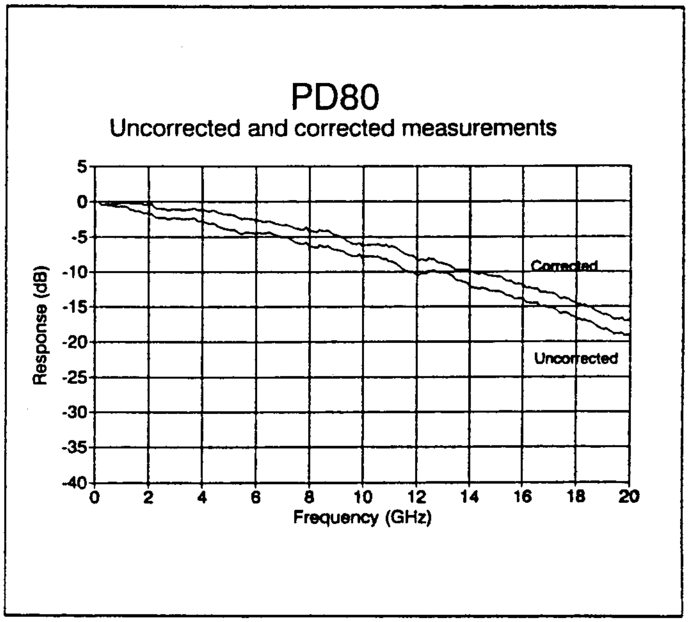
Calculating S11d

- **Reverse bias DUT**
- **Measure S11**
- $S11d = \dfrac{S_{11m} - S_{11z}}{S_{22z}(S_{11m} - S_{11z}) + S_{21z}S_{12z}}$

S11d is calculated by first reverse biasing the DUT and measuring S11. S11d is given by equation (5). Now, equation (1) can be solved for the true response of the photodiode.



This plot shows the Smith chart representation of S11d for a typical 80 um photodiode. Device model parameters, such as junction capacitance and series resistance can be inferred from this data.


PD80

Uncorrected and corrected measurements

This plot shows the data before and after the correction. Not that the series resistance in the ground path causes the response to roll off at a lower frequency.

OTHER MEASUREMENTS

- **Photodiodes or optical receivers with topside ground and signal contacts**
- **Capacitance**
- **Dark current**
- **Transit time effects**
- **Lasers and LEDs**

Photodiodes with ground and signal contacts on the topside of the wafer require less effort to test than photodiodes with backside ground. The measurement procedure is a subset of the procedure in the previous example.

Junction capacitance can be measured directly using a one-port microwave measurement using the HP Lightwave Component Analyzer.

Dark current can be measured with a sensitive current meter and an external bias-T on the test Port. A guarded chuck is available on the Summit Probe Station for sub nA current measurements.

Transit time effects in photodiodes can be studied by extracting the device model parameters (junction capacitance and series resistance) and comparing the theoretical RC limited response with the actual response.

Lasers and LEDs can be tested using the LWP Lightwave probe, however, the coupling losses are unpredictable. Therefore, although it may not be useful for measuring absolute power, it is useful for measuring modulation bandwidth and rise time.

CONCLUSIONS

On Wafer Testing

- **reduces test time and cost**
- **provides more accurate data**

Microwave on-wafer probing has proven to significantly reduce test time and test cost of GaAs and other high speed devices, as well as ensuring higher quality data. The same benefits are available for high speed optoelectronic device measurements. Cascade Microtech and Hewlett Packard can provide the tools and measurement expertise for optical microwave on-wafer testing.