Lower Limits To Specific Contact Resistivity

Ashish Baraskar\textsuperscript{1}, Arthur C. Gossard\textsuperscript{2,3}, Mark J. W. Rodwell\textsuperscript{3}

\textsuperscript{1}GLOBALFOUNDRIES, Yorktown Heights, NY
Depts. of \textsuperscript{2}Materials and \textsuperscript{3}ECE, University of California, Santa Barbara, CA

24th International Conference on Indium Phosphide and Related Materials
Santa Barbara, CA
**Ohmic Contacts: Critical for nm & THz Devices**

*Scaling laws to double bandwidth*

<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>transport effective mass</td>
<td>constant</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>

<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>
Ohmic Contacts: Critical for nm & THz Devices

**Scaling laws to double bandwidth**

<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>transport effective mass</td>
<td>constant</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>
<tr>
<td>$&gt; 0.5 , \Omega\cdot\mu\text{m}^2$ resistivity for 10 nm III-V MOSFET</td>
<td></td>
</tr>
</tbody>
</table>

<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>
<tr>
<td>$&gt; 2 , \Omega\cdot\mu\text{m}^2$ resistivity for 2 THz $f_{\text{max}}$</td>
<td></td>
</tr>
</tbody>
</table>
Ultra Low-Resistivity Refractory Contacts

Schottky Barrier is about one lattice constant
what is setting contact resistivity?
what resistivity should we expect?
<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>momentum</td>
<td>$k_f \propto m^{1/2} E_f^{1/2}$</td>
</tr>
<tr>
<td>velocity</td>
<td>$v_f \propto k_f / m \propto E_f^{1/2} / m^{1/2}$</td>
</tr>
<tr>
<td>density</td>
<td>$n \propto k_f^3 \propto m^{3/2} E_f^{3/2}$</td>
</tr>
<tr>
<td>current</td>
<td>$J \propto m E_f^2$</td>
</tr>
<tr>
<td>conductivity</td>
<td>$\frac{\partial J}{\partial E_f} \propto m E_f \propto m^0 n^{2/3}$</td>
</tr>
</tbody>
</table>
## Landauer (State-Density Limited) Contact Resistivity

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>momentum</td>
<td>$k_f \propto m^{1/2} E_f^{1/2}$</td>
</tr>
<tr>
<td>velocity</td>
<td>$v_f \propto k_f / m \propto E_f^{1/2} / m^{1/2}$</td>
</tr>
<tr>
<td>density</td>
<td>$n \propto k_f^3 \propto m^{3/2} E_f^{3/2}$</td>
</tr>
<tr>
<td>current</td>
<td>$J \propto m^1 E_f^2$</td>
</tr>
<tr>
<td>conductivity</td>
<td>$\frac{\partial J}{\partial E_f} \propto m^1 E_f^1 \propto m^0 n^{2/3}$</td>
</tr>
<tr>
<td>( \Gamma ) valley</td>
<td>$\sigma_c = \left( \frac{q^2}{\hbar} \right) \left( \frac{3}{8\pi} \right)^{2/3} \cdot n^{2/3}$</td>
</tr>
<tr>
<td>( L, X, \Delta ) valleys</td>
<td>$\sigma_c = \left( \frac{q^2}{\hbar} \right) \left( \frac{3}{8\pi} \right)^{2/3} \cdot \sum_{\text{valley}} \left( \frac{m_x m_y}{m_z^2} \right)^{1/6} \cdot n_{\text{valley}}^{2/3}$</td>
</tr>
</tbody>
</table>
About this work

Scope

• Analytical calculation of minimum feasible contact resistivities to n-type and p-type InAs and In$_{0.53}$Ga$_{0.47}$As.

Assumptions

• Conservation of transverse momentum and total energy across the interface
• Metal $E$-$k$ relationship treated as a single parabolic band
• Band gap narrowing due to heavy doping neglected for the semiconductor
Potential Energy Profile

- Schottky barrier modified by image forces
- Modeled potential barrier: piecewise linear approximation
- $\phi_{Bn}$ introduced to facilitate use of Airy functions for calculating transmission probability
Calculation of Contact Resistivity

Current density, $J$

$$J = \frac{2q}{(2\pi)^3} \int_{k_{sx}=-\infty}^{k_{sx}=\infty} \int_{k_{sy}=-\infty}^{k_{sy}=\infty} \int_{k_{sz}=0}^{k_{sz}=\infty} \mathbf{v}_{sz} \cdot (f_s - f_m) \cdot T \cdot dk_{sx} dk_{sy} dk_{sz}$$

$z$ : transport direction

$k_{sx}, k_{sy}, k_{sz}$ : wave vectors in the semiconductor

$\mathbf{v}_{sz}$ : electron group velocity in $z$ direction

$T$ : interface transmission probability

$f_s$ and $f_m$ : Fermi functions in the semiconductor and the metal

Contact Resistivity, $\rho_c$

$$\frac{1}{\rho_c} = \left. \frac{dJ}{dV} \right|_{V=0}$$
Results: Zero Barrier Contacts, Landauer Contacts

Step Potential Barrier:

- interface quantum reflectivity, resistivity > Landauer

Parabolic vs. non-parabolic bands:

- differing $E_{fs} - E_{cs}$ → differing interface reflectivity

Landauer resistivity lower in Si than in Γ-valley semiconductor

- multiple minima, anisotropic bands
Results: InGaAs

Assumes parabolic bands

At \( n = 5 \times 10^{19} \text{ cm}^{-3} \) doping, \( \Phi_B = 0.2 \text{ eV} \)
measured resistivity 2.3:1 higher than theory

Theory is 3.9:1 higher than Landauer

References:
1. Jain et. al., IPRM, 2009
2. Baraskar et al., JVST B, 2009
3. Yeh et al., JJAP, 1996
4. Stareev et al., JAP, 1993
Results: N-InAs

Assumes parabolic bands

At \( n = 10^{20} \text{ cm}^{-3} \) doping, \( \Phi_B = 0.0 \text{ eV} \)
measured resistivity 1.9:1 higher than theory

Theory is 3.6:1 higher than Landauer

References:
1. Baraskar et al., IPRM, 2010
2. Stareev et al., JAP, 1993
3. Shiraishi et al., JAP, 1994
4. Singisetti et al., APL, 2008
5. Lee et al., SSE, 1998
Results: P-InGaAs

Assumes parabolic bands

Theory and experiment agree well.

At \( n = 2.2 \times 10^{20} \text{ cm}^{-3}\) doping, \( \Phi_B = 0.6 \text{ eV} \)

theory is 13:1 higher than Landauer

→ Tunneling probability remains low.

References:
1. Chor et al., JAP, 2000
2. Baraskar et al., ICMBE, 2010
3. Stareev et al., JAP, 1993
4. Katz et al., APL, 1993
5. Jain et al., DRC, 2010
Conclusions

Correlation of experimental Contact resistivities with theory
   excellent for P-InGaAs
   ~4:1 discrepancy for N-InGaAs, N-InAs

N-contacts are approaching Landauer Limits
   theory vs. Landauer: 4:1 discrepancy
tunneling probability is high
Transmission Probability, $T$

Potential energy in various regions

$V_1(z) = 0, \quad z \leq 0$

$V_2(z) = \phi_m - d\phi_{Bn} + s_1 z, \quad 0 \leq z \leq d_1$

$V_3(z) = \phi_m + \frac{\phi_m - \phi_R}{d_2 - d_1} d_1 - s_2 z, \quad d_1 \leq z \leq d_2$

$V_4(z) = \phi_R, \quad z \geq d_2$

$\phi_m = \phi_R + \phi_{Bn} + \phi_s$

$\phi_s = E_{fs} - E_{cs}$

$s_1 = d\phi_{Bn} / d_1$

$s_2 = \frac{\phi_m - \phi_R}{d_2 - d_1}$
Transmission Probability, $T$

Solutions of Schrödinger equation in various regions

$$\frac{-\hbar^2}{2m_s} \frac{d^2 \psi}{dz^2} + (E_z - V(z))\psi = 0$$

\[
\psi_1(z) = \exp(ik_{mz}z) + R\exp(-ik_{mz}z), \quad z \leq 0
\]

\[
\psi_2(z) = C \cdot Ai[\rho_1(qV_1(z) - E_z)] + D \cdot Bi[\rho_1(qV_1(z) - E_z)], \quad 0 \leq z \leq d_1
\]

\[
\psi_3(z) = F \cdot Ai[\rho_2(qV_2(z) - E_z)] + G \cdot Bi[\rho_2(qV_2(z) - E_z)], \quad d_1 \leq z \leq d_2
\]

\[
\psi_4(z) = t \exp(ik_{mz}z), \quad z \geq d_2
\]

$Ai(z)$ and $Bi(z)$ are the Airy functions

\[
\rho_1 = \left(\frac{2m}{\hbar^2 s_1^2}\right)^{1/3} \quad \rho_2 = \left(\frac{2m}{\hbar^2 s_2^2}\right)^{1/3}
\]

Transmission probability is given by

$$T = \frac{k_{sz} m_m}{k_{mz} m_s} |t|^2$$