High Doping Effects on In-situ and Ex-situ Ohmic Contacts to n-InGaAs

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Intel Corporation, Technology Manufacturing Group, Santa Clara, CA
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:
  - Reduce thickness 2:1 😊
  - Capacitance increases 2:1 😞
- Cut RC delay 2x
  - **Scale contact resistivities by 4:1**

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

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

HBT: Heterojunction Bipolar Transistor

Uttam Singisetti, DRC 2007

InP Bipolar Transistor Scaling Roadmap

<table>
<thead>
<tr>
<th>Emitter:</th>
<th>512</th>
<th>256</th>
<th>128</th>
<th>64</th>
<th>32</th>
<th>width (nm)</th>
<th>access ( \rho ), (( \Omega \cdot \mu m^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base:</td>
<td>300</td>
<td>175</td>
<td>120</td>
<td>60</td>
<td>30</td>
<td>contact width (nm)</td>
<td>contact ( \rho ) (( \Omega \cdot \mu m^2 ))</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f_t ):</td>
<td>370</td>
<td>520</td>
<td>730</td>
<td>1000</td>
<td>1400</td>
<td>GHz</td>
<td></td>
</tr>
<tr>
<td>( f_{max} ):</td>
<td>490</td>
<td>850</td>
<td>1300</td>
<td>2000</td>
<td>2800</td>
<td>GHz</td>
<td></td>
</tr>
</tbody>
</table>

- Contact resistance serious barrier to THz technology

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

*M.J.W. Rodwell, CSICS 2008
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**
  - Ex-situ contacts: treatment with UV-O$_3$, HCl etch
  - In-situ contacts: no air exposure before metal deposition

• **Use of refractory metal for thermal stability**
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Epilayer Growth

Semiconductor epilayer growth by Solid Source Molecular Beam Epitaxy (SS-MBE) – n-InGaAs/InAlAs

- Semi insulating InP (100) substrate
- Unintentionally doped InAlAs buffer
- Electron concentration determined by Hall measurements

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
<th>Composition</th>
<th>Dopant</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 nm In$<em>{0.53}$Ga$</em>{0.47}$As: Si</td>
<td>n-type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 nm In$<em>{0.52}$Al$</em>{0.48}$As</td>
<td>NID buffer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-insulating InP Substrate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Two Types of Contacts Investigated

- **In-situ contacts: Mo**
  - Samples transferred under vacuum for contact metal deposition
  - no air exposure

- **Ex-situ contacts: Ti/Ti$_{0.1}$W$_{0.9}$**
  - exposed to air
  - surface treatment before contact metal deposition

<table>
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<th>Contact metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 nm In$<em>{0.53}$Ga$</em>{0.47}$As: Si (n-type)</td>
</tr>
<tr>
<td>150 nm In$<em>{0.52}$Al$</em>{0.48}$As: NID buffer</td>
</tr>
</tbody>
</table>

Semi-insulating InP Substrate
In-situ contacts

In-situ Molybdenum (Mo) deposition
- E-beam chamber connected to MBE chamber

Why Mo?
- Refractory metal (melting point ~ 2623 C)
- Work function ~ 4.6 (± 0.15) eV, close to the conduction band edge of InGaAs
- Easy to deposit by e-beam technique
- Easy to process and integrate in HBT process flow

<table>
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<th>Layer Description</th>
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<tr>
<td>20 nm in-situ Mo</td>
<td></td>
</tr>
<tr>
<td>100 nm In_{0.53}Ga_{0.47}As: Si (n-type)</td>
<td></td>
</tr>
<tr>
<td>150 nm In_{0.52}Al_{0.48}As: NID buffer</td>
<td></td>
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Ex-situ contacts

Ex-situ Ti/Ti\textsubscript{0.1}W\textsubscript{0.9} contacts on InGaAs

- Surface preparation
  - Oxidized with UV-ozone for 10 min
  - Dilute HCl (1:10) etch and DI rinse for 1 min each
- Immediate transfer to sputter unit for contact metal deposition
- Ti: Oxygen gettering property, forms good ohmic contacts*


2009 Electronic Materials Conference

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Ashish Baraskar
TLM (Transmission Line Model) fabrication

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

<table>
<thead>
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</tr>
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<tbody>
<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>Mo or Ti/TiW</td>
</tr>
<tr>
<td>100 nm In$<em>{0.53}$Ga$</em>{0.47}$As: Si (n-type)</td>
</tr>
<tr>
<td>150 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 varied from 0.6-26 µm; verified from scanning electron microscope

- TLM Width ~ 10 µm
Error Analysis

• Error due to extrapolation*
  – 4-point probe resistance measurements on Agilent 4155C
  – For the smallest TLM gap, $R_c$ is 40% of total measured resistance

• Metal Resistance
  – Minimized using thick metal stack
  – Minimized using small contact widths
  – Correction included in data

• Overlap Resistance
  – Higher for small contact widths
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Results: Doping Characteristics

Enhanced $n$ for colder growths

-hypothesis: As-rich surface drives Si onto group-III sites

$n$ saturates at high dopant concentration
## Results: Contact Resistivity

<table>
<thead>
<tr>
<th>Metal Contact</th>
<th>Active Carriers (cm(^{-3}))</th>
<th>(\rho_c) ((\Omega)-(\mu m^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ Mo</td>
<td>6 \times 10^{19}</td>
<td>1.1(\pm)0.6</td>
</tr>
<tr>
<td>In-situ Mo</td>
<td>4.2 \times 10^{19}</td>
<td>2.0(\pm)1.1</td>
</tr>
<tr>
<td>Ex-situ Ti/Ti(<em>{0.1})W(</em>{0.9})</td>
<td>4.2 \times 10^{19}</td>
<td>2.1(\pm)1.2</td>
</tr>
</tbody>
</table>

- Mo contacts: in-situ deposition; clean interface
- Ti: oxygen gettering property

\[
2 \cdot R_c = \frac{2 \cdot \sqrt{\rho_c \cdot R_{Sh}}}{W}
\]
Results: Effect of doping-I

- Contact resistivity ($\rho_c$) ↓ with ↑ in electron concentration

$T_{\text{sub}}$: 440 °C

Contact Resistivity (Ω-µm²)

Active Carriers ($\times 10^{19}$ cm⁻³)

Total Si atoms ($\times 10^{19}$ cm⁻³)
Results: Effect of doping-II

Data suggests tunneling.

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

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

High active carrier concentration is the key to low resistance contacts

* Physics of Semiconductor Devices, SM Sze
Contacts annealed under N\textsubscript{2} flow for 60 secs

- Mo contacts stable to at least 400°C
- Ti/Ti\textsubscript{0.1}W\textsubscript{0.9} contacts degrade on annealing*

Conclusion

• Extreme Si doping improves contact resistance
• In-situ Mo and ex-situ Ti/Ti$_{0.1}$W$_{0.9}$ give low contact resistance
  - Mo contacts are thermally stable
  - Ti/Ti$_{0.1}$W$_{0.9}$ contacts degrade
• $\rho_c \sim (1.1 \pm 0.6) \ \Omega \cdot \mu m^2$ for in-situ Mo contacts
  - less than $2 \ \Omega \cdot \mu m^2$ required for simultaneous THz $f_t$ and $f_{max}$

✓ 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

From hand analysis & finite element simulation

Error term ($-R_{metal}/3$) from metal resistance
Effect changes measured $\rho_c$ by $\sim40\%$ (@1.3 $\Omega$-$\mu m^2$)

All data presented corrects for this effect
Doping Vs As flux

\[ \text{As flux (x10^{-6}) torr} \]

\[ \text{Doping density (x10^{19}) cm}^{-3} \]

\[ T_{\text{sub}}: 440 \, \text{C} \]
Active Carrier, Mobility Vs Total Si

Active Carriers ($\times 10^{19} \text{cm}^{-3}$) vs Total Si atoms ($\times 10^{19} \text{cm}^{-3}$)

Active Carrier

Mobility ($\text{cm}^2/\text{V} \cdot \text{s}$)
Strain Effects

\[ [\text{Si}] = 1.5 \times 10^{20} \text{ cm}^{-3}, \quad n = 6 \times 10^{19} \text{ cm}^{-3} \]

\[
\frac{(a_{\text{sub}} - a_{\text{epi}})}{a_{\text{sub}}} = 5.1 \times 10^{-4}
\]

Random and Offset Error in 4155C

- Random Error in resistance measurement ~ 0.5 mΩ
- Offset Error < 5 mΩ*

*4155C datasheet
Accuracy Limits

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