Regrown Ohmic Contacts to $\text{In}_x\text{Ga}_{1-x}\text{As}$ Approaching the Quantum Conductivity Limit

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Outline

• Motivation

• Ballistic FET Current and TLM Quantum Conductance

• Process Flow

• Sample Structures
  − Regrowth TLM (RG-TLM)
  − Transmission Line Measurement (TLM)

• Results
  − Metal-semiconductor (TLM)
  − Metal-semiconductor and semiconductor-channel (RG-TLM)

• Theory Comparison

• Conclusion
Motivation

- Two interfaces of interest
  - Metal–regrowth interface
  - Regrowth–channel interface
- Sheet resistance of regrowth
- Sheet resistance of ungated region
- Must ascertain contribution to overall access resistance from all of above
FET Ballistic Current $=\text{TLM Quantum Conductance}$

- Fundamental limits to contact resistance to a two-dimensional channel?
- Quantum limited contact resistance$^{1,2}$ equivalent to ballistic transconductance

charge density $\mu \left( E_f, E_c \right)^1$

velocity $\mu \left( E_f, E_c \right)^{1/2}$

current $\mu \left( E_{f,s}, E_c \right)^{3/2} \left( E_{f,d}, E_c \right)^{3/2}$

$\mu \left( V_{gs}, V_{th} \right)^{3/2} \left( V_{gd}, V_{th} \right)^{3/2}$

current $\mu \left( E_{f,d} + q V E_c \right)^{3/2} \left( E_{f,d}, E_c \right)^{3/2}$

$\mu \cdot V \times \left( E_{f,s}, E_c \right)^{1/2}$

$\mu \cdot V \times \left( \text{carrier density} \right)^{1/2}$

conductivity $\mu \left( \text{carrier density} \right)^{1/2}$

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Regrowth TLM (RG TLM) Process Flow

- Understand source (regrowth) to channel interface
- Rudimentary process flow
- Approximates FET structure and process flow
  - Independent of high-k properties
- Four-point Kelvin measurement
TLM Process Flow

- Understand metal to source (regrowth) interface
- Rudimentary process flow
- Can be done on same die as RGTLM
- Four-point Kelvin measurement
Sample Structures: TLM

InAs RG on δ–doped 25 nm \( \text{In}_{0.53}\text{Ga}_{0.47}\)As channel

InAs RG on δ–doped 15 nm InAs channel

InAs RG on 100 nm \( n^+\) \( \text{In}_{0.53}\text{Ga}_{0.47}\)As channel

\( \text{In}_{0.53}\text{Ga}_{0.47}\)As → InAs RG on 100 nm \( n^+\) \( \text{In}_{0.53}\text{Ga}_{0.47}\)As channel
TLM Results

InAs RG on $\delta$–doped
25 nm $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ channel

Slope: 23.8 $\Omega$; Intercept/2: 2.1 $\Omega$–$\mu$m

InAs RG on 100 nm $n^+ \text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ channel

Slope: 7.4 $\Omega$; Intercept/2: 4.6 $\Omega$–$\mu$m

InAs RG on $\delta$–doped 15 nm InAs channel

Slope: 19.3 $\Omega$; Intercept/2: 3.0 $\Omega$–$\mu$m

In$_{0.53}$Ga$_{0.47}$As $\rightarrow$ InAs RG on 100 nm $n^+ \text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ channel

Slope: 11.3 $\Omega$; Intercept/2: 3.0 $\Omega$–$\mu$m
Sample Structures: RGTLM

InAs RG on δ-doped 25 nm \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) channel

InAs RG on δ-doped 15 nm InAs channel

InAs RG on 100 nm \(n^+\) \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) channel

\(\text{In}_{0.53}\text{Ga}_{0.47}\text{As} \rightarrow \text{InAs RG on 100 nm } n^+ \text{In}_{0.53}\text{Ga}_{0.47}\text{As channel}\)
Regrowth TLM Results

**InAs RG on δ-doped 25 nm In$_{0.53}$Ga$_{0.47}$As channel**

Slope: 540 $\Omega$; Intercept/2: 120.8 $\Omega$–$\mu$m

**InAs RG on 100 nm $n^+$ In$_{0.53}$Ga$_{0.47}$As channel**

Slope: 32 $\Omega$; Intercept/2: 55.6 $\Omega$–$\mu$m

**InAs RG on δ-doped 15 nm InAs channel**

Slope: 269 $\Omega$; Intercept/2: 68.2 $\Omega$–$\mu$m

**In$_{0.53}$Ga$_{0.47}$As → InAs RG on 100 nm $n^+$ In$_{0.53}$Ga$_{0.47}$As channel**

Slope: 15 $\Omega$; Intercept/2: 12.7 $\Omega$–$\mu$m
Results Summary

- Contact resistance to thin channels (small $n_s$) limited by quantum conductance
- Low contact resistance of $12.7 \Omega \cdot \mu m$ ($11.1 \Omega \cdot \mu m^2$)
- Contact resistance low $n_s$ channels $136.4 \Omega \cdot \mu m$ close to theoretical $80 \Omega \cdot \mu m$

### $N^+$ Regrowth

<table>
<thead>
<tr>
<th></th>
<th>Composition</th>
<th>Thickness</th>
<th>Doping</th>
<th>Sheet Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>InAs</td>
<td>60 nm</td>
<td>$5-10 \times 10^{19} \text{ cm}^{-3}$</td>
<td>$23.8 \Omega$</td>
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<tr>
<td></td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As → InAs</td>
<td>60 nm</td>
<td>$5-10 \times 10^{19} \text{ cm}^{-3}$</td>
<td>$11.3 \Omega$</td>
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### Channel

<table>
<thead>
<tr>
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<th>Doping</th>
<th>Sheet Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>25 nm</td>
<td>$9 \times 10^{12} \text{ cm}^{-2}$</td>
<td>$540 \Omega$</td>
</tr>
<tr>
<td></td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>100 nm</td>
<td>$3-5 \times 10^{19} \text{ cm}^{-3}$</td>
<td>$32 \Omega$</td>
</tr>
<tr>
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</tbody>
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<th>Access Resistivity</th>
<th>$120.8 \Omega \cdot \mu m$</th>
<th>$55.6 \Omega \cdot \mu m$</th>
<th>$68.2 \Omega \cdot \mu m$</th>
<th>$12.7 \Omega \cdot \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metal/Regrowth Contact Resistivity</td>
<td>$2.1 \Omega \cdot \mu m$</td>
<td>$4.6 \Omega \cdot \mu m$</td>
<td>$3.0 \Omega \cdot \mu m$</td>
<td>$3.0 \Omega \cdot \mu m$</td>
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<tr>
<td></td>
<td></td>
<td>$0.2 \Omega \cdot \mu m^2$</td>
<td>$1.5 \Omega \cdot \mu m^2$</td>
<td>$0.4 \Omega \cdot \mu m^2$</td>
<td>$0.8 \Omega \cdot \mu m^2$</td>
</tr>
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</table>
Conclusion

• Ballistic FET current equivalent to quantum conductance of TLM
• Should not add to FET contact resistance
• Material independent, i.e. true for all semiconductor materials
• Metal–regrowth contact resistance is small portion of overall $R_c$
  – ~ $3.0 \, \Omega \cdot \mu m$ (1.0 $\Omega \cdot \mu m^2$)
• Regrown ohmic contacts (136 $\Omega \cdot \mu m$) within a factor of 2 of theoretical 80 $\Omega \cdot \mu m$
• 12.7 $\Omega \cdot \mu m$ (11.1 $\Omega \cdot \mu m^2$) is true measure of interface properties
  – This includes regrowth to channel and metal to regrowth
Backup slides
MBE Regrowth by Migration Enhance Epitaxy (MEE)

**InAs Quasi MEE**

- In, As, and Si shutters open
- As shutter open

**InGaAs Quasi MEE**

- In, Ga, As, and Si shutters open
- As shutter open
MBE Regrowth: Close to 2-D Quantum conductivity Limit:

Unidirectional 2D density of states: \( c_{dos,1} = \frac{q^2 g m^*}{2\pi \hbar^2} \)

Charge density in left-moving states: \( \rho_{s1} = c_{dos,1} V_{f1} \)

Leftward-moving Fermi Velocity: \( E_{f1} = q V_{f1} = \frac{m^* v_{f1}^2}{2} \rightarrow v_{f1} = \sqrt{2 q V_{f1} / m^*} \)

Mean leftward electron velocity: \( \bar{v}_1 = \frac{4}{3\pi} v_{f1} = \frac{4}{3\pi} \cdot \sqrt{2 q V_{f1} / m^*} \)

Leftward current: \( J_1 = \rho_{s1} \bar{v}_1 = c_{dos,1} V_{f1} \left( \frac{4}{3\pi} \right) \cdot \sqrt{2 q V_{f1} / m^*} \)

Total current: \( J = c_{dos,1} \left( \frac{4}{3\pi} \right) \cdot \sqrt{\frac{2 q}{m^*} \left( V_{f1}^{3/2} - V_{f2}^{3/2} \right)} \)

Conductivity: \( G = \frac{\partial J}{\partial V_f} = c_{dos,1} \left( \frac{4}{3\pi} \right) \cdot \sqrt{\frac{2 q}{m^*} \cdot \frac{3}{2} V_f^{1/2}} \)

\[
G_{valley} = \frac{q^2}{\hbar} \cdot \frac{2^{1/2}}{\pi^{3/2}} \cdot n_s^{1/2, valley} \text{ including spin degeneracy.}
\]

Total conductivity found by summing over valleys and vertical eigenstates:

UCSB regrowth resistance measurements are being limited by this effect.