High Doping Effects on *in-situ* Ohmic Contacts to n-InAs

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Outline

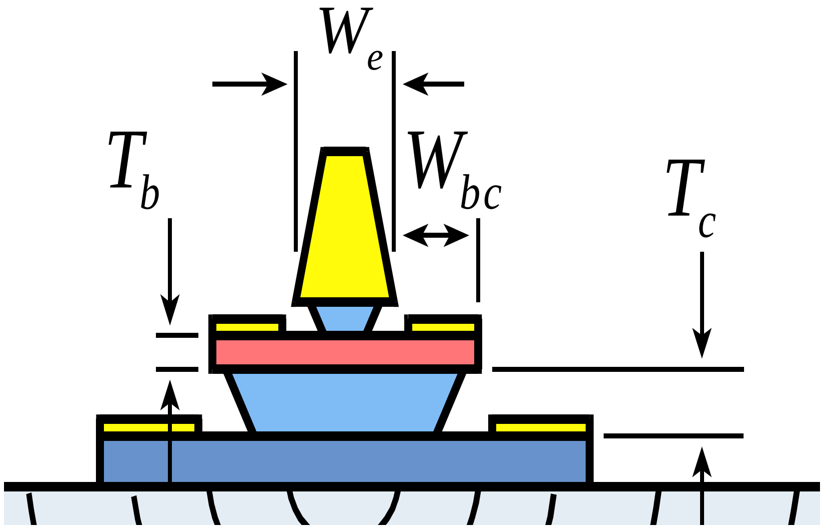
- Motivation
  - Low resistance contacts for high speed HBTs
  - Approach
- Experimental details
  - Contact formation
  - Fabrication of Transmission Line Model structures
- Results
  - InAs doping characteristics
  - Effect of doping on contact resistivity
  - Effect of annealing
- Conclusion

Device Bandwidth Scaling Laws for HBT

To double device bandwidth*:

- Cut transit time 1:2
- Cut RC delay 1:2

→ Scale contact resistivities by 1:4



$$\frac{1}{2\pi f_\tau} = \tau_{in} + RC$$

$$f_{max} = \sqrt{\frac{f_\tau}{8 \cdot \pi \cdot (R_{bb} \cdot C_{cb})_{eff}}}$$

*M.J.W. Rodwell, IEEE Trans. Electron. Dev., 2001

InP Bipolar Transistor Scaling Roadmap

Emitter:	512	256	128	64	32	width (nm)
	16	8	4	2	1	access ρ, (Ω·μm²)
Base:	300	175	120	60	30	contact width (nm)
	20	10	5	2.5	1.25	contact ρ (Ω·μm²)
f_t:	370	520	730	1000	1400	GHz
f_{max}:	490	850	1300	2000	2800	GHz

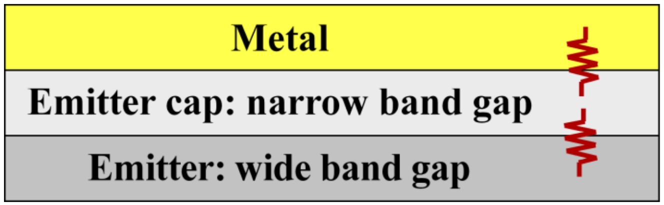
- Contact resistivity serious barrier to THz technology

Less than 2 Ω-μm² contact resistivity required for simultaneous THz f_t and f_{max}*

*M.J.W. Rodwell, CSICS 2008

Emitter Ohmics-I

Metal contact to narrow band gap material

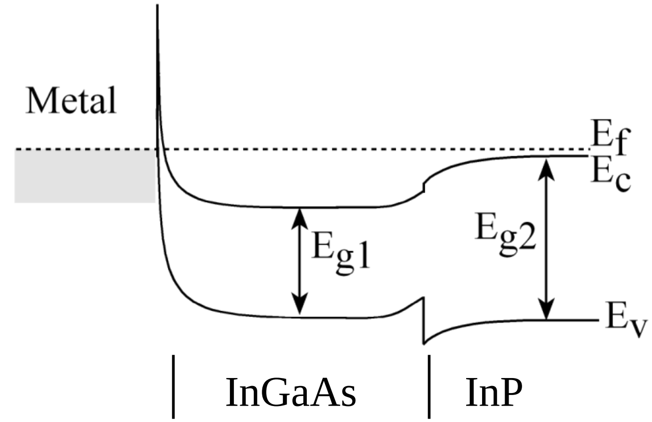


Narrow band gap material:

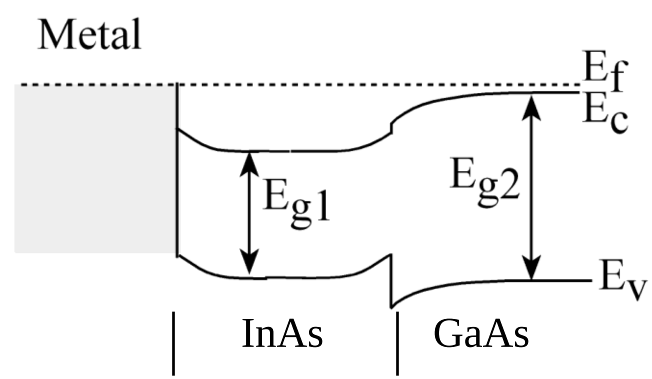
- lower Schottky barrier height
- lower m* → easier tunneling across Schottky barrier

Better ohmic contacts with narrow band gap materials[1,2]

1. Fermi level pinned in the band-gap



2. Fermi level pinned in the conduction band

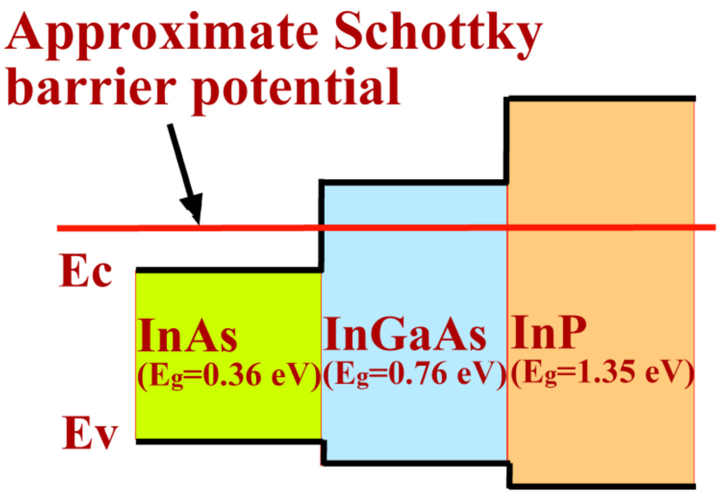


1.Peng *et. al.*, *J. Appl. Phys.*, 64, 1, 429–431, (1988).
2.Shiraishi *et. al.*, J. Appl. Phys., **76**, 5099 (1994).

Emitter Ohmics-II

Choice of material:

- $In_{0.53}Ga_{0.47}As$: lattice matched to InP
  - E_f pinned 0.2 eV below conduction band[1]
- Relaxed InAs on $In_{0.53}Ga_{0.47}As$
  - E_f pinned 0.2 eV above conduction band[2]



Other considerations:

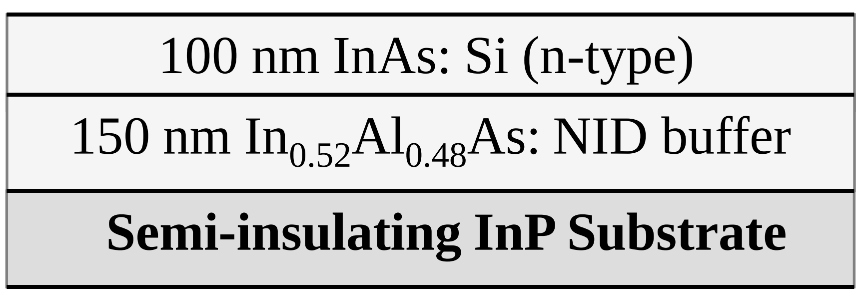
- Better surface preparation techniques
  - For efficient removal of oxides/impurities
- Refractory metal for thermal stability

1. J. Tersoff, *Phys. Rev. B* **32**, 6968 (1985)
2. S. Bhargava *et. al.*, *Appl. Phys. Lett.*, **70**, 759 (1997)

Thin Film Growth

Semiconductor layer growth by Solid Source Molecular Beam Epitaxy (SS-MBE): n-InAs/InAlAs

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



In-situ Metal Contacts

In-situ molybdenum (Mo) deposition

- E-beam chamber connected to MBE chamber
- No air exposure after film growth

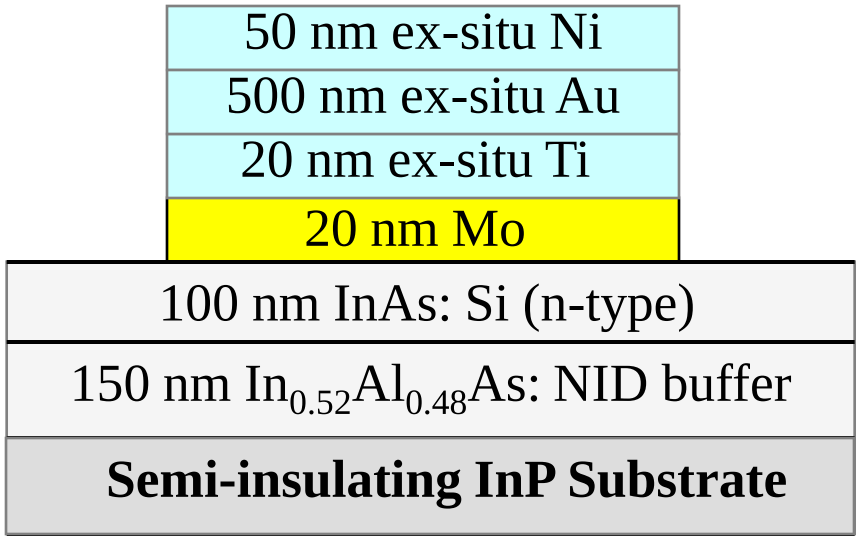
Why Mo?

- Refractory metal (melting point ~ 2620 ^{o}C)
- Easy to deposit by e-beam technique
- Easy to process and integrate in HBT process flow

20 nm Mo
100 nm InAs: Si (n-type)
150 nm $In_{0.52}Al_{0.48}As$: NID buffer
Semi-insulating InP Substrate

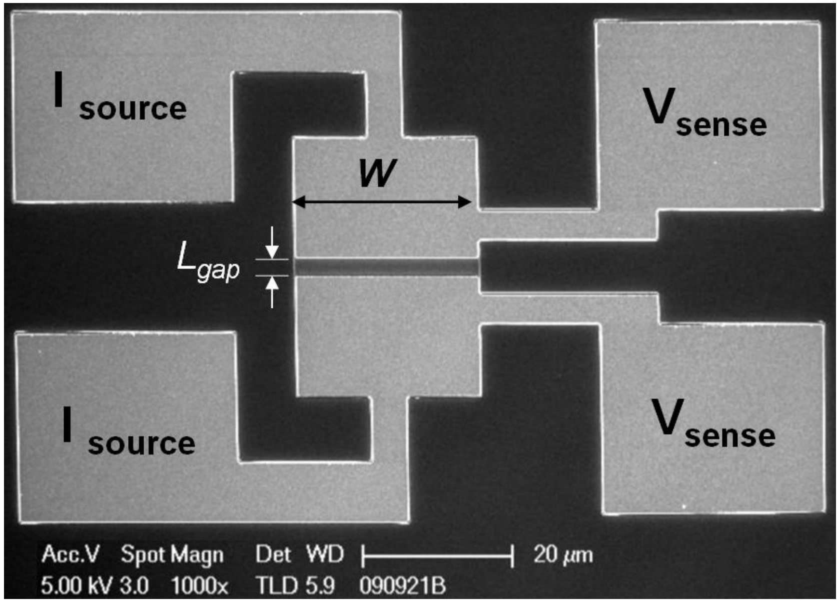
TLM (Transmission Line Model) Fabrication

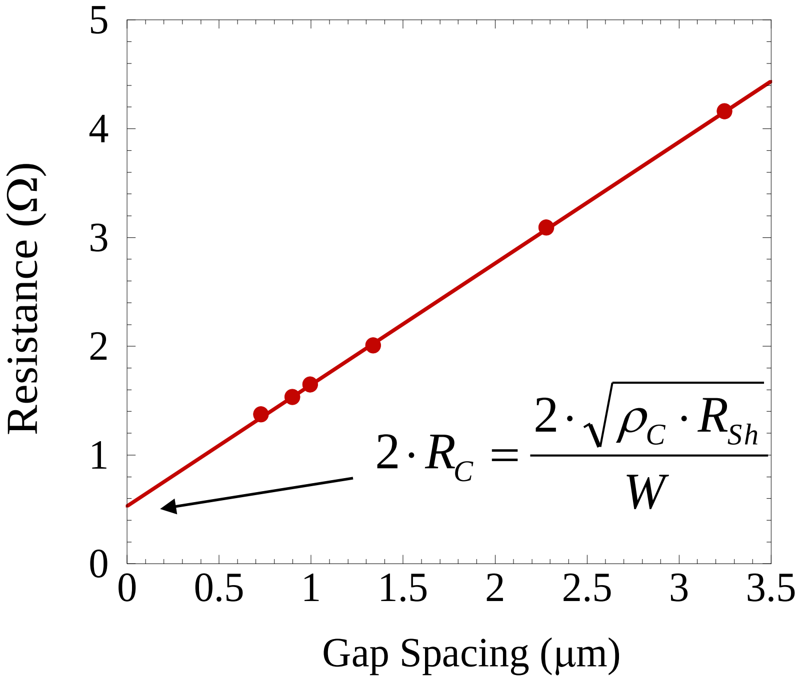
- E-beam deposition of Ti, Au and Ni layers
- Samples processed into TLM structures by photolithography and liftoff
- Mo was dry etched in SF_6/Ar with Ni as etch mask, isolated by wet etch



Resistance Measurement

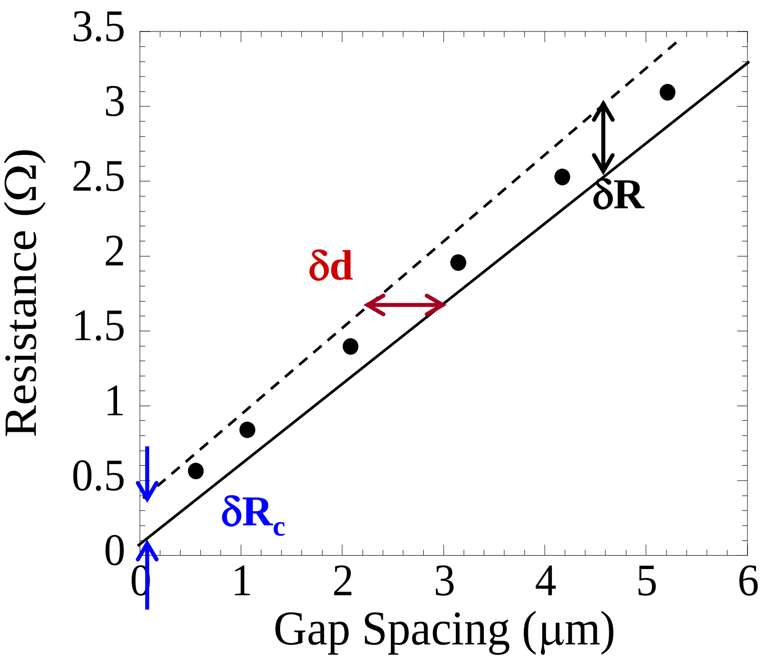
- Resistance measured by Agilent 4155C semiconductor parameter analyzer
- TLM pad spacing (L_{gap}) varied from 0.5-26 μm; verified from scanning electron microscope (SEM)
- TLM Width ~ 25 μm

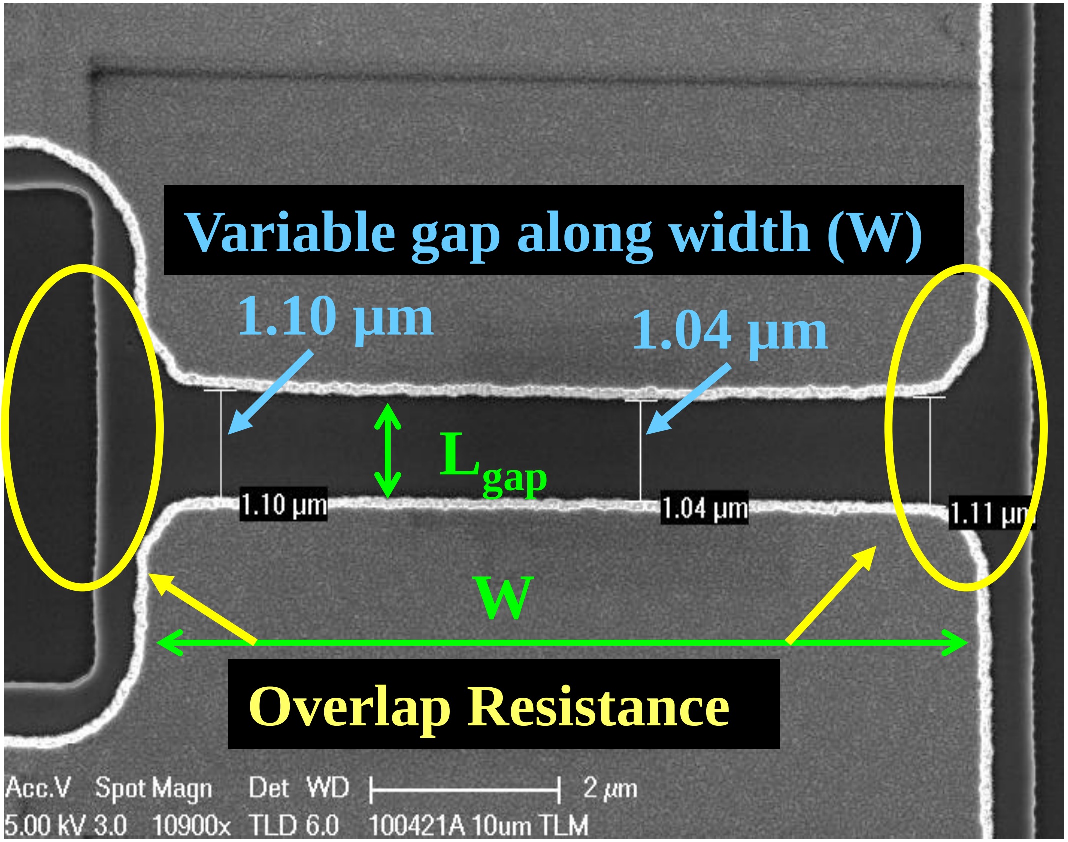




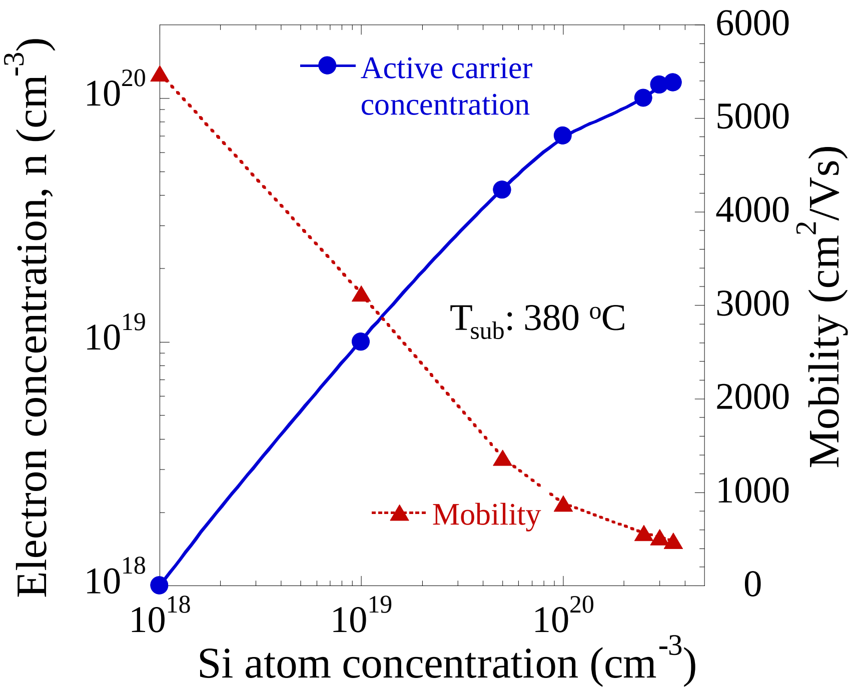
Error Analysis

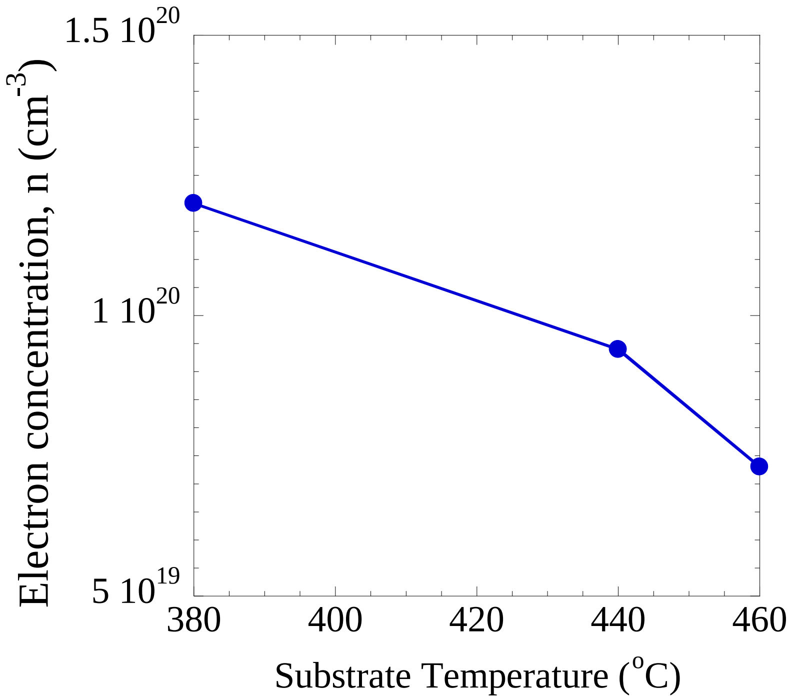
- Extrapolation errors:
  - 4-point probe resistance measurements on Agilent 4155C
  - Resolution error in SEM
- Processing errors:
  - Variable gap spacing along width (W)
  - Overlap resistance





Results: Doping Characteristics



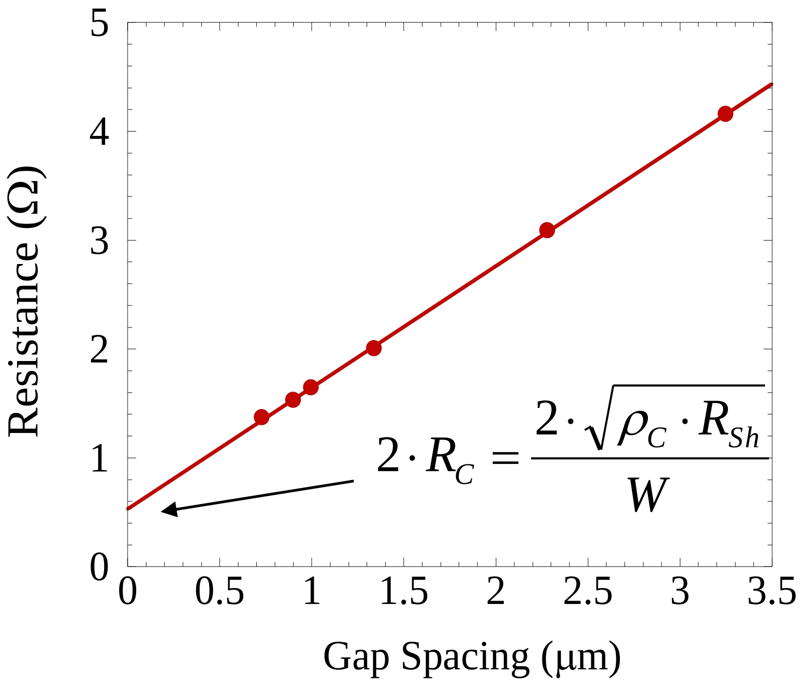


n saturates at high dopant concentration

- Enhanced *n* for colder growths
- hypothesis: As-rich surface drives Si onto group-III sites

Results: Contact Resistivity - I

Metal Contact	ρ_c (Ω-μm^2)	ρ_h (Ω-μm)
In-situ Mo	**0.6 ± 0.4**	**2.0 ± 1.5**



- Electron concentration, n = 1×10^{20} cm^{-3}
- Mobility, μ = 484 cm^2/Vs
- Sheet resistance, R_{sh} = 11 ohm/□ (100 nm thick film)

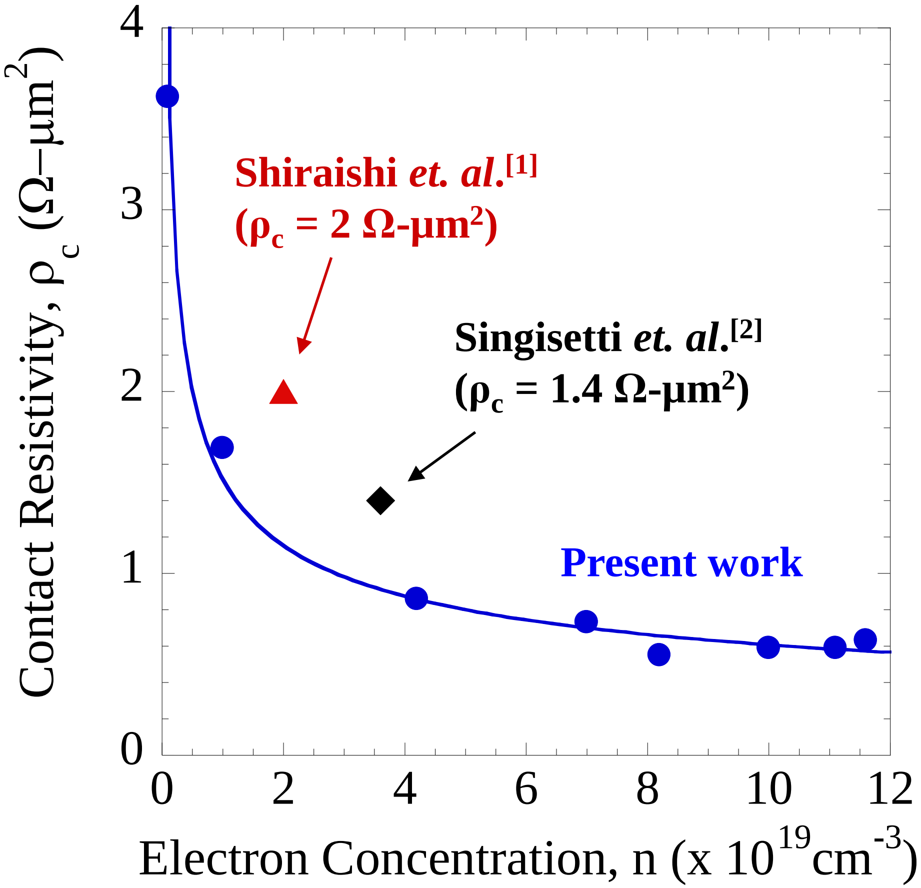
Lowest ρ_c reported to date for n-type InAs

Results: Contact Resistivity - II

- ρ_c measured at various n
  - ρ_c decreases with increase in n

- Shiraishi *et. al.*[1] reported $\rho_c = 2\ \Omega\text{-}\mu m^2$ for *ex-situ* Ti/Au/Ni contacts to n-InAs

- Singisetti *et. al.*[2] reported $\rho_c = 1.4\ \Omega\text{-}\mu m^2$ for *in-situ* Mo/n-InAs/n-InGaAs



Extreme Si doping improves contact resistance

[1]Shiraishi *et. al.*, J. Appl. Phys., **76**, 5099 (1994). [2]Singisetti *et. al.*, Appl. Phys. Lett., **93**, 183502 (2008).

Results: Contact Resistivity - III

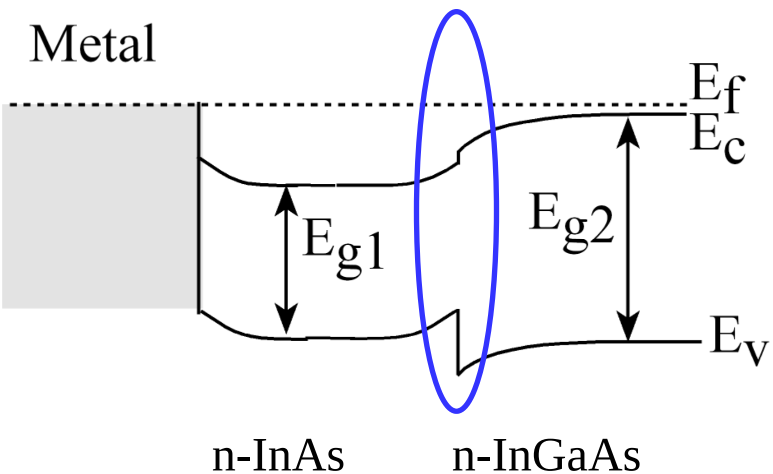
Thermal Stability

- Contacts annealed under N_2 flow at 250 ^{o}C for 60 minutes (replicating the thermal cycle experienced by a transistor during fabrication)
- Observed variation in ρ_c less than the margin of error

Contacts are thermally stable

Application in transistors !

- Optimize n-InAs/n-InGaAs interface resistance
- Mo contacts to n-InGaAs*: $\rho_c = 1.1 \pm 0.6\ \Omega\text{-}\mu m^2$



*Baraskar *et. al.*, J. Vac. Sci. Tech. B, **27**, 2036 (2009).

Conclusions:

- Extreme Si doping improves contact resistance

- **ρ_c = 0.6±0.4 Ω-μm^2** for *in-situ* Mo contacts to n-InAs with 1×10^{20} cm^{-3} electron concentration

- Need to optimize n-InAs/n-InGaAs interface resistance for transistor application

Thank You !

Questions?

Acknowledgements

ONR, DARPA-TFAST, DARPA-FLARE

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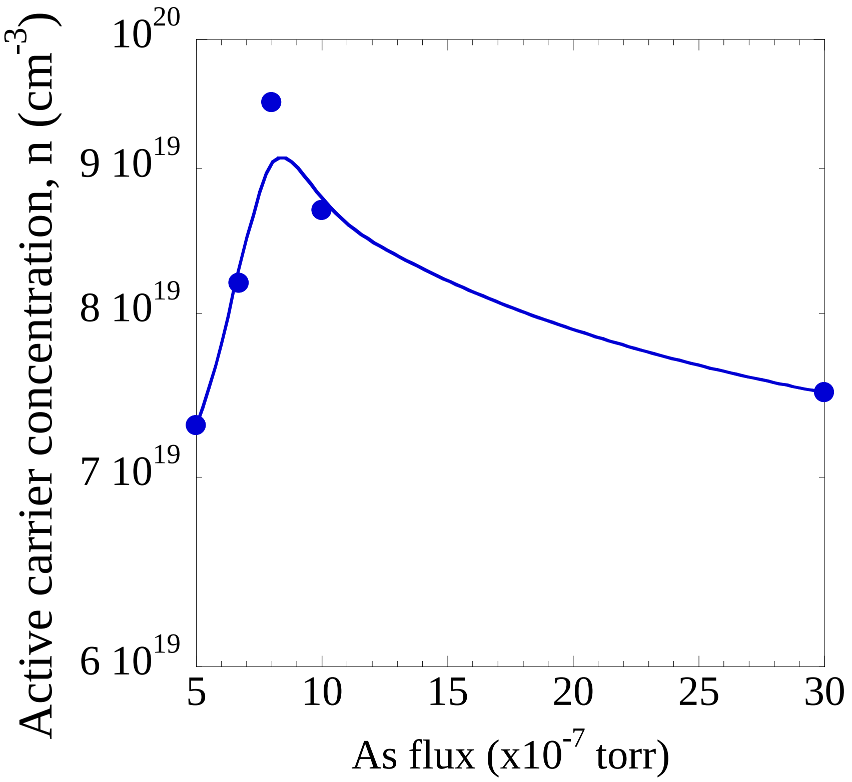
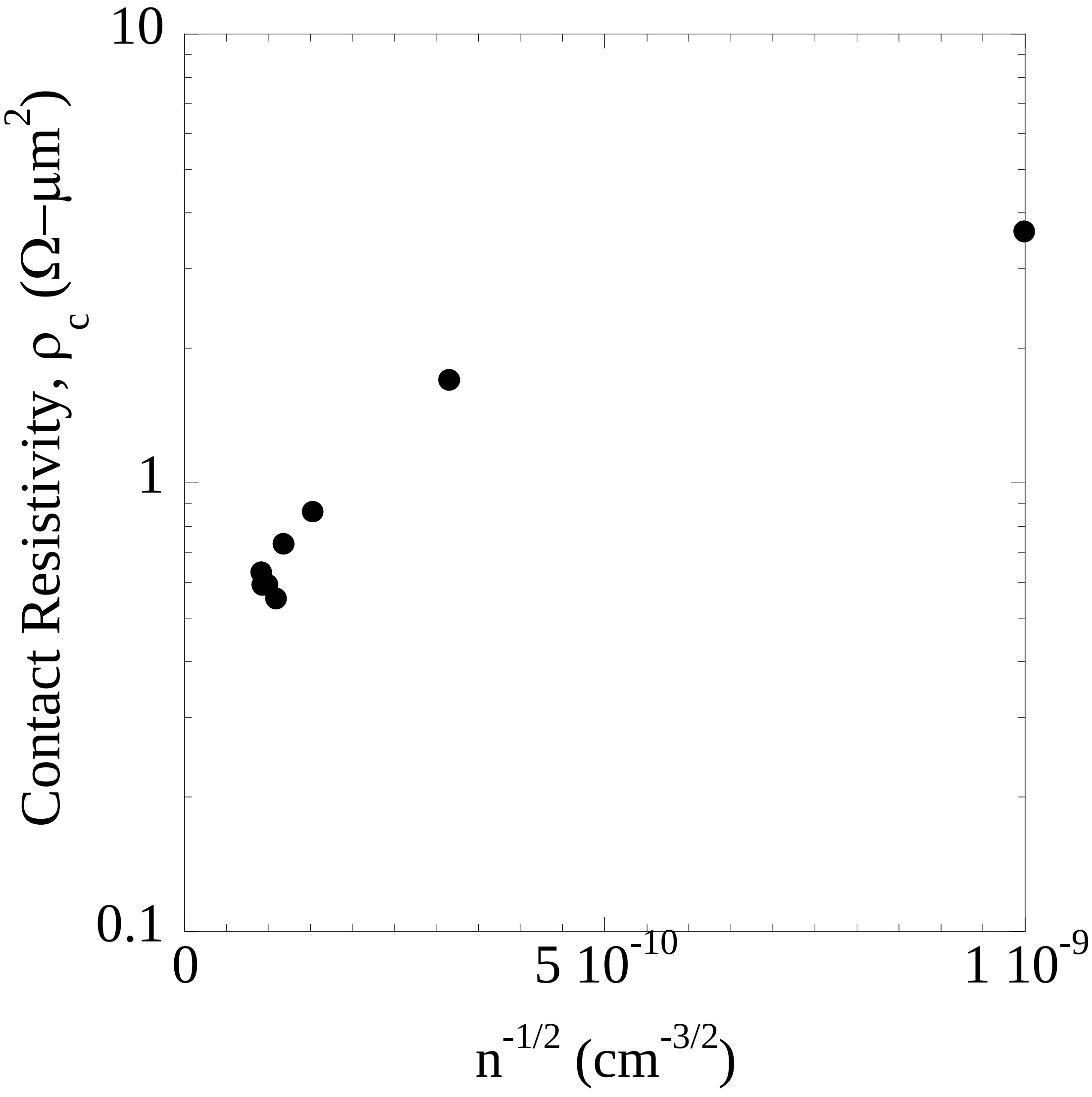
Extra Slides

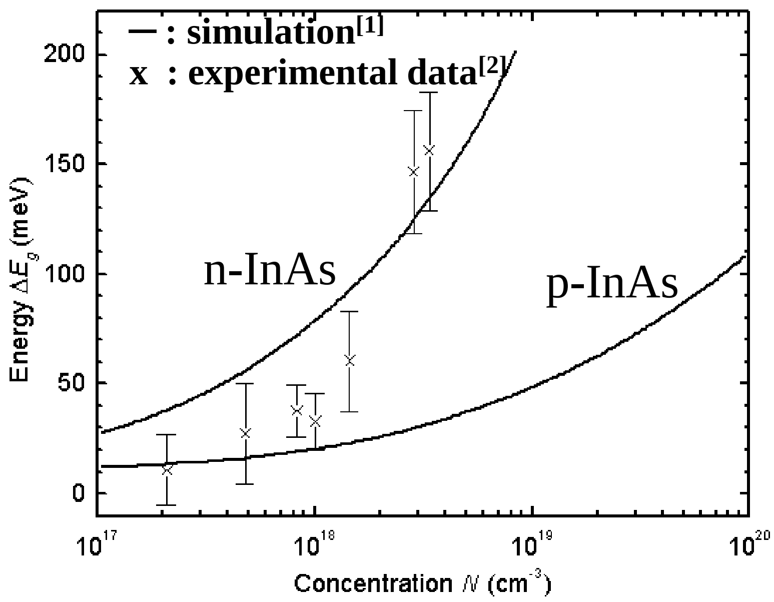
Results

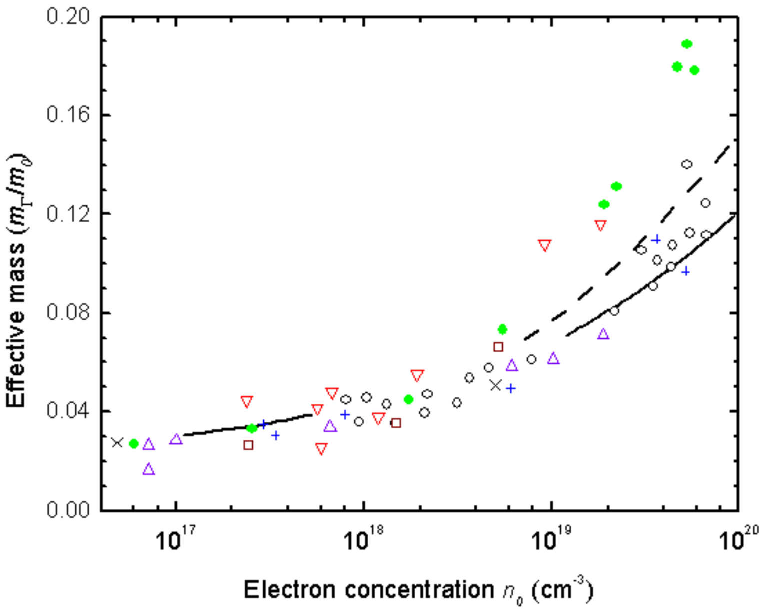
1. Doping Characteristics




10
1
0.1
Contact Resistivity, ρc (Ω–µm2)
0
5 10-10
1 10-9
n-1/2 (cm-3/2)

Results: Contact Resistivity - III





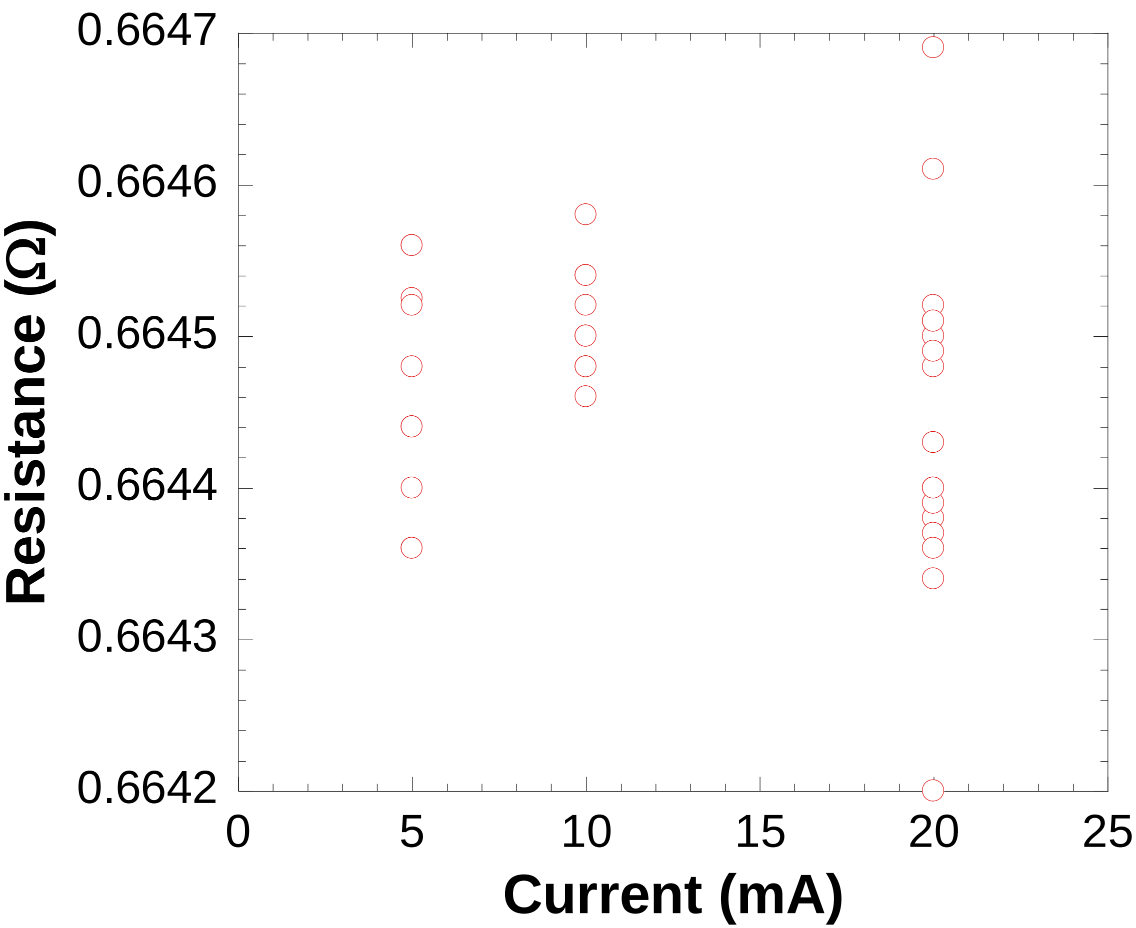
Possible reasons for decrease in contact resistivity with increase in electron concentration

- Band gap narrowing
- Strain due to heavy doping
- Variation of effective mass with doping

Accuracy Limits

- Error Calculations
  - dR = 50 mΩ (Safe estimate)
  - dW = 0.2 μm
  - dGap = 20 nm
- Error in ρ_c ~ 50% at 1 $\Omega\text{-}\mu m^2$

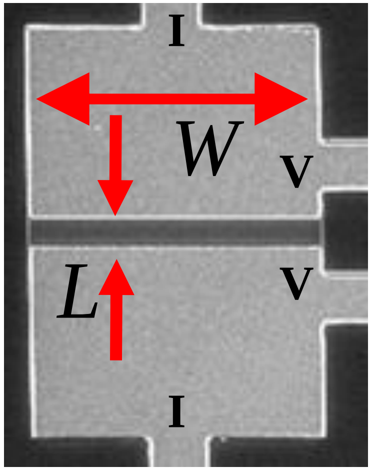
Random and Offset Error in 4155C

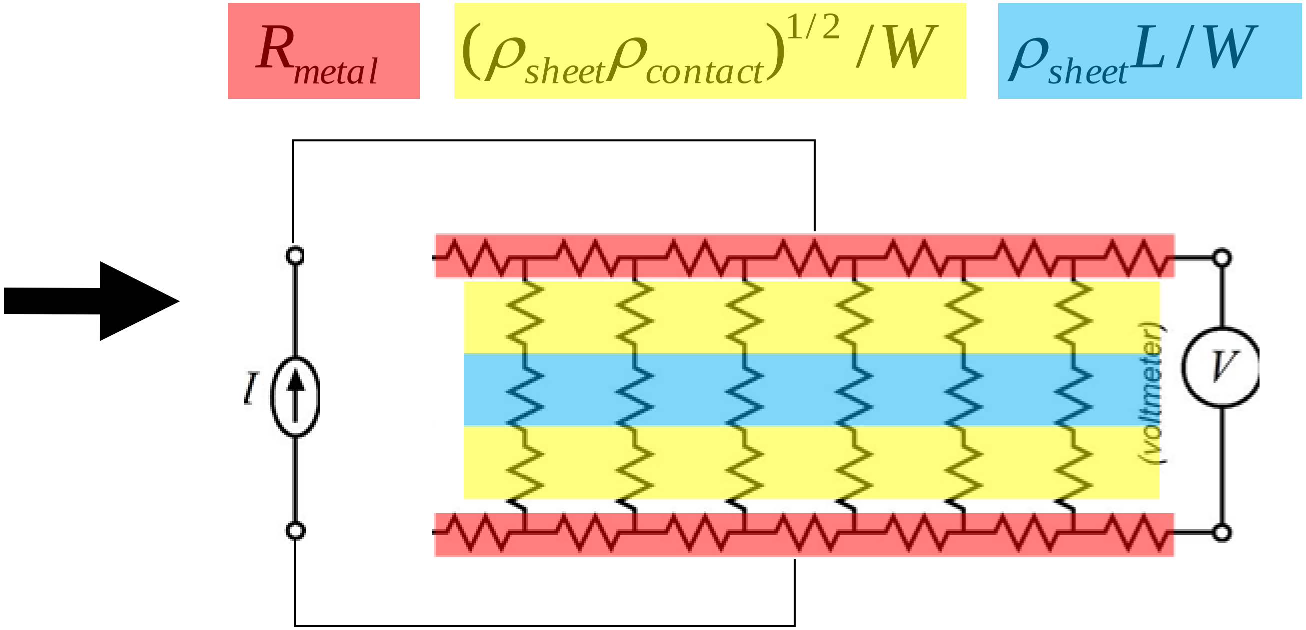


- Random Error in resistance measurement ~ 0.5 mΩ
- Offset Error < 5 mΩ*

*4155C datasheet

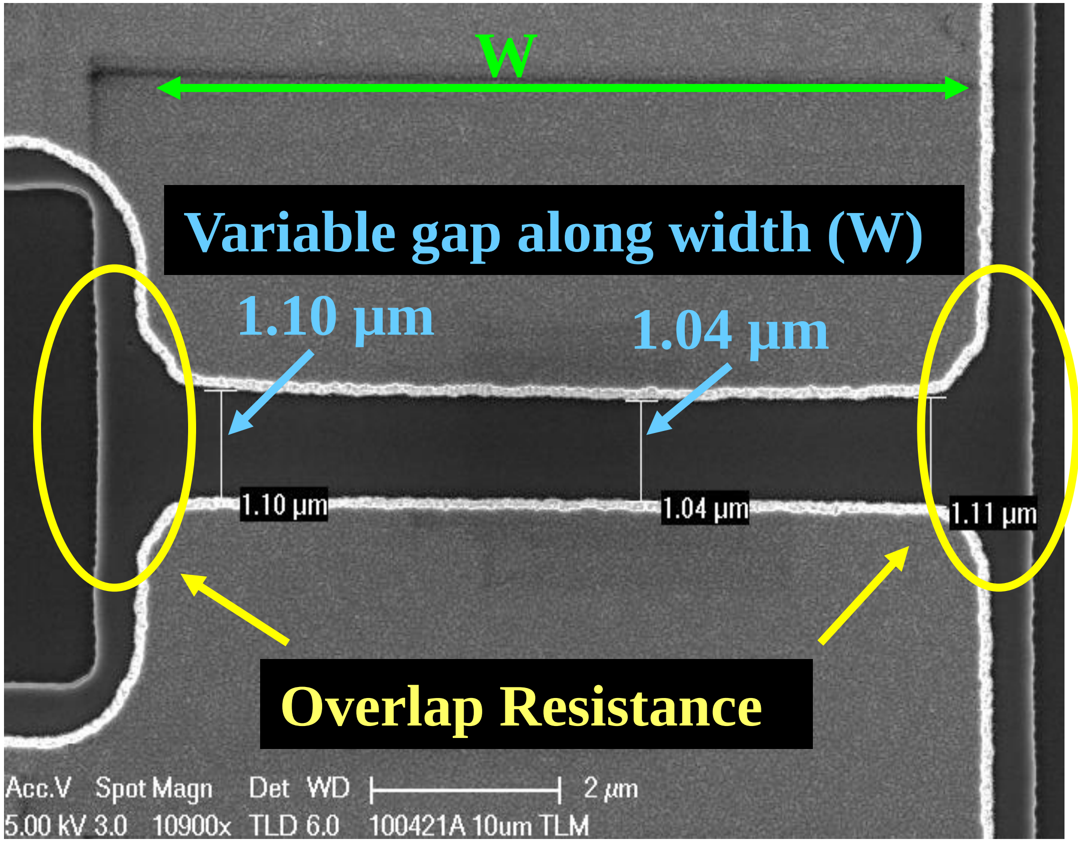
Correction for Metal Resistance in 4-Point Test Structure





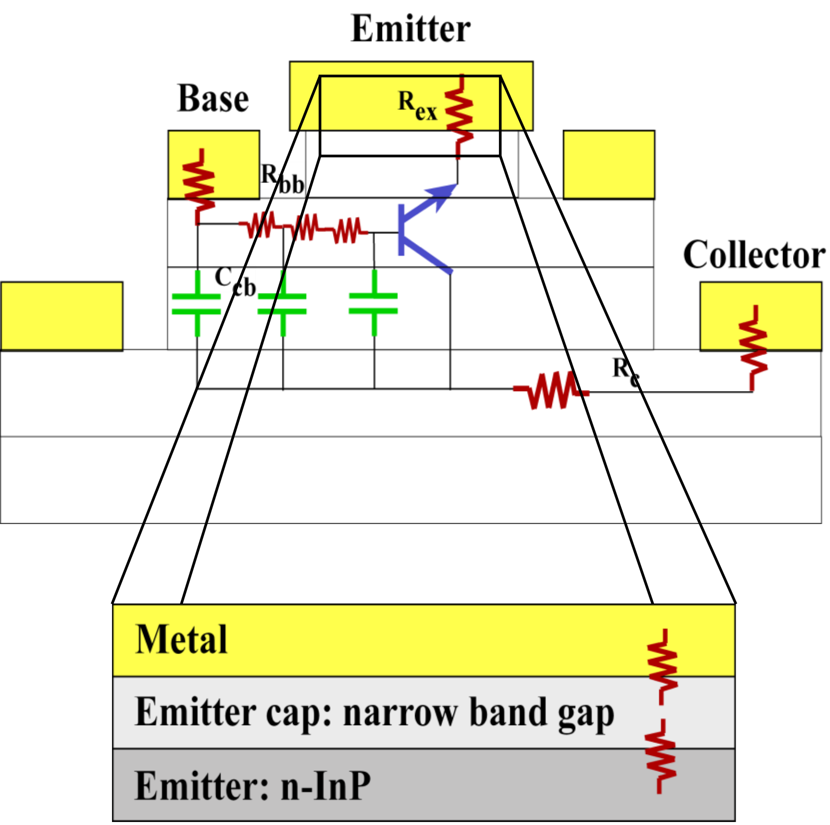
$$(\rho_{sheet}\rho_{contact})^{1/2}/W + \rho_{sheet}L/W + R_{metal}/x$$

Error term (R_{metal}/x) from metal resistance

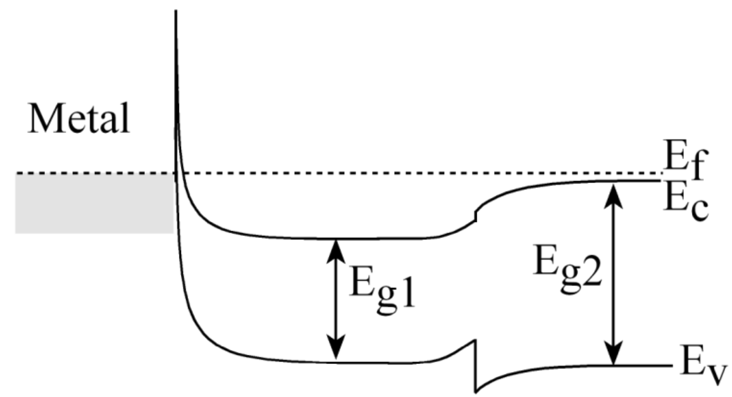

W
Variable gap along width (W)
1.10 µm
1.04 µm
1.10 µm
1.04 µm
1.11 µm
Overlap Resistance
Acc.V Spot Magn Det WD 2 µm
5.00 kV 3.0 10900x TLD 6.0 100421A 10um TLM

- Variation of effective mass with doping
- Non-parabolicity
- Thickness dependence
- SXPS (x-ray photoemission spectroscopy)
- BEEM (ballistic electron emission microscopy)
- Band gap narrowing
- Strain due to heavy doping

Emitter Ohmics-I



Metal contact to narrow band gap material



For the same number of active carriers
(in the degenerate regime)

$$E_f - E_c > E_f - E_c$$

(narrow gap, E_{g1}) (wide gap, E_{g2})

$$m^*_{e(Eg1)} < m^*_{e(Eg2)}$$