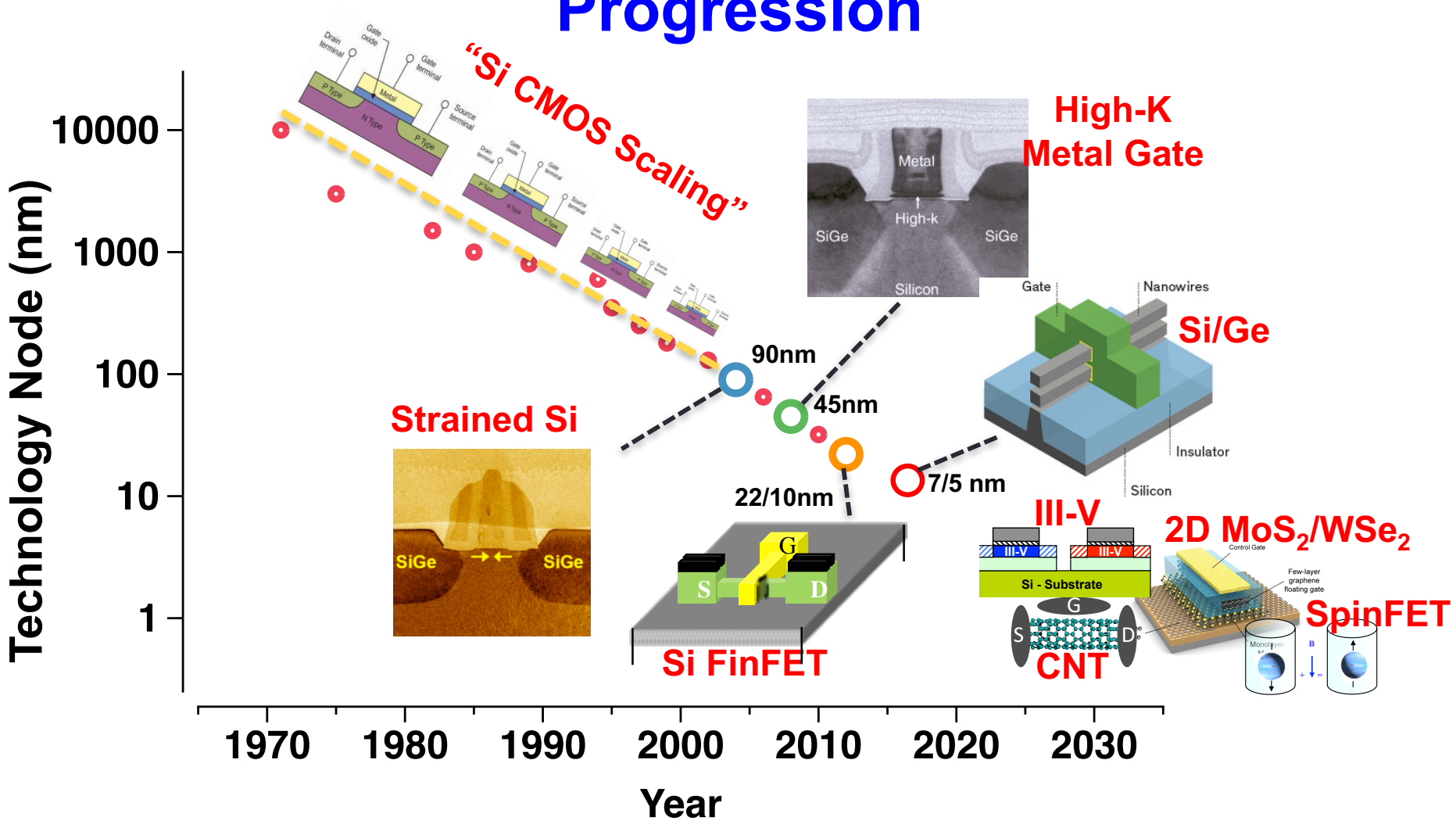
Low resistance Contact to Nanoscale FETs

Prof. Krishna Saraswat

Department of Electrical Engineering
Stanford University, Stanford, CA

New Materials/Structures for MOSFET Technology Progression



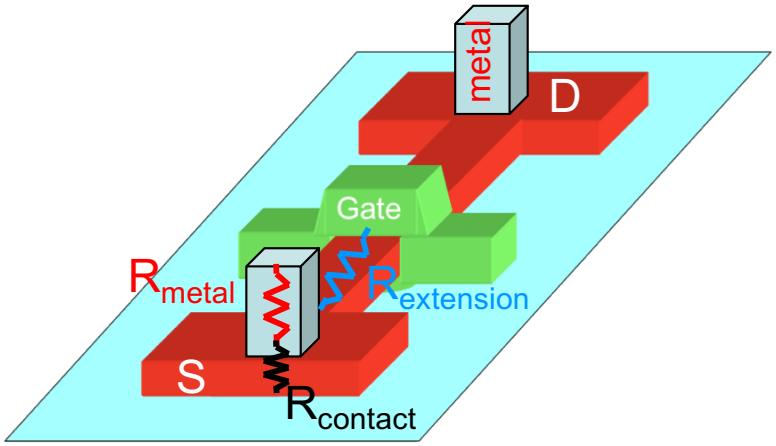
- Moore's law in the past relied on shrinking Si MOSFETs
- Moore's law in future demands more than just shrinking transistors
  - New materials and device structures integrated on Si

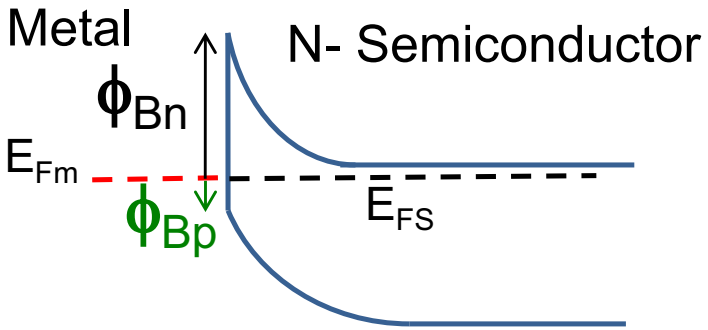
What is the Problem?

- To go beyond limits of Si higher performance material like Ge, III-Vs (?), carbon nanotubes and 2D materials like MoS_2 provide a promising path to continue Moore's law

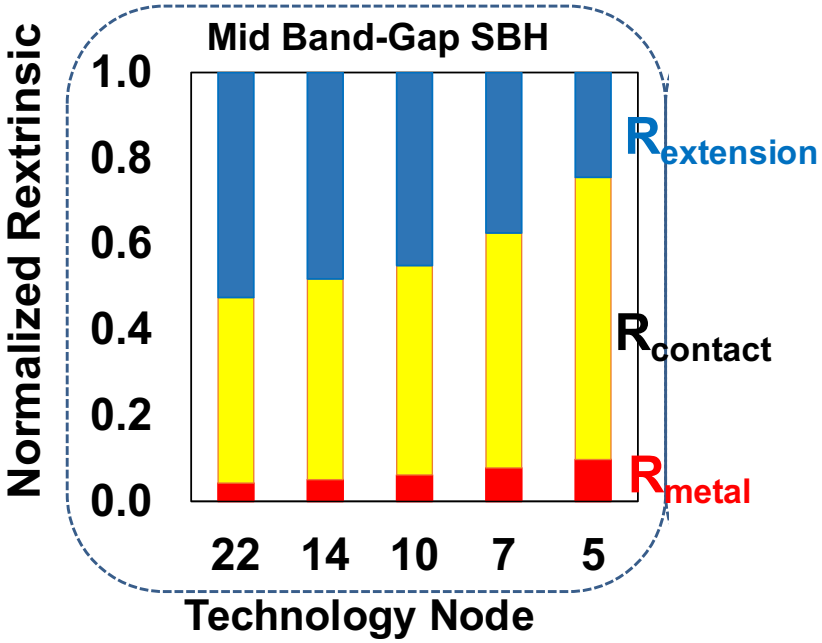
- However, as device scaling continues, parasitic source resistance largely dominated by contact resistance, is beginning to limit the device performance

Contact Resistance





$$I_{DS}^{SAT} = \left[\left(V_{GS} - V_T \right) - I_{DS} R_{SD} \right]^2$$

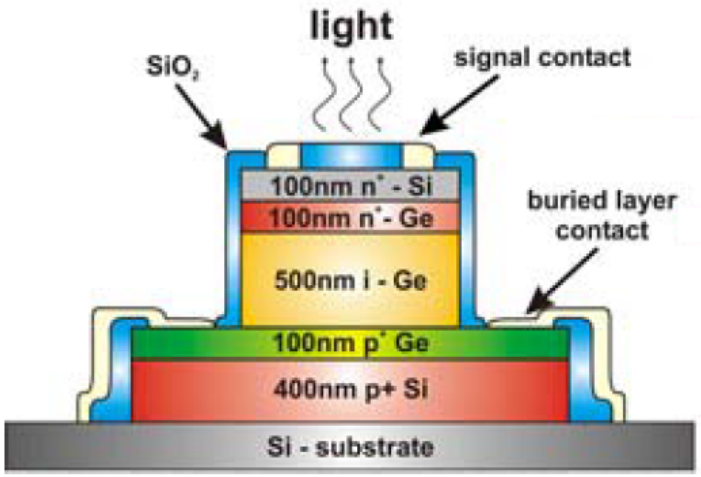


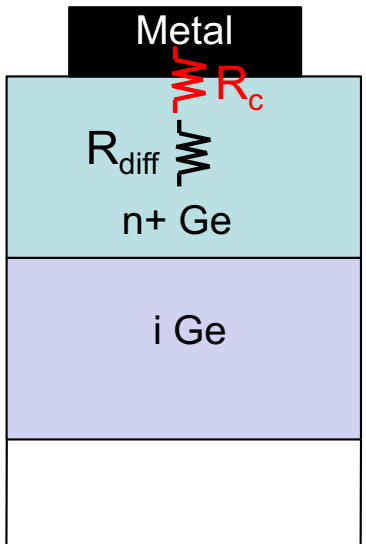
S. Datta, et al., VLSI Symp, 2014

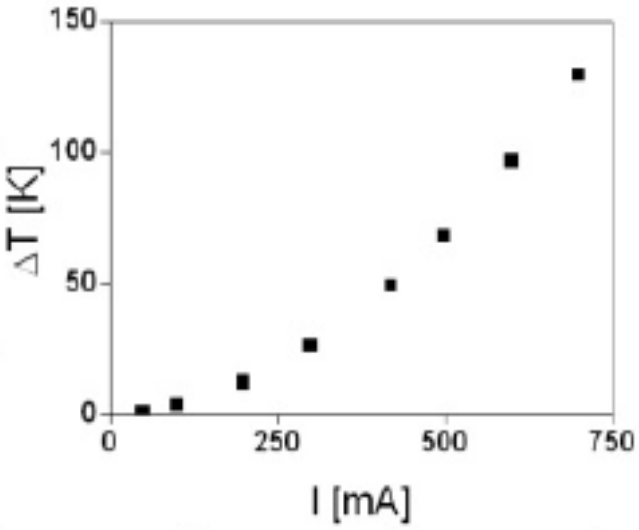
$$\rho_c = \rho_{co} \exp\left(\frac{2\phi_B}{q\hbar} \sqrt{\frac{\varepsilon_s m^*}{N}} \right) \quad ohm - cm^2$$

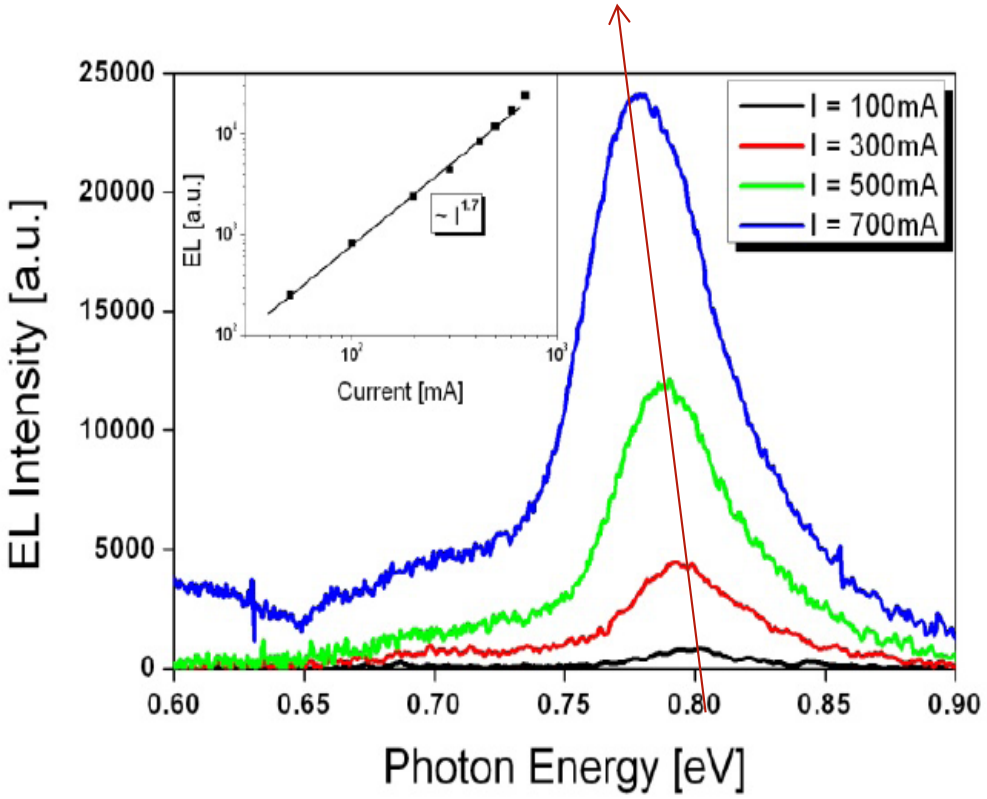
- Contact resistance $R_c \propto \rho_c / A_c$
- Contact area A_c goes down with scaling
- Active doping N limited by solid solubility
- Barrier height ϕ_B needs to be reduced

Contact Resistance Problem: Photonics









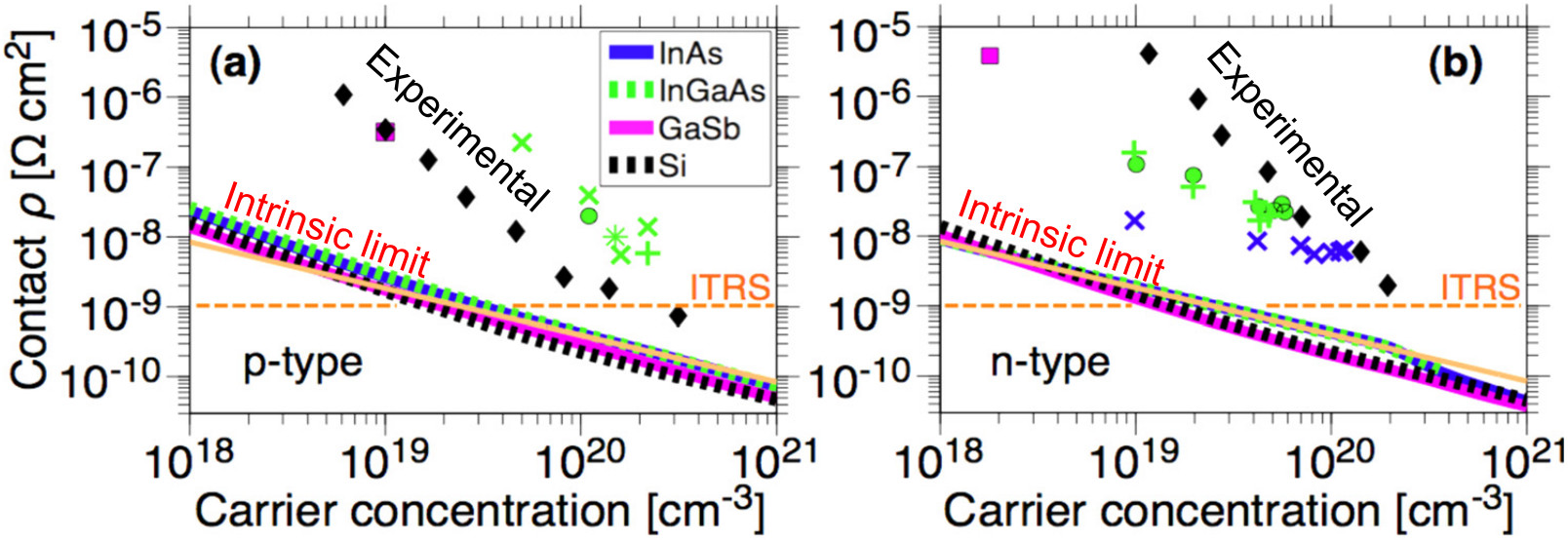
- Direct band gap emission from Ge p-i-n heterojunction photodiode.
- Shift in wavelength with higher current density
- Power dissipation through R_c + R_{diff} heats the diode
- Need contacts with $\rho_c \sim 10^{-9}$ ohm.cm^2 for future electronics and photonics

Courtesy: E. Kasper et al, University of Stuttgart, Germany

Conductance Quantum: Landaur Limit

- **Conductance quantum** in ideal 1D wire with M propagating modes and T transmission probability
  $G = (2q^2/h)MT$
- Using this approach the intrinsic lower limit of **contact resistivity** is:

$$\frac{1}{\rho_c^{LL}} = \frac{4q^2}{h}\int_{-\infty}^{+\infty} M(\epsilon)\left[-\frac{\partial f}{\partial \epsilon}\right]d\epsilon, \quad [\Omega^{-1}-\mathrm{m}^{-2}]$$

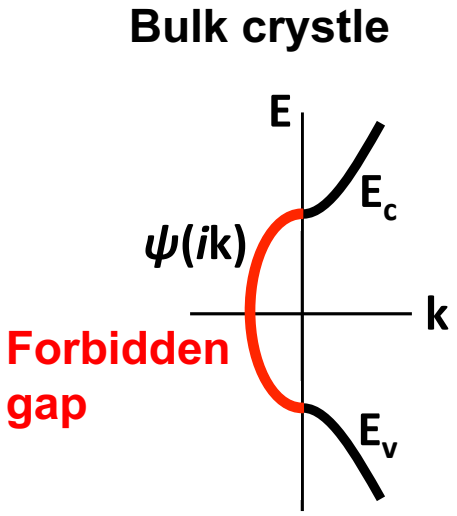


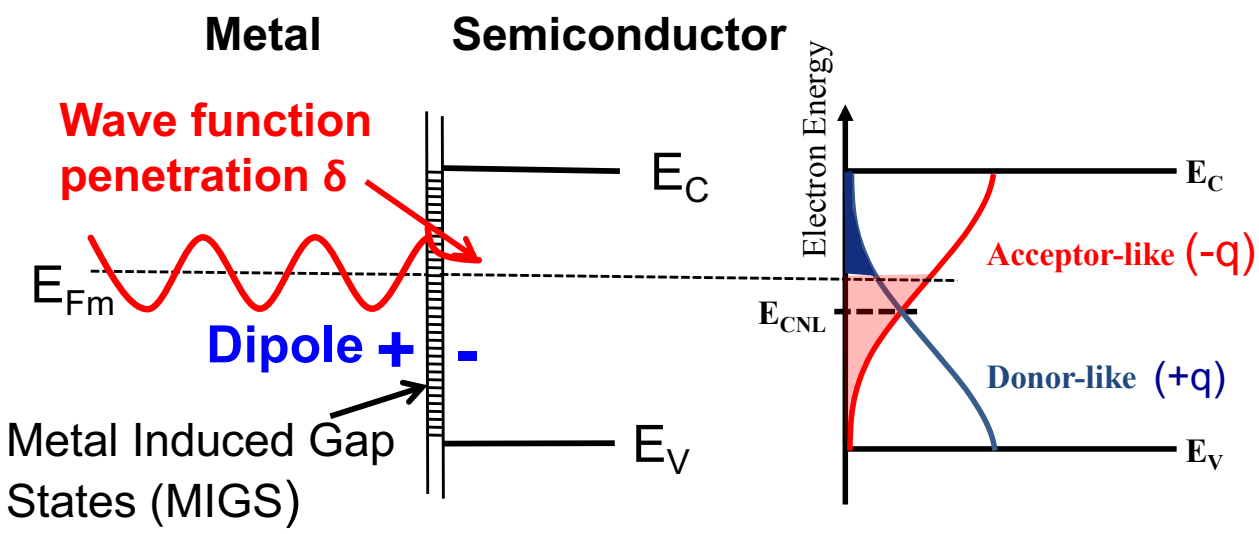
- Assumptions in QM modeling
  - Ideal metal with enough conducting channels (very large M)
  - Realistic band structure of semiconductors (limited M)
  - Ballistic transport between metal and semiconductor - no scattering
  - Zero Schottky barrier, no Fermi level pinning, transmission coefficient T = 1

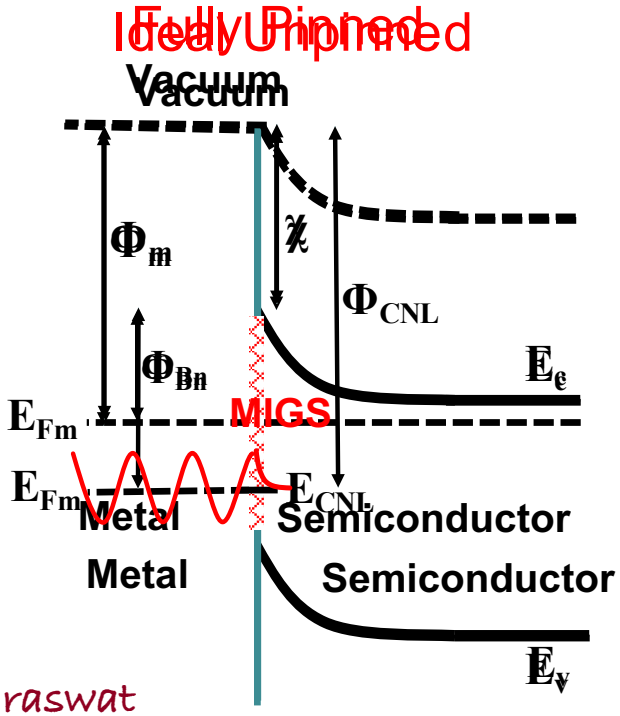
Need zero M/S barrier and heavy doping to lower ρ_c

Maassen, Jeong, Baraskar, Rodwell and Lundstrom, Appl. Phys. Lett. **102,** 111605 (2013)

Fermi Level Pinning ➔ Fixes ϕ_B







MIGS density $D_{IS} = 2/(\pi a^2 E_g)$

Unpinned barrier height $\phi_{Bn} = \phi_m - \chi$

Pinned barrier height

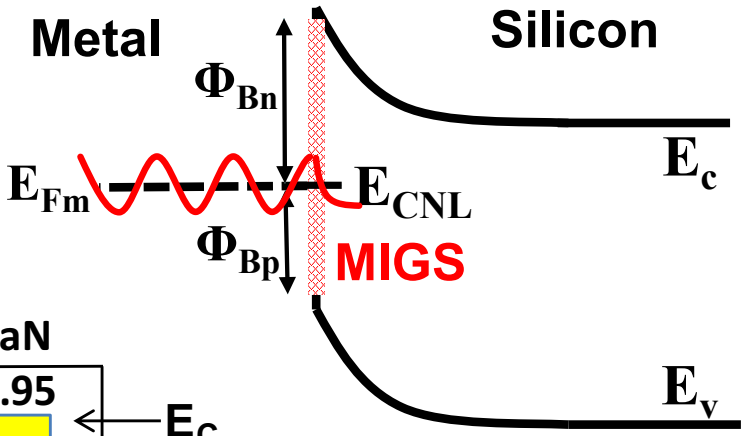
$\phi_{Bn} = S(\phi_m - \phi_{CNL}) + (\phi_{CNL} - \chi)$

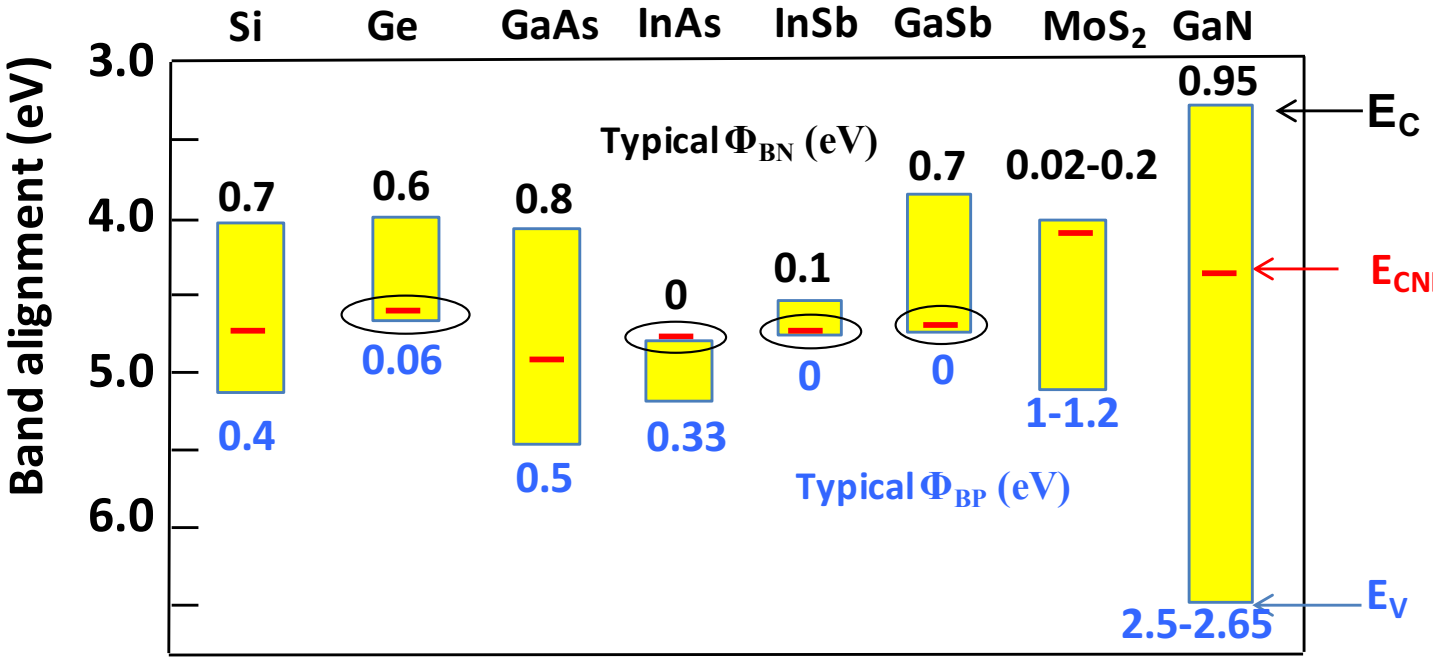
Pinning factor $S = \frac{d\phi_{Bn}}{d\phi_m} = \left[1 + \frac{D_{is} e^2 \delta}{\varepsilon}\right]^{-1}$

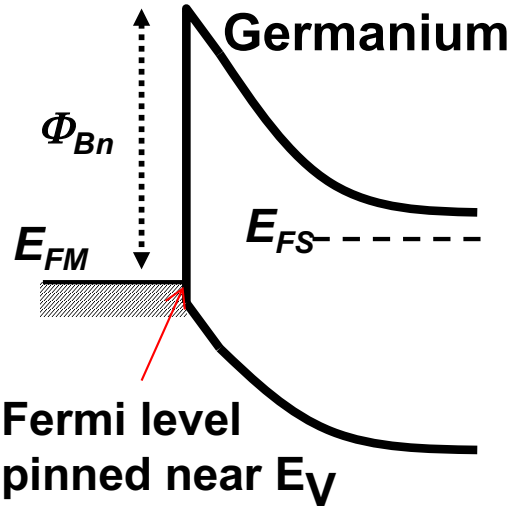
W. Monch, Phys. Rev. Lett., **58,**1260, March 1987.

Fermi Level Pinning ➔ Fixes Barrier Height ϕ_B

- Metal wave function penetration
- Metal induced gap states (MIGS)
- Fermi level pins near E_{CNL}



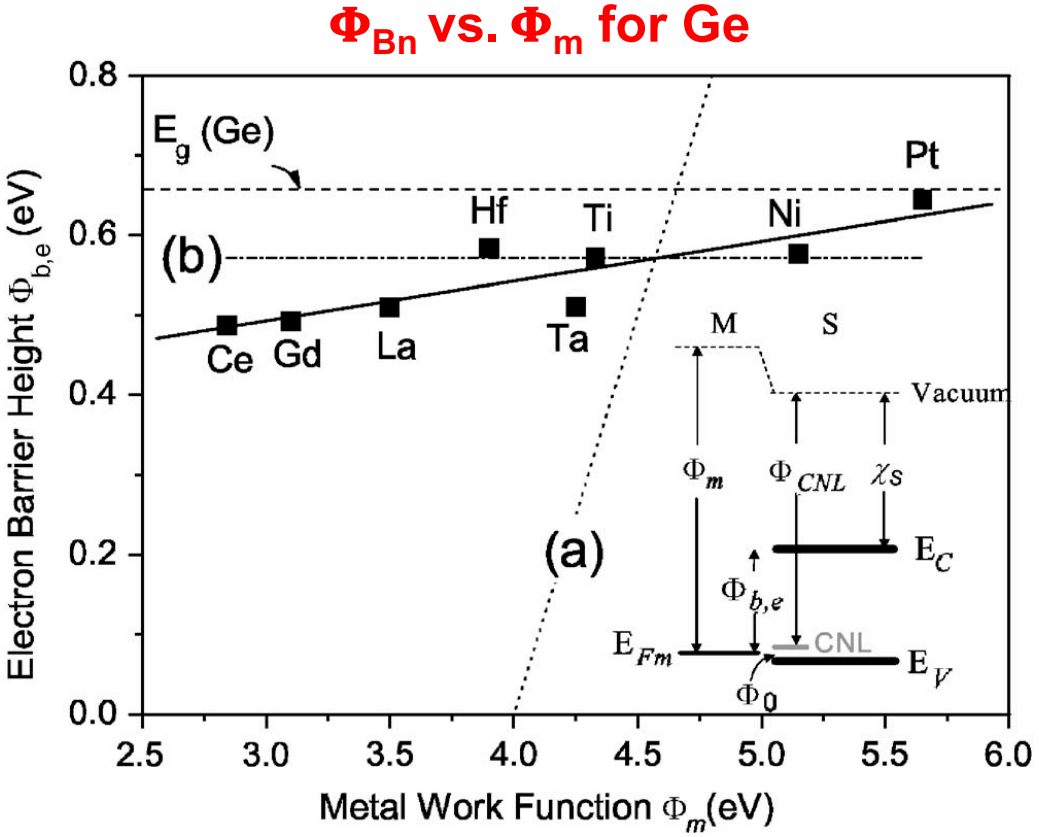




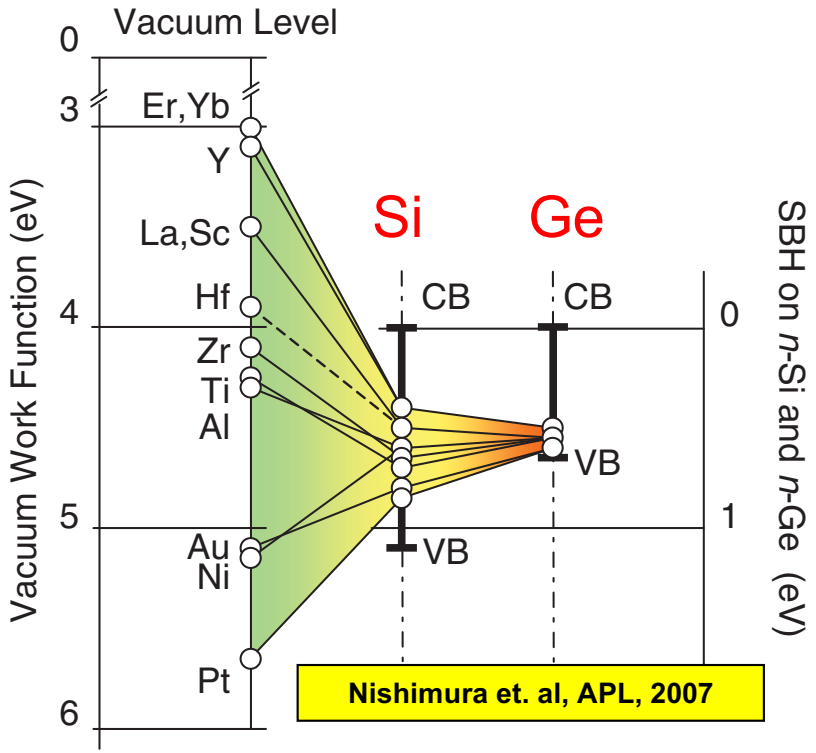
- Most semiconductors have strong pinning
- Excellent ohmic contacts to p-Ge, n-InAs, p-InSb
- Poor contacts to n-Ge, p-InAs, n-InSb, n-GaSb.

$\Phi_{Bp} \approx 0$ *and*
$\Phi_{Bn} \approx E_g$

Pinned Schottky Barrier Height



Dimoulas, APL 89, 252110 (2006)



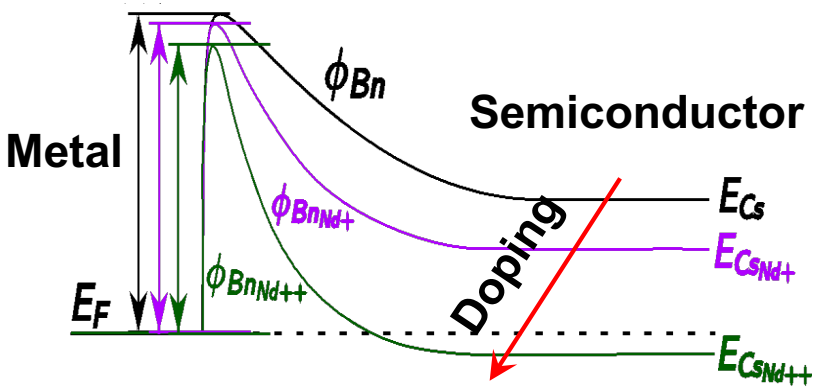
Nishimura et. al, APL, 2007

Ge $\Phi_{Bp} \approx 0$ and $\Phi_{Bn} \approx E_g$

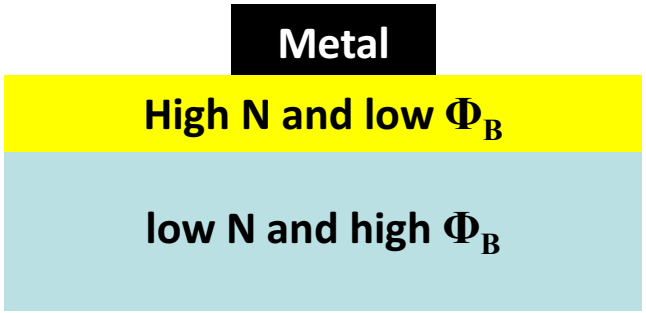
Si $\Phi_{Bp} \approx E_g / 3$ and $\Phi_{Bn} \approx 2E_g / 3$

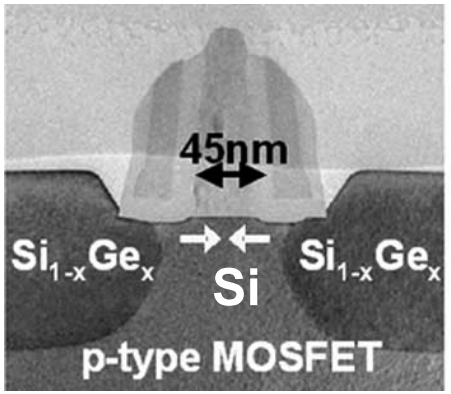
Approaches for Low Resistance Contacts

Decrease barrier thickness by increasing doping.
Best for n-Si, p-Ge, n-InAs

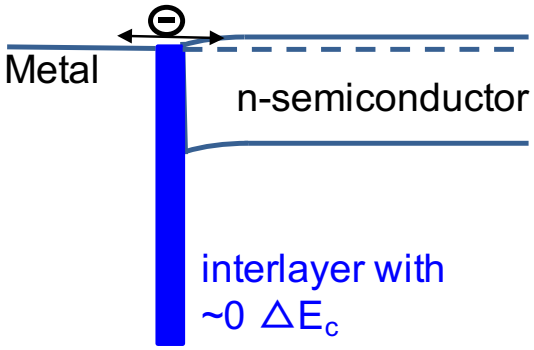


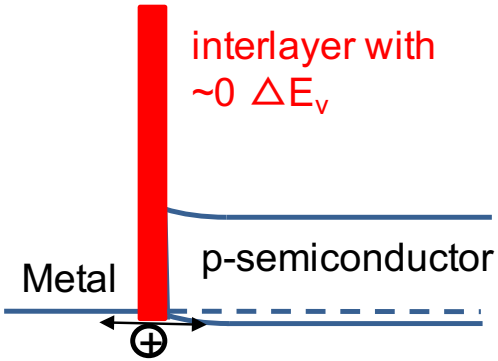
Heterostructures
e.g., p-Ge on p-Si
n-InGaAs on n-Ge



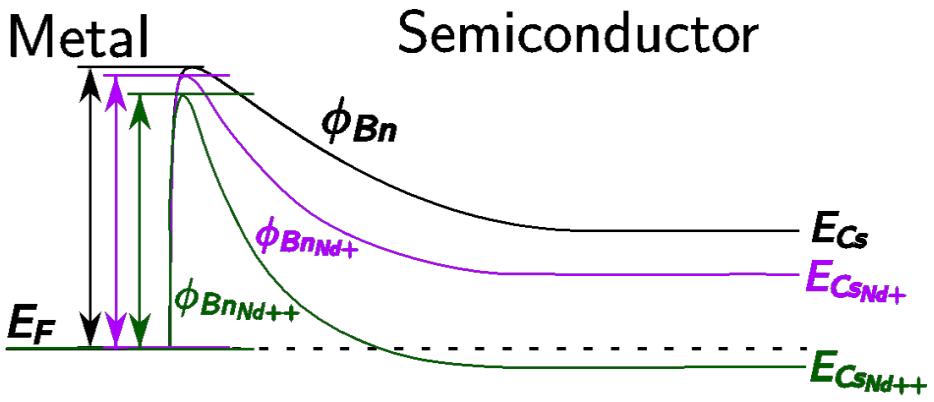


De-pinning Fermi level by metal - interlayer - semiconductor (MIS)
ZnO, ITO for n-contacts
NiO for p-contacts





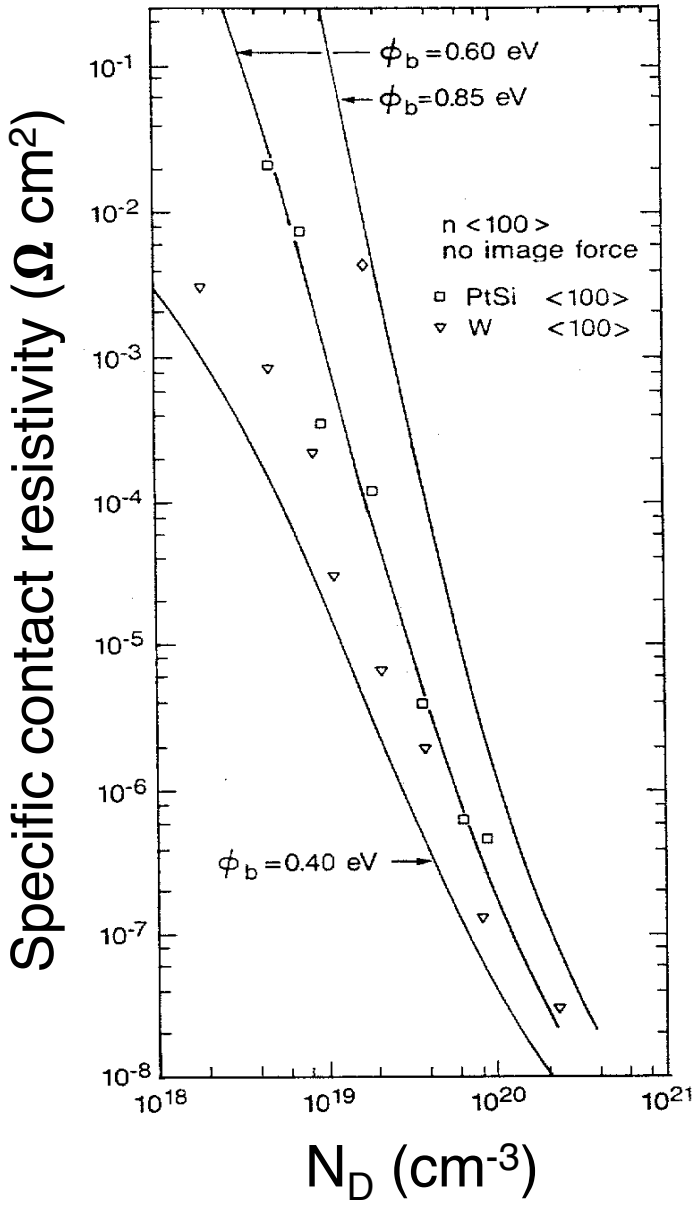
Specific Contact Resistivity of MS Contacts to Si



$$\rho_c = \rho_{co} \exp\left(\frac{2\phi_B}{q\hbar}\sqrt{\frac{\varepsilon_s m^*}{N}}\right) \quad ohm - cm^2$$

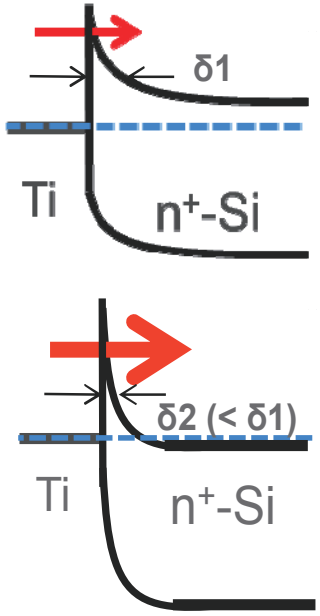
Specific contact resistivity ⬇

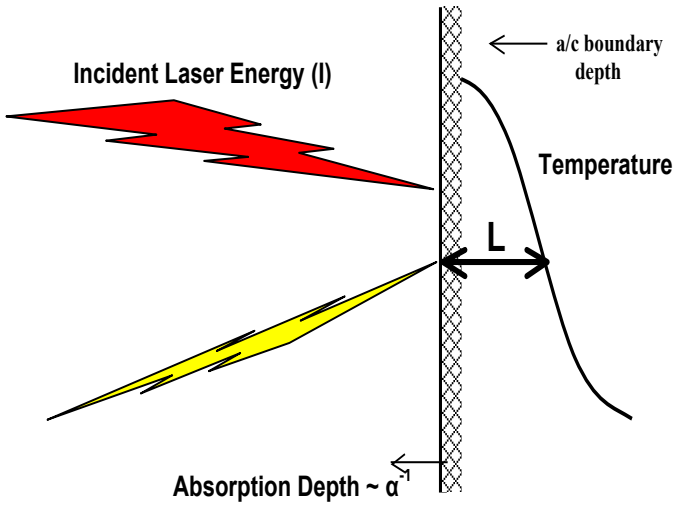
- **As doping density ⬆**
- **Barrier height ⬇**
- **Need to reduce barrier height ϕ_B and increase active dopant density N**

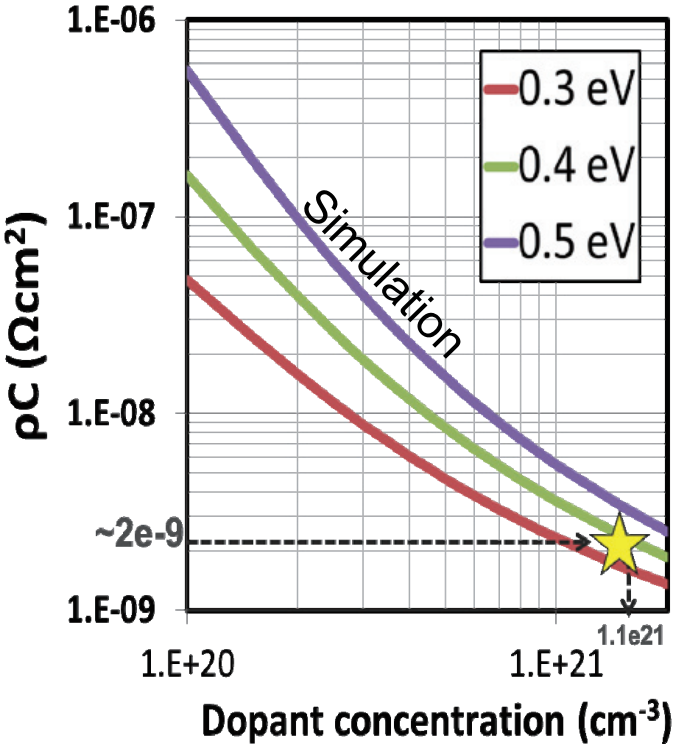


S. Swirhun, Electrochem. Soc. 1988

Low ρ_C by heavy doping in contacts to n-Si





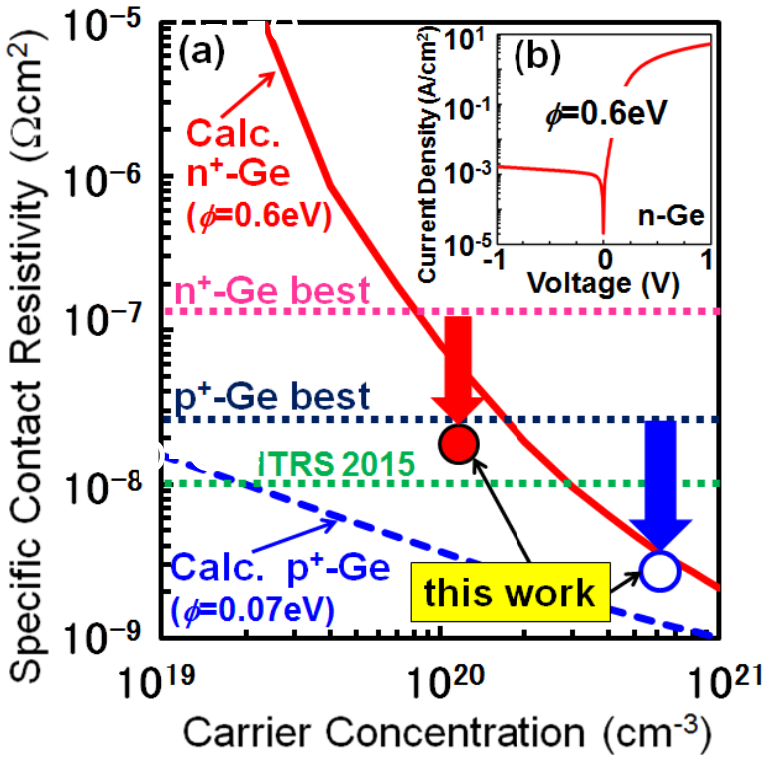


- Heavy doping
- Reduced barrier
- Higher tunneling

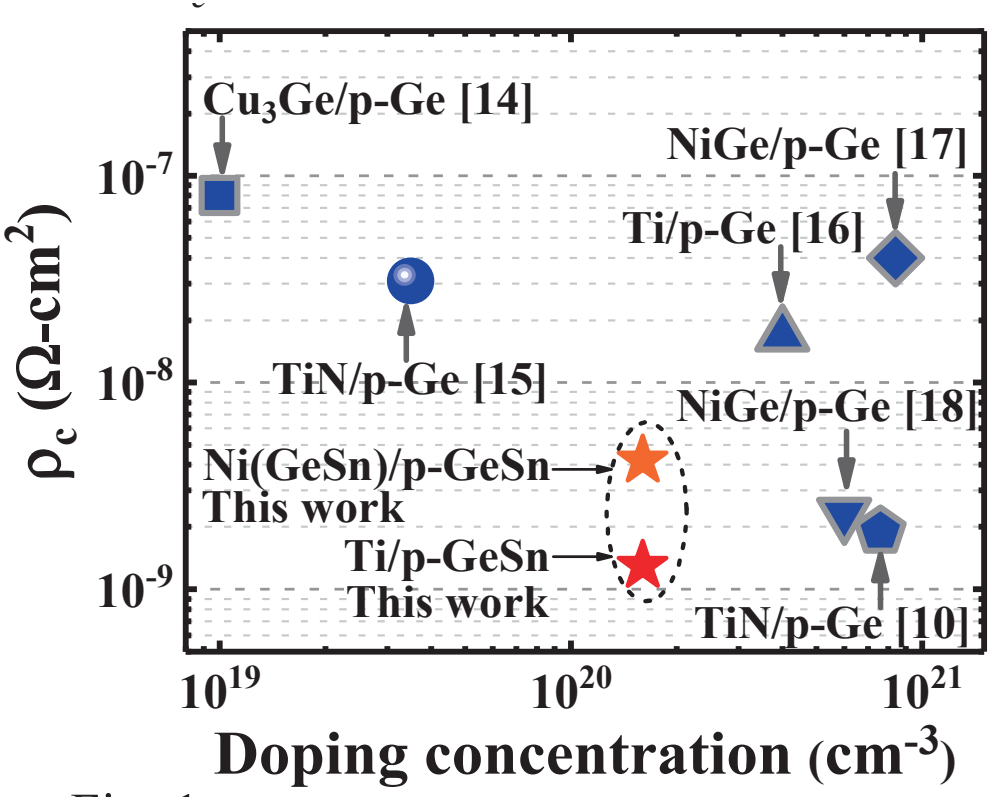
C.-N. Ni, et al., 2015 Symposium on VLSI Technology

- Conventional doping methods give $\rho_c \sim 10^{-8}$ ohm.cm^2
- It is possible to get *metastable* electrically active doping density higher than the equilibrium doping density > 10^{21} cm^{-3}
- Low contact resistivity has been demonstrated in n-Si
- Thermal stability of laser annealing is problematic?

Low ρ_C by heavy doping in contacts to p-Ge/GeSn



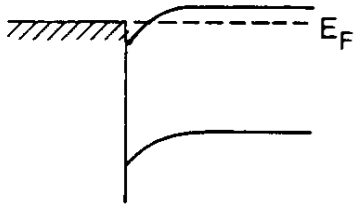
H. Miyoshi, et al., 2014 Symp. VLSI Tech.



Y. Wu, et al., 2017 Symp. VLSI Tech.

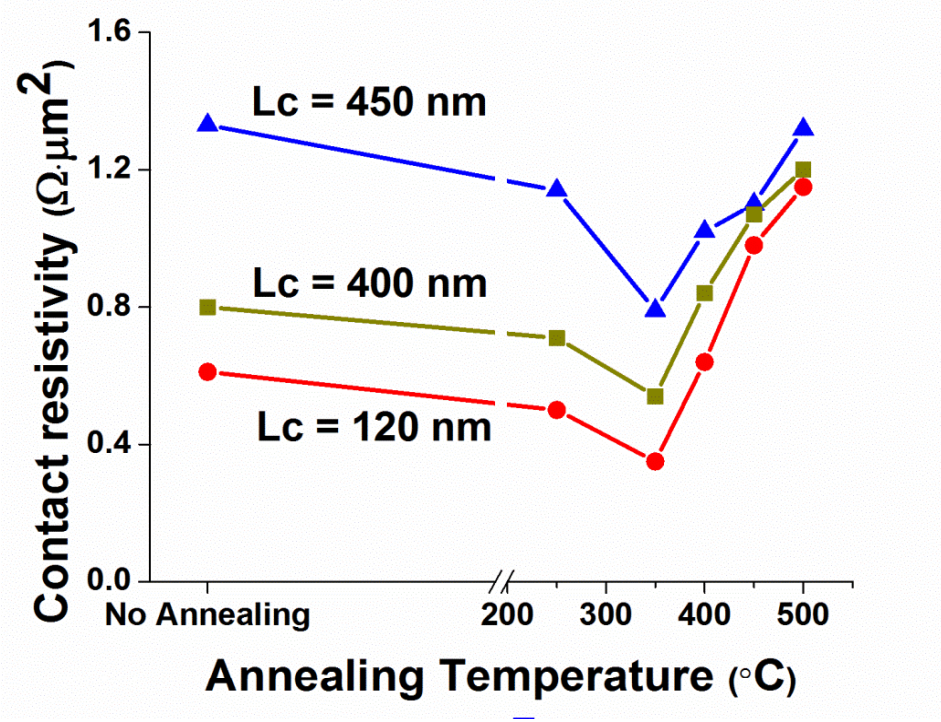
- p-Ge: ρ_c = 2x10^{-9} Ωcm^2
- p-GeSn: ρ_c = 1.2x10^{-9} Ωcm^2 with Ga doping
- N-Ge: Laser anneal enhances n = 1.9x10^{20}cm^{-3} and ρ_c =1.9x10^{-8}Ωcm^2
  - ➢ ρ_c to n-Ge still higher than to p-Ge

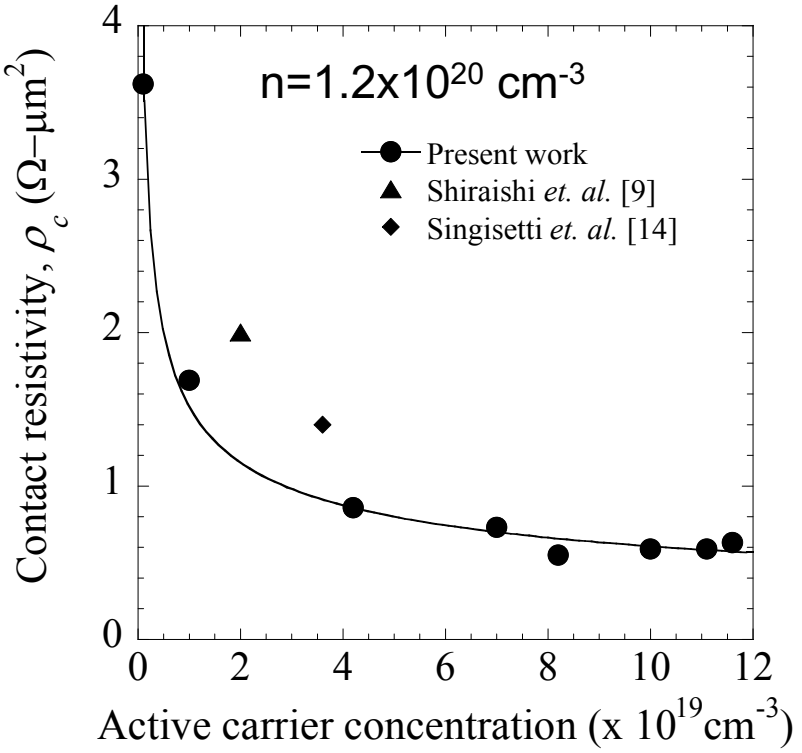
Contacts to III-V NMOS (InGaAs)



- Fermi level pins in the conduction band ➔ $\Phi_{BN} \sim 0$
- With moderate doping it is possible to get low ρ_c

Mo/InGaAs





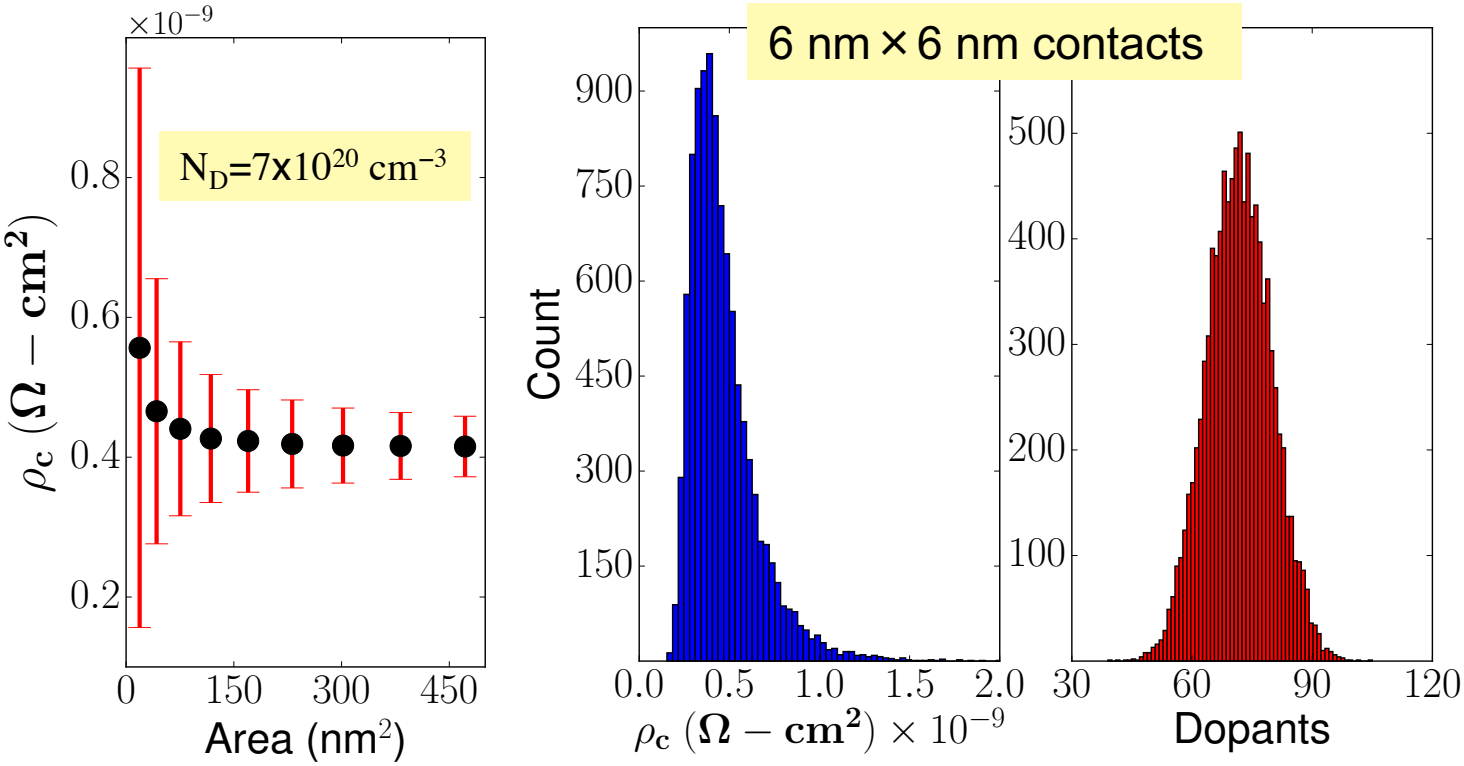
ρ_c= ~6.7x10^{-8} ohm-cm^2

J. A. del Alamo, et al., IEDM 2013

ρ_c (min) ~5x10^{-9} ohm-cm^2

A. Baraskar, et al., 2010 IPRM

Statistical Variation in Nanoscale Contacts in Si

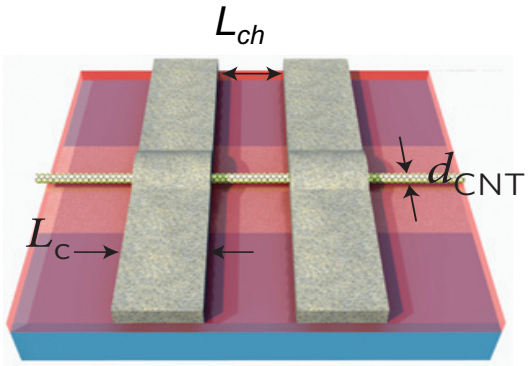


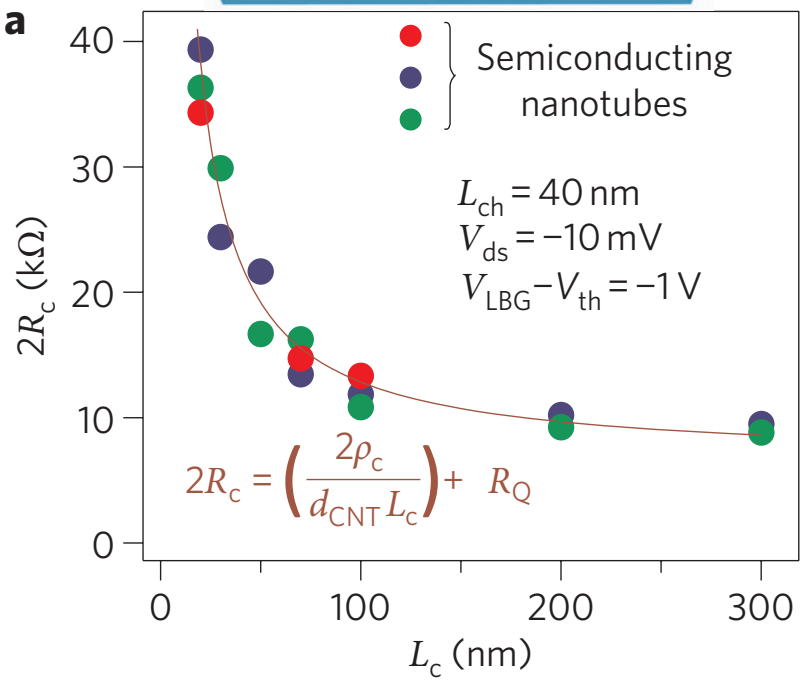
- Si with $N_D = 7x10^{20}$ cm^{-3}
- Contact resistivity shows increasing mean and variance as dimensions decrease
- The empirical distribution of ρ_c in 6 nm × 6 nm contacts shows high variance and skew.

G. Shine & K. Saraswat, IEEE TED, Sept. 2017.

Contacts to Carbon Nanotubes

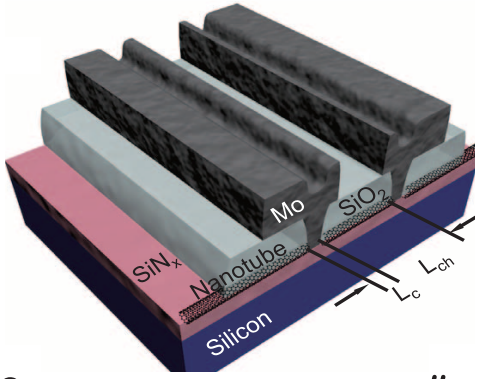
Top contact

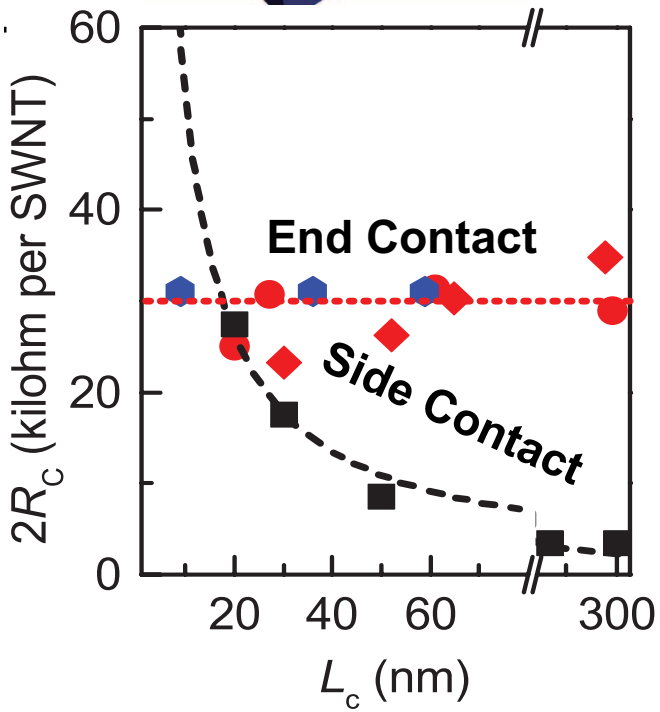




Franklin and Chen, Nature Nanotech. Dec. 2010

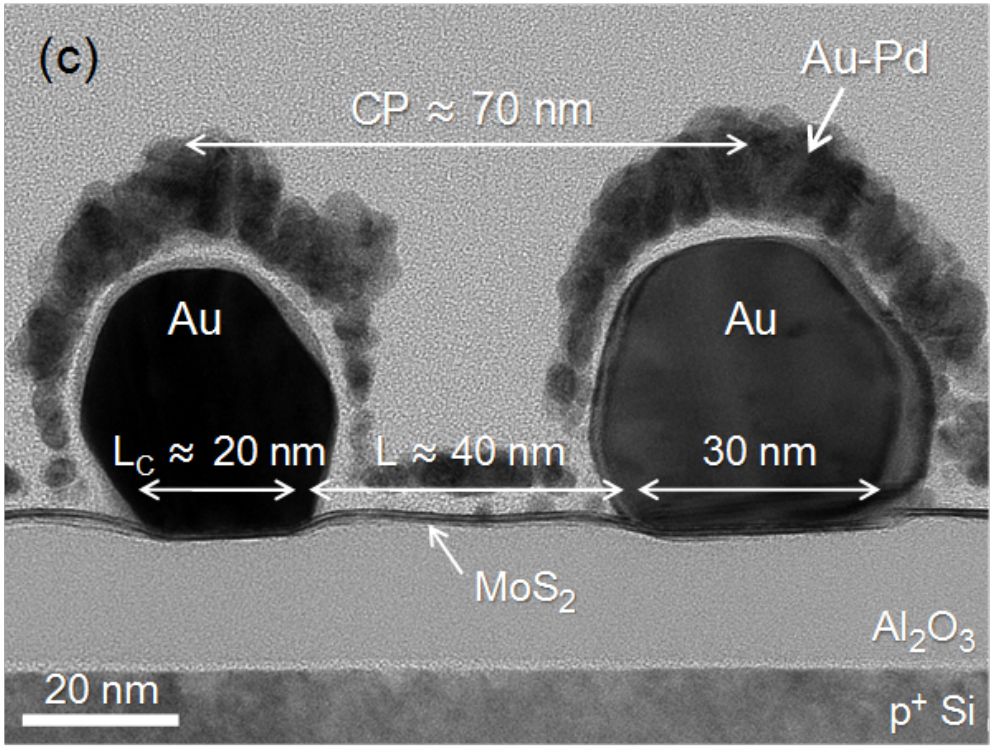
Side contact

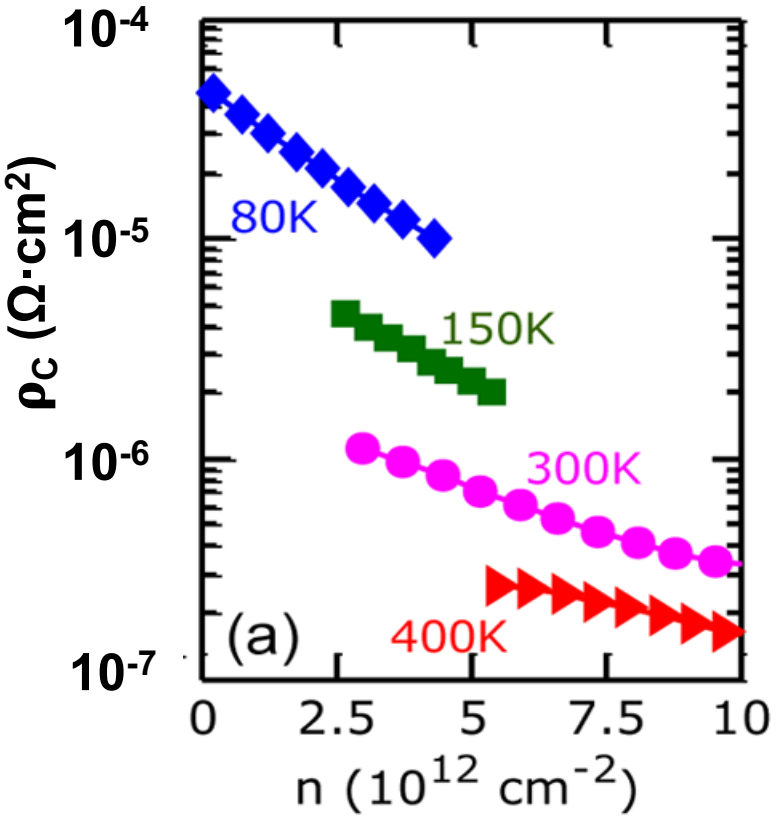




Qing Cao, et al., Science, Oct. 2015

Contacts to MoS_2



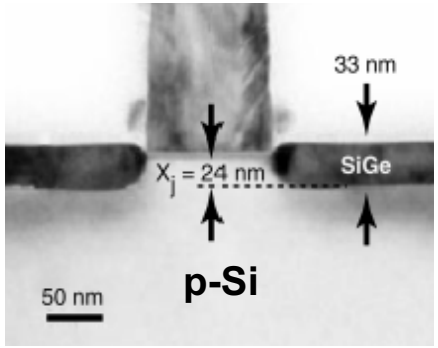


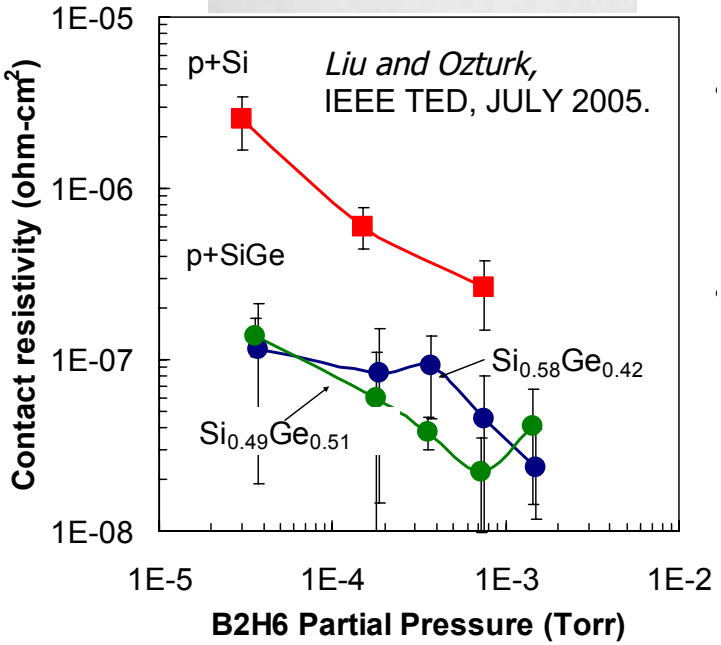
- **Smallest MoS_2 contacts to date**
  - L = 40 nm and variable contacts (L_C = 20 to 100 nm)
  - Smallest contact pitch CP ~ 70 nm, **equivalent to "14 nm" tech. node**
- **Contacts are limiting** the performance of small MoS_2 transistors

C. English, G. Shine, V. Dorgan, K. Saraswat, E. Pop, *Nano Lett.* 16, 3824 (2016)

Heterostructure Contacts: p-Si and n-Ge

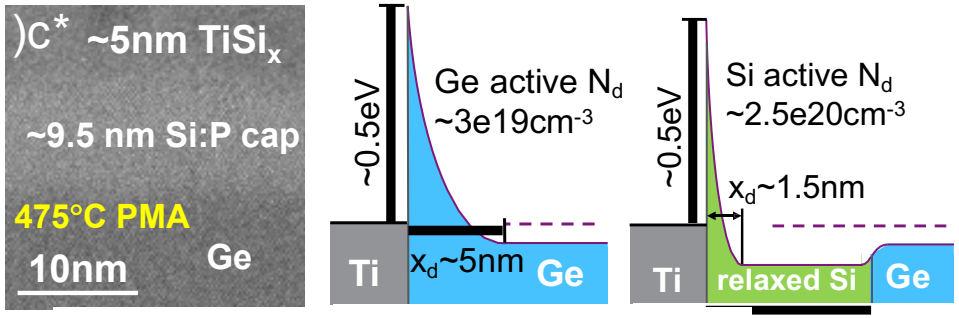
p-SiGe on p-Si

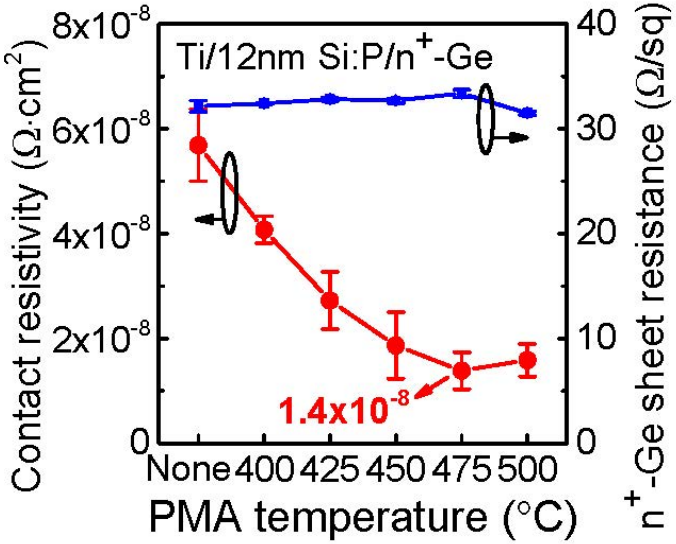




- B activation higher in $Si_{1-x}Ge_x$
- lower ϕ_{Bp} > reduction in ρ_c
- Used widely in Si PMOS

n-Si on n-Ge

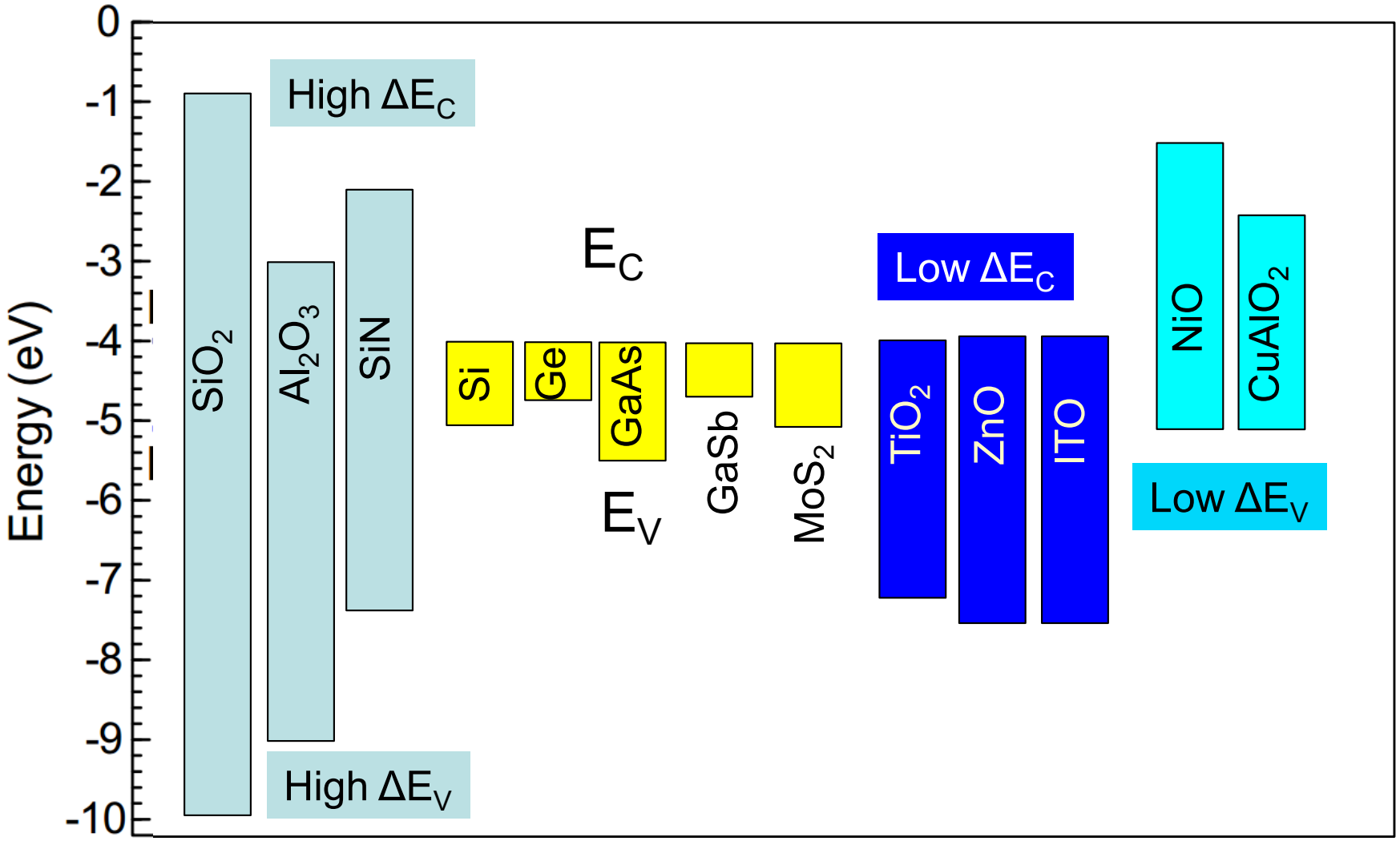




Hao Yu, et al., IEDM 2016

- P activation higher in Si than in Ge
- lower ϕ_{Bn} > reduction in ρ_c
- Potential use in Ge NMOS

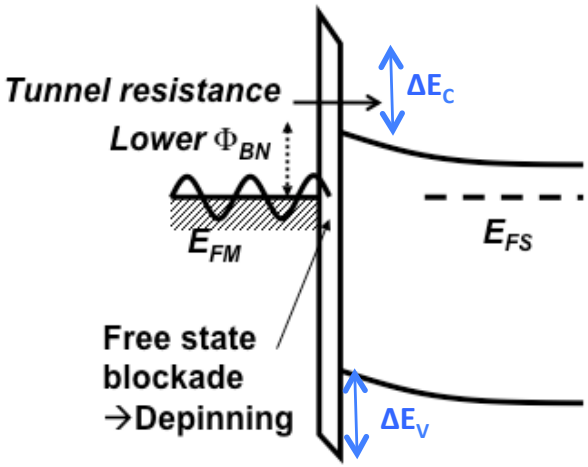
MIS Considerations: Band Alignment



Low band offset needed to minimize tunneling resistance

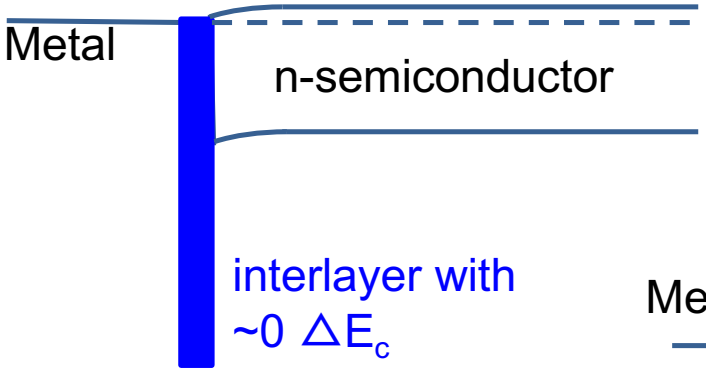
Ideal MIS Contacts

(a) Metal / insulator / semiconductor contact



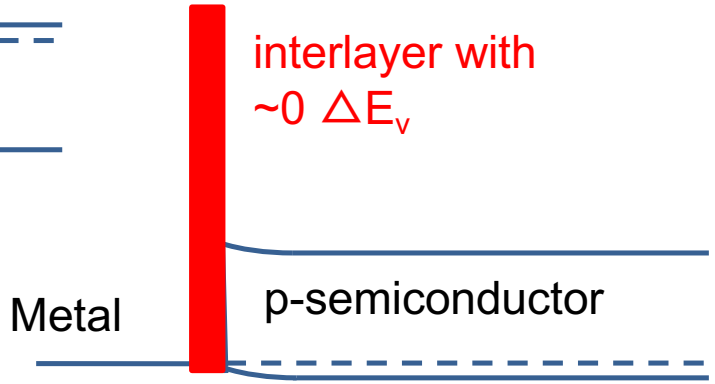
SiO_2
Al_2O_3

(b) Metal / ~0ΔE_c interlayer/ n-semiconductor



TiO_2
ZnO
ITO

(c) Metal / ~0ΔE_v interlayer/ p-semiconductor

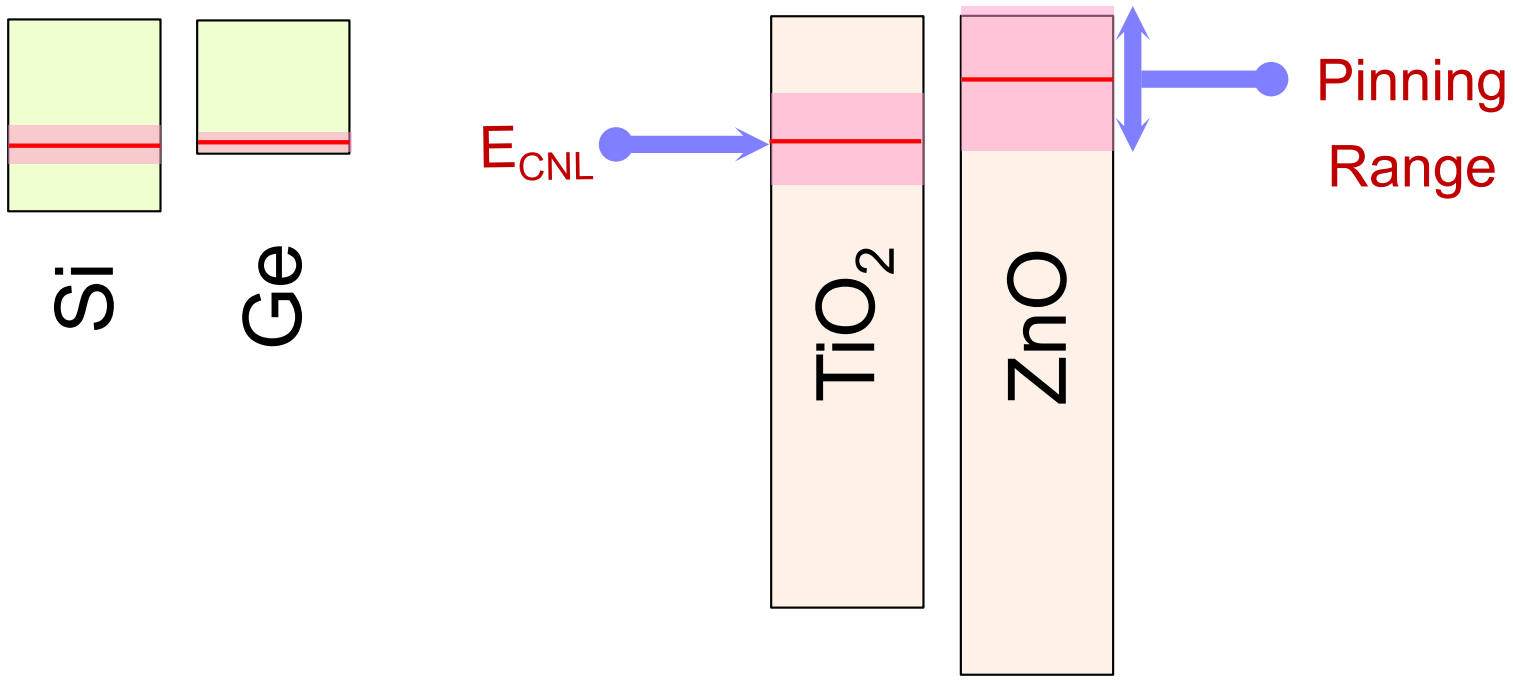


NiO
$CuAlO_2$

- Large band offset causes tunnel resistance
- Choose interlayer with ~0 band offset with semiconductor, pinning factor S closer to 1 and E_{CNL} closer to band edge
- Choose metal with workfunction to align it with the band edges of interlayer and semiconductor

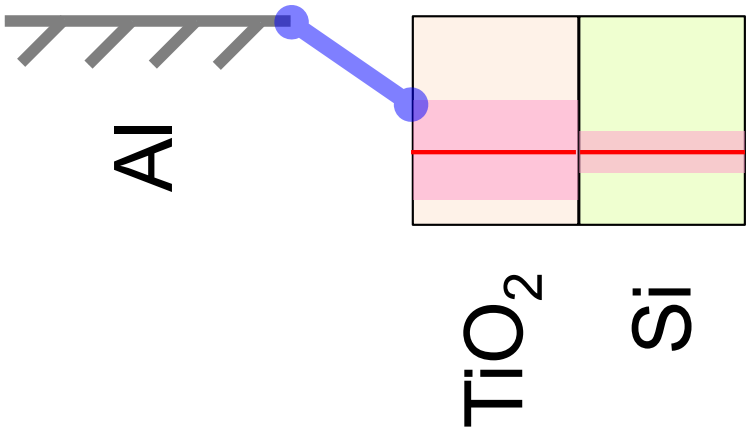
Charge Neutrality Levels

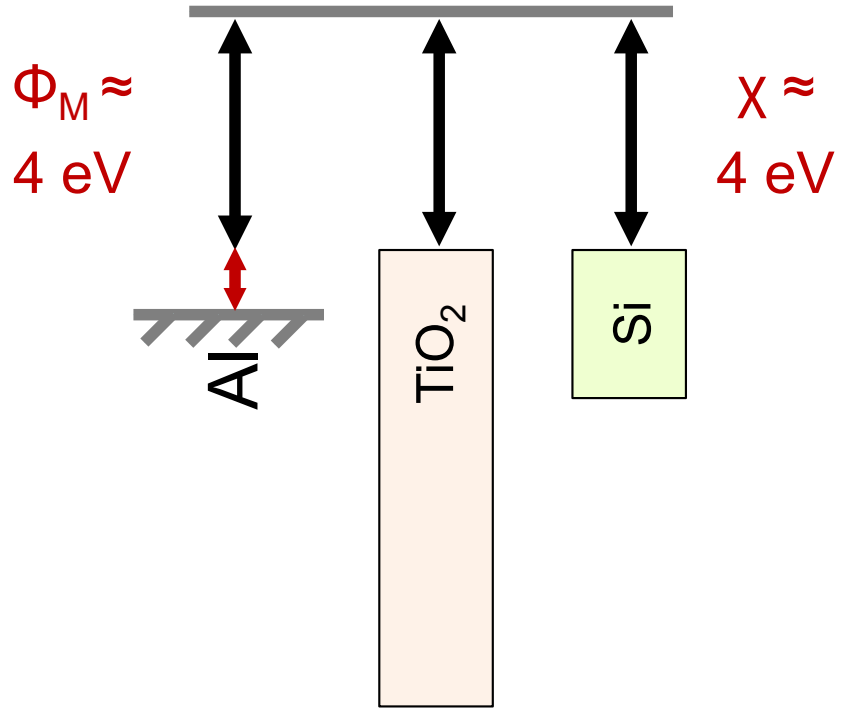
- Band offsets are only part of the story
- ZnO has pinning near the conduction band



Fermi Level Repinning: TiO_2

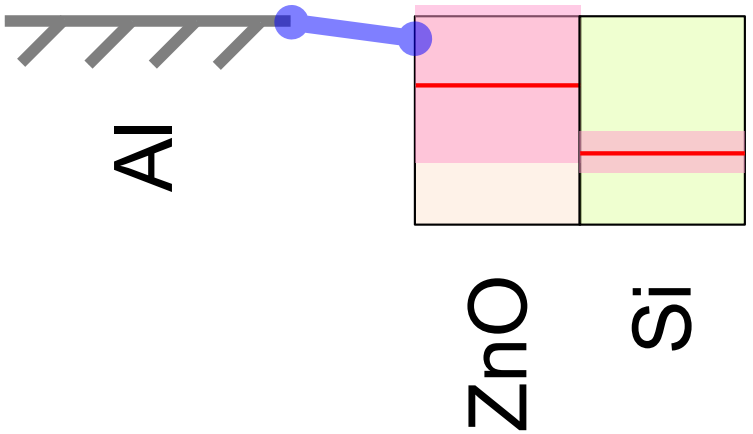
- Charge neutrality level is higher up
- More responsive to low metal work functions

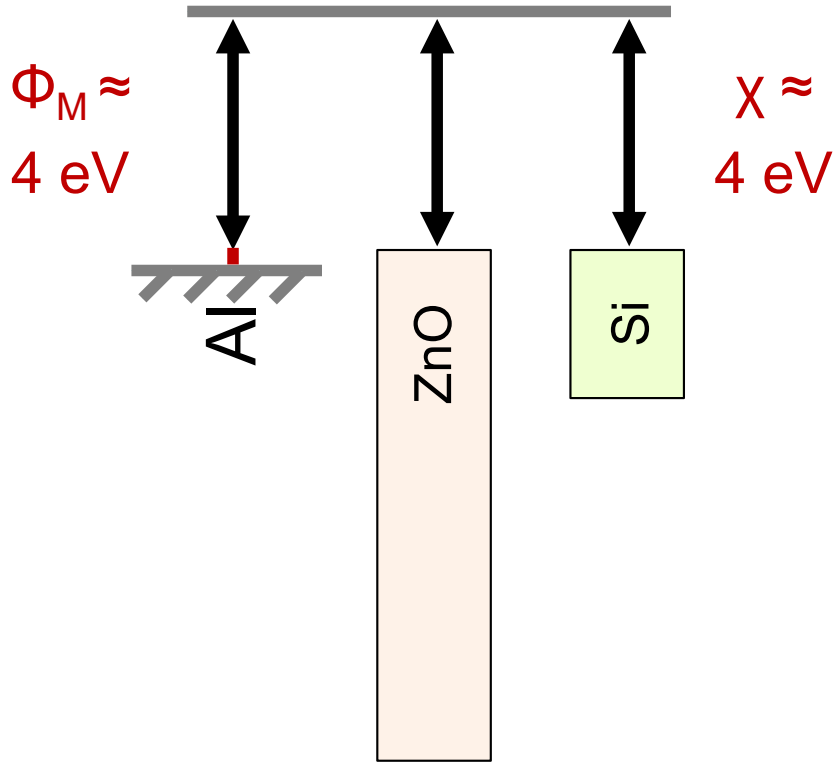




Fermi Level Repinning: ZnO

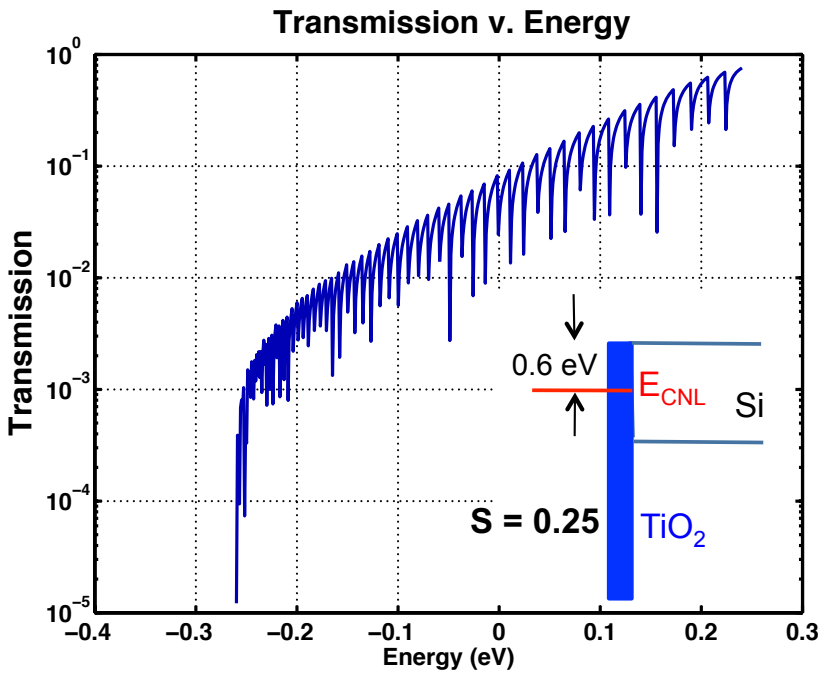
- Charge neutrality level is higher up
- More responsive to low metal work functions



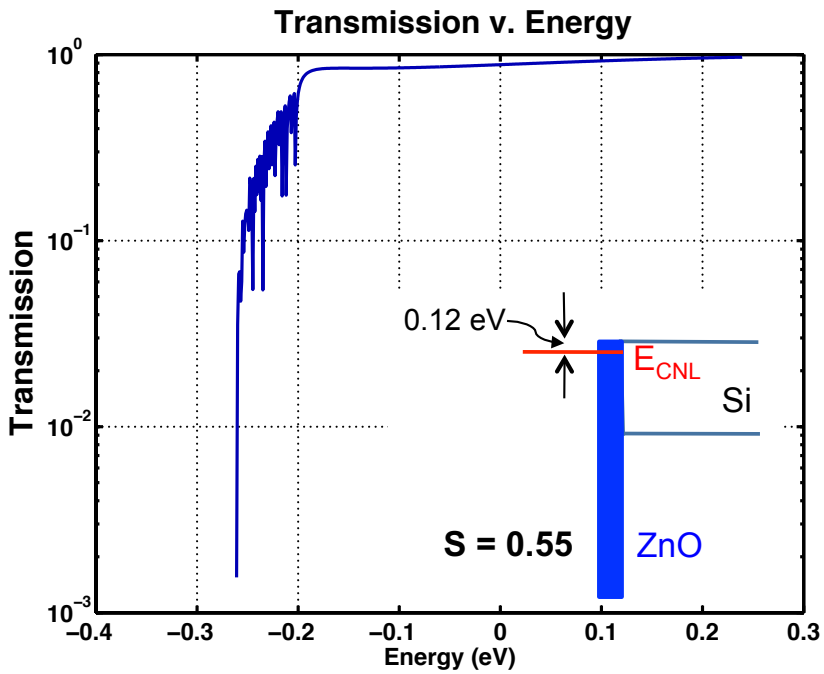


Transmission in MIS Contacts: TiO_2 vs. ZnO

TiO_2



ZnO

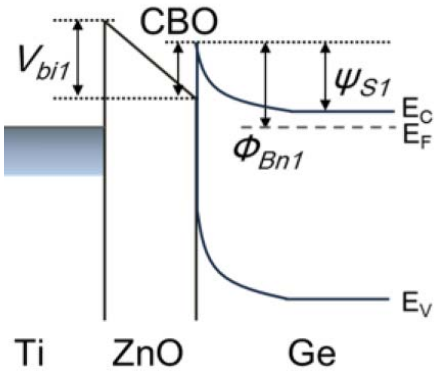


- 10^{-9} Ω · cm^2 requires T ~ 0.1 or higher near E_F
- ZnO can achieve this and comes within ~2x of the Landauer limit
- ZnO has lower barrier height with metal from better pinning location (E_{CNL} close to conduction band) and is more responsive to metal work function (higher S factor)

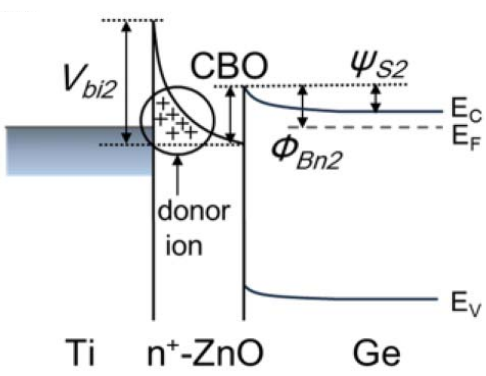
Metal/ZnO/n⁺-Ge Contacts: Simulations

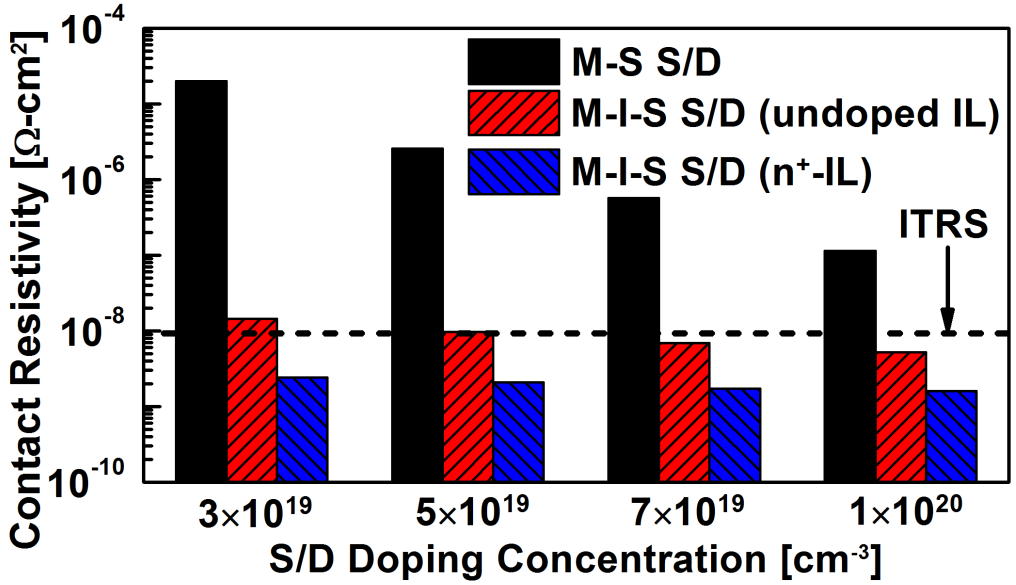
ZnO Interlayer n =1x10^{21} cm^{-3}

Undoped ZnO



Doped N+ ZnO





J.-K. Kim, ……..,K. Saraswat, H. Y. Yu, IEEE Elec. Dev. Lett. Dec. 2014

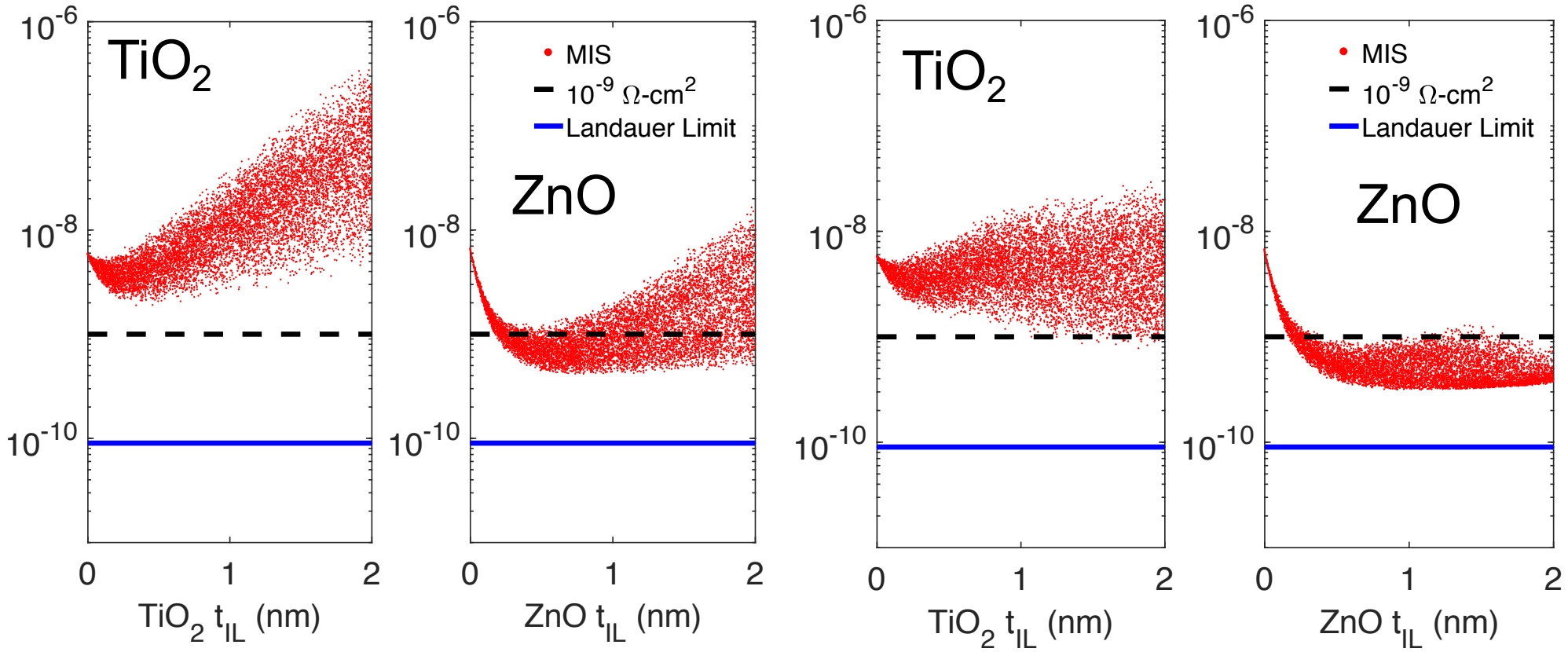
- ZnO and ITO can be heavily doped to n ~10^{21} cm^{-3} ➡ low ρ_c
- Ge S/D doping in most of the published work around 1-3 x10^{19} cm^{-3}
- With higher active doping in Ge ρ_c ~ 2x10^{-9} Ω.cm^2 can be achieved

Simulated ρ_c for MIS Contacts to n-Si

Effect of interlayer parameters variation

Interlayer undoped

Interlayer doping of 3×10^{20} cm^{-3}

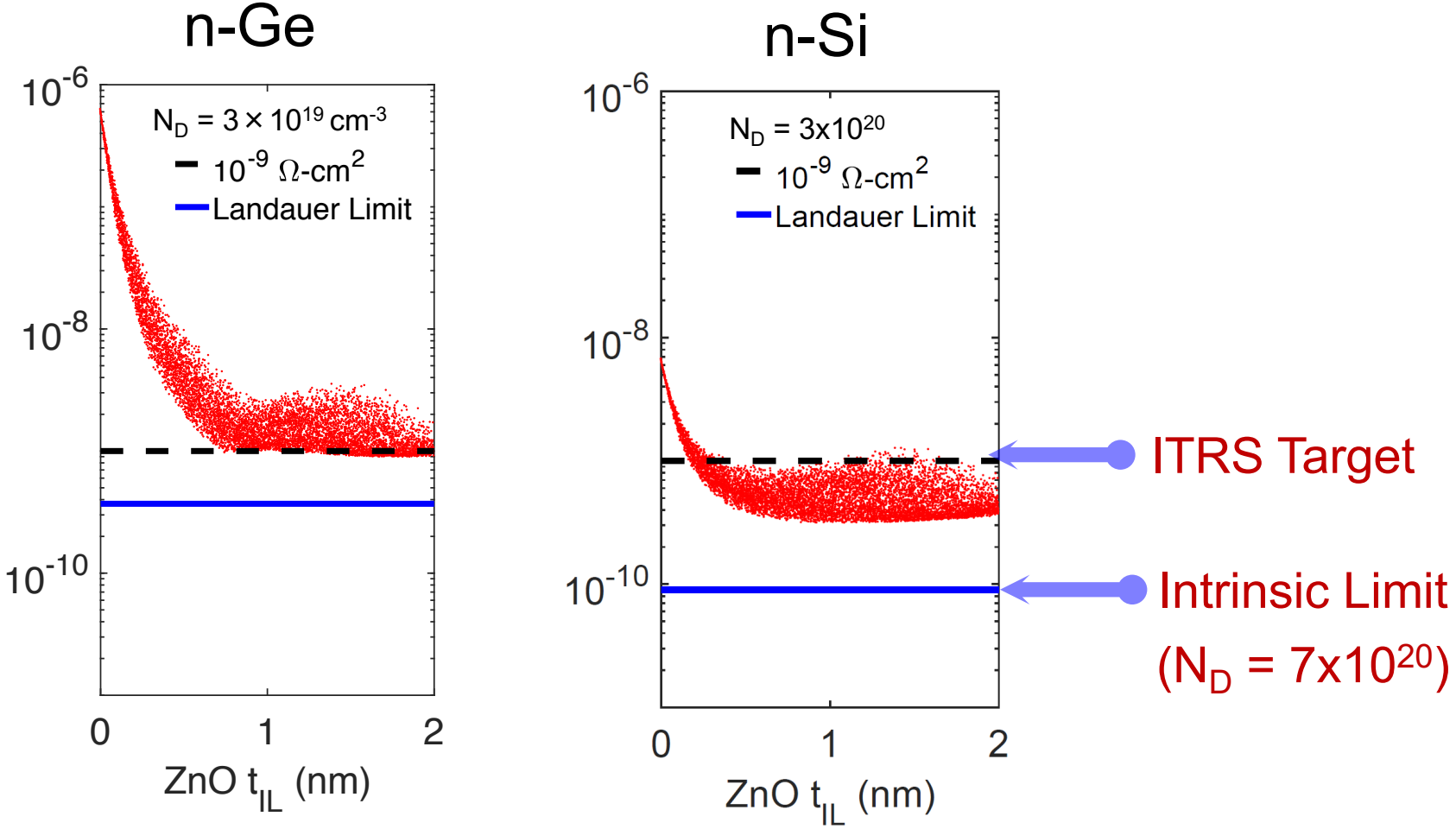


- Silicon $N_D = 3 \times 10^{20}$ cm^{-3}
- TiO_2 unsuitable for MIS contacts to n-Si
- ZnO is a good candidate togive low ρ_c

G. Shine & K. Saraswat, IEEE TED, Sept. 2017.

Simulated ρ_c for MIS Contacts

Effect of interlayer parameters variation



- ZnO Interlayer doping of $3x10^{20}$ cm^{-3}
- Even with low Ge doping of $3x10^{19}$ cm^{-3} ZnO can give low ρ_c and small variation

G. Shine & K. Saraswat, IEEE TED, Sept. 2017.

Conclusion

- ☹ Contact resistance a major impediment to continued scaling
- ☺ Several methods to reduce contact resistance show promise
  - Heavy doping, heterostructurs, depinning Fermi level by MIS
- ☺ For future nodes the materials giving lowest contact resistance may be the choice for MOSFETs.