In-situ Ohmic Contacts to p-InGaAs

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Outline

• Motivation
  – Low resistance contacts for high speed HBTs
  – Approach

• Experimental details
  – Contact formation
  – Fabrication of Transmission Line Model structures

• Results
  – Doping characteristics
  – Effect of doping on contact resistivity
  – Effect of annealing

• Conclusion
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Device Bandwidth Scaling Laws for HBT

To double device bandwidth:

• Cut transit time 2x
• Cut RC delay 2x

Scale contact resistivities by 4:1*

\[
\frac{1}{2\pi f_{\tau}} = \tau_{in} + RC
\]

\[
f_{\text{max}} = \sqrt{\frac{f_{\tau}}{8 \cdot \pi \cdot (R_{bb} \cdot C_{cb})_{\text{eff}}}}
\]

HBT: Heterojunction Bipolar Transistor

*M.J.W. Rodwell, CSICS 2008
# InP Bipolar Transistor Scaling Roadmap

<table>
<thead>
<tr>
<th>Emitter</th>
<th>256</th>
<th>128</th>
<th>64</th>
<th>32</th>
<th>(\text{nm width})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>(\Omega \cdot \mu \text{m}^2 \text{ access } \rho)</td>
</tr>
<tr>
<td>Base</td>
<td>175</td>
<td>120</td>
<td>60</td>
<td>30</td>
<td>(\text{nm contact width})</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5</td>
<td>2.5</td>
<td>1.25</td>
<td>(\Omega \cdot \mu \text{m}^2 \text{ contact } \rho)</td>
</tr>
<tr>
<td>Collector</td>
<td>106</td>
<td>75</td>
<td>53</td>
<td>37.5</td>
<td>(\text{nm thick})</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>18</td>
<td>36</td>
<td>72</td>
<td>(\text{mA/} \mu\text{m}^2 \text{ current})</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.3</td>
<td>2.75</td>
<td>2-2.5</td>
<td>(\text{V breakdown})</td>
</tr>
<tr>
<td>(f_t)</td>
<td>520</td>
<td>730</td>
<td>1000</td>
<td>1400</td>
<td>(\text{GHz})</td>
</tr>
<tr>
<td>(f_{\text{max}})</td>
<td>850</td>
<td>1300</td>
<td>2000</td>
<td>2800</td>
<td>(\text{GHz})</td>
</tr>
</tbody>
</table>

**Contact resistivity serious barrier to THz technology**

Less than 2 \(\Omega \cdot \mu \text{m}^2\) contact resistivity required for simultaneous THz \(f_t\) and \(f_{\text{max}}\)
Approach

To achieve low resistance, stable ohmic contacts

- **Higher number of active carriers**
  - Reduced depletion width
  - Enhanced tunneling across metal-semiconductor interface

- **Better surface preparation techniques**
  - For efficient removal of oxides/impurities
Approach (contd.)

- Scaled device → thin base
  (For 80 nm device: $t_{\text{base}} < 25 \text{ nm}$)
- Non-refractory contacts may diffuse at higher temperatures through base and short the collector
- Pd/Ti/Pd/Au contacts diffuse about 15 nm in InGaAs on annealing

Need a **refractory** metal for thermal stability
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Epilayer Growth

Epilayer growth by Solid Source Molecular Beam Epitaxy (SS-MBE) – p-InGaAs/InAlAs
- Semi insulating InP (100) substrate
- Un-doped InAlAs buffer
- $\text{CBr}_4$ as carbon dopant source
- Hole concentration determined by Hall measurements

<table>
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<th>Layer</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>100 nm In$<em>{0.53}$Ga$</em>{0.47}$As: C</td>
<td>(p-type)</td>
</tr>
<tr>
<td>100 nm In$<em>{0.52}$Al$</em>{0.48}$As:</td>
<td>NID buffer</td>
</tr>
<tr>
<td>Semi-insulating InP Substrate</td>
<td></td>
</tr>
</tbody>
</table>
In-situ contacts

In-situ molybdenum (Mo) deposition
- E-beam chamber connected to MBE chamber
- No air exposure after film growth

Why Mo?
- Refractory metal (melting point ~ 2620 °C)
- Easy to deposit by e-beam technique
- Easy to process and integrate in HBT process flow

20 nm in-situ Mo

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<tr>
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TLM (Transmission Line Model) fabrication

- E-beam deposition of Ti, Au and Ni layers
- Samples processed into TLM structures by photolithography and liftoff
- Contact metal was dry etched in SF$_6$/Ar with Ni as etch mask, isolated by wet etch

<table>
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<tr>
<td>50 nm ex-situ Ni</td>
</tr>
<tr>
<td>500 nm ex-situ Au</td>
</tr>
<tr>
<td>20 nm ex-situ Ti</td>
</tr>
<tr>
<td>20 nm in-situ Mo</td>
</tr>
<tr>
<td>100 nm In$<em>{0.53}$Ga$</em>{0.47}$As: C (p-type)</td>
</tr>
<tr>
<td>100 nm In$<em>{0.52}$Al$</em>{0.48}$As: NID buffer</td>
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Resistance Measurement

- Resistance measured by Agilent 4155C semiconductor parameter analyzer
- TLM pad spacing ($L_{\text{gap}}$) varied from 0.5-26 $\mu m$; verified from scanning electron microscope (SEM)
- TLM Width $\sim 25 \, \mu m$

\[ 2 \cdot R_C = \frac{2 \cdot \sqrt{\rho_C \cdot R_{Sh}}}{W} \]
Error Analysis

- **Extrapolation errors:**
  - 4-point probe resistance measurements on Agilent 4155C
  - Resolution error in SEM

- **Processing errors:**
  - Variable gap spacing along width (W)
  - Overlap resistance
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Doping Characteristics-I

- Hole concentration saturates at high CBr fluxes
- Number of di-carbon defects ↑ as CBr flux ↑

Hole concentration Vs CBr$_4$ flux

$T_{\text{sub}} = 460 \, ^{\circ}\text{C}$
Doping Characteristics-II

Hole concentration Vs V/III flux

As V/III ratio ↓ hole concentration ↑

hypothesis: As-deficient surface drives C onto group-V sites
Doping Characteristics-III

Hole concentration Vs substrate temperature

Tendency to form di-carbon defects ↑ as Tsub ↑

Hole concentration Vs substrate temperature

![Graph showing hole concentration vs substrate temperature](image)

Tendency to form di-carbon defects ↑ as Tsub ↑*

Results: Contact Resistivity - I

<table>
<thead>
<tr>
<th>Metal Contact</th>
<th>$\rho_c$ ($\Omega\mu m^2$)</th>
<th>$\rho_h$ ($\Omega\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ Mo</td>
<td>2.2 ± 0.8</td>
<td>15.4 ± 2.6</td>
</tr>
</tbody>
</table>

- Hole concentration, $p = 1.6 \times 10^{20}$ cm$^{-3}$
- Mobility, $\mu = 36$ cm$^2$/Vs
- Sheet resistance, $R_{sh} = 105$ ohm/$\mu$m
  (100 nm thick film)

$\rho_c$ lower than the best reported contacts to pInGaAs ($\rho_c = 4$ $\Omega\mu m^2$)$^{[1,2]}$

Results: Contact Resistivity - II

Contact Resistivity, \( \rho_c \) (\( \Omega \cdot \mu m^2 \))

Tunneling \( \rightarrow \) \( \rho_c \propto \exp\left(\frac{1}{\sqrt{p}}\right) \)

Thermionic Emission \( \rightarrow \) \( \rho_c \sim \text{constant} \)

Data suggests tunneling

High active carrier concentration is the key to low resistance contacts

* Physics of Semiconductor Devices, S M Sze
Thermal Stability - I

Mo contacts annealed under N$_2$ flow for 60 mins. at 250 °C

<table>
<thead>
<tr>
<th></th>
<th>Before annealing</th>
<th>After annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_c$ (Ω-μm$^2$)</td>
<td>2.2 ± 0.8</td>
<td>2.8 ± 0.9</td>
</tr>
</tbody>
</table>

- $\rho_c$ increases on annealing
- Mo reacts with residual interfacial carbon?


Thermal Stability - II

Mo contacts annealed under N\textsubscript{2} flow for 60 mins. at 250 °C

TEM of Mo-pInGaAs interface
- Suggests sharp interface
- Minimal/No intermixing
Summary

• Maximum hole concentration obtained = $1.6 \times 10^{20}$ cm$^{-3}$ at a substrate temperature of 350 °C

• Low contact resistivity with in-situ metal contacts (lowest $\rho_c = 2.2 \pm 0.8 \ \Omega \cdot \mu$m$^2$)

✓ Contacts suitable for THz transistors
Thank You!

Questions?

Acknowledgements
ONR, DARPA-TFAST, DARPA-FLARE
Extra Slides
Correction for Metal Resistance in 4-Point Test Structure

\[
R_{\text{metal}} \quad (\rho_{\text{sheet}} \rho_{\text{contact}})^{1/2} / W \quad \rho_{\text{sheet}} L / W
\]

\[
(\rho_{\text{sheet}} \rho_{\text{contact}})^{1/2} / W + \rho_{\text{sheet}} L / W + R_{\text{metal}} / x
\]

Error term \((R_{\text{metal}} / x)\) from metal resistance
Random and Offset Error in 4155C

- Random Error in resistance measurement \(\sim 0.5 \text{ m}\Omega\)
- Offset Error < 5 m\(\Omega\)^*
Accuracy Limits

- Error Calculations
  - \( dR = 50 \text{ m}\Omega \) (Safe estimate)
  - \( dW = 1 \mu\text{m} \)
  - \( \text{dGap} = 20 \text{ nm} \)
- Error in \( \rho_c \sim 40\% \) at \( 1.1 \Omega-\mu\text{m}^2 \)