100-340GHz Systems: Transistors and Applications

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Why 100-340GHz Wireless?

Wireless networks: exploding demand.

Immediate industry response: 5G.
28, 38, 57-71(WiGig), 71-86GHz
increased spectrum, extensive beamforming

Next generation (6G ??): above 100GHz.
greatly increased spectrum, massive spectral multiplexing

Plus, TV-like imaging/sensing/radar: cars, airplanes, drones
100-340GHz: Benefits & Challenges

Large available spectrum

Massive # parallel channels

Need phased arrays (overcome high attenuation)

Need mesh networks

\[
\frac{P_{\text{received}}}{P_{\text{transmit}}} \propto N_{\text{receive}} N_{\text{transmit}} \frac{\lambda^2}{R^2} e^{-\alpha R}
\]
**100-340GHz: Potential Applications**

**MIMO hub:** 128 beams/face, 1Gb/s/user

140 GHz

**Point-point MIMO:** 340GHz: Tb/s links
massive spatial multiplexing

**220, 340GHz imaging:** drive/fly in fog/rain/snow
300m, 512×64 image, 60Hz, 15dB SNR

**Ultra-compact imaging:** drones
unlike visible: image through fog/smoke/rain
140 GHz Spatially Multiplexed Base Station

Each face supports 128 beams @ 1Gb/s/beam.

225 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins (20dB total)

PAs: 16 dBm $P_{\text{out}}$ (per element)

LNAs: 3 dB noise figure
340 GHz 640 Gb/s MIMO Backhaul

1.6m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

500 meters range in 50 mm/hr rain; 29 dB/km

Realistic packaging loss, operating & design margins

PAs: 82mW $P_{\text{out}}$ (per element)

LNAs: 4 dB noise figure
Millimeter-Wave Wireless Transceiver Architecture

custom PAs, LNAs $\rightarrow$ power, efficiency, noise
Si CMOS beamformer $\rightarrow$ integration scale

...similar to today's cell phones.
## 100-1000 GHz Transistors and ICs

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{max}}$ GHz</th>
<th>Good ICs to (GHz)</th>
<th>complexity</th>
<th>LNAs</th>
<th>PAS</th>
<th>increased bandwidth ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>350</td>
<td>150/200</td>
<td>transceivers</td>
<td>ok</td>
<td>poor: 1-5 mW</td>
<td>not easy</td>
</tr>
<tr>
<td>Production SiGe</td>
<td>300</td>
<td>200/250</td>
<td>transceivers</td>
<td>good</td>
<td>OK: 20-100 mW</td>
<td>depends on $$</td>
</tr>
<tr>
<td>R&amp;D SiGe</td>
<td>700</td>
<td>300/500</td>
<td>transceivers</td>
<td>good</td>
<td>OK: 20-100 mW</td>
<td>2-3THz</td>
</tr>
<tr>
<td>R&amp;D InP HBT</td>
<td>1150</td>
<td>400/650</td>
<td>PA, converters</td>
<td>poor</td>
<td>good: 100-200 mW</td>
<td>2-3THz</td>
</tr>
<tr>
<td>R&amp;D InP HEMT</td>
<td>1500</td>
<td>500/1000</td>
<td>LNA</td>
<td>great</td>
<td>weak: 20-50 mW</td>
<td>2-3THz</td>
</tr>
<tr>
<td>R&amp;D GaN</td>
<td>400</td>
<td>120/140</td>
<td>PAs</td>
<td>good</td>
<td>excellent: 0.1-1W</td>
<td>600GHz</td>
</tr>
</tbody>
</table>

ICs with useful performance, hero experiments

There are **THz transistors today**; their bandwidth will **increase**

**Challenge:** reducing costs, increasing market size
Gallium Nitride Power Technologies

**GaN is the leading high-frequency power technology**

![Graph showing power output vs. frequency for GaN, GaAs, and InP. GaN is dominant at high frequencies.]

- **N-polar GaN**: Mishra, UCSB

![Diagram illustrating GaN device structure with key features like GaN Cap, AlGaN Cap, and layers for improved performance.]

- **94 GHz power**
  - N-polar
  - Quaternary Ga-Polar
  - Ga-Polar

**Pout (W/mm) vs. Year**

- Traditional
- Ga-Polar
- Quaternary Ga-Polar
- N-polar

**GaN is the leading high-frequency power technology**
130nm / 1.1THz InP HBT Technology

1.1THz $f_{\text{max}}$ HBT, 3.5 V breakdown

Teledyne/UCSB: M. Urteaga et al: 2011 DRC

![Graph showing $f_{\text{max}}$ and breakdown voltage for HBTs](image)

220 GHz, 0.18W power amplifier

UCSB/Teledyne: T. Reed et al: 2013 CSICS

![Integrated ~600GHz transmitter](image)

325 GHz, 16mW power amplifier

UCSB/Teledyne: A. Ahmed, 2018 EuMIC Symp.

![Integrated ~600GHz transmitter](image)
InP HBTs: 1.07 THz @200nm, ?? @ 130nm

Rode et al., IEEE TED, Aug. 2015
THz Transistor Measurements

Simple pads:
- Substrate coupling: need small pads, narrow CPW
- Ambiguity in pad stripping order.
- UCSB 130nm HBTs: order not important.
- Add through & load to remove ambiguity

On-wafer through-reflect-line:
- No ambiguity from pad stripping.
- Calibration to line Zo
- Still must avoid substrate resonances
  CPW does not work.
- needs thin-film microstrip
  or ~25 µm substrate with TSV's

![](image)
Bipolar Transistor Scaling Laws

Narrow junctions.

Thin layers

High current density

Ultra low resistivity contacts

to double the bandwidth:

<table>
<thead>
<tr>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter &amp; collector junction widths</td>
</tr>
<tr>
<td>current density (mA/μm²)</td>
</tr>
<tr>
<td>current density (mA/μm)</td>
</tr>
<tr>
<td>collector depletion thickness</td>
</tr>
<tr>
<td>base thickness</td>
</tr>
<tr>
<td>emitter &amp; base contact resistivities</td>
</tr>
</tbody>
</table>
Challenges at the 64nm/2THz & 32nm/3THz Nodes

Need high base contact doping >$10^{20}$/cm$^3$ for good contacts high Auger recombination very low $\beta$.

Need moderate contact penetration
Pd or Pt contacts react with 3++ nm of base penetrate surface contaminants too deep for thin base

Solution: base regrowth:
thin, moderately-doped intrinsic base thick, heavily-doped extrinsic base
Regrown-Base InP HBTs: Images

- **Before regrowth**
  - TiW (in SiN)
  - Mo
  - Emitter (under Mo)
  - Intrinsic base surface

- **After 100nm p-GaAs regrowth**
  - p-GaAs extrinsic surface
  - Different faceting angles

- **Cross-section**
  - Dry-etched TiW emitter contact
  - 100nm emitter after base regrowth
Regrown-Base InP HBTs: DC Data

Good \( \beta \), low \( R_{ex} \), high-current operation
Regrown-Base InP HBTs: Base Resistance

0.9Ω–µm² resistivity for GaAs/metal contact ✓
294Ω sheet resistivity for regrown base ✓

1.0Ω–µm² resistivity for InGaAs/GaAs contact ✓
4300Ω/ sheet resistivity for intrinsic base ✗

Base contact resistivity sufficient for 64nm/2THz node.
Improvements: anneal after regrowth, grade interface

Regrowth: base contacts suitable for 64nm/2THz & 32nm/3THz nodes
FETs (HEMTs): key for low noise

2:1 to 4:1 increase in $f_\tau$: improved noise
less required transmit power
smaller PAs, less DC power
or higher-frequency systems

First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process

Xiaobing Mei, et al, IEEE EDL, April 2015 (Northrop-Grumman)
Towards faster HEMTs: MOS-HEMTs

Scaling limit: gate insulator thickness
HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO$_2$ ($\varepsilon_r=25$): adequately low leakage

Scaling limit: source access resistance
HEMT: InAlAs barrier is under N+ source/drain
solution: regrowth, place N+ layer on InAs channel

Target ~10nm node
~0.3nm EOT, 3nm thick channel
1.2 to 1.5 THz $f_T$. 
Towards Faster HEMTs: MOS-HEMTs

Double regrowth
modulation-doped access regions
N+ contacts

High-K gate dielectric: 3 nm ZrO2.

Highly scaled
5nm InAs channel, 10-30nm gate lengths

channel HSQ mask regrowth: modulation-doped layer 2nd HSQ mask
epitaxy

regrowth: N+ S/D dielectric ALD liftoff gate liftoff S/D

Jun Wu, UCSB, IEEE EDL, 2018
100-340GHz Wireless Systems:

100-340 GHz wireless systems
massive capacities via spatial multiplexing
compact, high-resolution imaging systems
short range: few 100 meters

Many challenges
spatial multiplexing: computational complexity, dynamic range
packaging: fitting signal channels in very small areas

IC Technology
All-silicon for short ranges below 250 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

Device opportunity: better PAs, LNAs for 140, 220, 340GHz.
In case of questions
Towards faster HEMTs: next step

No N- material between channel and contacts
reduced source/drain access resistance

Sacrificial layer
reduces parasitic gate-channel overlap
less gate-source capacitance

2.5nm ZrO$_2$ dielectric, 3nm InAs channel
higher $g_m$, lower $g_{ds}$
## FET Scaling Laws (these now broken)

<table>
<thead>
<tr>
<th>FET parameter</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td>gate length</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>current density (mA/mm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>specific transconductance (mS/mm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>transport mass</td>
<td>constant</td>
</tr>
<tr>
<td>2DEG electron density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>gate-channel capacitance density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>dielectric equivalent thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel state density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>contact resistivities</td>
<td>decrease 4:1</td>
</tr>
</tbody>
</table>

**Gate dielectric can't be much further scaled.**

\[
g_m / W_g \text{ hard to increase} \implies C_{\text{end}} / g_m \text{ prevents } f_r \text{ scaling.}
\]

**Shorter } L_g \implies \text{ poor electrostatics} \implies \text{ reduced } g_m / G_{ds}\]
Towards faster HEMTs: MOS-HEMTs

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1st demonstration: Fraunhofer IAF