High Doping Effects on In-situ and Ex-situ Ohmic Contacts to n-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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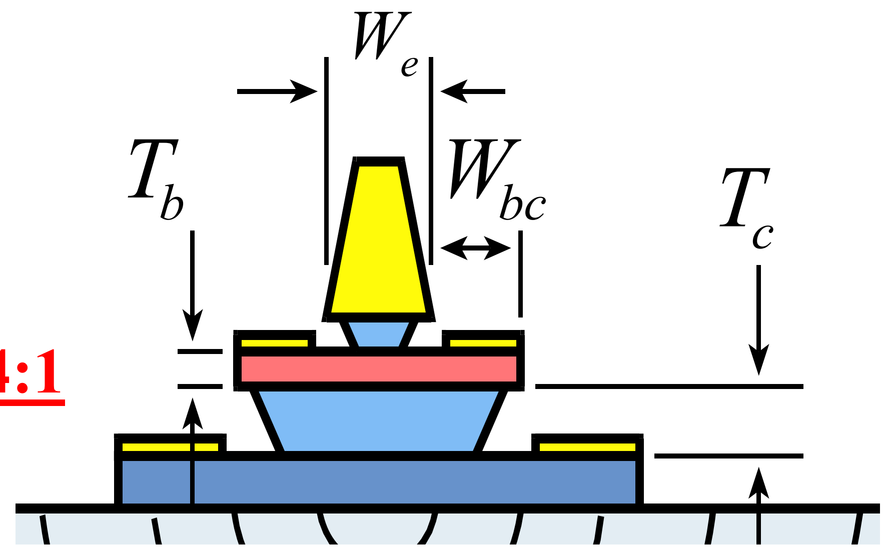
Device Bandwidth Scaling Laws for HBT

To double device bandwidth:

- Cut transit time 2x:
  - Reduce thickness 2:1 ☺
  - Capacitance increases 2:1 ☹
- Cut RC delay 2x
  - **<u>Scale contact resistivities by 4:1</u>**



HBT: Heterojunction Bipolar Transistor

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

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

Uttam Singisetti, DRC 2007

*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 resistance serious barrier to THz technology

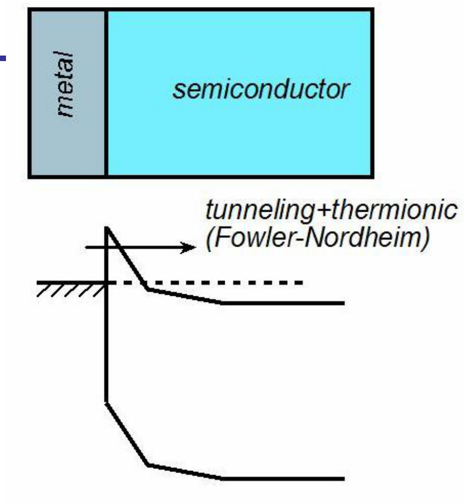
Less than 2 *Ω-μm²* contact resistivity required for simultaneous THz f_t and f_{max}*

*M.J.W. Rodwell, CSICS 2008

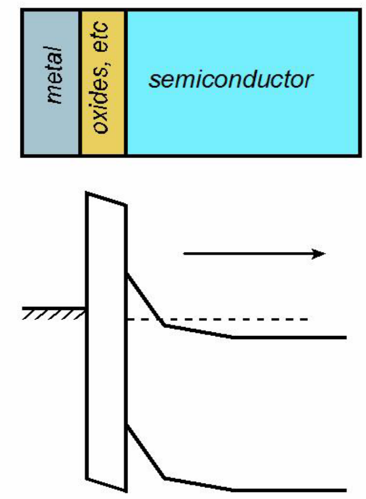
Approach

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**
  - Ex-situ contacts: treatment with UV-O_3, HCl etch
  - In-situ contacts: no air exposure before metal deposition
- **Use of refractory metal for thermal stability**



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Epilayer Growth

Semiconductor epilayer growth by Solid Source Molecular Beam Epitaxy (SS-MBE)– n-InGaAs/InAlAs

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

100 nm $In_{0.53}Ga_{0.47}As$: Si (n-type)
150 nm $In_{0.52}Al_{0.48}As$: NID buffer
Semi-insulating InP Substrate

Two Types of Contacts Investigated

- In-situ contacts: **Mo**
  - Samples transferred under vacuum for contact metal deposition
  - no air exposure
- Ex-situ contacts: **Ti/$Ti_{0.1}W_{0.9}$**
  - exposed to air
  - surface treatment before contact metal deposition

Contact metal
100 nm $In_{0.53}Ga_{0.47}As$: Si (n-type)
150 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

Why Mo?

- Refractory metal (melting point ~ 2623 C)
- Work function ~ 4.6 (± 0.15) eV, close to the conduction band edge of InGaAs
- Easy to deposit by e-beam technique
- Easy to process and integrate in HBT process flow

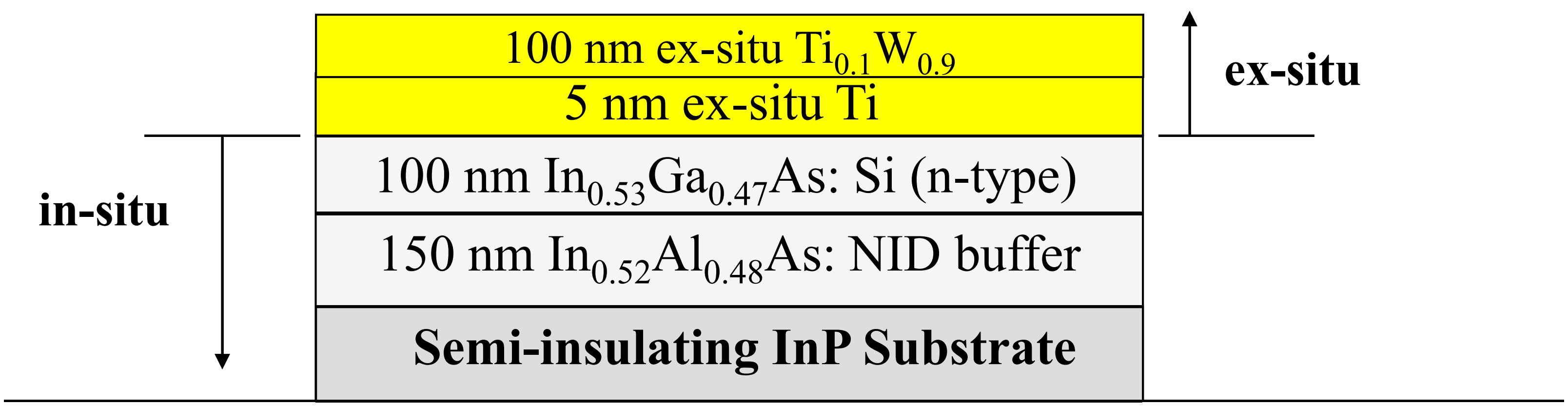
20 nm in-situ Mo
100 nm $In_{0.53}Ga_{0.47}As$: Si (n-type)
150 nm $In_{0.52}Al_{0.48}As$: NID buffer
Semi-insulating InP Substrate

Ex-situ contacts

Ex-situ **$Ti/Ti_{0.1}W_{0.9}$** contacts on InGaAs

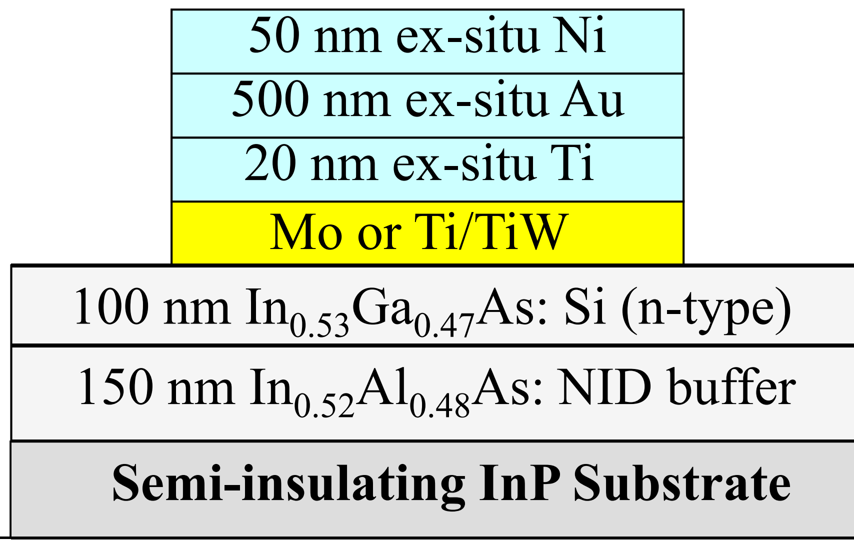
- Surface preparation
  - Oxidized with UV-ozone for 10 min
  - Dilute HCl (1:10) etch and DI rinse for 1 min each
- Immediate transfer to sputter unit for contact metal deposition
- Ti: Oxygen gettering property, forms good ohmic contacts*

*G. Stareev, H. Künzel, and G. Dortmann, *J. Appl. Phys.*, 74, 7344 (1993).

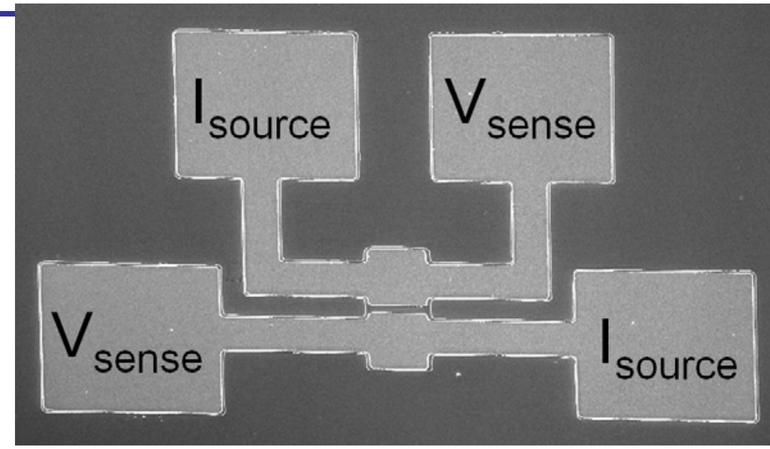


TLM (Transmission Line Model) fabrication

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



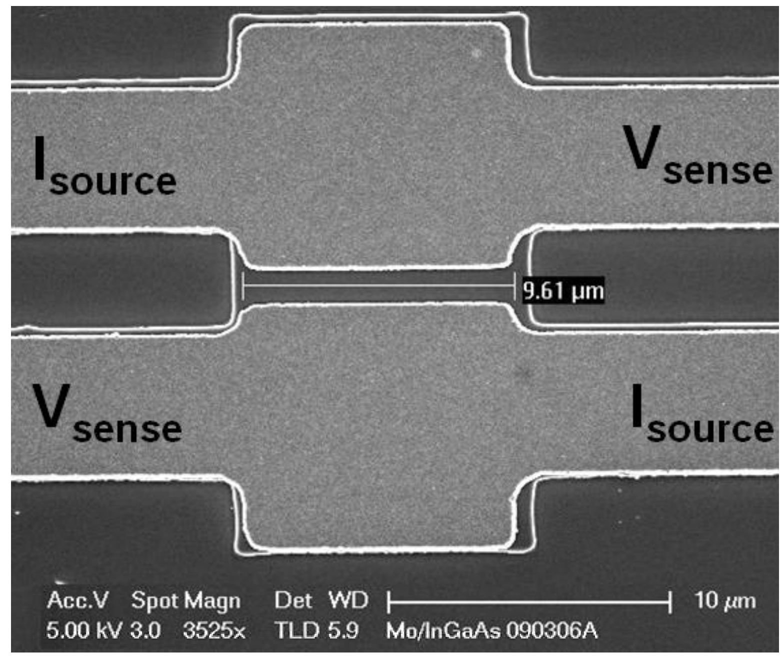
Resistance Measurement



- Resistance measured by Agilent 4155C semiconductor parameter analyzer

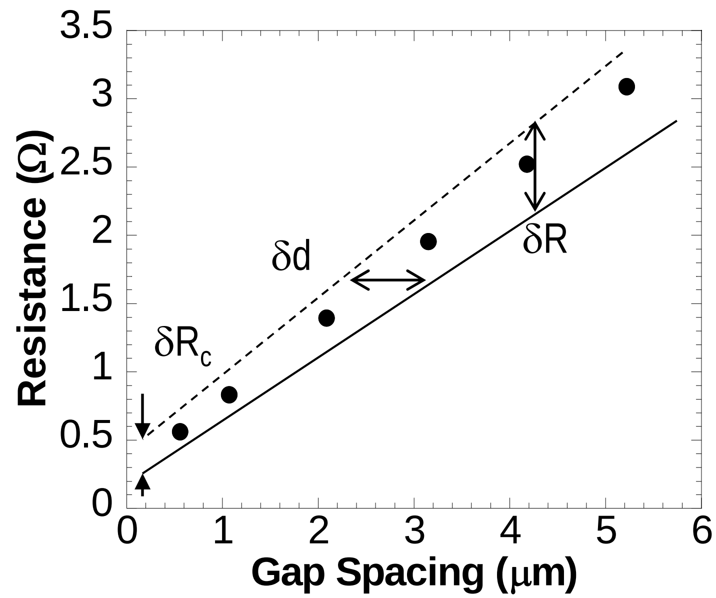
- TLM pad spacing varied from 0.6-26 μm; verified from scanning electron microscope

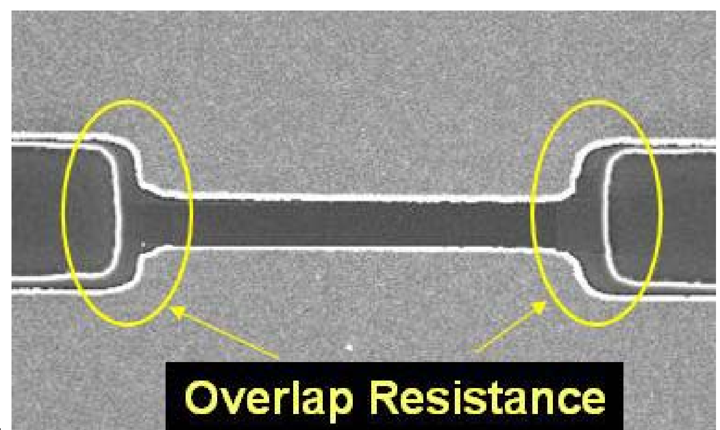
- TLM Width ~ 10 μm



Error Analysis

- Error due to extrapolation*
  - 4-point probe resistance measurements on Agilent 4155C
  - For the smallest TLM gap, R_c is 40% of total measured resistance
- Metal Resistance
  - Minimized using thick metal stack
  - Minimized using small contact widths
  - Correction included in data
- Overlap Resistance
  - Higher for small contact widths





*Haw-Jye Ueng, IEEE TED 2001

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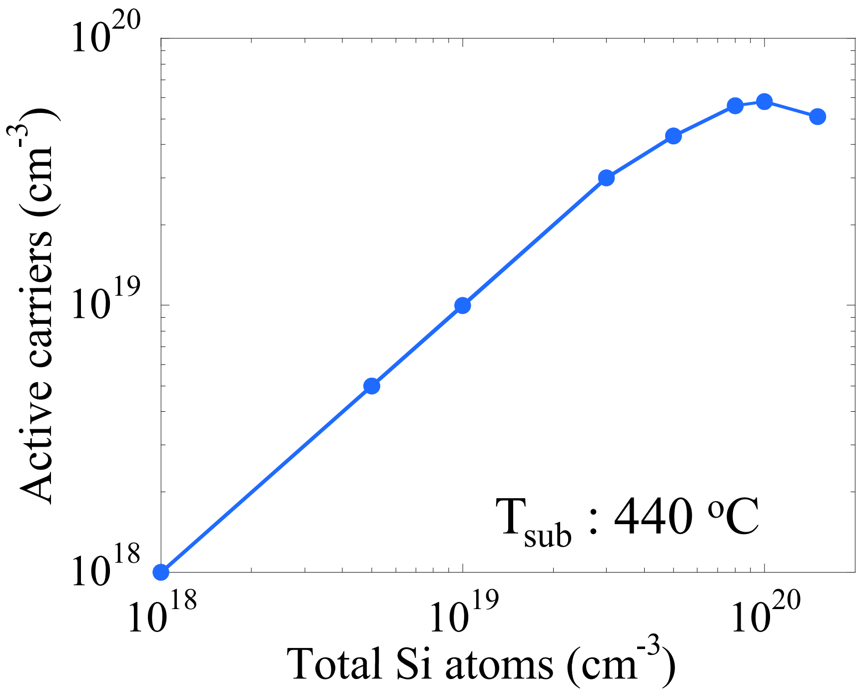
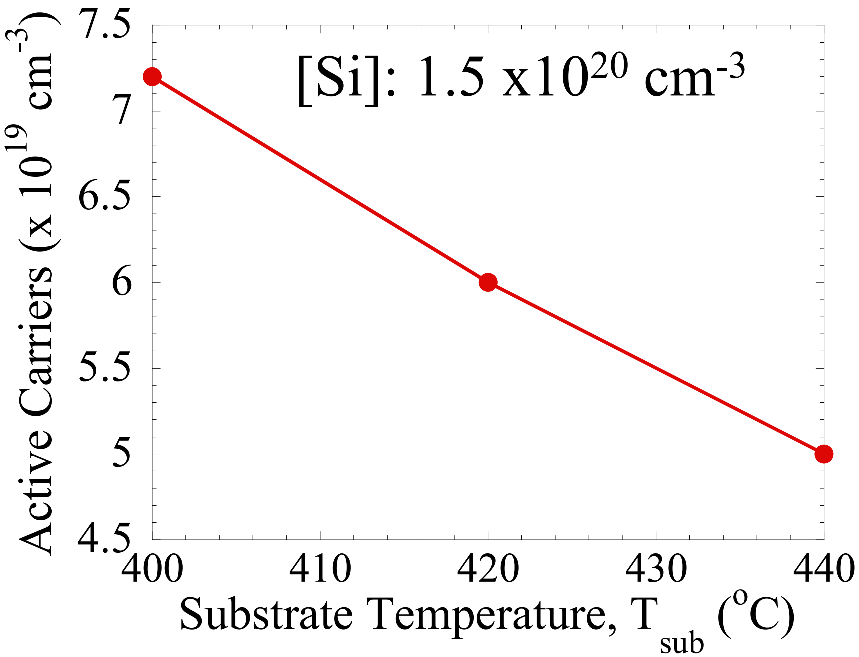
Results: Doping Characteristics



n saturates at high dopant concentration



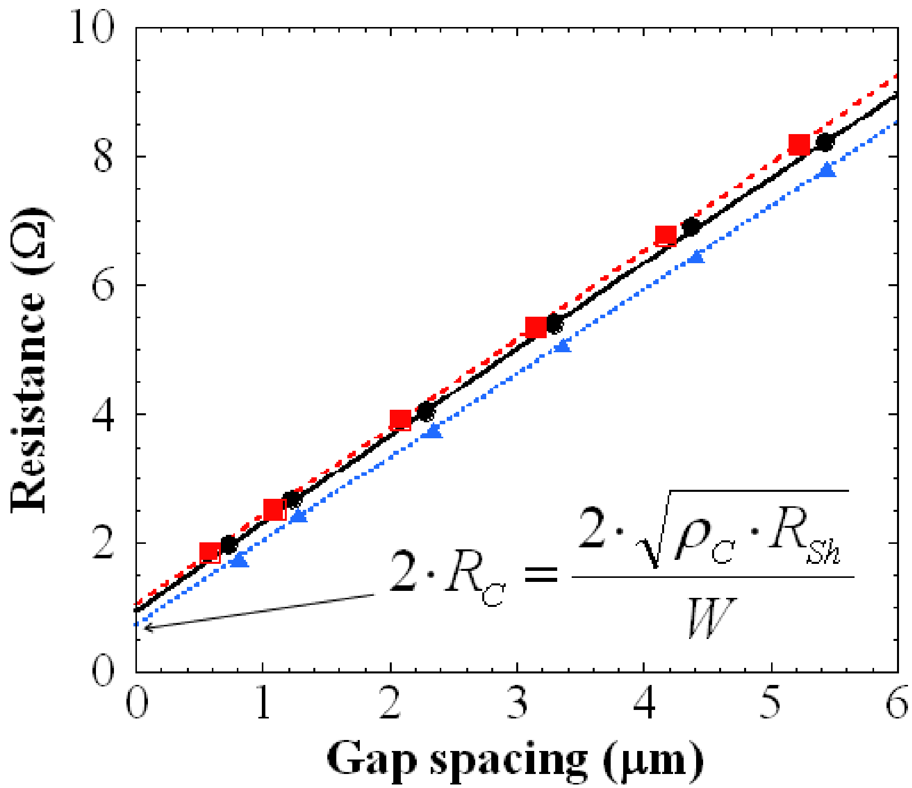
Enhanced *n* for colder growths

-hypothesis: As-rich surface drives Si onto group-III sites

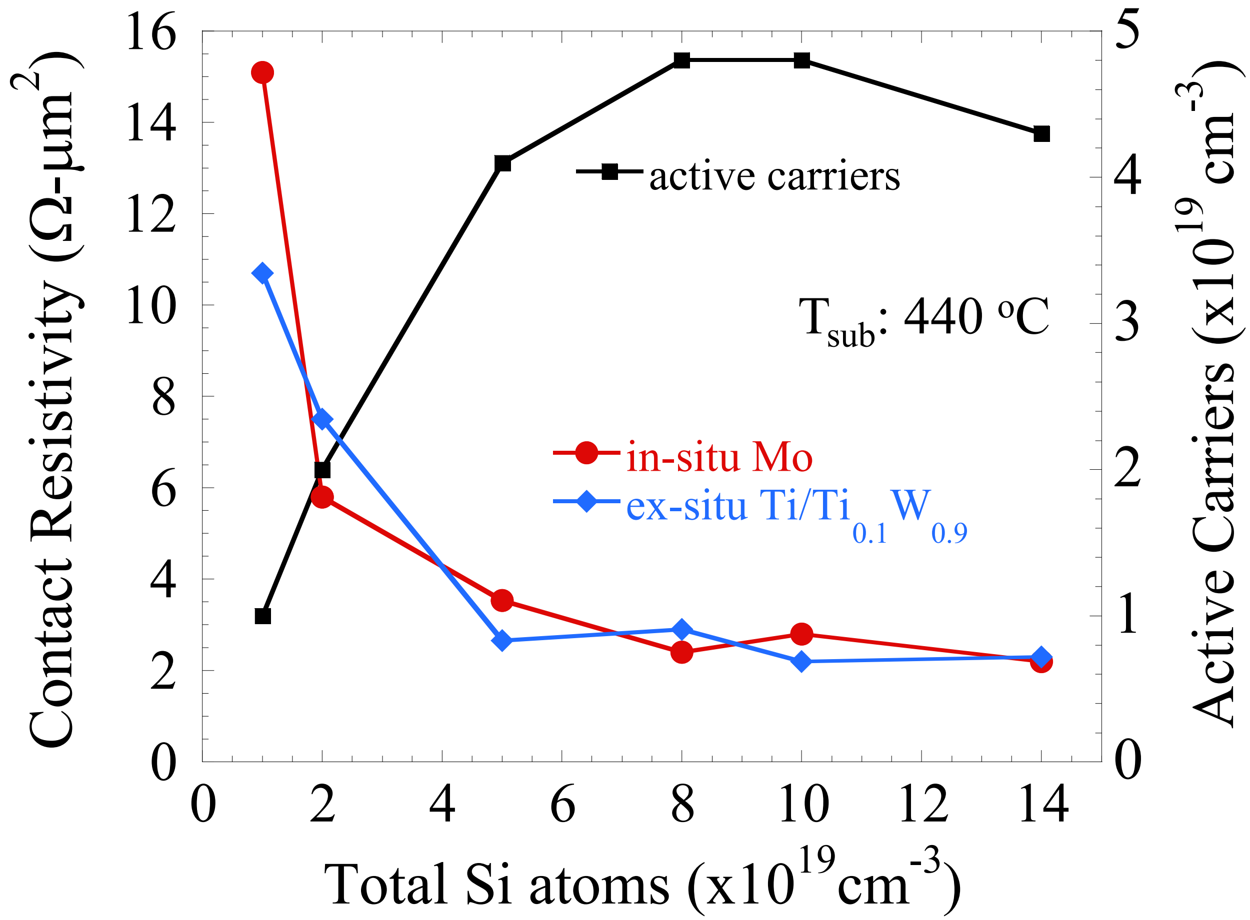
Results: Contact Resistivity

Metal Contact	Active Carriers (cm^{-3})	ρ_c (Ω-μm^2)
In-situ Mo	6 x10^{19}	1.1±0.6
In-situ Mo	4.2 x10^{19}	2.0±1.1
Ex-situ $Ti/Ti_{0.1}W_{0.9}$	4.2 x10^{19}	2.1±1.2

- Mo contacts: in-situ deposition; clean interface
- Ti: oxygen gettering property

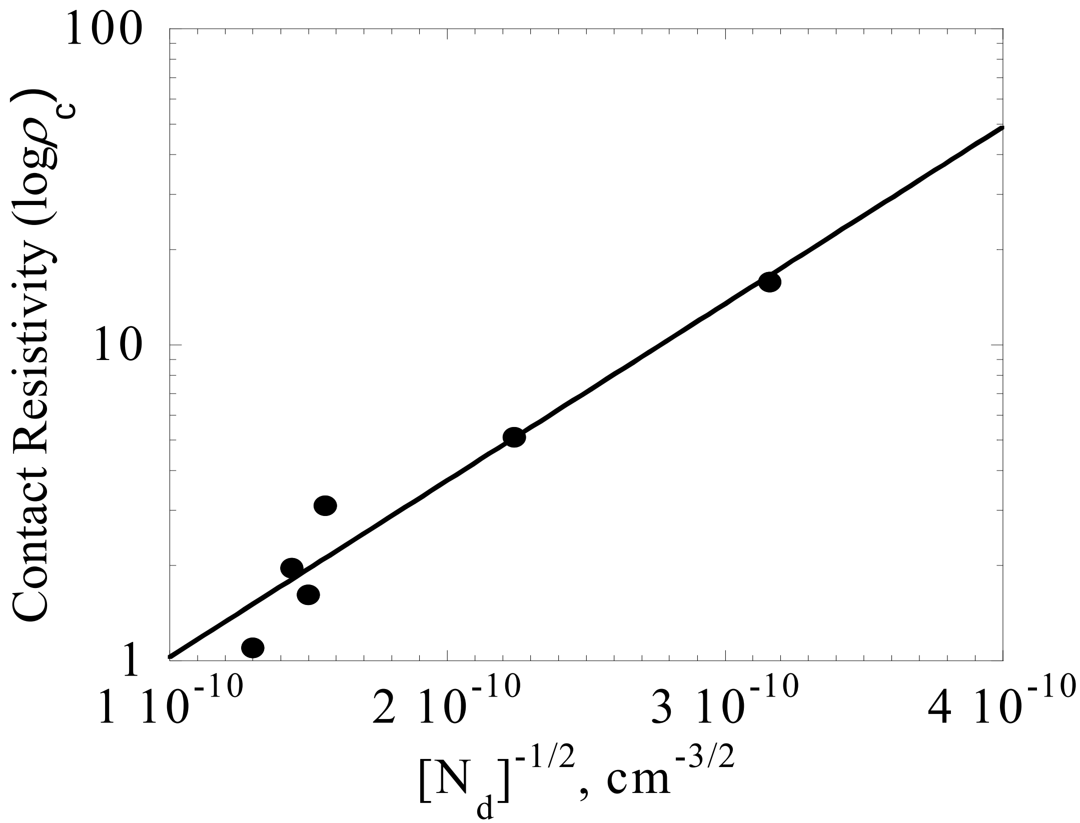


Results: Effect of doping-I



- Contact resistivity (ρ_c) ↓ with ↑ in electron concentration

Results: Effect of doping-II



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

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

Data suggests tunneling.

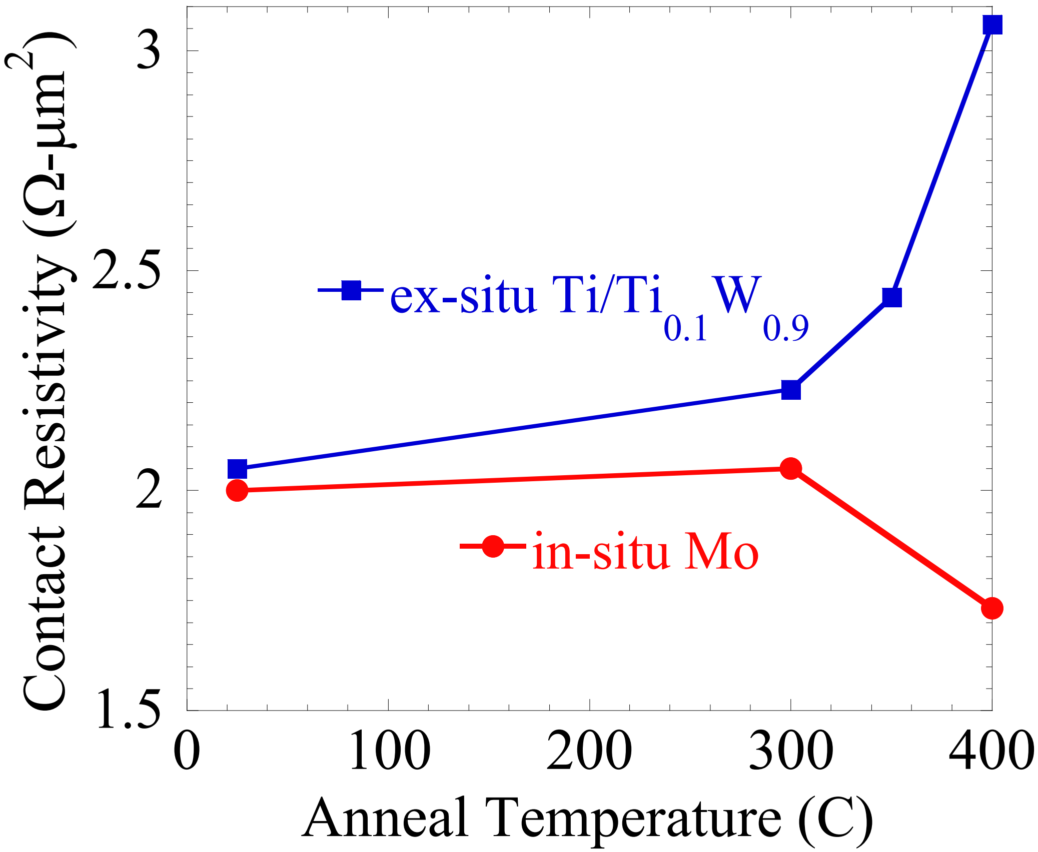
High active carrier concentration is the key to low resistance contacts

* Physics of Semiconductor Devices, SM Sze

Results: Thermal Stability

Contacts annealed under N_2 flow for 60 secs

- Mo contacts stable to at least 400 C
- $Ti/Ti_{0.1}W_{0.9}$ contacts degrade on annealing*



*T. Nittono, H. Ito, O. Nakajima, and T. Ishibashi, *Jpn. J. Appl. Phys., Part 1* **27**, 1718 (1988).

Conclusion

- Extreme Si doping improves contact resistance
- In-situ Mo and ex-situ $Ti/Ti_{0.1}W_{0.9}$ give low contact resistance
  - Mo contacts are thermally stable
  - $Ti/Ti_{0.1}W_{0.9}$ contacts degrade
- $\rho_c \sim (1.1 \pm 0.6)$ Ω-μm^2 for in-situ Mo contacts
  - less than 2 Ω-μm^2 required for simultaneous THz f_t and f_{max}

✓ Contacts suitable for THz transistors

Thank You !

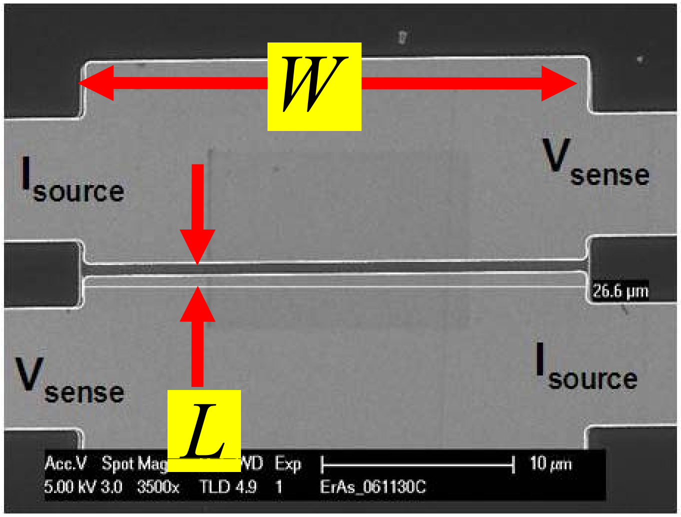
Questions?

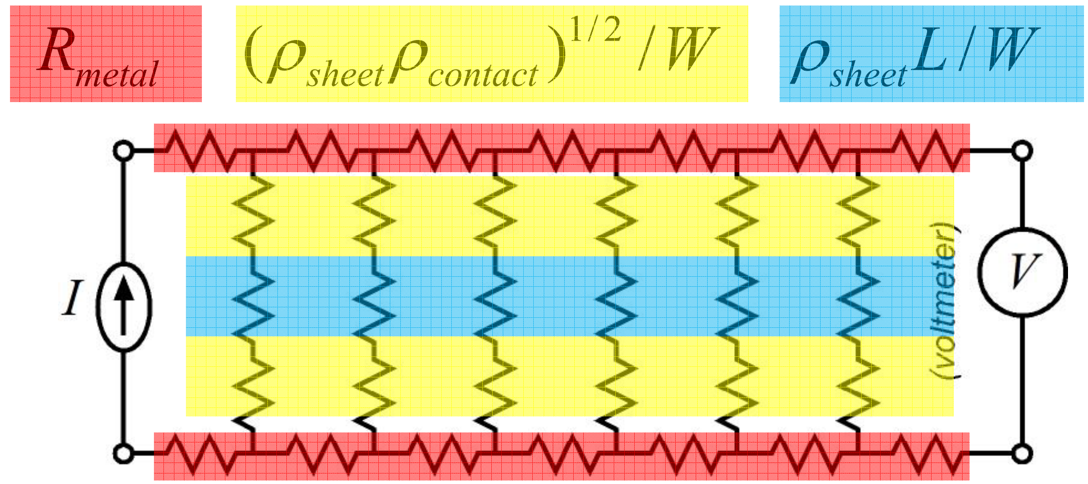
Acknowledgements

ONR, DARPA-TFAST, DARPA-FLARE

Extra Slides

Correction for Metal Resistance in 4-Point Test Structure

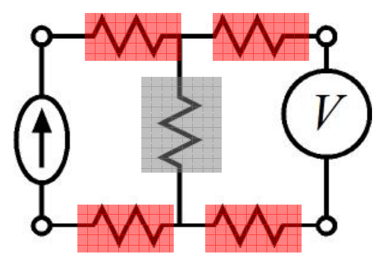




$$(\rho_{sheet}\rho_{contact})^{1/2}/W + \rho_{sheet}L/W - R_{metal}/3$$

From hand analysis & finite element simulation

$R_{metal}/2$

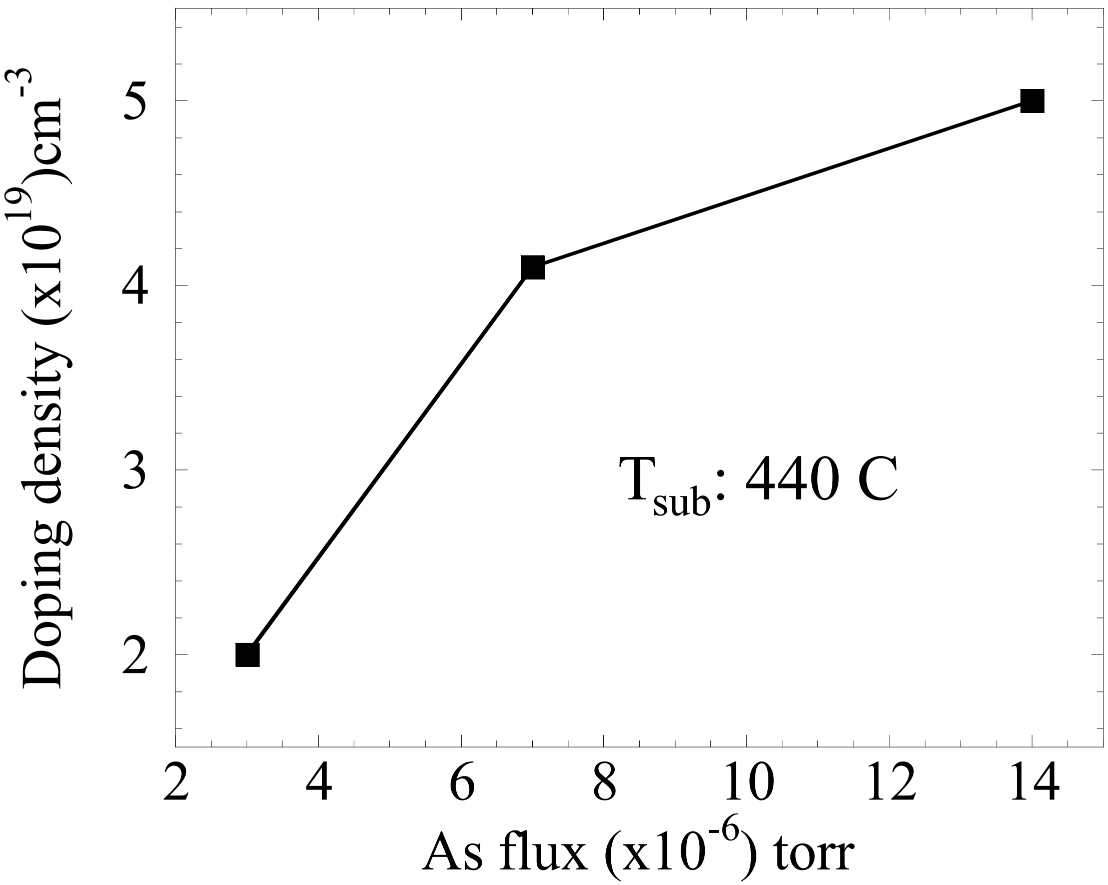


Error term ($-R_{metal}/3$) from metal resistance

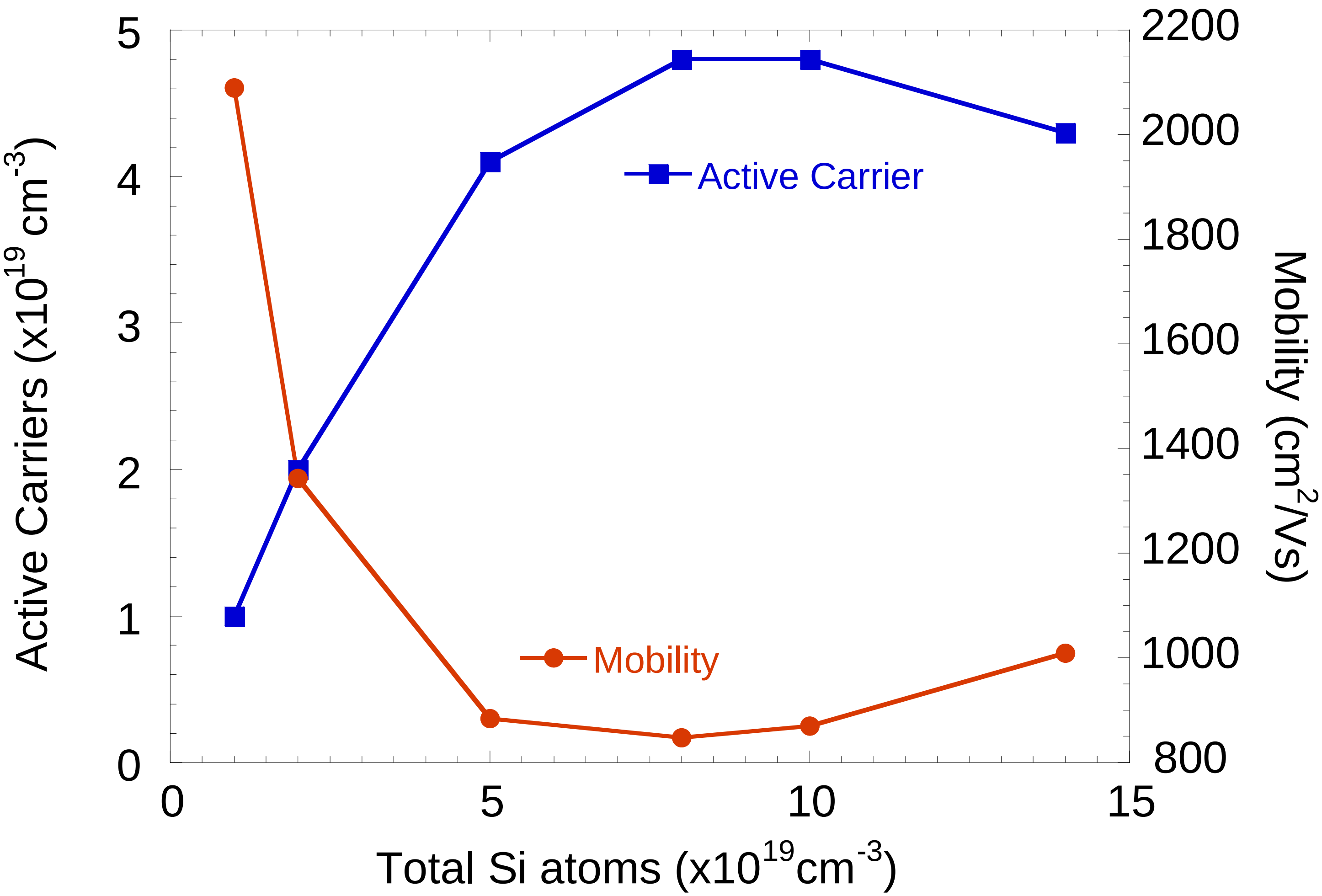
Effect changes measured ρ_c by ~40% (@1.3 Ω-μm^2)

All data presented corrects for this effect

Doping Vs As flux



Active Carrier, Mobility Vs Total Si



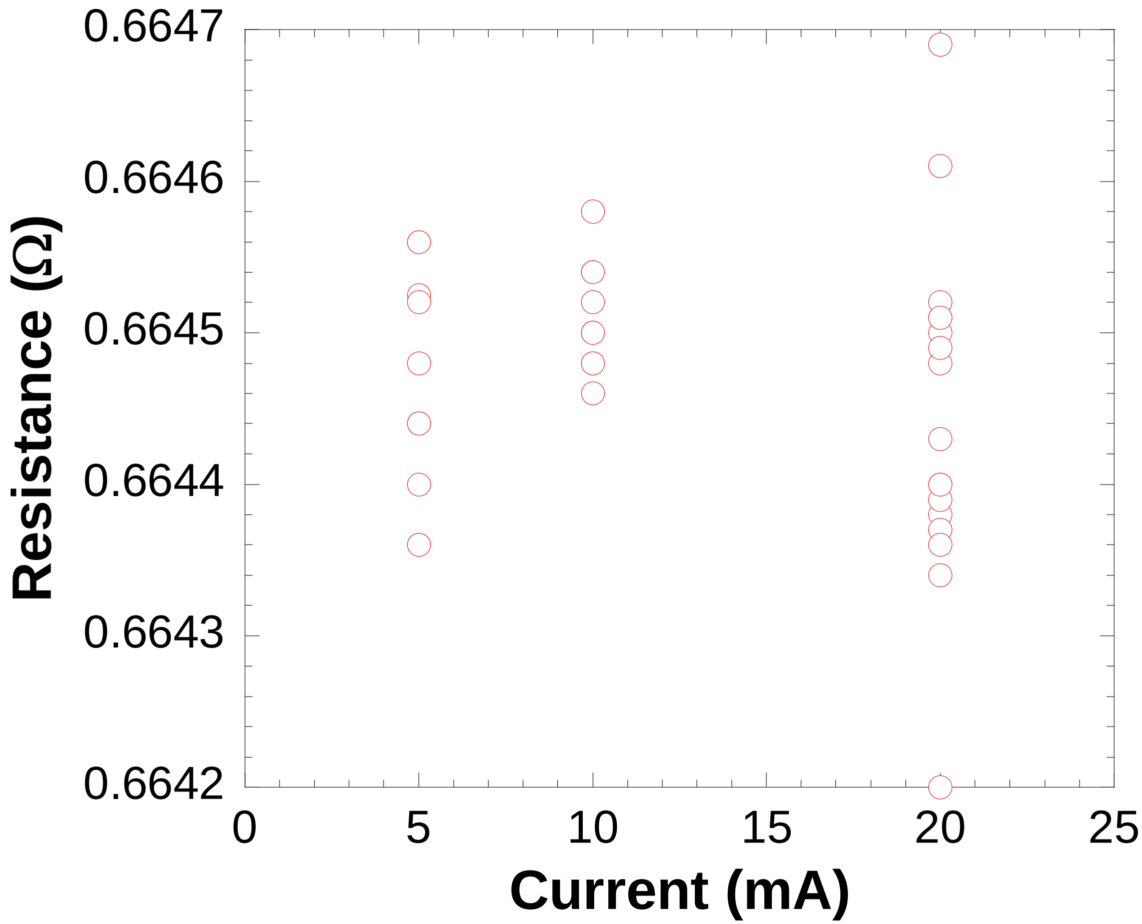
Strain Effects

$[Si]=1.5 \times 10^{20}$ cm^{-3}, $n=6 \times 10^{19}$ cm^{-3}

$$(a_{sub} - a_{epi})/a_{sub} = 5.1 \times 10^{-4}$$

Van de Walle, C. G., Phys. Rev. B **39,** 3 (1989) 1871

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 $\rho_c \sim 40\%$ at 1.1 $\Omega\text{-}\mu m^2$**