Sub-mm-Wave Technologies: Systems, ICs, THz Transistors

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50-500 GHz Electronics: What Is It For?

820 GHz transistor ICs today

2 THz clearly feasible

*ITU band designations
**IR bands as per ISO 20473

Applications

100+ Gb/s wireless networks

Video-resolution radar → fly & drive through fog & rain

near-Terabit optical fiber links

- 820 GHz transistor ICs today
- 2 THz clearly feasible

Applications

100+ Gb/s wireless networks

Video-resolution radar → fly & drive through fog & rain

near-Terabit optical fiber links
50-500 GHz Wireless Has High Capacity

very large bandwidths available

short wavelengths $\rightarrow$ many parallel channels

angular resolution $\approx \frac{\text{wavelength}}{\text{array width}}$

$N = \frac{B^2}{\lambda R} + 1$

$B = ND$

#channels $\propto (\text{aperture area})^2 / (\text{wavelength} \cdot \text{distance})^2$
50-500 GHz Wireless Needs Phased Arrays

**isotropic antenna** → weak signal → short range

\[
\left( \frac{P_{\text{received}}}{P_{\text{transmitted}}} \right) \propto \left( \frac{\lambda^2}{R^2} \right) e^{-\alpha R}
\]

**highly directional antenna** → strong signal, but must be aimed

\[
\left( \frac{P_{\text{received}}}{P_{\text{transmitted}}} \right) \propto D_t D_r \left( \frac{\lambda^2}{R^2} \right) e^{-\alpha R}
\]
	no good for mobile

must be precisely aimed → too expensive for telecom operators

**beam steering arrays** → strong signal, steerable

\[
\frac{P_{\text{received}}}{P_{\text{transmit}}} \propto N_{\text{receive}} N_{\text{transmit}} \left( \frac{\lambda^2}{R^2} \right) e^{-\alpha R}
\]

32-element array → 30 (45?) dB increased SNR
Object having area $\sim \lambda R$ will block beam.

...high-frequency signals are easily blocked.

Blockage is avoided using beamsteering and mesh networks.

...this is easier at high frequencies.
50-500 GHz Wireless Has **High** Attenuation

**High Rain Attenuation**

- Five-9's rain @ 50-1000 GHz:
  - $\rightarrow 30 \text{ dB/km}$

**High Fog Attenuation**

- $\sim(25 \text{ dB/km}) \times (\text{frequency}/500 \text{ GHz})$

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50-500 GHz links must tolerate $\sim30 \text{ dB/km}$ attenuation

mm-Waves for Terabit Mobile Communications

Goal: 1Gb/s per mobile user

spatially-multiplexed mm-wave base stations
mm-Waves for Terabit Mobile Communications

Goal: 1Gb/s per mobile user

spatially-multiplexed mm-wave base stations

mm-wave backhaul

or optical backhaul
mm-Waves for Terabit Mobile Communications

Goal: 1Gb/s per mobile user

spatially-multiplexed mm-wave base stations
mm-Waves for Terabit Mobile Communications

Goal: \textit{1Gb/s per mobile user}

- spatially-multiplexed mm-wave base stations
- mm-wave backhaul
- or optical backhaul
140 GHz, 10 Gb/s Adaptive Picocell Backhaul

array: 2x32

individual antennas 1.4x12 mm

90° (h) by 10° (v) scan

4 units
140 GHz, 10 Gb/s Adaptive Picocell Backhaul

350 meters range in five-9's rain

Realistic packaging loss, operating & design margins

PAs: 24 dBm $P_{sat}$ (per element) $\rightarrow$ GaN or InP

LNAs: 4 dB noise figure $\rightarrow$ InP HEMT
60 GHz, 1 Tb/s Spatially-Multiplexed Base Station

2x64 array on each of four faces.
Each face supports 128 users, 128 beams: 512 total users.
Each beam: 2Gb/s.

200 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins

PAs: 20 dBm $P_{\text{out}}$, 26 dBm $P_{\text{sat}}$ (per element)

LNAs: 3 dB noise figure
400 GHz frequency-scanned imaging radar

What your eyes see-- in fog

What you see with X-band radar

What you would like to see
400 GHz frequency-scanned imaging car radar

Eight 1x8 modules

individual antennas: 0.4mm x 5.0mm

1x64 endfire array

30cm x 30cm diffraction grating

cylindrical lens: 30cm x 30cm aperture

frequency-scanned beam
400 GHz frequency-scanned imaging car radar

Range: see a basketball at 300 meters (10 seconds warning) in heavy fog (10 dB SNR, 25 dB/km, 30cm diameter target, 10% reflectivity, 100 km/Hr)

Image refresh rate: 60 Hz

Resolution 64×512 pixels

Angular resolution: 0.14 degrees

Angular field of view: 9 by 73 degrees

Aperture: 35 cm by 35 cm

Component requirements:
50 mW peak power/element,
3% pulse duty factor
6.5 dB noise figure,
5 dB package losses
5 dB manufacturing/aging margin
50-500 GHz Wireless Transceiver Architecture

III-V LNAs, III-V PAs → power, efficiency, noise
Si CMOS beamformer → integration scale

...similar to today's cell phones.

High antenna array gain → large array area
→ far to large for monolithic integration
III-V PAs and LNAs in today's wireless systems...

http://www.chipworks.com/blog/recentteardowns/2012/10/02/apple-iphone-5-the-rf/
Transistors for 50-500 GHz systems
THz InP Heterojunction Bipolar Transistors

- HBT parameter | change
- emitter & collector junction widths | decrease 4:1
- current density (mA/μm²) | increase 4:1
- current density (mA/μm) | constant
- collector depletion thickness | decrease 2:1
- base thickness | decrease 1.4:1
- emitter & base contact resistivities | decrease 4:1

Challenges:
Narrow junctions
low-resistivity contacts.
high current densities
Sub-200-nm Emitter Contact & Post

Refractory contact, refractory post → high-current operation

Fabrication: blanket sputter, dry-etch
Ultra Low-Resistivity Refractory Contacts

Contact Resistivity ($\Omega \cdot \text{cm}^2$) vs. concentration (cm$^{-3}$)

- **N-InAs**
  - Mo

- **N-InGaAs**
  - Mo

- **P-InGaAs**
  - Ir
  - W
  - Mo

32 nm/3THz node requirements

*Refractory: robust under high-current operation*

*Low penetration depth, ~1 nm*

*Contact performance sufficient for 32 nm /2.8 THz node.*
Needed: Greatly Improved Ohmic Contacts

Pt/Ti/Pd/Au

~5 nm Pt contact penetration
(into 25 nm base)
Refractory Base Process (1)

Blanket liftoff; refractory base metal

Patterned liftoff; Thick Ti/Au

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*base surface not exposed to photoresist chemistry: no contamination*

*low contact resistivity, shallow contacts*

*low penetration depth allows thin base, pulsed-doped base contacts*
Increased surface doping: reduced contact resistivity, but increased Auger recombination.

→ Surface doping spike at most 2-5 thick.

Refractory contacts do not penetrate; compatible with pulse doping.
Refractory Base Ohmic Contacts

Ru / Ti / Au

<2 nm
Ru contact penetration

(surface removal during cleaning)
3-4 THz Bipolar Transistors are Feasible.

4 THz HBTs realized by:
Extremely low resistivity contacts
Extreme current densities
Processes scaled to 16 nm junctions

Impact:
efficient power amplifiers
and complex signal processing
from 100-1000 GHz.

<table>
<thead>
<tr>
<th>Scaling Node</th>
<th>64</th>
<th>32</th>
<th>16</th>
<th>nm</th>
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<tbody>
<tr>
<td>Emitter Width</td>
<td>64</td>
<td>32</td>
<td>16</td>
<td>nm</td>
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<tr>
<td>Resistivity</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>Ω-μm²</td>
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<tr>
<td>Base Thickness</td>
<td>18</td>
<td>15</td>
<td>13</td>
<td>nm</td>
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<tr>
<td>Contact width</td>
<td>60</td>
<td>30</td>
<td>15</td>
<td>nm</td>
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<tr>
<td>Contact ρ</td>
<td>2.5</td>
<td>1.25</td>
<td>0.63</td>
<td>Ω-μm²</td>
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<tr>
<td>Collector Width</td>
<td>180</td>
<td>90</td>
<td>45</td>
<td>nm</td>
</tr>
<tr>
<td>Thickness</td>
<td>53</td>
<td>37.5</td>
<td>26</td>
<td>nm</td>
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<tr>
<td>Current Density</td>
<td>36</td>
<td>72</td>
<td>140</td>
<td>mA/μm²</td>
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<tr>
<td>$f_r$</td>
<td>1.0</td>
<td>1.4</td>
<td>2.0</td>
<td>THz</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>2.0</td>
<td>2.8</td>
<td>4.0</td>
<td>THz</td>
</tr>
</tbody>
</table>
2-3 THz Field-Effect Transistors are Feasible.

3 THz FETs realized by:
- Regrown low-resistivity source/drain
- Very thin channels, high-K dielectrics
- Gates scaled to 9 nm junctions

Impact:
Sensitive, low-noise receivers from 100-1000 GHz.

3 dB less noise → need 3 dB less transmit power.
InP HBT Integrated Circuits: 600 GHz & Beyond

614 GHz fundamental VCO
M. Seo, TSC / UCSB

585-600 GHz amplifier, > 34 dB gain, 2.8 dBm output
M. Seo, TSC
IMS 2013

204 GHz static frequency divider (ECL master-slave latch)
Z. Griffith, TSC
CSIC 2010

340 GHz dynamic frequency divider
M. Seo, UCSB/TSC
IMS 2010

300 GHz fundamental PLL
M. Seo, TSC
IMS 2011

220 GHz 180 mW power amplifier
T. Reed, UCSB
Z. Griffith, Teledyne
CSICS 2013

Integrated 300/350GHz Receivers:
LNA/Mixer/VCO
M. Seo, TSC

600 GHz Integrated Transmitter
PLL + Mixer
M. Seo, TSC
220 GHz 180mW Power Amplifier (330 mW design)

2.3 mm x 2.5 mm

T. Reed, UCSB
Z. Griffith, Teledyne
Teledyne 250 nm InP HBT
PAs using **Sub-λ/4** Baluns for Series-Combining

80-90 GHz Power Amplifier

17.5dB Gain, >200mW $P_{SAT}$, >30% PAE

Power per unit IC die area*

- $=307$ mW/mm² (pad area included)
- $=497$ mW/mm² (if pad area not included)
800 mW 1.3mm² Design Using 4:1 Baluns

Baluns for 4:1 series-connected power-combining

\[ V_3 \text{ and } V_4 \text{ must be delayed by time delay } \tau \text{ relative to } V_1 \text{ and } V_2. \]

4:1 Two-Stage Schematic

Small-signal data looks good. Need driver amp for \( P_{\text{sat}} \) testing.
50-500 GHz Wireless Electronics

Mobile communication @ 2Gb/s per user, 1 Tb/s per base station

Requires: large arrays, complex signal processing, high $P_{out}$, low $F_{min}$

VLSI beamformers
VLSI equalizers
III-V LNAs & PAs

III-V Transistors will perform well enough for 1.5-2 THz systems.
(backup slides follow)
50-500 GHz Wireless Has Low Attenuation?

Low attenuation on a sunny day

Wiltse, 1997
IEEE Int. APS Symposium, July
mm/sub-mm-waves: Not my usual presentation

My typical THz electronics presentation:
THz transistor design & fabrication, mm/sub-mm-wave IC design

Today a different emphasis:

50+ GHz systems: potential high-volume applications

Link analysis → what performance do we need?

What will the hardware look like?

What components, packages, devices should we develop?

(wrap up with a quick summary of THz transistor & IC results)
Low transmitter PAE & high receiver noise are partially offset using arrays,

but DC power, system complexity still suffer

→ Proper array size minimizes DC power

Large arrays:
more directivity, more complex ICs
Small arrays:
less directivity, less complex ICs

200 mW phase shifters in TRX & RCVR, 0.1 W LNAs