In-situ Ohmic Contacts to p-InGaAs

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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**
  - Doping characteristics
  - Effect of doping on contact resistivity
  - Effect of annealing
- **Conclusion**

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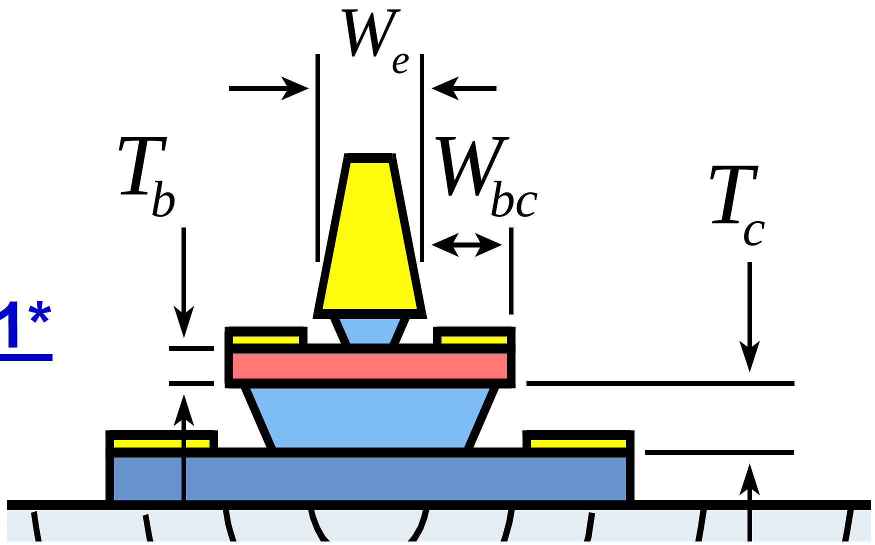
Device Bandwidth Scaling Laws for HBT

To double device bandwidth:

- Cut transit time 2x
- Cut RC delay 2x

Scale contact resistivities by 4:1*



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

HBT: Heterojunction Bipolar Transistor

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

*M.J.W. Rodwell, CSICS 2008

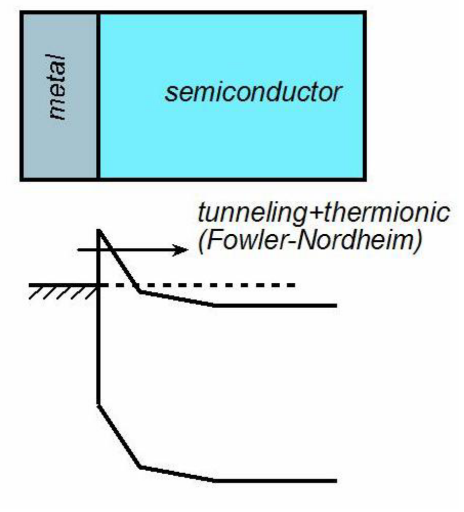
InP Bipolar Transistor Scaling Roadmap

Emitter	256	128	64	32	nm **width**
	8	**4**	**2**	**1**	Ω·µm^2 **access ρ**
Base	**175**	**120**	**60**	**30**	nm **contact width**
	10	**5**	**2.5**	**1.25**	Ω·µm^2 **contact ρ**
Collector	**106**	**75**	**53**	**37.5**	nm **thick**
	9	**18**	**36**	**72**	mA/µm^2 **current**
	4	**3.3**	**2.75**	**2-2.5**	V **breakdown**
f_T	**520**	**730**	**1000**	**1400**	GHz
f_{max}	**850**	**1300**	**2000**	**2800**	GHz

Contact resistivity serious barrier to THz technology

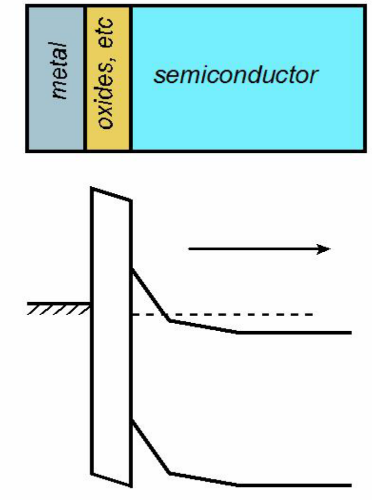
Less than 2 Ω-µm^2 contact resistivity required for simultaneous THz f_t and f_{max}*

Approach



To achieve low resistance, stable ohmic contacts

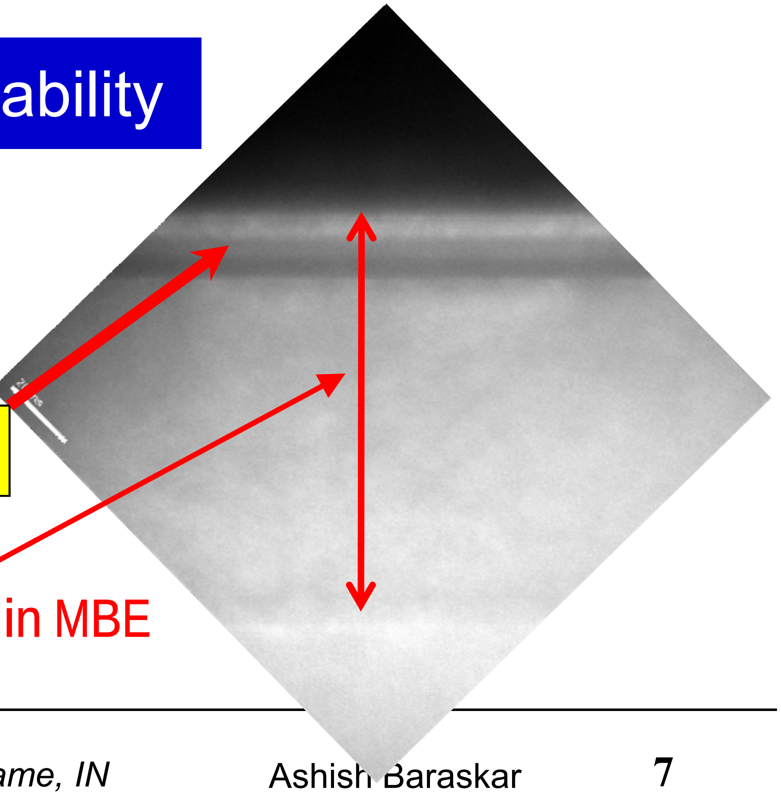
- **Higher number of active carriers**
  - Reduced depletion width
  - Enhanced tunneling across metal-semiconductor interface
- **Better surface preparation techniques**
  - For efficient removal of oxides/impurities



Approach (contd.)

- Scaled device ⟶ thin base
  (For 80 nm device: $\mathbf{t_{base} < 25\ nm}$)
- Non-refractory contacts may diffuse at higher temperatures through base and short the collector
- Pd/Ti/Pd/Au contacts diffuse about 15 nm in InGaAs on annealing

Need a refractory metal for thermal stability



15 nm Pd/Ti diffusion

100 nm InGaAs grown in MBE

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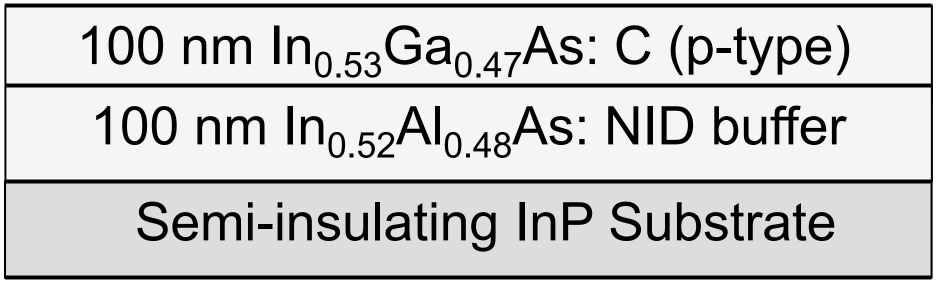
Epilayer Growth

Epilayer growth by Solid Source Molecular Beam Epitaxy (SS-MBE)– p-InGaAs/InAlAs

- Semi insulating InP (100) substrate
- Un-doped InAlAs buffer
- CBr_4 as carbon dopant source
- Hole concentration determined by Hall measurements



100 nm $In_{0.53}Ga_{0.47}As$: C (p-type)

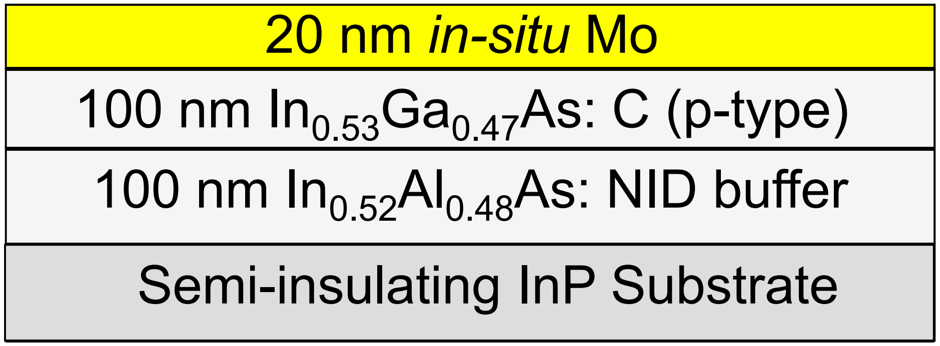
100 nm $In_{0.52}Al_{0.48}As$: NID buffer

Semi-insulating InP Substrate

In-situ 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 *in-situ* Mo

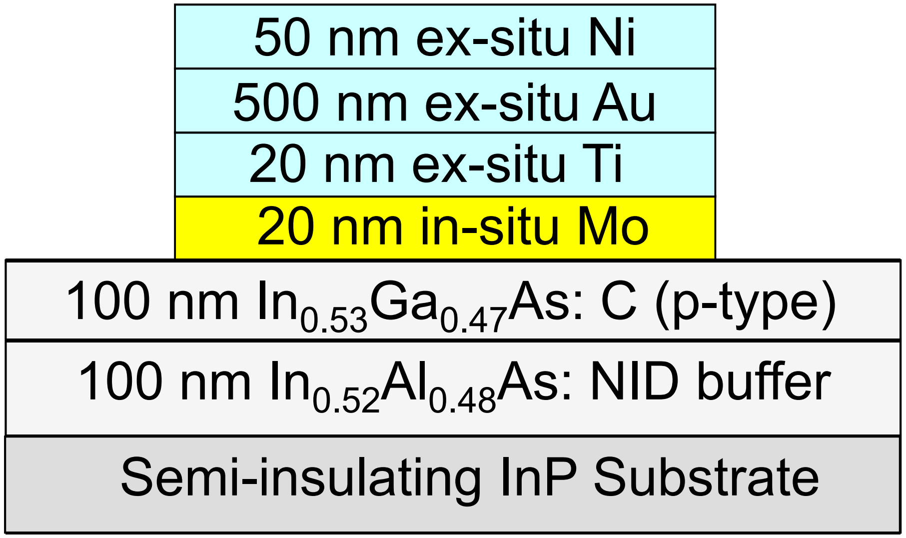
100 nm $In_{0.53}Ga_{0.47}As$: C (p-type)

100 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
- Contact metal was dry etched in SF_6/Ar with Ni as etch mask, isolated by wet etch



50 nm ex-situ Ni

500 nm ex-situ Au

20 nm ex-situ Ti

20 nm in-situ Mo

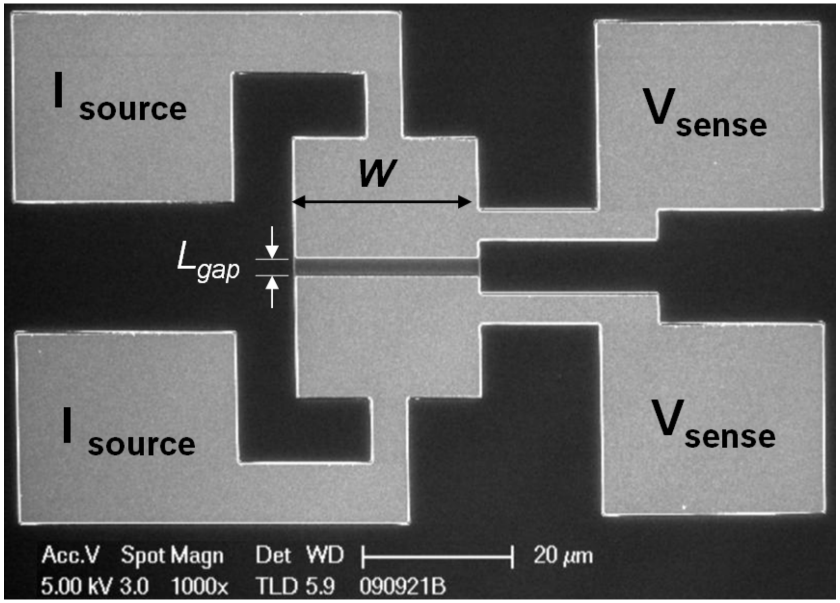
100 nm $In_{0.53}Ga_{0.47}As$: C (p-type)

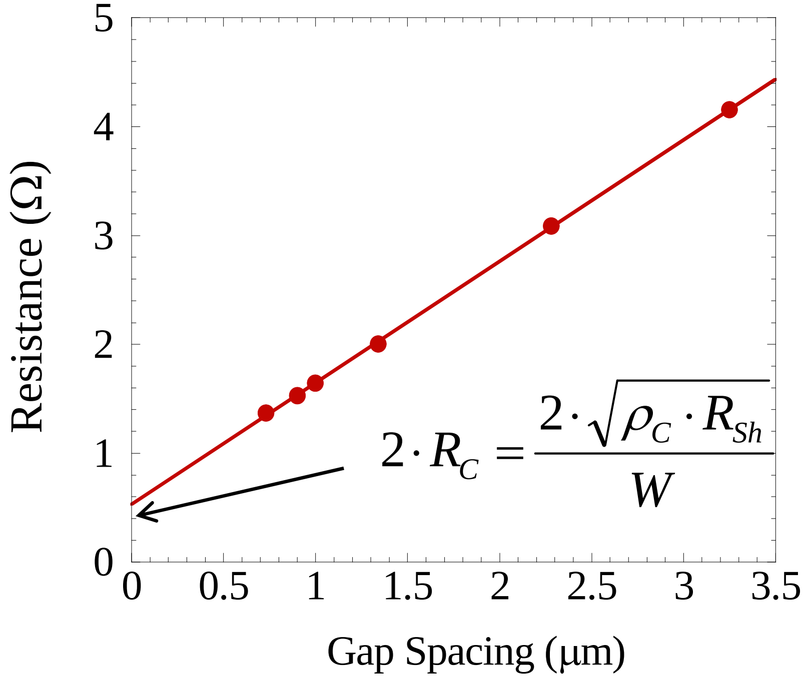
100 nm $In_{0.52}Al_{0.48}As$: NID buffer

Semi-insulating InP Substrate

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*

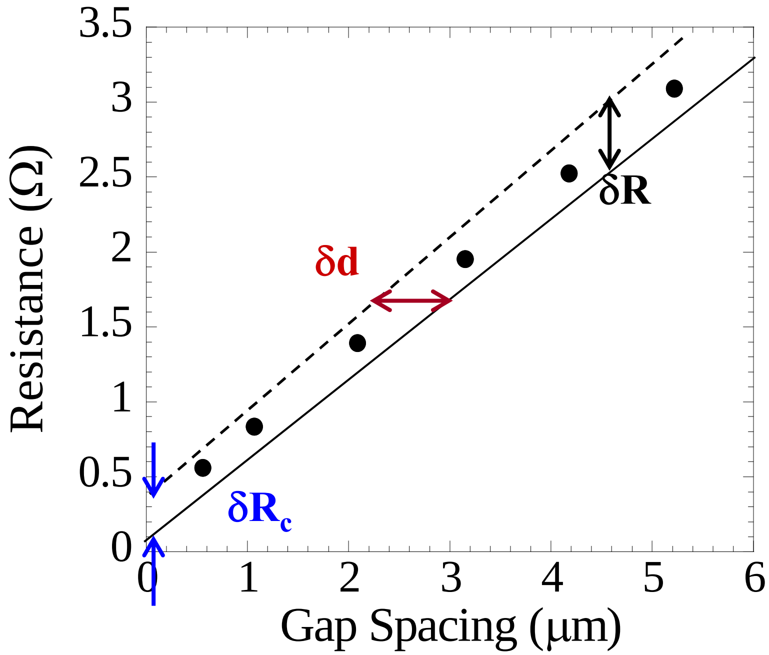


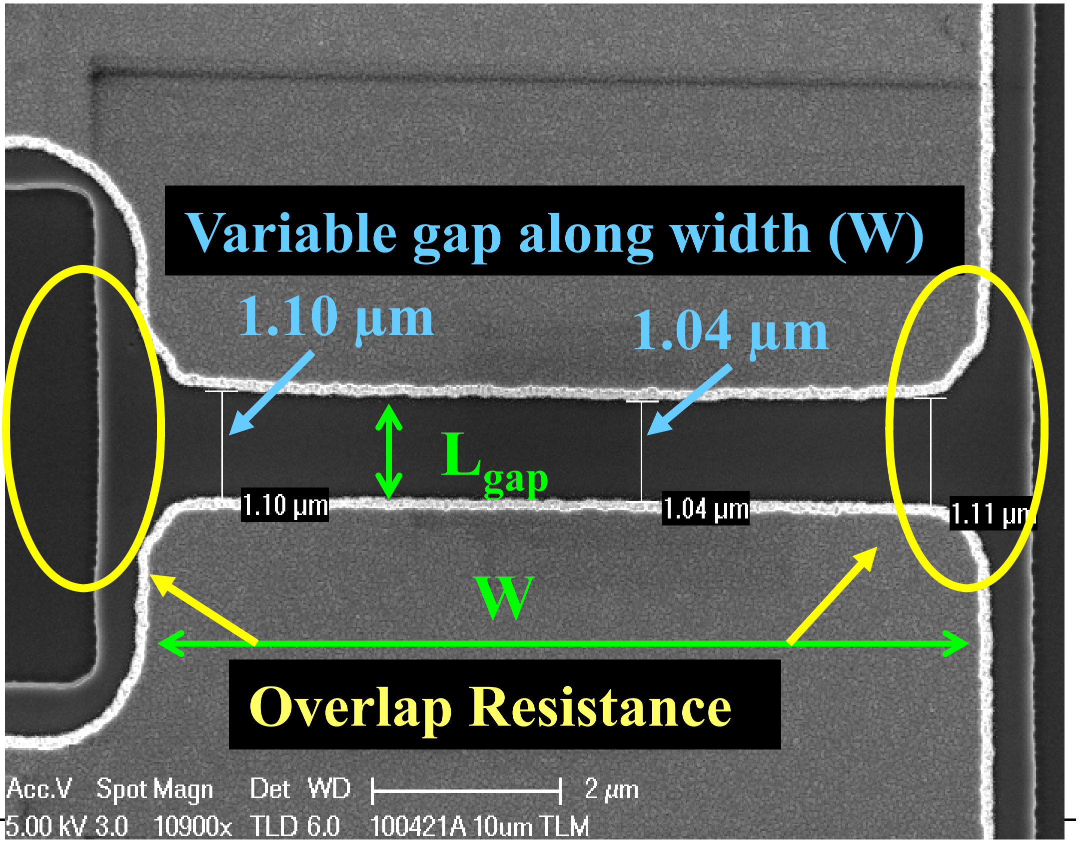


$$2 \cdot R_C = \frac{2 \cdot \sqrt{\rho_C \cdot R_{Sh}}}{W}$$

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





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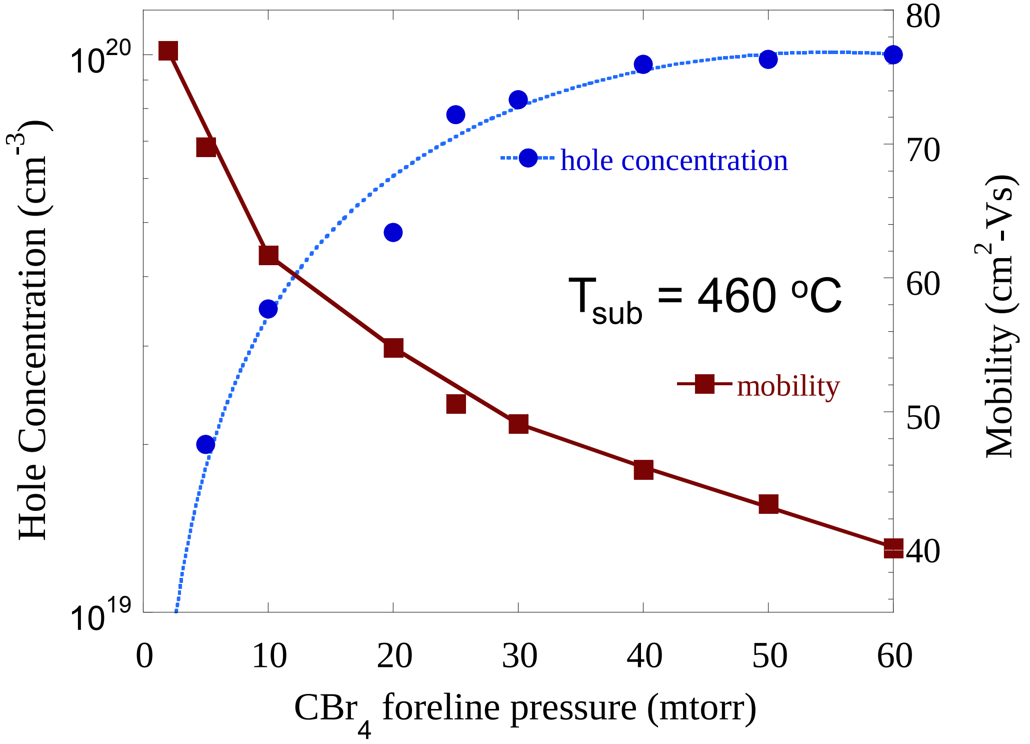
Doping Characteristics-I

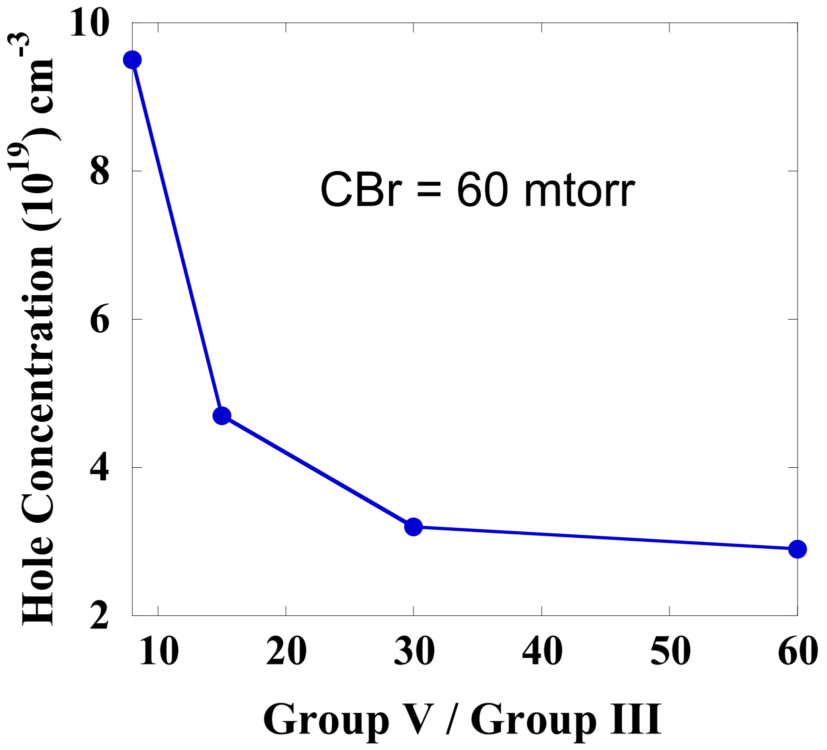
Hole concentration Vs CBr_4 flux



- – Hole concentration saturates at high CBr fluxes
- – Number of di-carbon defects ↑ as CBr flux ↑

Doping Characteristics-II

Hole concentration Vs V/III flux

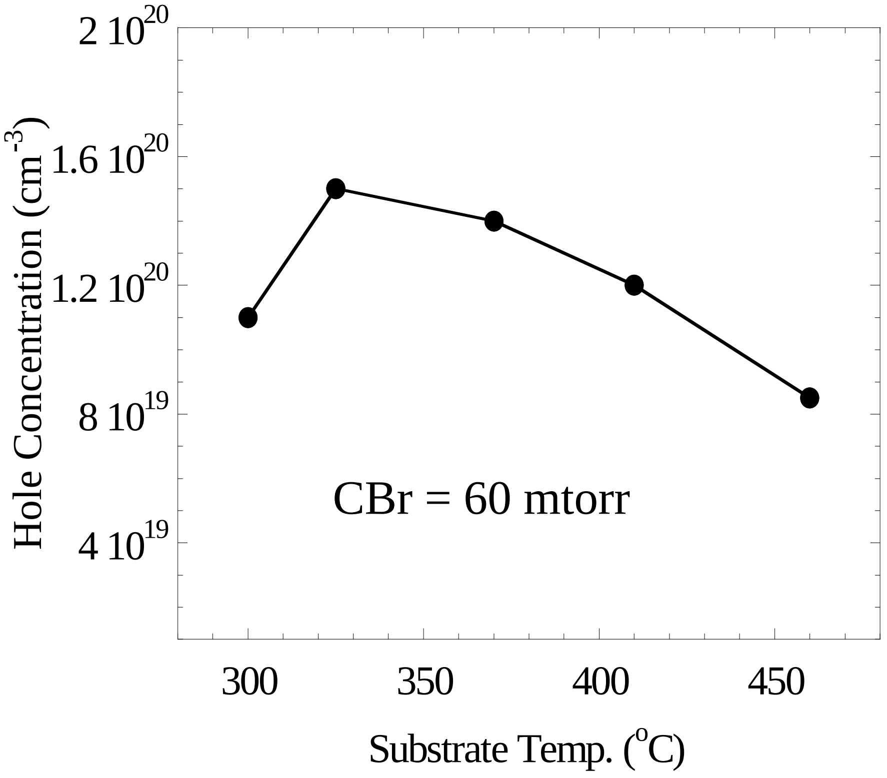


As V/III ratio ↓ hole concentration ↑

hypothesis: As-deficient surface drives C onto group-V sites

Doping Characteristics-III

Hole concentration Vs substrate temperature

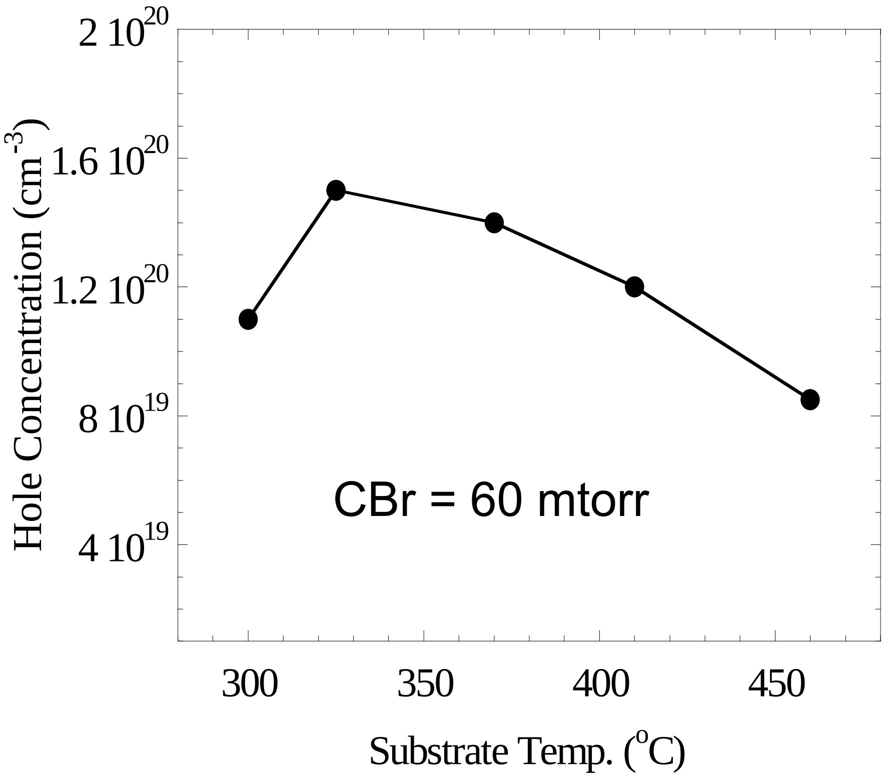


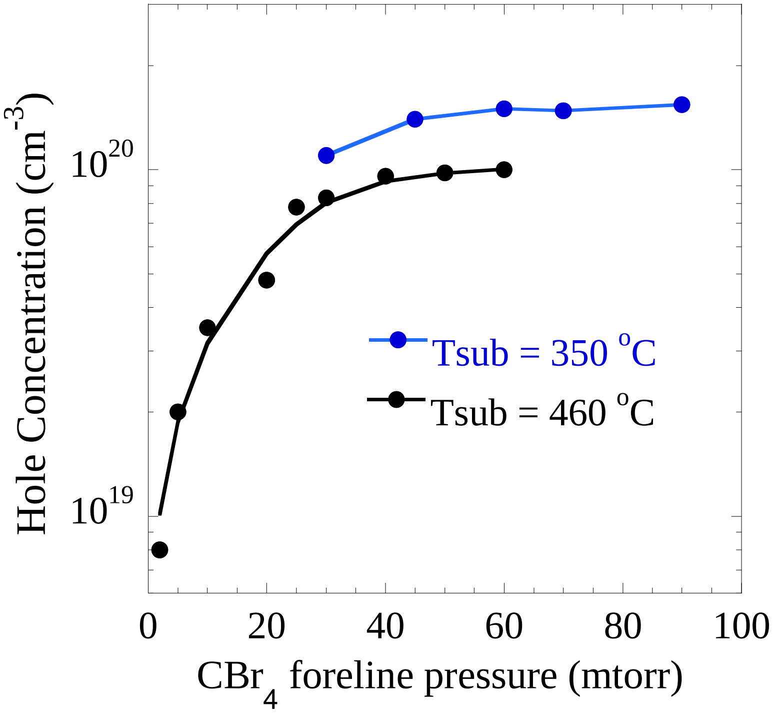
Tendency to form di-carbon defects ↑as Tsub ↑*

*Tan *et. al*. Phys. Rev. B 67 (2003) 035208

Doping Characteristics-III

Hole concentration Vs substrate temperature





Tendency to form di-carbon defects ↑as Tsub ↑*

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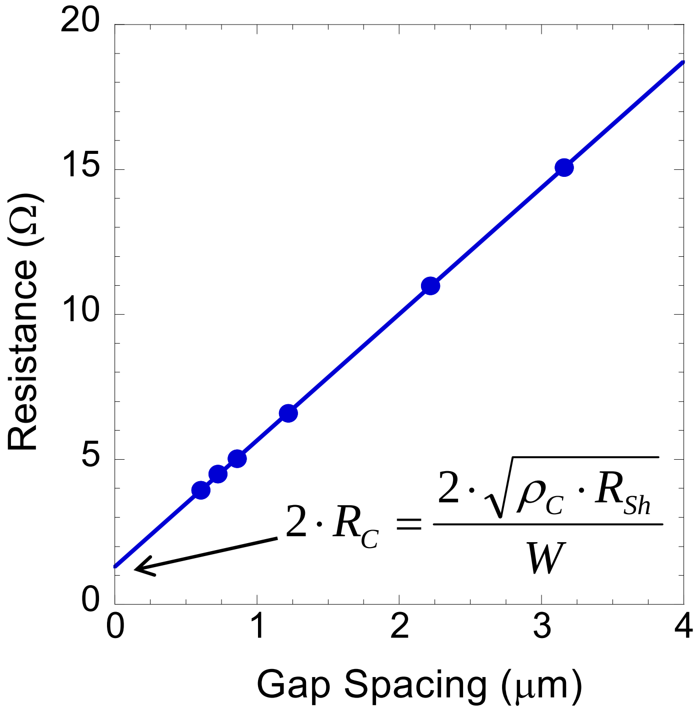
Results: Contact Resistivity - I

Metal Contact	ρ_c (Ω-μm^2)	ρ_h (Ω-μm)
In-situ Mo	2.2 ± 0.8	15.4 ± 2.6

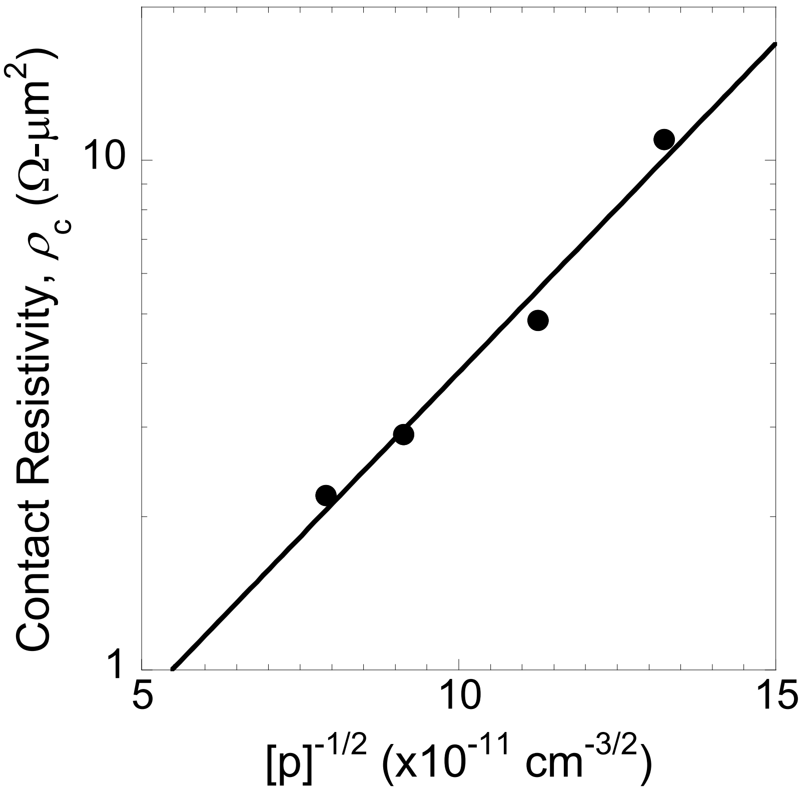
- Hole concentration, $p = 1.6 \times 10^{20}$ cm^{-3}
- Mobility, $\mu = 36$ cm^2/Vs
- Sheet resistance, $R_{sh} = 105$ ohm/□
  (100 nm thick film)

ρ_c lower than the best reported contacts to pInGaAs ($\rho_c = 4\ \Omega$-μm^2)[1,2]



1. Griffith *et al*, Indium Phosphide and Related Materials, 2005.
2. Jain *et al*, IEEE Device Research Conference, 2010.

Results: Contact Resistivity - II



Tunneling → $\rho_C \propto \exp\left(\frac{1}{\sqrt{p}}\right)^*$

Thermionic Emission → $\rho_c \sim \text{constant}^*$

Data suggests tunneling

High active carrier concentration is the key to low resistance contacts

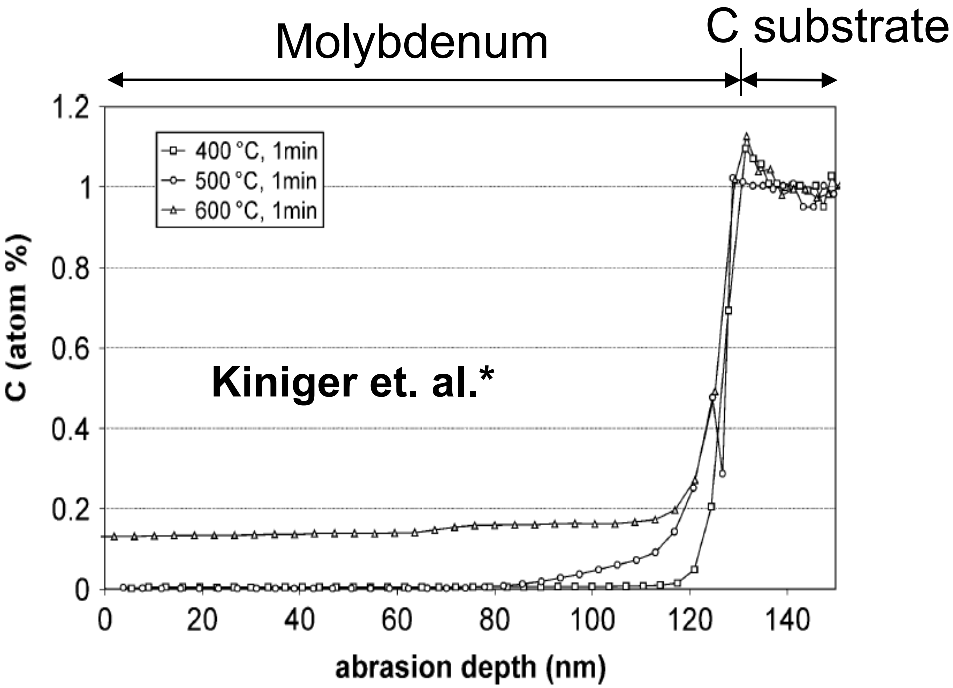
* Physics of Semiconductor Devices, S M Sze

Thermal Stability - I

Mo contacts annealed under N_2 flow for 60 mins. at 250 ^oC

	Before annealing	After annealing
ρ_c (Ω-μm^2)	2.2 ± 0.8	2.8 ± 0.9

- ρ_c increases on annealing
- Mo reacts with residual interfacial carbon?*



***Kiniger et. al.**, Surf. Interface Anal. 2008, **40**, 786–789

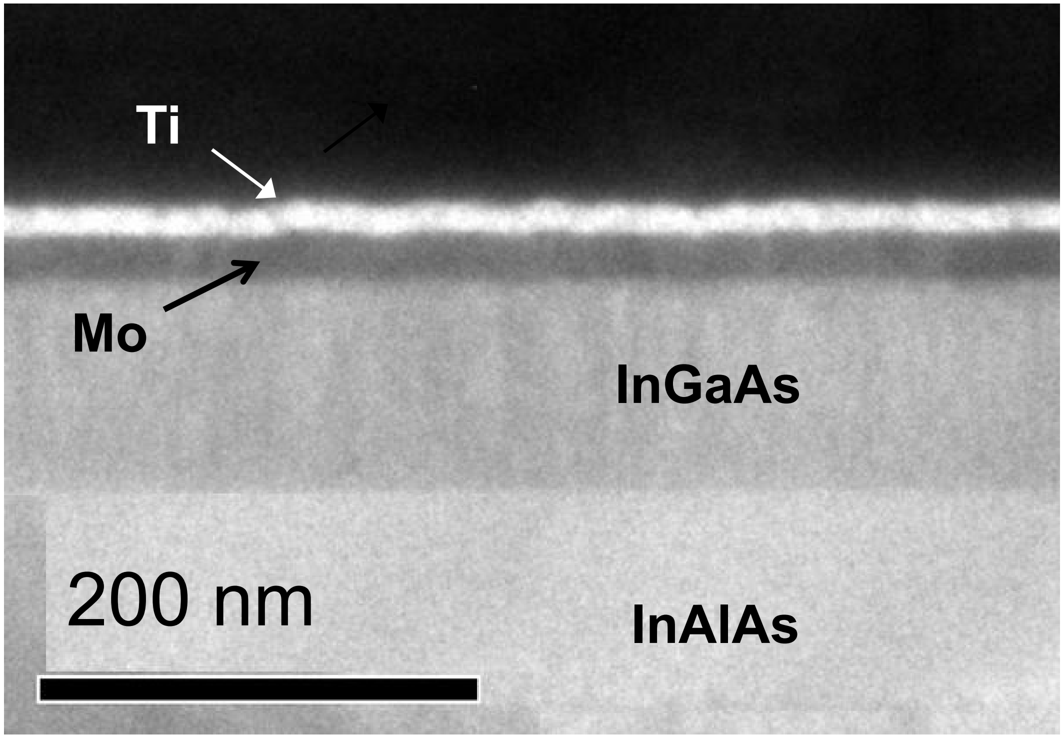
Thermal Stability - II

Mo contacts annealed under N_2 flow for 60 mins. at 250 ^oC

TEM of Mo-pInGaAs interface

- Suggests sharp interface

- Minimal/No intermixing



Summary

- Maximum hole concentration obtained = 1.6 x10^{20} cm^{-3} at a substrate temperature of 350 ^{o}C

- Low contact resistivity with *in-situ* metal contacts (lowest **ρ_c=2.2 ± 0.8 Ω-μm^2**)

✓ Contacts suitable for THz transistors

Thank You !

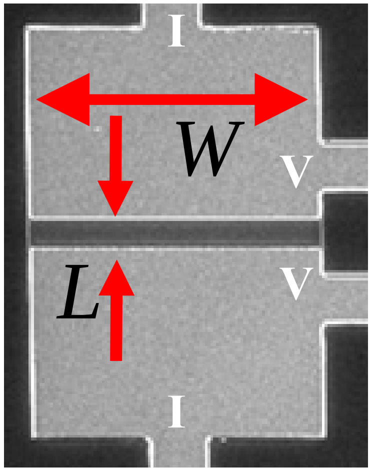
Questions?

Acknowledgements

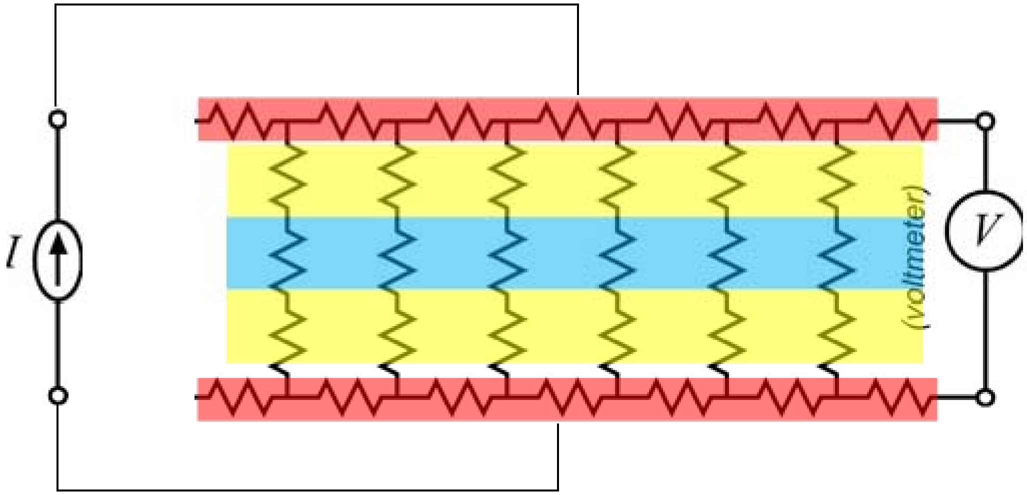
ONR, DARPA-TFAST, DARPA-FLARE

Extra Slides

Correction for Metal Resistance in 4-Point Test Structure



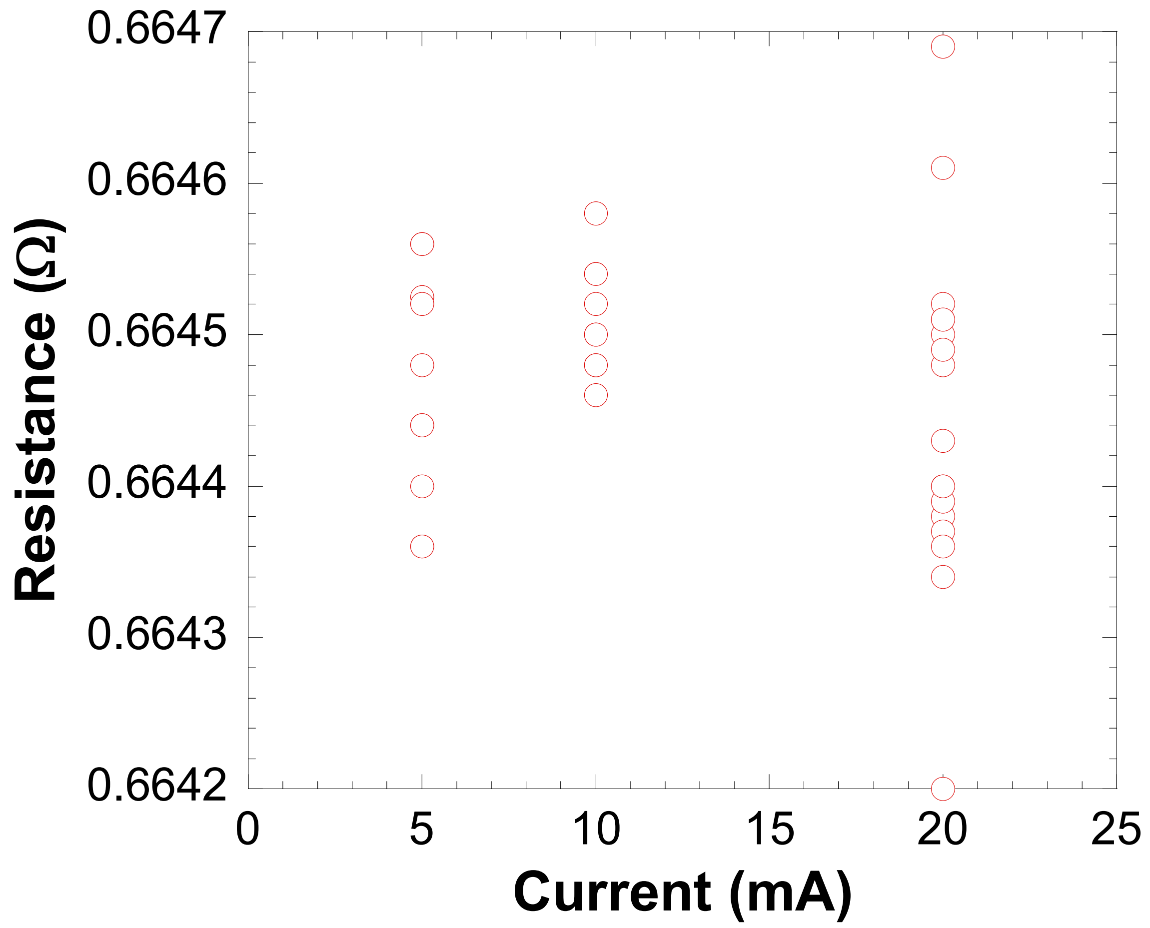
R_{metal} $(\rho_{sheet}\rho_{contact})^{1/2}/W$ $\rho_{sheet}L/W$



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

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

Random and Offset Error in 4155C



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

*4155C datasheet

Accuracy Limits

- **Error Calculations**
  - **dR = 50 mΩ (Safe estimate)**
  - **dW = 1 μm**
  - **dGap = 20 nm**
- **Error in ρ_c ~ 40% at 1.1 Ω-μm^2**