THz Bipolar Transistors: Design and Process Technologies

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Why

THz Transistors ?
Why Build THz Transistors?

- 500 GHz digital logic → fiber optics
- THz amplifiers → THz radios → imaging, sensing, communications
- Precision analog design at microwave frequencies → high-performance receivers
- Higher-Resolution Microwave ADCs, DACs, DDSs
Why Bipolars for Fast Analog Applications?

digital frequency synthesis

mm-wave phased arrays

jammer on chip

high resolution ADCs and DACs for 2-20, 38 GHz

CMOS does not serve all ICs

low analog gain

low analog precision

low breakdown voltage

high $C_{ds}/C_{gs}$, high $C_{gd}/C_{gs}$ → less bandwidth than $f_{\tau}$ suggests

BJTs, particularly InP, have high breakdown

BJTs, particularly InP, have high breakdown voltage
How to Make THz Transistors
Changes required to double transistor bandwidth

<table>
<thead>
<tr>
<th>HBT parameter</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter &amp; collector junction widths</td>
<td>decrease 4:1</td>
</tr>
<tr>
<td>current density (mA/μm²)</td>
<td>increase 4:1</td>
</tr>
<tr>
<td>current density (mA/μm)</td>
<td>constant</td>
</tr>
<tr>
<td>collector depletion thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>base thickness</td>
<td>decrease 1.4:1</td>
</tr>
<tr>
<td>emitter &amp; base contact resistivities</td>
<td>decrease 4:1</td>
</tr>
</tbody>
</table>

**nearly constant junction temperature → linewidths vary as (1 / bandwidth)^2**

<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/μm), g_m (mS/μm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>channel 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 density of states</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>source &amp; drain contact resistivities</td>
<td>decrease 4:1</td>
</tr>
</tbody>
</table>

**constant voltage, constant velocity scaling**

**fringing capacitance does not scale → linewidths scale as (1 / bandwidth)**
256 nm Generation InP HBT

340 GHz dynamic frequency divider

340 GHz VCO M. Seo, UCSB/TSC

324 GHz amplifier J. Hacker, TSC

150 nm thick collector

\[ f_{\text{max}} = 780 \text{ GHz} \]
\[ f_T = 424 \text{ GHz} \]

70 nm thick collector

\[ f_{\text{max}} = 560 \text{ GHz} \]
\[ f_T = 560 \text{ GHz} \]

60 nm thick collector

\[ f_{\text{max}} = 218 \text{ GHz} \]
\[ f_T = 660 \text{ GHz} \]
# InP Bipolar Transistor Scaling Roadmap

<table>
<thead>
<tr>
<th>Component</th>
<th>Width (nm)</th>
<th>Contact Width (nm)</th>
<th>Contact Resistivity ($\Omega \cdot \mu m^2$)</th>
<th>Current Density (mA/\mu m$^2$)</th>
<th>Breakdown Voltage (V)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emitter</strong></td>
<td>512</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>256</td>
<td>8</td>
<td>2.5</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>128</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>300</td>
<td>20</td>
<td>1.25</td>
<td>72</td>
<td>2-2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Collector</strong></td>
<td>150</td>
<td>4.5</td>
<td>37.5</td>
<td>72</td>
<td>2-2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>106</td>
<td>9</td>
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<td></td>
<td>75</td>
<td>18</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>53</td>
<td>36</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- **Emitter Dimensions**: 32 nm width, 1 $\Omega \cdot \mu m^2$ contact resistivity.
- **Base Dimensions**: 30 nm contact width, 1.25 $\Omega \cdot \mu m^2$ contact resistivity.
- **Collector Dimensions**: 37.5 nm thickness, 72 mA/\mu m$^2$ current density.

**Power Amplifiers and Digital 2:1 Divider**

- **EMI power amplifiers**
  - $f_\tau$: 370, 520, 730, 1000, 1400 GHz
  - $f_{max}$: 490, 850, 1300, 2000, 2800 GHz
  - Collector Thickness: 150, 240, 330, 480, 660 GHz

- **Digital 2:1 divider**
  - $f_\tau$: 245, 430, 660, 1000, 1400 GHz
  - $f_{max}$: 150, 240, 330, 480, 660 GHz
Conventional ex-situ contacts are a mess

*THz transistor bandwidths: very low-resistivity contacts are required*

- **textbook contact**
  - Metal
  - Semiconductor

- **with surface oxide**
  - Metal
  - Oxides, etc.
  - Semiconductor

- **with metal penetration**
  - Metal
  - Semiconductor

*Interface barrier → resistance*

*Further intermixing during high-current operation → degradation*
In-Situ Refractory Ohmics on Regrown N-InGaAs

In-situ Mo on n-InAs

\[ \rho_c = 0.6 \pm 0.4 \, \Omega \cdot \mu m^2 \]

\[ n = 1 \times 10^{20} \, \text{cm}^{-3} \]

In-situ Mo on n-InGaAs

\[ \rho_c = 1.0 \pm 0.6 \, \Omega \cdot \mu m^2 \]

\[ n = 5 \times 10^{19} \, \text{cm}^{-3} \]

In-situ emitter contacts good enough for 64 nm node

HAADF-STEM

Interface

2 nm

TEM by Dr. J. Cagnon, Stemmer Group, UCSB

A. Baraskar
Process Must Change Greatly for 128 / 64 / 32 nm Nodes

control undercut \[\rightarrow\] thinner emitter
\[\rightarrow\] thinner base metal
\[\rightarrow\] excess base metal resistance

Undercutting of emitter ends

\{101\}A planes: fast

\{111\}A planes: slow
128 / 64 nm process: Dry-Etched Emitter Metal

In-situ MBE emitter contacts:
refractory → high J
low contact $\rho$ : $\sim 0.7 \ \Omega \cdot \mu m^2$

Refractory emitter contact
dry-etched → nm resolution
refractory → high current

Wet/dry etched emitter
dry-etched → nm resolution

conventional base liftoff
high penetration → thick bases
moderate contact $\rho$ $\sim 4 \ \Omega \cdot \mu m^2$
yield issues ?

V. Jain
E. Lobisser
Dry-Etched W/TiW Emitter Contact Process

Sputtered W/ Ti\textsubscript{0.1}W\textsubscript{0.9} process

Vertical ICP etch profile

Low-stress film

Good adhesion between layers

Refractory Metals

W/TiW bilayer: stress and etch bias compensation

V. Jain
E. Lobisser
Sub-100 nm devices: lifted-off base metal

After Sidewall Etch

Base Contact, Post and Mesa Etch

Device Isolation Etch

HBT before BCB processing
Sub-100 nm devices: lifted-off base metal
Sub-100 nm devices: lifted-off base metal

MAG/MSG

Gain (dB)

\[ I_c = 8.9 \text{mA}; \quad V_{ce} = 1.74 \text{V} \]
\[ J_e = 23.1 \text{mA/}\mu\text{m}^2; \quad V_{cb} = 0.7 \text{V} \]

\[ f_t = 400 \text{ GHz} \quad f_{max} = 660 \text{ GHz} \]

Gain (dB)

\[ I_c = 9.1 \text{mA}; \quad V_{ce} = 1.75 \text{V} \]
\[ J_e = 23.6 \text{mA/}\mu\text{m}^2; \quad V_{cb} = 0.7 \text{V} \]

\[ f_t = 465 \text{ GHz} \quad f_{max} = 660 \text{ GHz} \]

Gain (mW/\mu m^2)

\[ A_{je} = 0.11\mu\text{m} \times 3.5\mu\text{m} \]
\[ I_{b, step} = 0.2 \text{ mA} \]
\[ V_{cb} = 0 \text{ V} \]
\[ V_{ce} = 0 \text{ V} \]

\[ J_e = 40 \text{ mW/}\mu\text{m}^2 \]
\[ J_e = 50 \text{ mW/}\mu\text{m}^2 \]

\[ f_{max} (\text{GHz}) \]

\[ f_{max} (\text{GHz}) \]

\[ f_{max}^2 (\text{GHz})^2 \]

\[ f_{max}^2 (\text{GHz})^2 \]

\[ f_{max}^2 (\text{GHz})^2 \]
128 / 64 nm process: Sputtered Refractory Base

- In-situ MBE emitter contacts: refractory → high J
- low contact ρ: ~0.7 Ω-µm²
- Refractory emitter contact dry-etched → nm resolution
- refractory → high current
- Wet/dry etched emitter dry-etched → nm resolution
- Refractory base contacts low penetration → thin bases
- low contact ρ ~2.5 Ω-µm²
- self-aligned/ liftoff-free

V. Jain
E. Lobisser
In-Situ Refractory Ohmics on P-InGaAs

<table>
<thead>
<tr>
<th>Metal Contact</th>
<th>$\rho_c$ (Ω-µm²)</th>
<th>$\rho_h$ (Ω-µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ Ir</td>
<td>$1.0 \pm 0.7$</td>
<td>$11.5 \pm 3.3$</td>
</tr>
</tbody>
</table>

In-situ base contacts good enough for 32 nm node
Remaining work: contacts on *processed* surfaces
contact thermal stability & reliability

A. Baraskar
Benefits of refractory base contacts

After 250°C anneal, Pd/Ti/Pd/Au diffuses 15nm into semiconductor
deposited Pd thickness: 2.5nm
base now 30 nm thick: observed to degrade with thinner bases

Refractory Mo contacts do not diffuse measurably

Refractory, non-diffusive metal contacts for thin base semiconductor

A.. Baraskar
Sputtered Process for in-situ base contacts

- Blanket ex-situ \( Pd/W \) contacts
- Planarization and etch back
- Low contact resistivity
- Lift-off free and Au free base process
- Self-aligned process for thin emitters
- Enables refractory, in-situ base contacts

\[ \rho_c = 1.0 \pm 0.7 \ \Omega \cdot \mu m^2 \]

Planarization boundary
Si\(_N_x\) Sidewall

V. Jain
E. Lobisser
Sub-100 nm HBTs: planarized base contact

Emitter projecting from PR for planarization

Base Contact, Post and Mesa Etch

Planarized Emitter

Contact Via Etch
670 GHz Transceiver Simulations in 128 nm InP HBT

**Transmitter Exciter**

![Transmitter Exciter Diagram]

- LNA: 9.5 dB Fmin at 670 GHz
- PA: 9.1 dBm Pout at 670 GHz

**Receiver**

![Receiver Diagram]

- VCO: -50 dBC (1 Hz)
  @ 100 Hz offset at 620 GHz (phase 1)

**3-layer thin-film THz Interconnects**

- Thick-substrate -> high-Q TMIC
- Thin -> high-density digital

- Dynamic divider: novel design, simulates to 950 GHz

- Mixer: 10.4 dB noise figure, 11.9 dB gain
Differential Topology, Cascode output buffer, ECL outputs
Fixed frequency and voltage controlled designs
Topoogy: Double-balanced mixer with emitter follower feedback and resonant loading

Modified version of modern dynamic divider (H. M. Rein)

Inverted microstrip wiring

Design variations with input for external clock source and with integrated fixed frequency and voltage controlled oscillators for testing.

Output spectrum with 331.2 GHz clock input

"Signal identification" test at $f_{\text{in}} = 331.2$ GHz

Chip photograph
THz 240 GHz PA Design

Teledyne InP HBTs $W_e=256\text{nm}$, $T_c=150\text{nm}$

Two-finger design achieves $S_{21} = 4.9\text{dB} @ 238\text{GHz}$
THz Transistors
THz Integrated Circuits

Device scaling (Moore's Law) is not yet over.

Scaling → multi-THz transistors.

Challenges in scaling:
  contacts, dielectrics, heat

Multi-THz transistors:
  for systems at very high frequencies
  for better performance at moderate frequencies

Vast #s of THz transistors
  complex systems
  new applications.... imaging, radio, and more
On-Wafer TRL Calibration Environment

Ref Plane for TRL

Ref Plane for TRL
0.5-67GHz Data: Lumped Pads, Off Wafer LRRM Cal.

Ft_fit = 400GHz

Fmax_fit = 660GHz

Standard Off Wafer OSLT

Open & Short Pad Cap Extraction
THz
Bipolar Transistors
Sub-100 nm devices: lifted-off base metal

\[ A_{je} = 0.11 \mu m \times 3.5 \mu m \]

\[ f_t = 400 \text{ GHz} \]

\[ f_{max} = 660 \text{ GHz} \]

\[ I_c = 8.9 mA; V_{ce} = 1.74 V \]

\[ J_e = 23.1 mA/\mu m^2; V_{cb} = 0.7 V \]

\[ f = 465 \text{ GHz} \]

\[ f_{max} = 660 \text{ GHz} \]
Sub-100 nm devices: lifted-off base metal

- Solid Line: $V_{cb} = 0$ V
- Dashed Line: $V_{cb} = 0.7$ V

$I_b, I_c$

$J_e (mA/\mu m^2)$

$V_{be} (V)$

$V_{ce} (V)$

- $A_{je} = 0.11 \mu m \times 3.5 \mu m$
- $I_{b,\text{step}} = 0.2$ mA
- $V_{cb} = 0$ V
- $I_b = 0.01$ mA

Peak $f/f_{max}$

$C_{cb}$ (fF)

$J_e (mA/\mu m^2)$

$V_{cb} = 0$ V

$V_{cb} = 0.4$ V

$V_{cb} = 0.7$ V
2008 UCSB Dry-Etched Ti/TiW Emitter Process

- Litho
- pattern metal
- sidewall
- dry etch
- wet etch

- SiO2
- TiW
- InGaAs n++
- InP n
- InGaAs p++ Base

- InGaAs n++
- InP n
- InGaAs p++ Base

- InGaAs n++
- InP n
- InGaAs p++ Base

- InP n
- InGaAs p++ Base

- BHF

- Worked well @ 200 nm
- Low yield @ 128 nm: stress → poor adhesion
- Substantial revision required

- base contact by liftoff

- f_max = 560 GHz
- f = 560 GHz
- H_21