InGaAs/InP DHBTs in a planarized, etch-back technology for base contacts

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Outline

- HBT Scaling Laws
- Refractory base ohmics
- Fabrication
- DHBT – Epitaxial Design and Results
- Summary
Bipolar transistor scaling laws

\[
\frac{1}{2\pi f_{tr}} = \tau_{tr} + RC \,
\]
\[
f_{\text{max}} = \sqrt{\frac{f_{\tau}}{8\pi R_{bb,\text{eff}} C_{cb,\text{eff}}}}
\]

To **double cutoff frequencies** of a mesa HBT, must:

Keep constant all resistances and currents

Reduce all capacitances and transit delays by 2

\[
\tau_b \approx T_b^2 / 2D_n + T_b / v_{\text{exit}}
\]
\[
\tau_c = T_c / 2v_{\text{sat}}
\]
\[
C_{cb} = \varepsilon A_c / T_c
\]
\[
I_{c,\text{max}} \propto v_{\text{eff}} A_e (V_{cb} + \phi_{bi}) / T_c^2
\]
\[
R_{ex} = \rho_{\text{contact}} / A_e
\]
\[
R_{bb} = \rho_{\text{sheet}} \left( \frac{W_e}{12L_e} + \frac{W_{bc}}{6L_e} \right) + \frac{\rho_{\text{contact}}}{A_{\text{contacts}}}
\]

Epitaxial scaling

Lateral scaling

Ohmic contacts

(emitter length \(L_e\))
<table>
<thead>
<tr>
<th>Design</th>
<th>Emitter</th>
<th>Base</th>
<th>Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (nm)</td>
<td>256</td>
<td>175</td>
<td>106</td>
</tr>
<tr>
<td>Access $\rho$ (Ω·µm²)</td>
<td>8</td>
<td>10</td>
<td>106</td>
</tr>
<tr>
<td>Contact width (nm)</td>
<td>128</td>
<td>120</td>
<td>75</td>
</tr>
<tr>
<td>Contact $\rho$ (Ω·µm²)</td>
<td>64</td>
<td>60</td>
<td>53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th>Current density</th>
<th>Breakdown voltage</th>
<th>$f_T$</th>
<th>$f_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mA/µm²</td>
<td>9</td>
<td>4</td>
<td>520</td>
<td>850</td>
</tr>
<tr>
<td>V</td>
<td>18</td>
<td>3.3</td>
<td>730</td>
<td>1300</td>
</tr>
<tr>
<td>GHz</td>
<td>36</td>
<td>2.75</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>2-2.5</td>
<td></td>
<td></td>
<td>1400</td>
<td>2800</td>
</tr>
</tbody>
</table>

Rodwell, Le, Brar, Proceedings of IEEE, 2008
Contact diffusion

- Pd contacts diffuse in base (p-InGaAs)
- Contact resistance ↑ for thin base
- Limits base thickness
  → Scaling Limitation

15 nm Pd diffusion

100 nm InGaAs grown in MBE

Need for non-diffusive, refractory base metal
Refractory base ohmics

<table>
<thead>
<tr>
<th>Doping</th>
<th>Metal</th>
<th>Type</th>
<th>$\rho_c$ (Ω-μm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5E20</td>
<td>Mo</td>
<td>As deposited</td>
<td>2.5</td>
</tr>
<tr>
<td>1.5E20</td>
<td>Ru/Mo</td>
<td>As deposited</td>
<td>1.3</td>
</tr>
<tr>
<td>1.5E20</td>
<td>W/Mo</td>
<td>As deposited</td>
<td>1.2</td>
</tr>
<tr>
<td>1.5E20</td>
<td>Ir/Mo</td>
<td>As deposited</td>
<td>1.0</td>
</tr>
<tr>
<td>2.2E20</td>
<td>Ir/Mo</td>
<td>As deposited</td>
<td>0.6</td>
</tr>
<tr>
<td>2.2E20</td>
<td>Ir/Mo</td>
<td>Annealed</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Refractory metal base contacts

Require a blanket deposition and etch-back process
Emitter process flow

- Mo contact to n-InGaAs for emitter
- W/TiW/SiO₂/Cr deposition
- SF₆/Ar etch
- SiNₓ Sidewall

**Mo**

**Emitter cap**

**Emitter**

**Base**

**N-collector**

**Sub collector**

**InP substrate**

*Mo* contact to *n*-InGaAs for emitter

**W/TiW** interface acts as shadow mask for base lift off

**Collector** formed via *lift off* and *wet etch*

**BCB** used to passivate and planarize devices
Base process flow – I

Blanket refractory metal

PR Planarization
Isotropic Dry etch of metal
Removes any Emitter-Base short
Base process flow – II

Lift-off Ti/Au
Low base metal resistance

Blanket SiN$_x$ mask
Etch base contact metal in the field

Ti$_{0.1}$W$_{0.9}$
W
Mo
InGaAs
InP

p+ InGaAs Base

SiN$_x$

Ti$_{0.1}$W$_{0.9}$
W
Mo
InGaAs
InP

p+ InGaAs Base
Base Planarization

Planarization: Emitter projecting from PR for W dry etch

Etch Back

Planarization Boundary
Epitaxial Design

<table>
<thead>
<tr>
<th>T (nm)</th>
<th>Material</th>
<th>Doping (cm$^{-3}$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>8·10$^{19}$ : Si</td>
<td>Emitter Cap</td>
</tr>
<tr>
<td>15</td>
<td>InP</td>
<td>5·10$^{19}$ : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>15</td>
<td>InP</td>
<td>2·10$^{19}$ : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>30</td>
<td>InGaAs</td>
<td>9·5·10$^{19}$ : C</td>
<td>Base</td>
</tr>
<tr>
<td>4.5</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>9·10$^{16}$ : Si</td>
<td>Setback</td>
</tr>
<tr>
<td>10.8</td>
<td>InGaAs / InAlAs</td>
<td>9·10$^{16}$ : Si</td>
<td>B-C Grade</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>6·10$^{18}$ : Si</td>
<td>Pulse doping</td>
</tr>
<tr>
<td>81.7</td>
<td>InP</td>
<td>9·10$^{16}$ : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>7.5</td>
<td>InP</td>
<td>1·10$^{19}$ : Si</td>
<td>Sub Collector</td>
</tr>
<tr>
<td>7.5</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>2·10$^{19}$ : Si</td>
<td>Sub Collector</td>
</tr>
<tr>
<td>300</td>
<td>InP</td>
<td>2·10$^{19}$ : Si</td>
<td>Sub Collector</td>
</tr>
<tr>
<td></td>
<td>Substrate</td>
<td>SI : InP</td>
<td></td>
</tr>
</tbody>
</table>

Low Base doping

→ Good refractory ohmics not possible
→ Pd/W contacts used

$V_{be} = 1 \text{ V}, V_{cb} = 0.7 \text{ V}, J_e = 25 \text{ mA/μm}^2$
Results - DC Measurements

BV_{ceo} = 2.4 V @ J_e = 1 kA/cm^2

\beta = 26

J_{KIRK} = 21 mA/\mu m^2

Common emitter I-V

@Peak f_{\tau}, f_{\text{max}}

J_e = 17.9 mA/\mu m^2

P = 30 mW/\mu m^2

Gummel plot
**1-67 GHz RF Data**

- $I_c = 22.4 \text{ mA}$
- $V_{ce} = 1.67 \text{ V}$
- $J_e = 17.9 \text{ mA/µm}^2$
- $V_{cb} = 0.7 \text{ V}$

**Diagram Notes**
- Single-pole fit to obtain cut-off frequencies
- $f_\tau = 410 \text{ GHz}$
- $f_{\text{max}} = 690 \text{ GHz}$
- $A_{je} = 0.22 \times 5.7 \text{ µm}^2$
\( R_{\text{ex}} = 6 \, \Omega \cdot \mu \text{m}^2 \)

Hybrid-\( \pi \) equivalent circuit from measured RF data
TEM

Large undercut in base mesa

Pd/W adhesion issue

→ High $R_{bb}$

→ Low $f_{\text{max}}$
Summary

- Demonstrated a **planarized, etch back process** for refractory base contacts
- Demonstrated DHBTs with peak $f_T/f_{max} = 410/690$ GHz
- Higher base doping, thinner base and refractory base ohmics needed to enable higher bandwidth devices
Thank You

Questions?

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