Lower Limits To Specific Contact Resistivity

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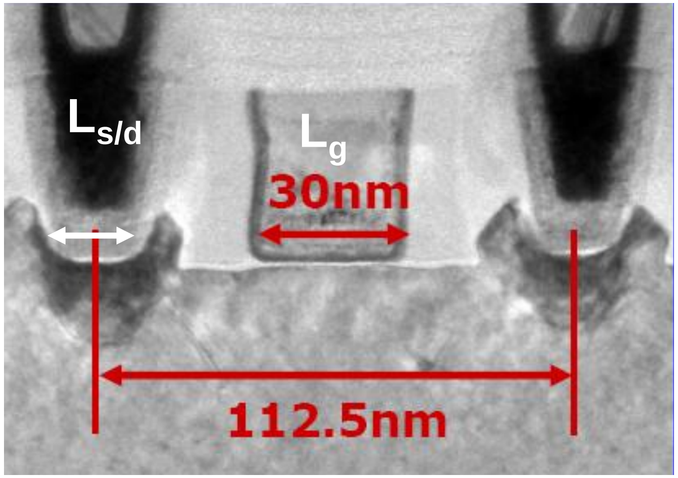
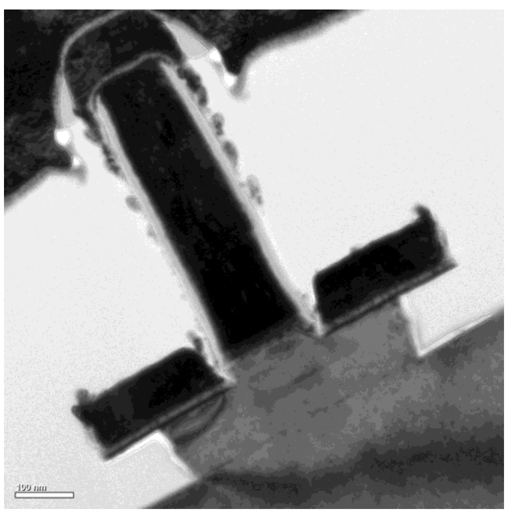
Ohmic Contacts: Critical for nm & THz Devices

Scaling laws to double bandwidth



Intel 32 nm HKMG IEDM 2009

FET parameter	change
gate length	decrease 2:1
current density (mA/μm), g_m (mS/μm)	increase 2:1
transport effective mass	constant
channel 2DEG electron density	increase 2:1
gate-channel capacitance density	increase 2:1
dielectric equivalent thickness	decrease 2:1
channel thickness	decrease 2:1
channel density of states	increase 2:1
source & drain contact resistivities	decrease 4:1

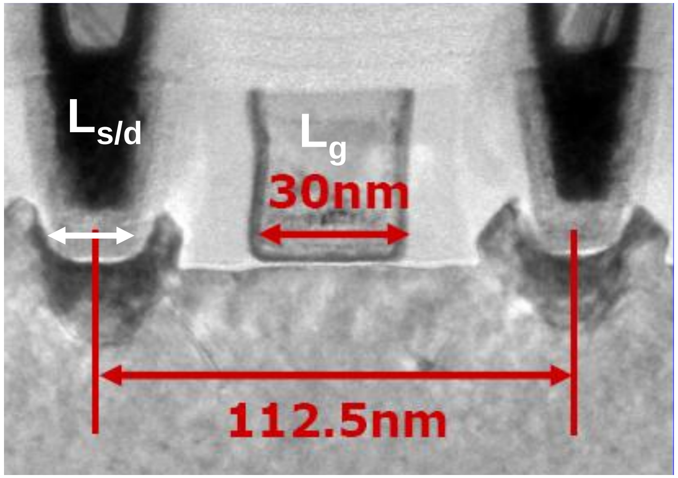


THz HBT: Lobisser ISCS 2012

HBT parameter	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm^2)	increase 4:1
current density (mA/μm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1

Ohmic Contacts: Critical for nm & THz Devices

Scaling laws to double bandwidth



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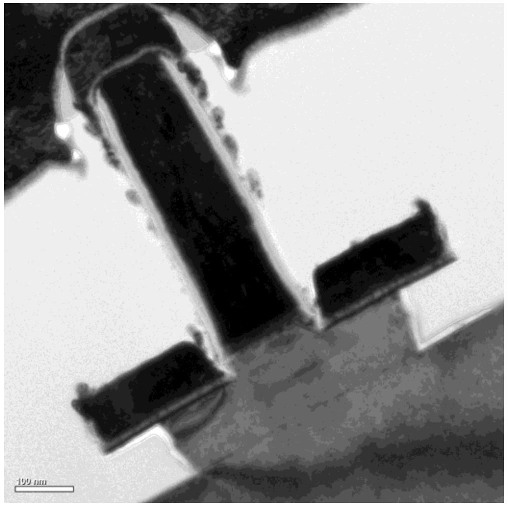

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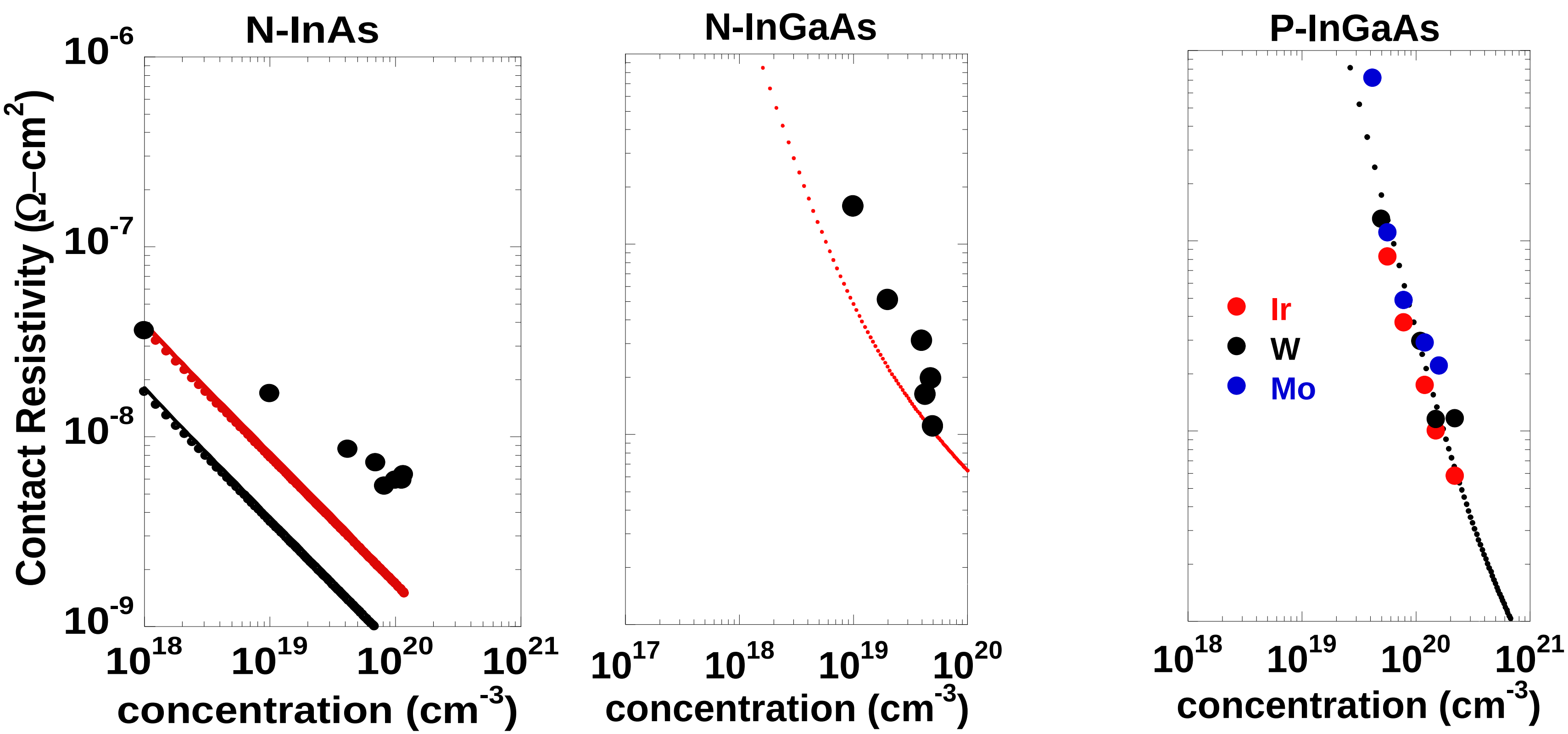
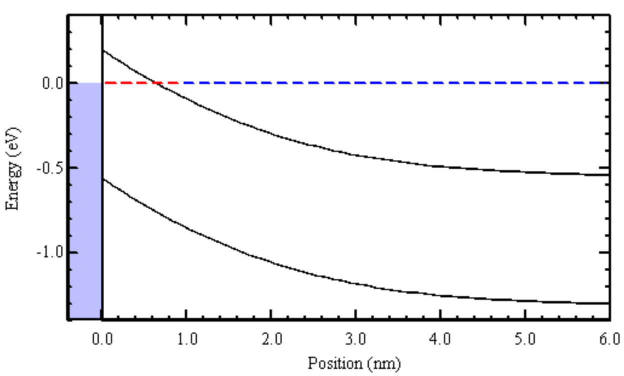
source & drain contact resistivities	decrease 4:1
> 0.5 Ω-μm² resistivity for 10 nm III-V MOSFET	

HBT parameter	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm²)	increase 4:1
current density (mA/μm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1
> 2 Ω-μm² resistivity for 2 THz f_{max}	

Ultra Low-Resistivity Refractory Contacts





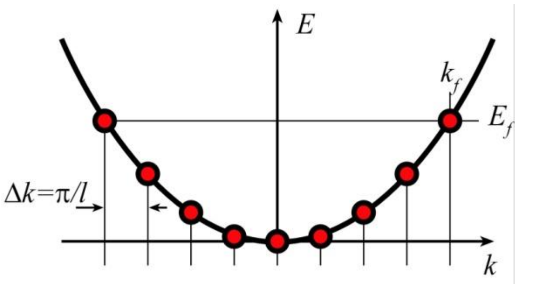
Schottky Barrier is about one lattice constant

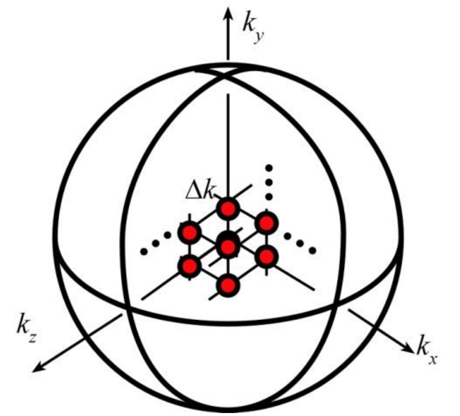
what is setting contact resistivity ?

what resistivity should we expect ?

Landauer (State-Density Limited) Contact Resistivity

momentum	$k_f \propto m^{1/2} E_f^{1/2}$
velocity	$v_f \propto k_f / m \propto E_f^{1/2} / m^{1/2}$
density	$n \propto k_f^3 \propto m^{3/2} E_f^{3/2}$
current	$J \propto m^1 E_f^2$
conductivity	$\frac{\partial J}{\partial E_f} \propto m^1 E_f^1 \propto m^0 n^{2/3}$





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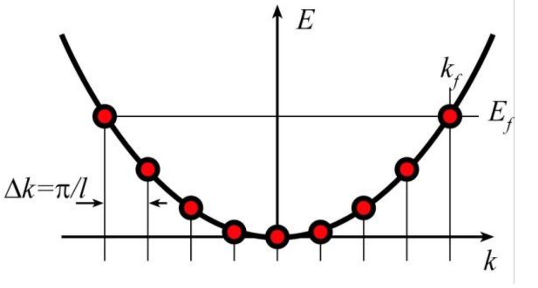
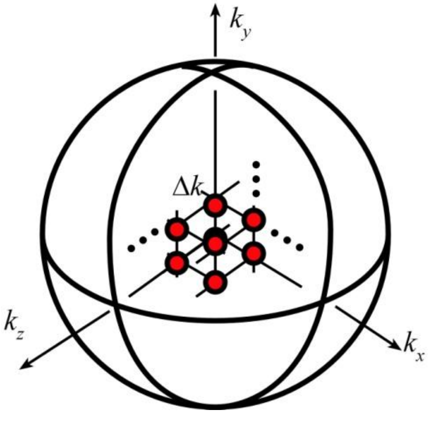
conductivity	$\frac{\partial J}{\partial E_f} \propto m^1 E_f^1 \propto m^0 n^{2/3}$
Γ valley	$\sigma_c = \left(\frac{q^2}{\hbar}\right) \cdot \left(\frac{3}{8\pi}\right)^{2/3} \cdot n^{2/3}$
L, X, Δ valleys	$\sigma_c = \left(\frac{q^2}{\hbar}\right)\left(\frac{3}{8\pi}\right)^{2/3} \cdot \sum_{\text{valley}} \left(\frac{m_x m_y}{m_z^2}\right)^{1/6} \cdot n_{\text{valley}}^{2/3}$





About this work

Scope

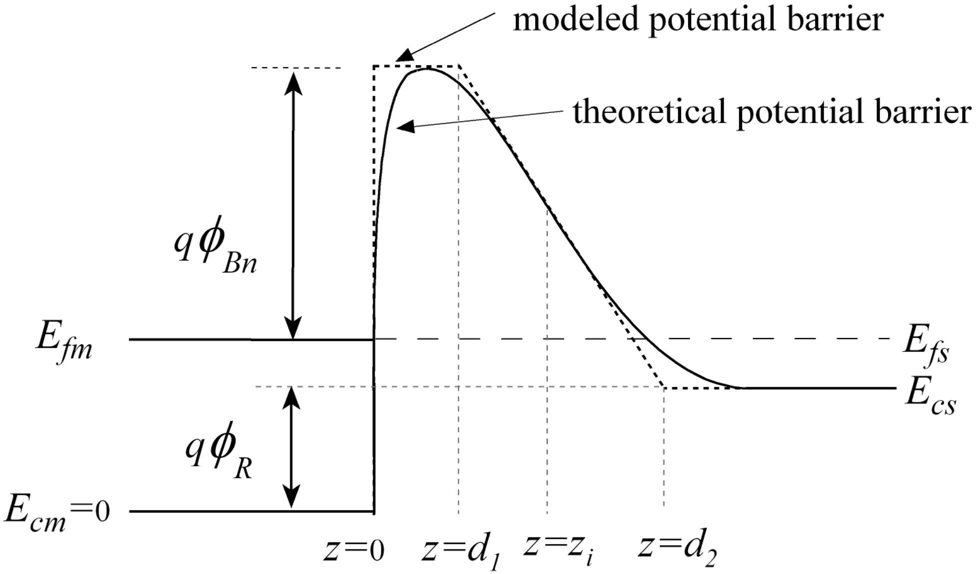
- Analytical calculation of minimum feasible contact resistivities to n-type and p-type InAs and $In_{0.53}Ga_{0.47}As$.

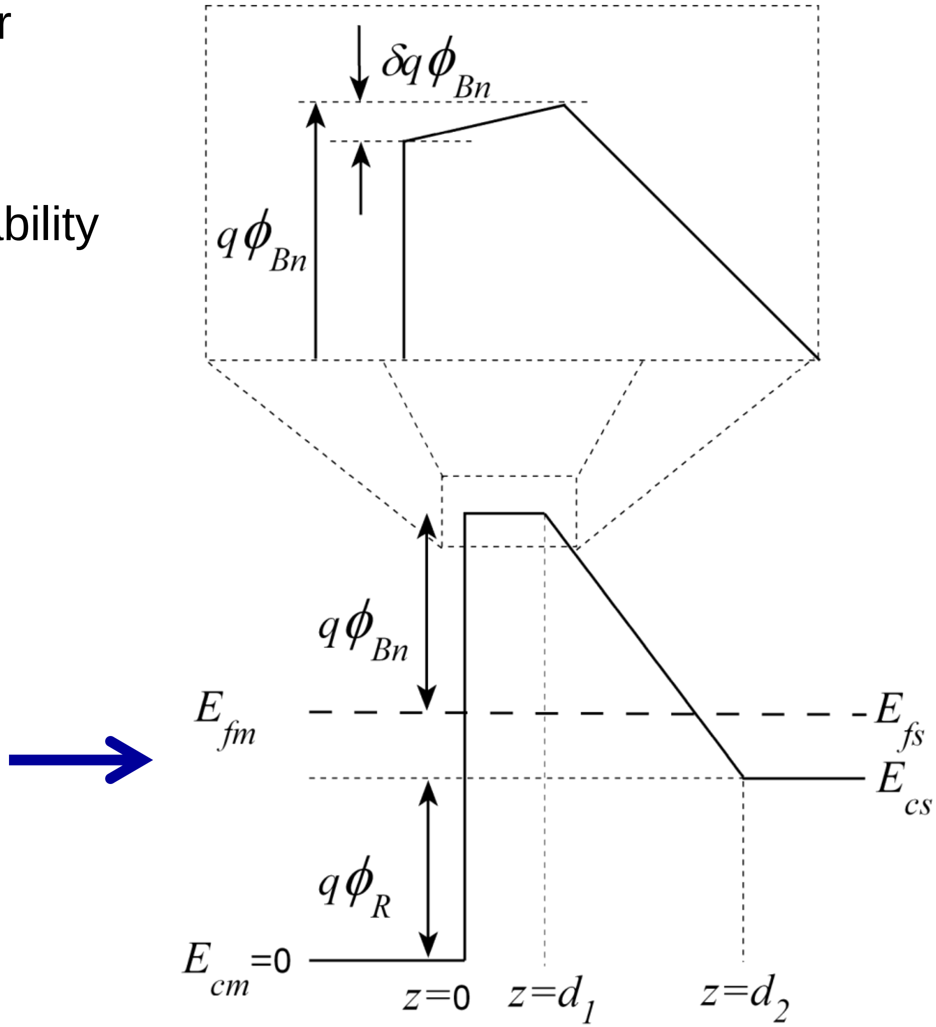
Assumptions

- 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
- $\delta q\phi_{Bn}$ introduced to facilitate use of Airy functions for calculating transmission probability





Calculation of Contact Resistivity

Current density, J

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

z : transport direction

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

v_{sz} : electron group velocity in z direction

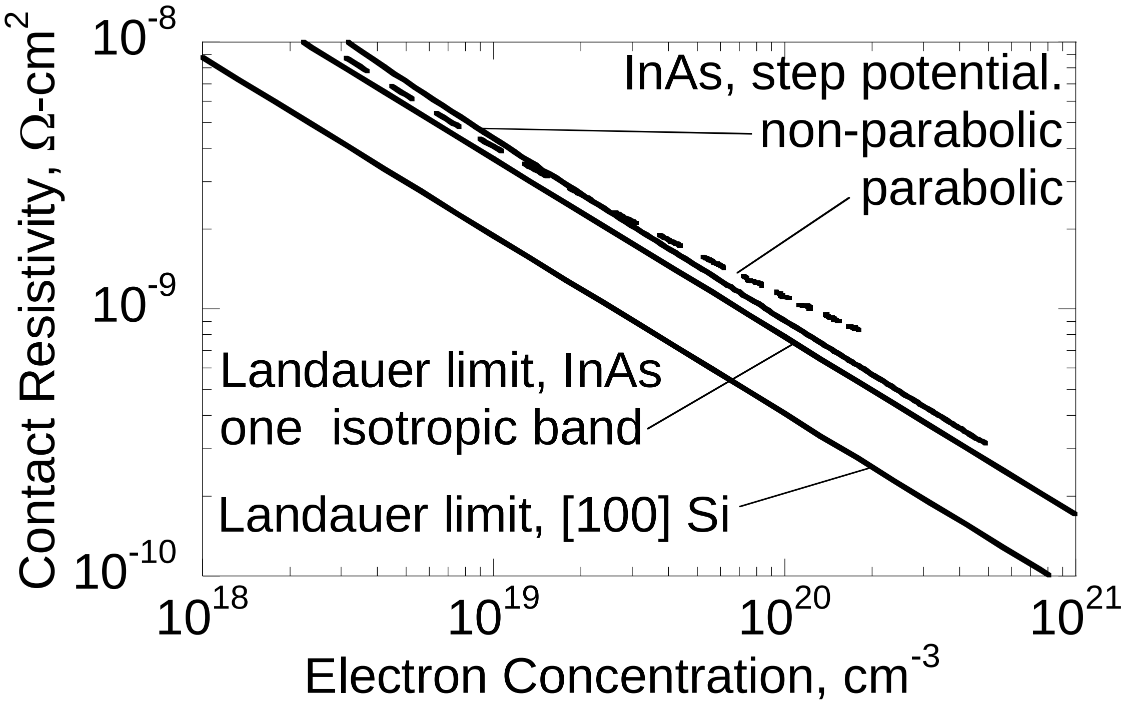
T : interface transmission probability

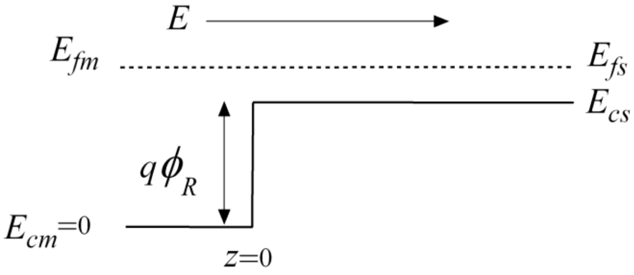
f_s and f_m : Fermi functions in the semiconductor and the metal

Contact Resistivity, ρ_c

$$\frac{1}{\rho_c} = \left.\frac{dJ}{dV}\right|_{V=0}$$

Results: Zero Barrier Contacts, Landauer Contacts





Step potential energy profile

Step Potential Barrier:

interface quantum reflectivity, resistivity >Landauer

Parabolic vs. non-parabolic bands:

differing E_{fs}-E_{cs} $\rightarrow$ differing interface reflectivity

Landauer resistivity lower in Si than in Γ-valley semiconductorfs

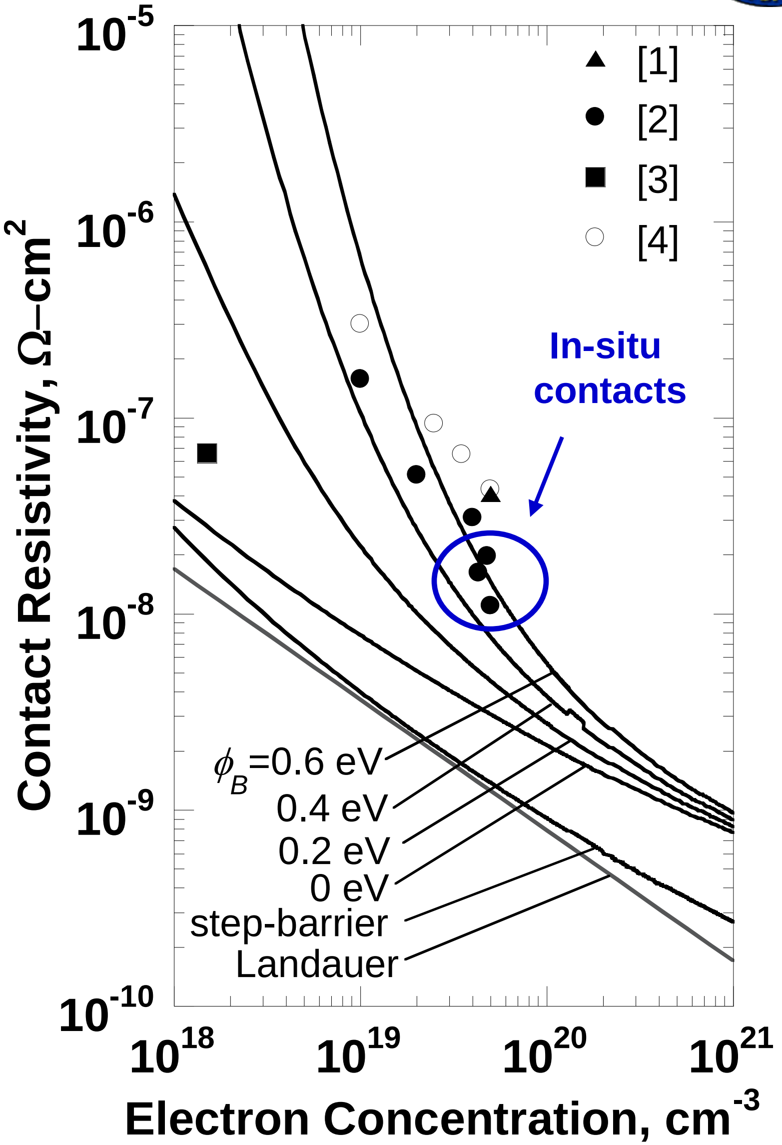
multiple minima, anisotropic bands

Results: InGaAs

Assumes parabolic bands

At $n = 5\times10^{19}$ cm^{-3} doping, Φ_B=0.2 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

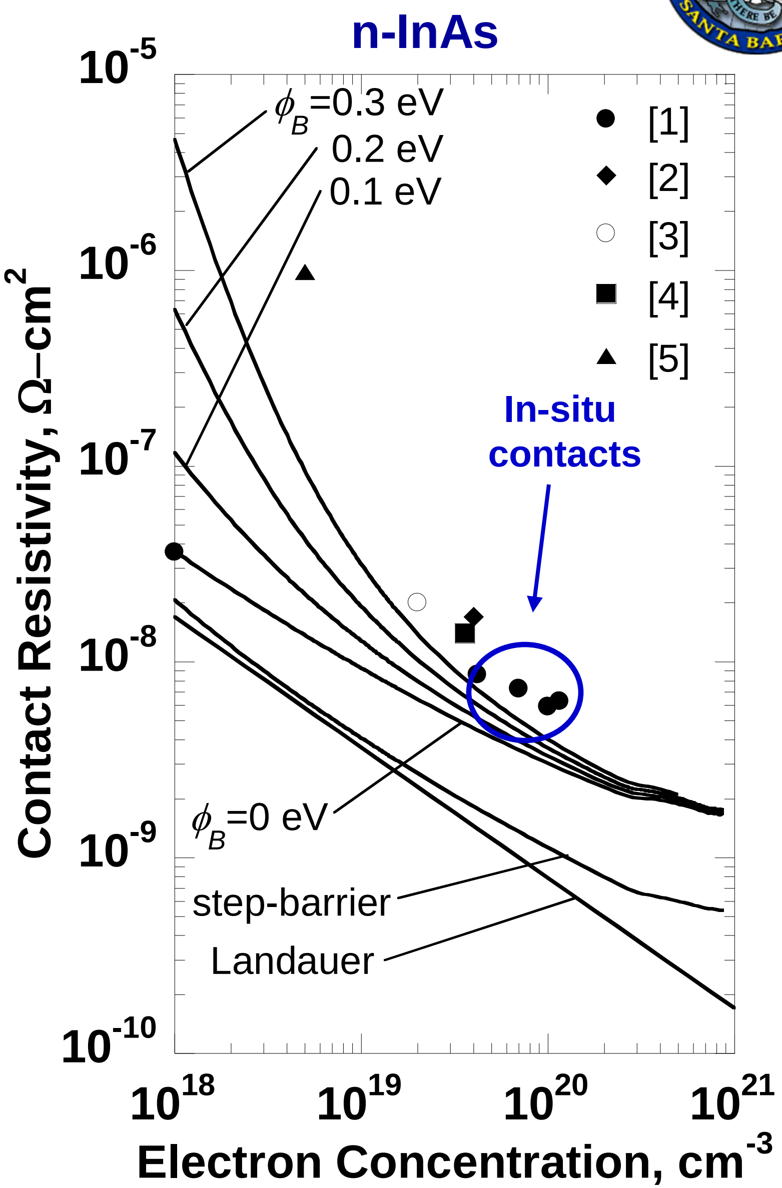
4. Stareev *et al.*, JAP, 1993

Results: N-InAs

Assumes parabolic bands

At n = 10^{20} cm^{-3} doping, Φ_B=0.0 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

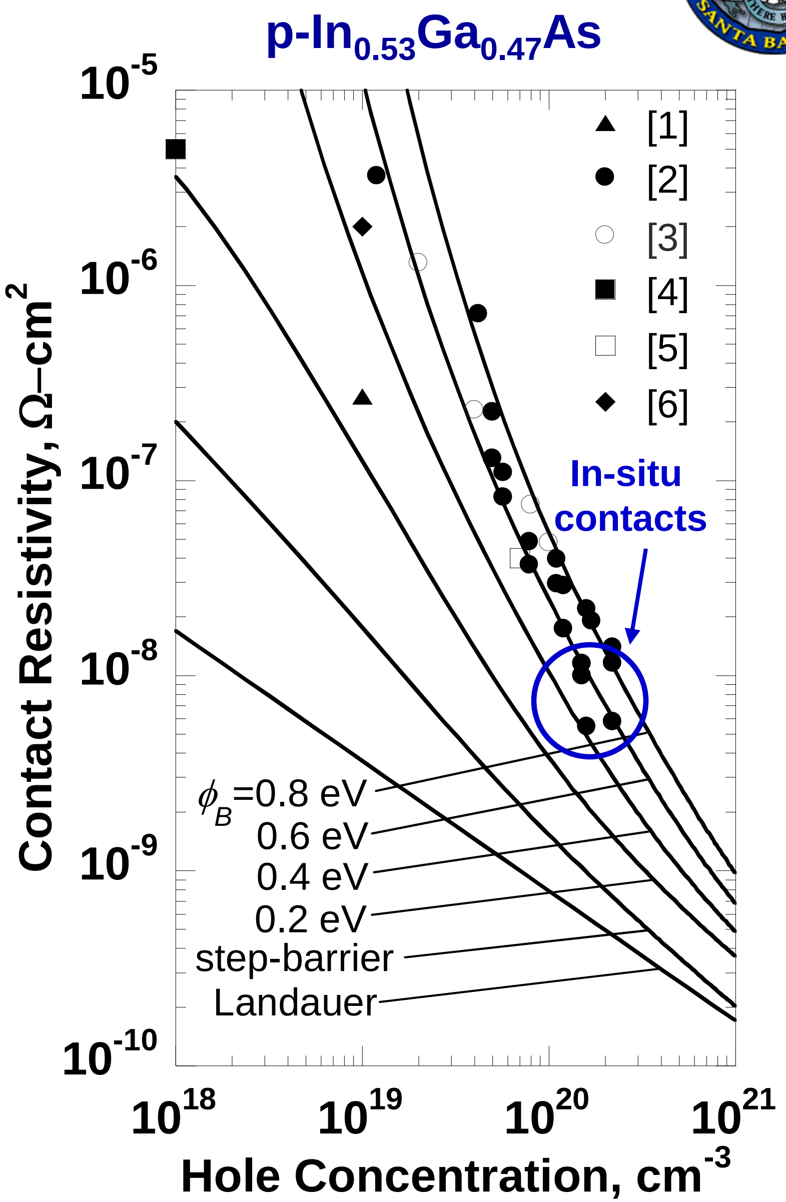
Results: P-InGaAs

Assumes parabolic bands

Theory and experiment agree well.

At $n = 2.2\times10^{20}$ cm^{-3} doping, $\Phi_B=0.6$ 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
6. Jian et al., Matl. Eng., 1996

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

$$V_1(z) = 0, \qquad z \le 0$$

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

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

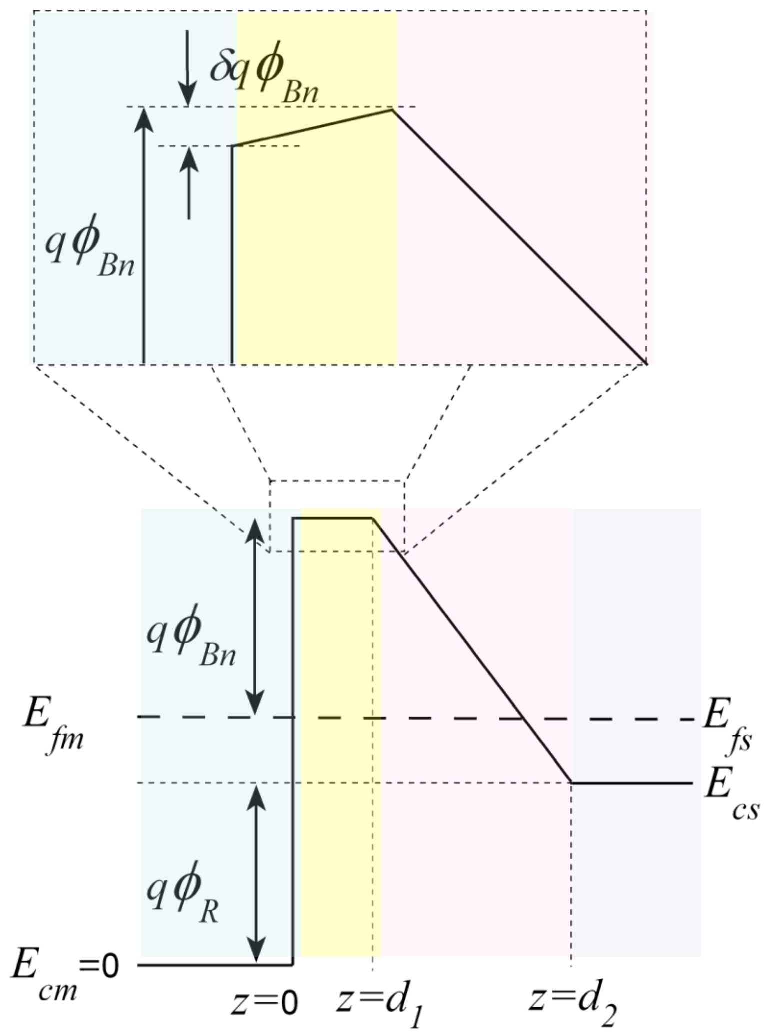
$$V_4(z) = \phi_R, \qquad z \ge d_2$$

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

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

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

$$s_2 = \frac{\phi_m - \phi_R}{d_2 - d_1}$$



Transmission Probability, T

Solutions of Schrodinger equation in various regions

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

$$\psi_1(z)=\exp(ik_{mz}z)+R\exp(-ik_{mz}z), \qquad z\le 0$$

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

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

$$\psi_4(z)=t\exp(ik_{mz}z), \qquad z\ge d_2$$

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

$$\rho_1=\left(\frac{2m_s}{\hbar^2 s_1^2}\right)^{1/3} \qquad \rho_2=\left(\frac{2m_s}{\hbar^2 s_2^2}\right)^{1/3}$$

Transmission probability is given by

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