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High-Power High-Speed Photodiode for LIGO II

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March 15th, 2001

LIGO-G010122-00-Z

Outline

- Introduction
  - Photodiode Specifications & Development
  - Device Structure & Materials
- Diode Electrical Characterization
  - Contact Resistance
  - I-V Characteristics
  - C-V Characteristics
- Future Plans

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Photodiode Specifications

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Parameter	LIGO I	LIGO II (old)	LIGO II (new)
Steady-State Power	0.6 W	~10 W	~1 W
Operating Frequency	< 29 MHz	~100 MHz	~100 kHz
Quantum Efficiency	> 80%	> 90%	> 90%
Transient Damage	3 Joules / 10 ms	100 Joules / 10 ms (?)	100 Joules / 10 ms (?)
Signal/Noise	1.4e10 √Hz	3.1e10 √Hz	3.1e10 √Hz
Spatial Uniformity	1% RMS	0.1% RMS	0.1% RMS
Surface Backscatter	1e-4 / sr	1e-6 / sr	1e-6 / sr
Detector Design	Bank of 6(+) PDs	1 PD (~3 mm dia.)	1 PD (1-3 mm dia.)

Photodiode Development

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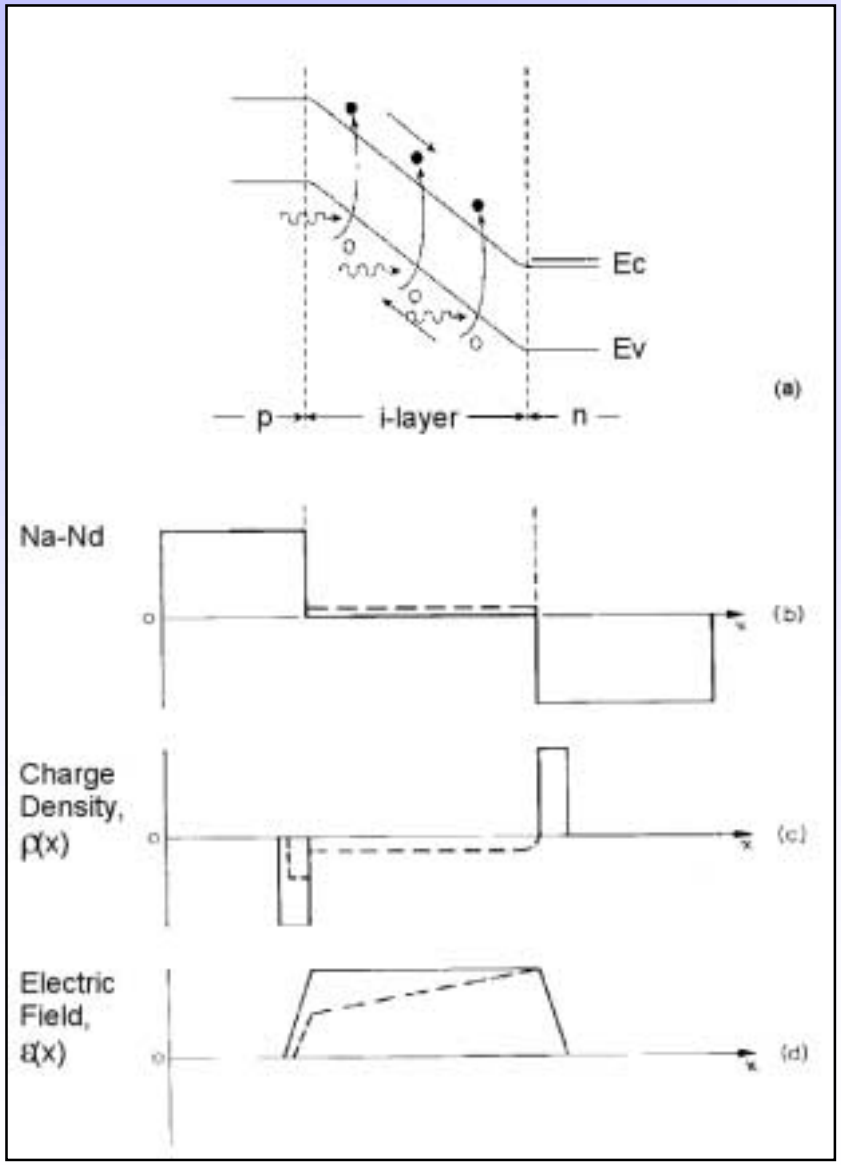
- **June 1999- Came on the project**
  - **Passed Quals**
  - **Began Training on MBE Machine and Processing Procedure**
- **March 2000: 1st Round Wafers**
  - **Materials Analysis**
  - **Electronic Properties Not Good**
- **June 2000: 2nd Round Wafers**
  - **Materials Analysis (Transmission, XRD, TEM, SEM)**
  - **Electronic Properties Characterized (TLM, I-V, C-V)**
- **March 2001- Future: 3rd Round Wafers**
  - **Electronic Properties**
  - **Optoelectronic Properties (Bandwidth, QE, Power Response)**

P-I-N Device Characteristics



- **Large E-field in I-region**
- **Depletion Width ≈ Width of I- region**
  - **Frequency response**

$$f_{max} \approx (\nu_{sat} / W_I)$$

  - **RC time constant**

$$\approx R_s C_J$$

$$C_J = K_s \varepsilon_0 A / W_I$$

  - **Tuned to a specific λ**

$$W_I >> \frac{1}{\alpha}$$

Band Gap Diagram w/ Heterojunctions

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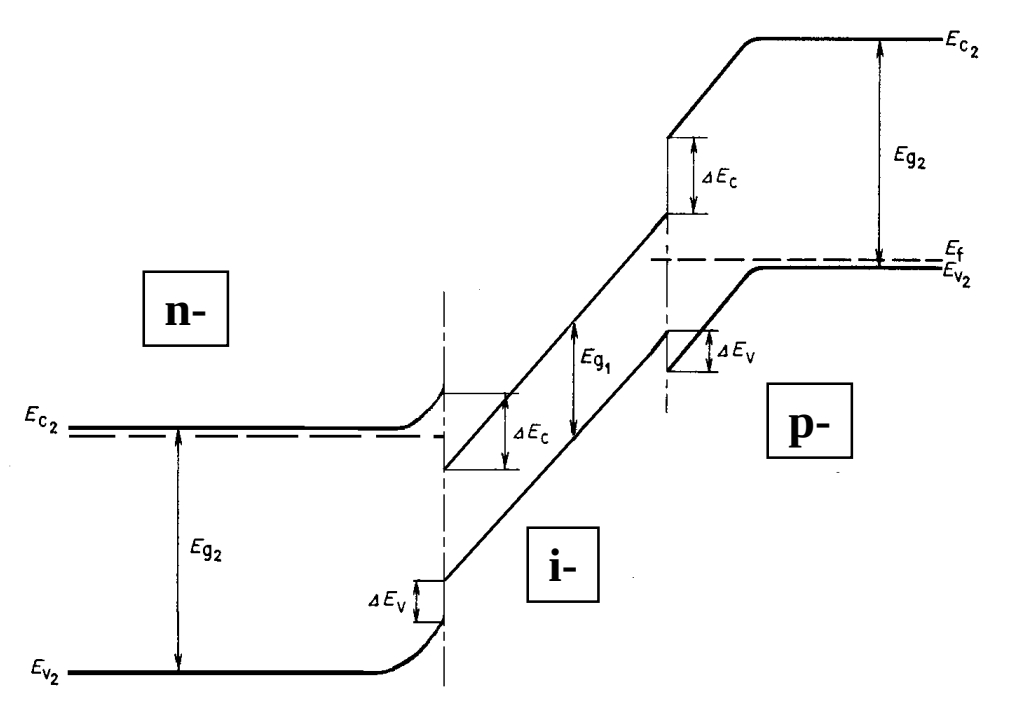

- **InAlAs Optically transparent to 1.06μm radiation**
- **Absorption occurs in i-region**

N-layer:	I-layer:	P-layer:
$In_{.22}Al_{.78}As$	$In_{.22}Ga_{.78}As$	$In_{.22}Al_{.78}As$
$E_{g2} = 2.0eV$	$E_{g1} = 1.1eV$	$E_{g2} = 2.0eV$

InGaAs/GaAs PD Structure

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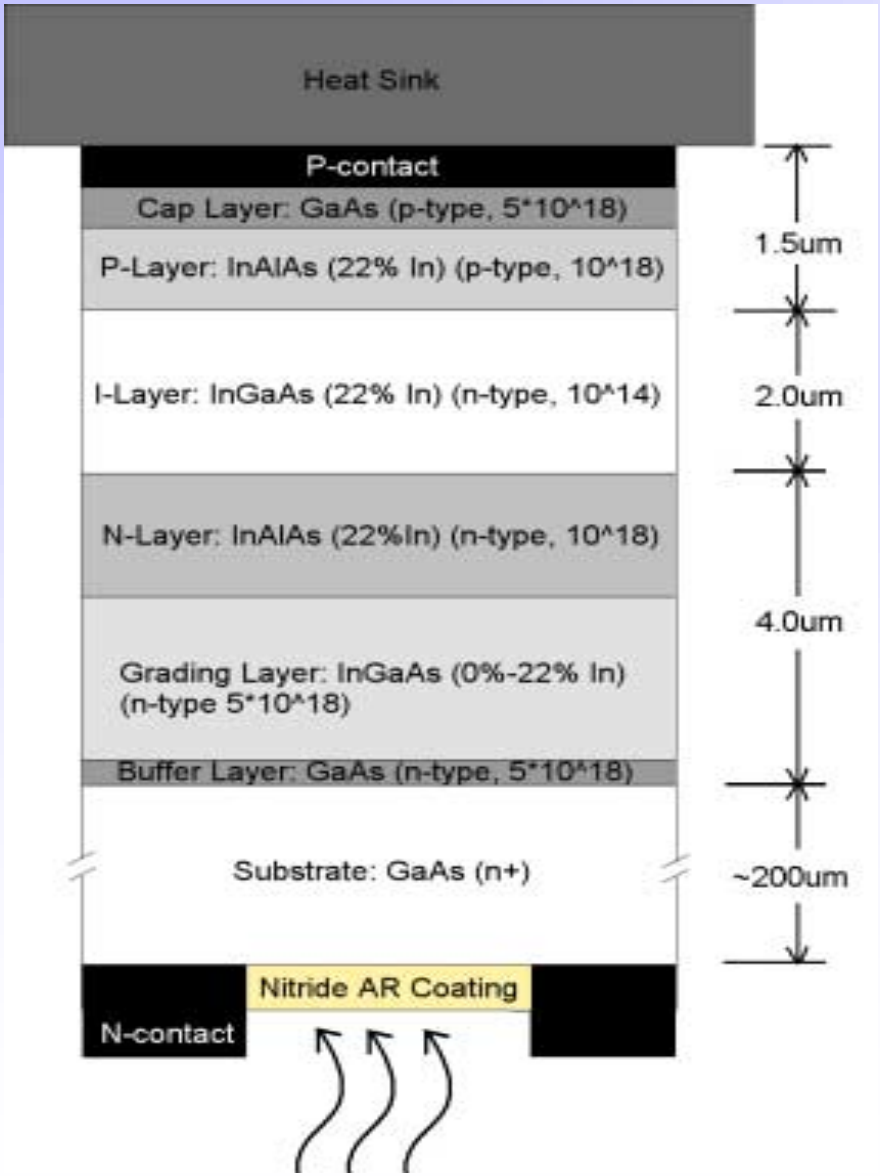
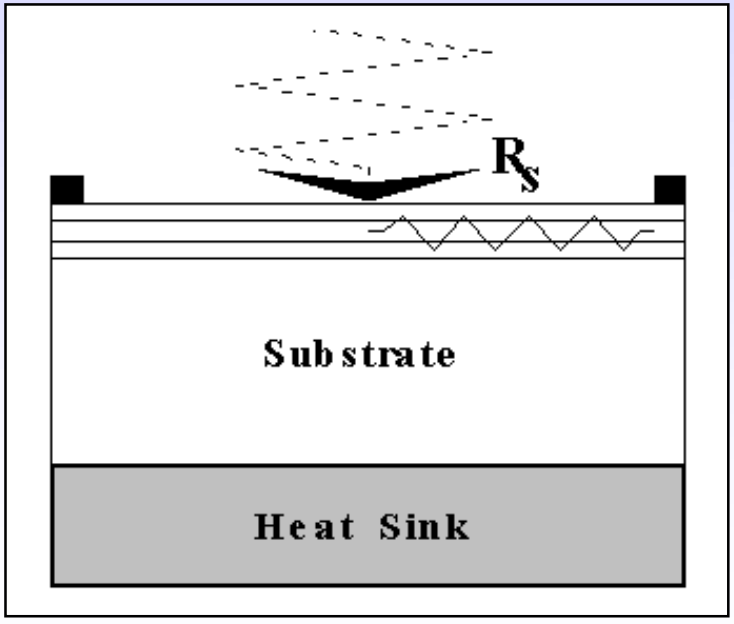


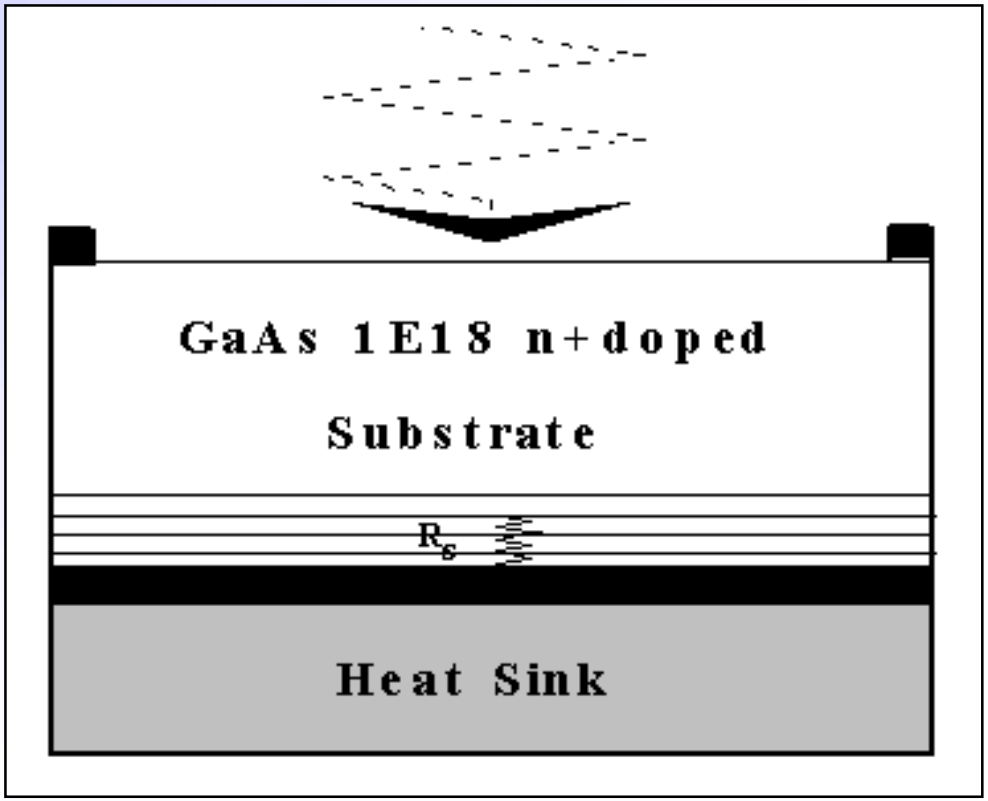
- **P-I-N structure**
- **InGaAs for i-layer**
- **InAlAs for the n- and p- layers**
- **MBE**
- **Grading layer**
- **AR coating & Au/Pt contacts**

Rear-Illuminated PD Advantages

- **High Power**
- **Linear Response**
- **High Speed**



Conventional PD



Proposed PD (Rear-Illuminated)

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MBE Surface Kinetics

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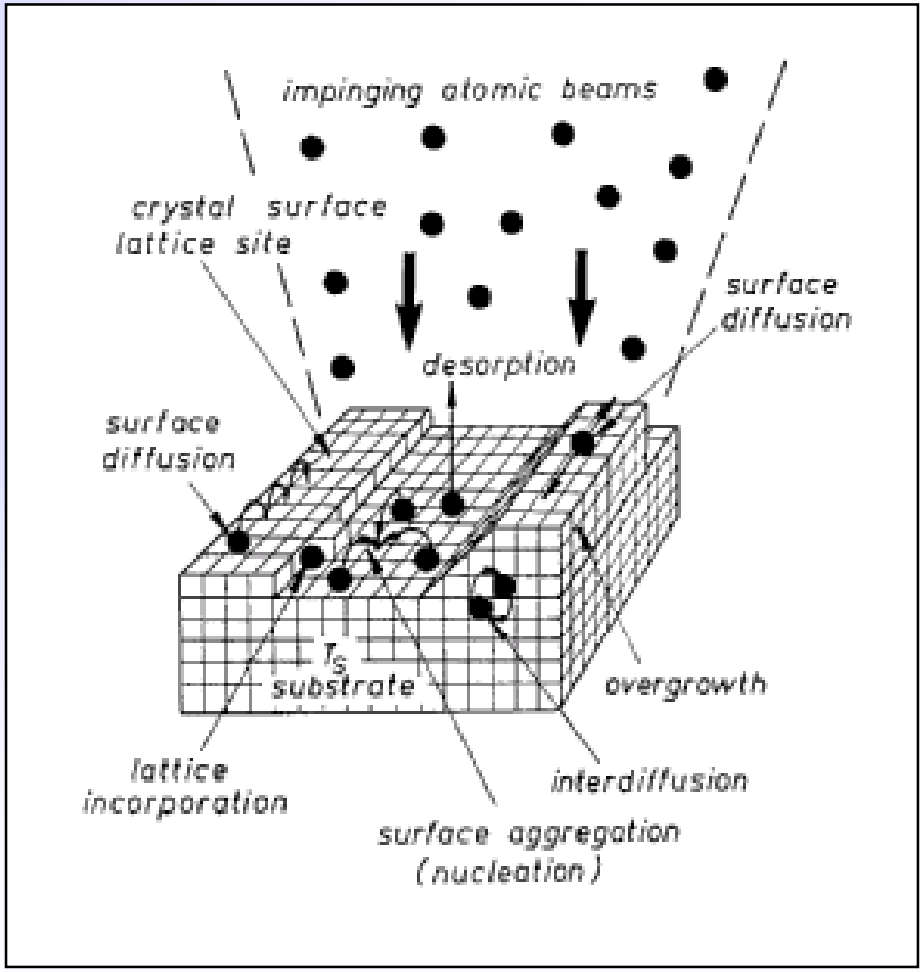
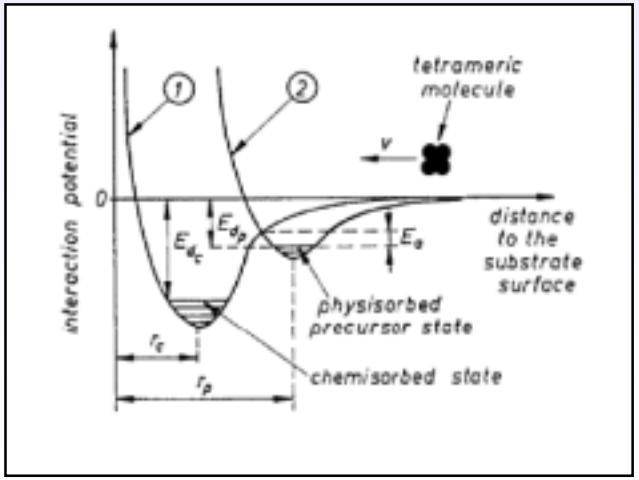
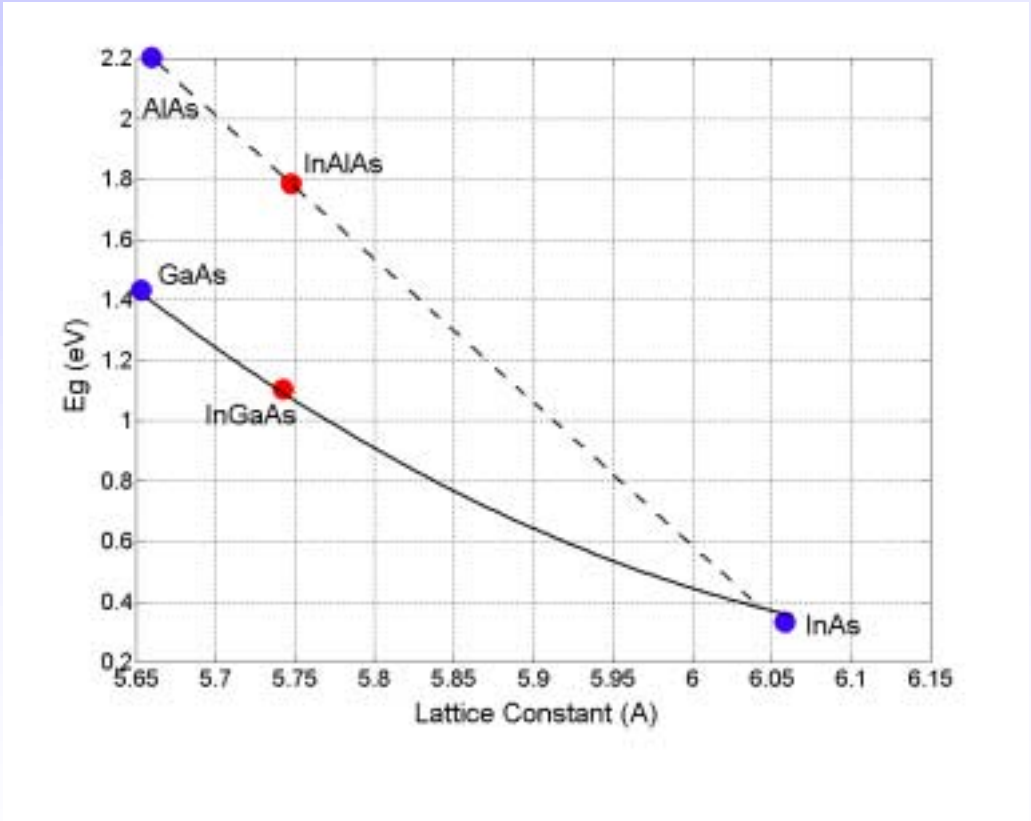
- **Adsorption**
  - **Physisorption**
  - **Chemisorption**
- **Surface migration**
- **Incorporation**
- **Thermal desorption**





III-V Lattice Constants and Band Gaps



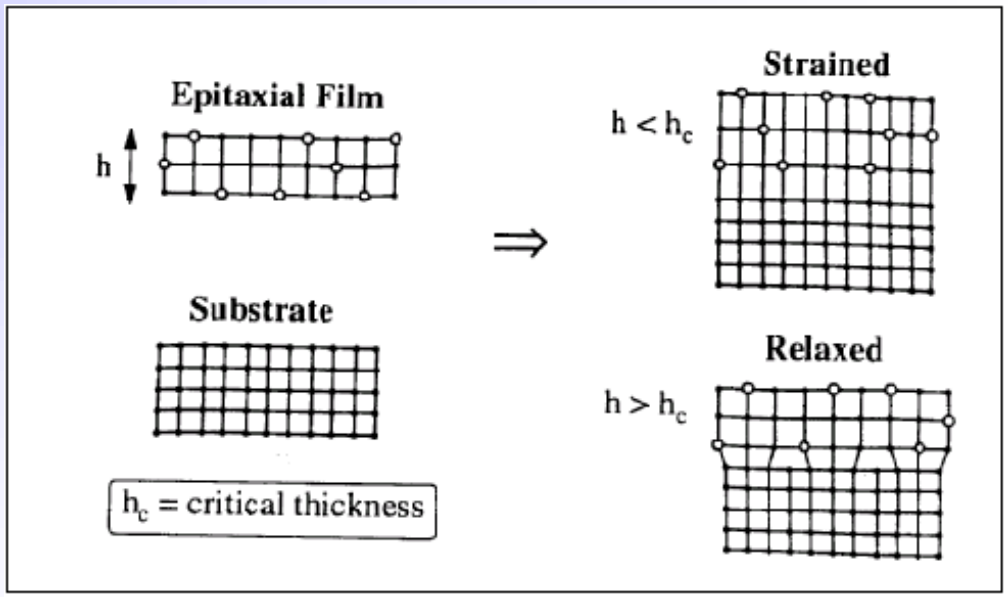
- **InAlAs and InGaAs well lattice matched**
- **InAlAs much wider band gap**

Lattice Mismatched Growth

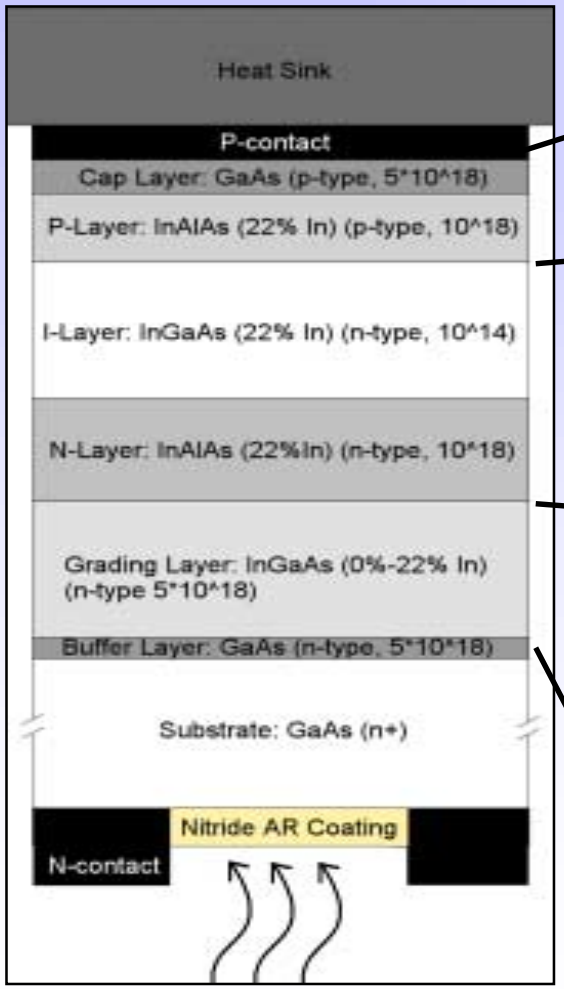
- **Lattice Constant for $In_xGa_{(1-x)}As$:**

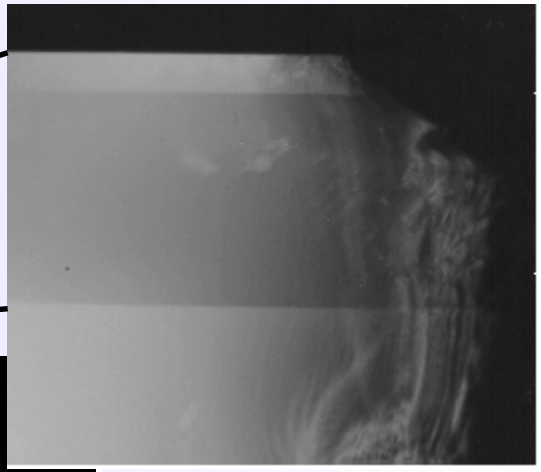
  $a=5.6536+0.4054x$

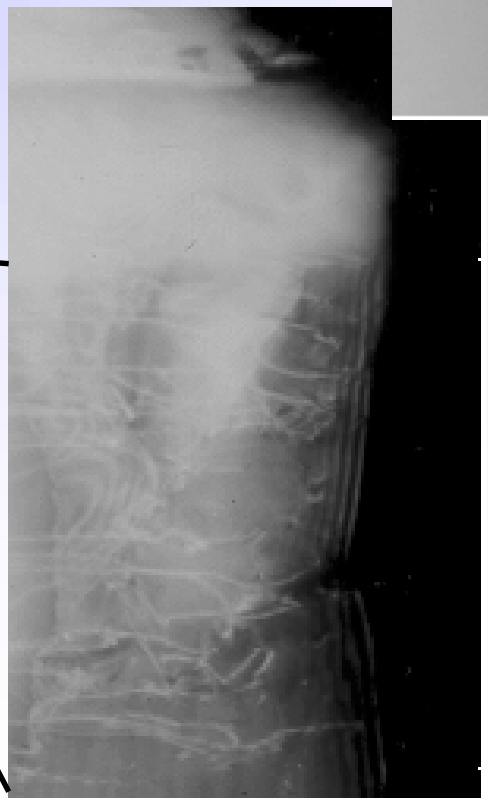
- **$In_{.4}Ga_{.6}As$: $h_c \approx 100Å$**



TEM Images of Confined Dislocations







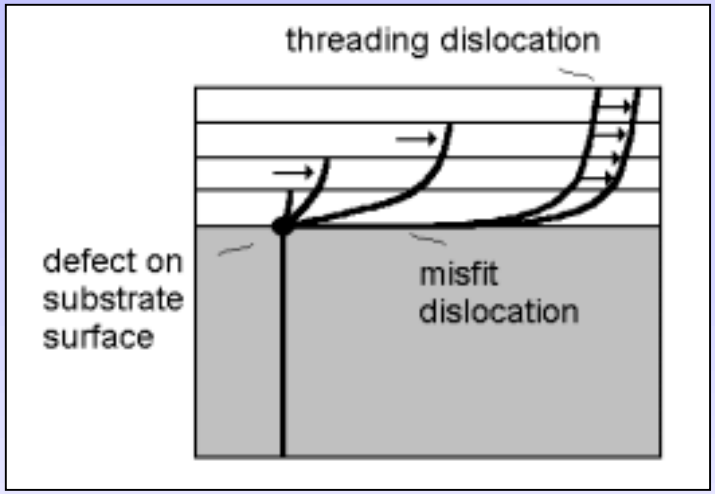
Device Layers:

-few dislocations

Graded Buffer:

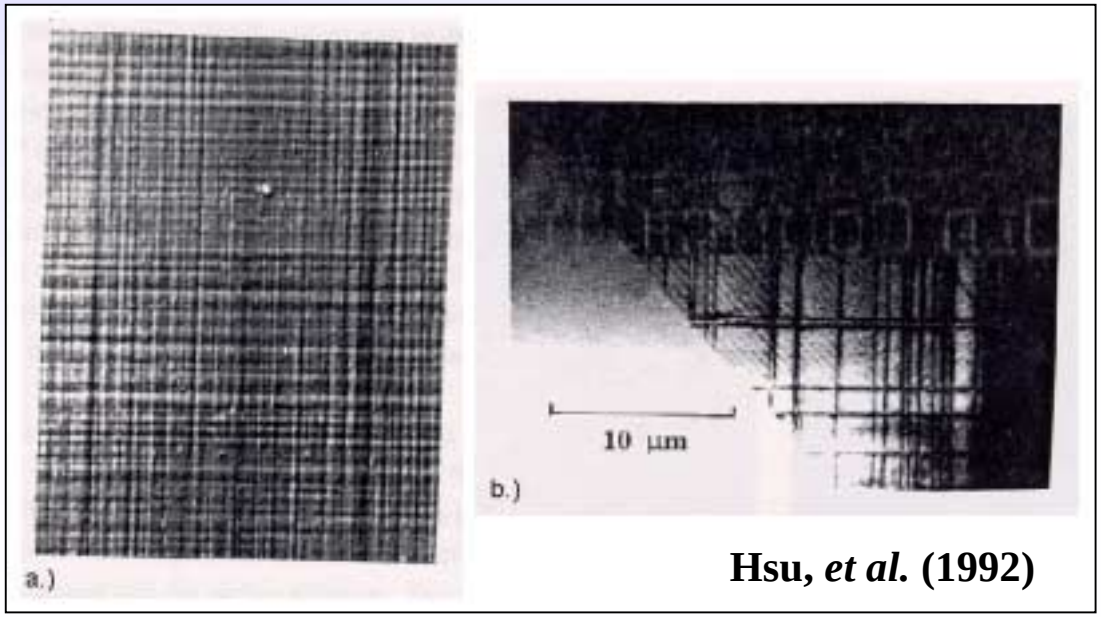
-many dislocations

Graded Buffer Dislocations



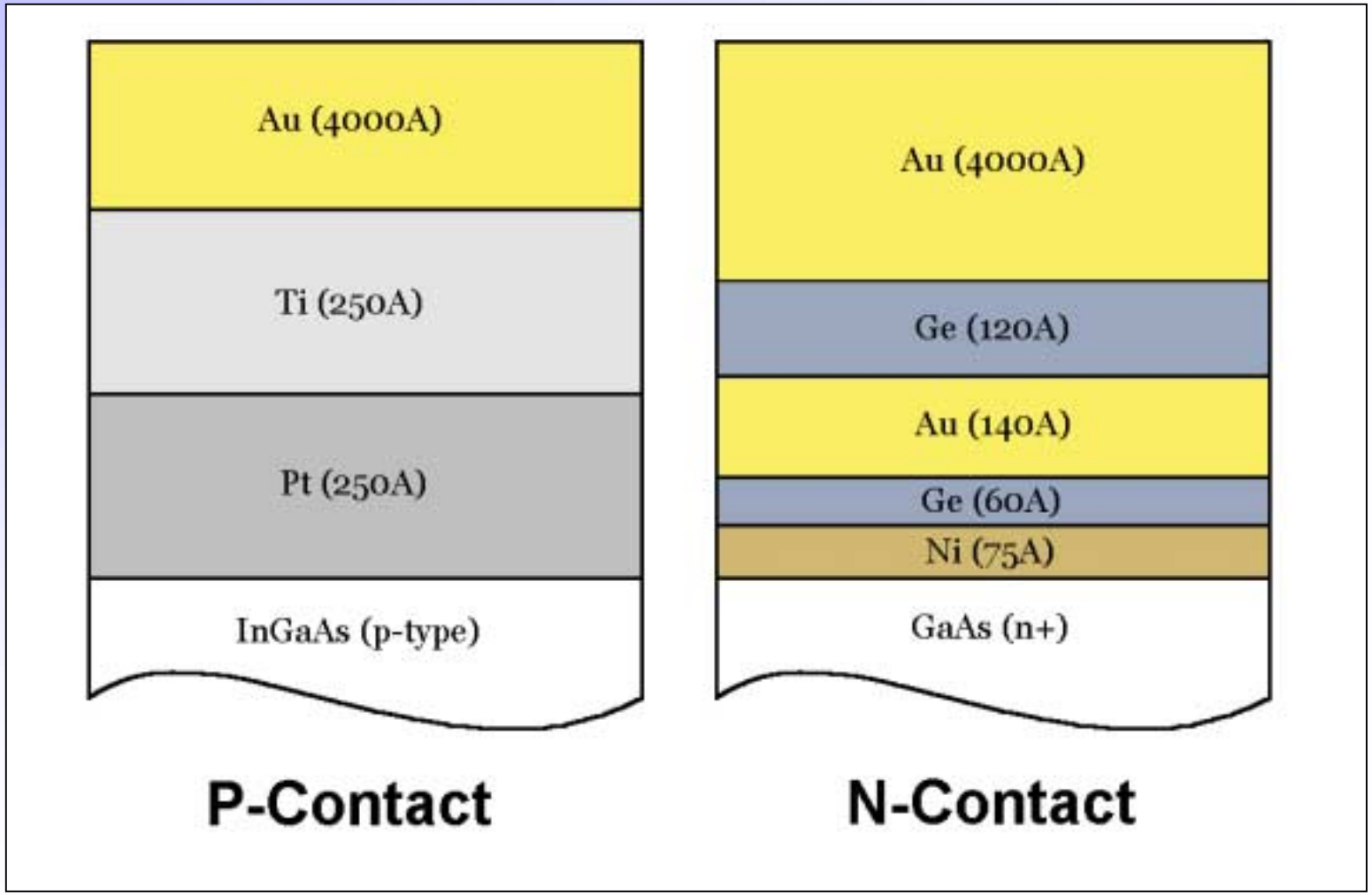
Biaxial stress in film causes dislocations to glide

Misfit growth often results in surface striations

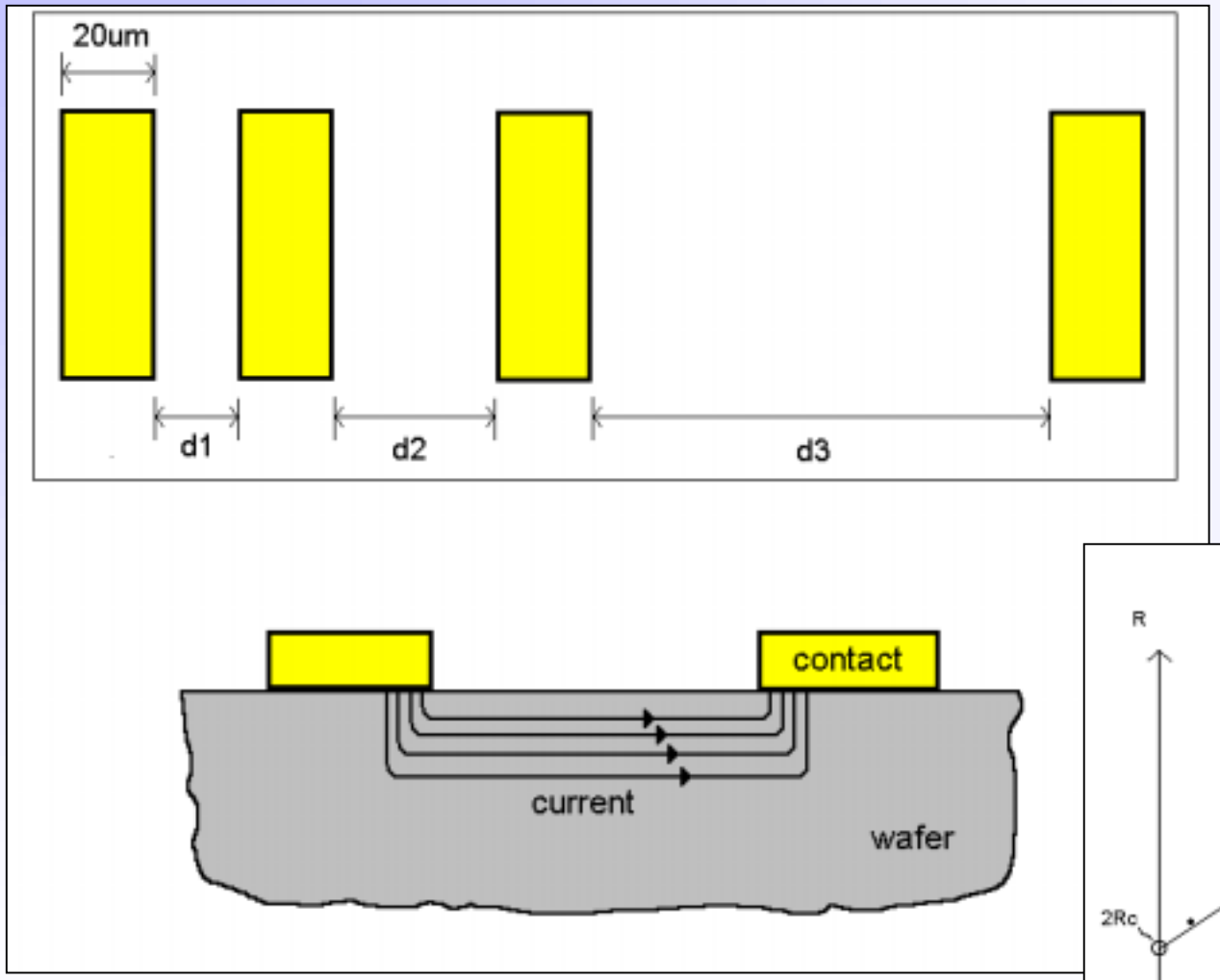


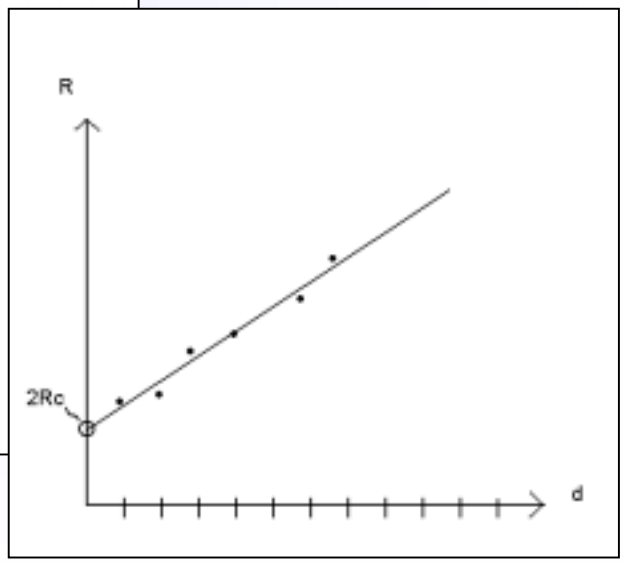
Hsu, *et al.* (1992)

P- and N- Contacts



TLM (Transmission Line Model)





TLM Measurements: P-Contact

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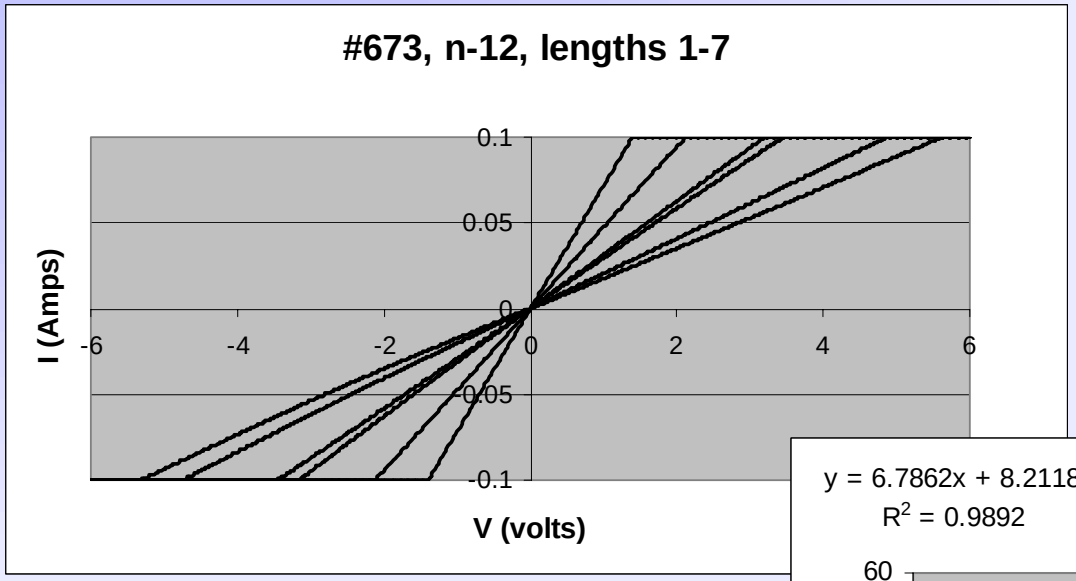
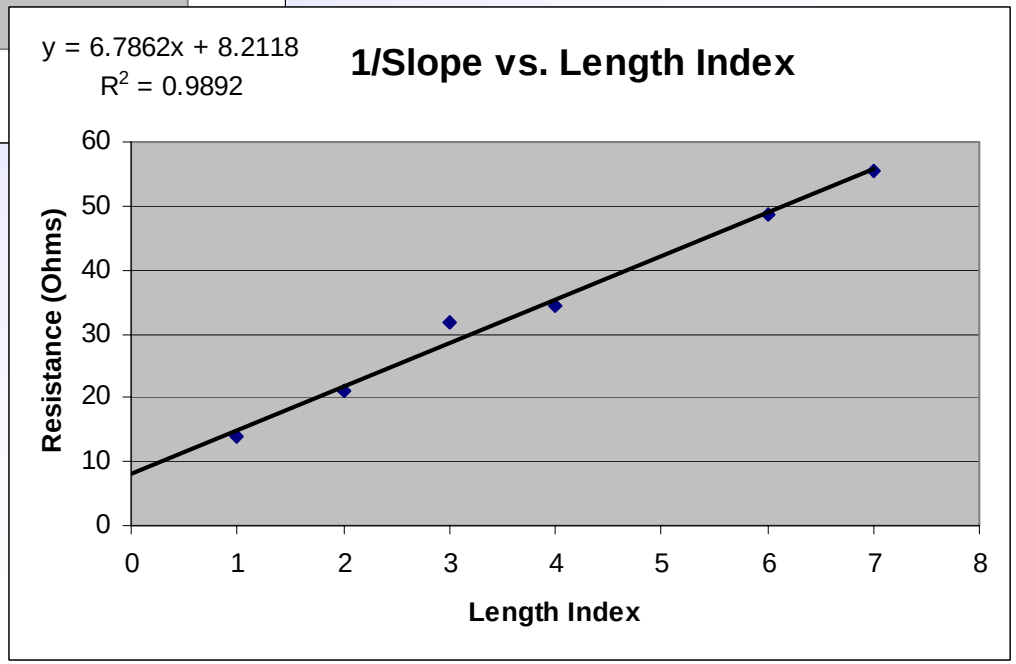


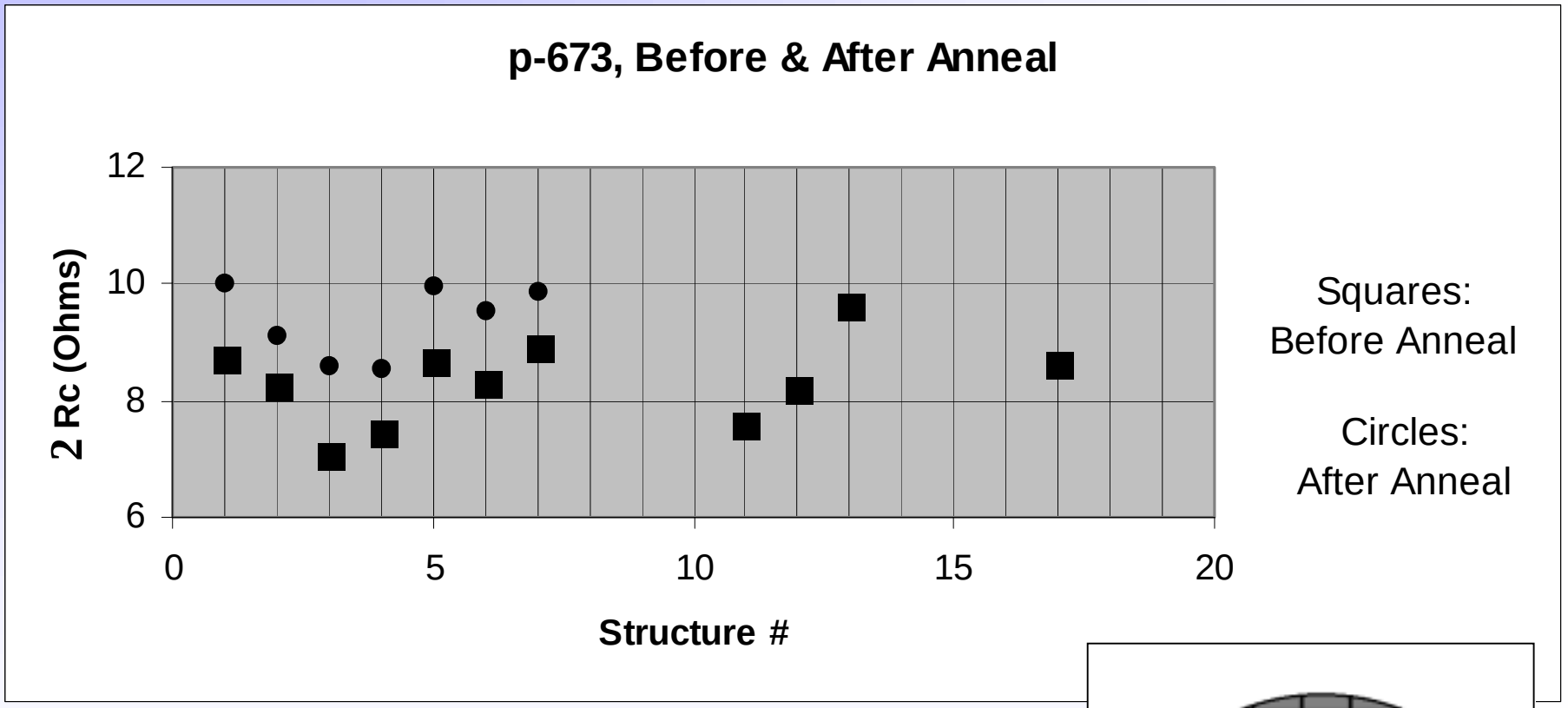
- **Short d, ↓R, ↑Slope**
- **Long d, ↑R, ↓Slope**

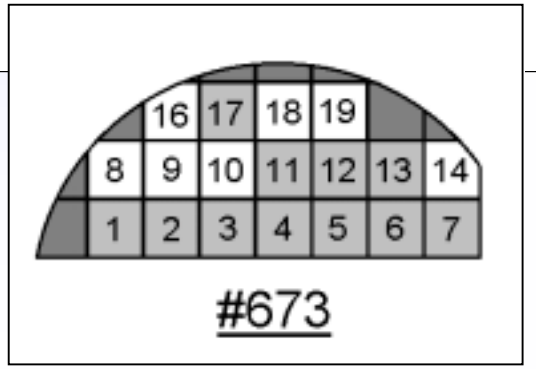


$R_c = 8.2\Omega/2 = 4.1\Omega$

$R_s = 6.8\Omega / 10\mu m = 0.68\Omega/\mu m$

P-Contact Resistance (#673)





P-Contact Resistance (#649)

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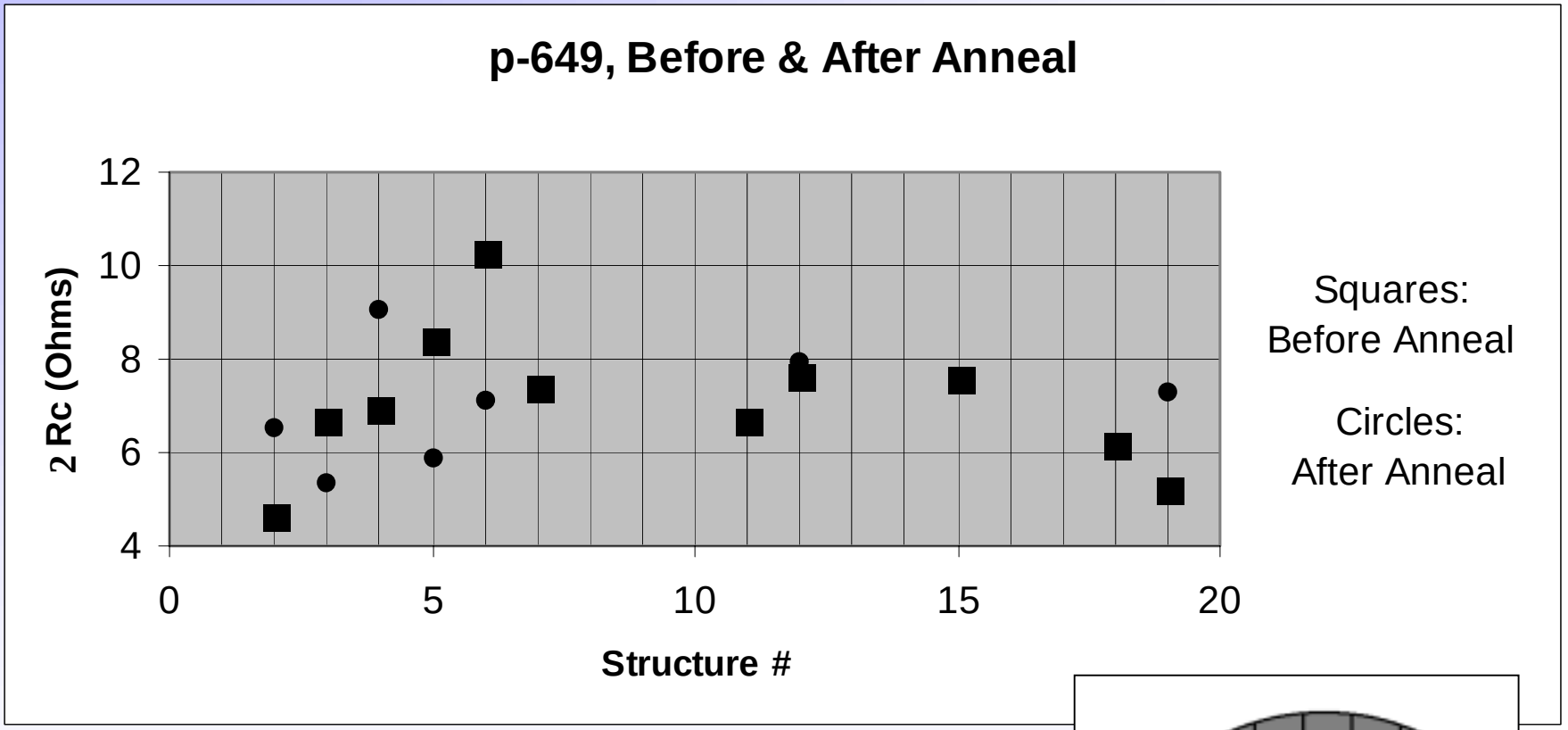

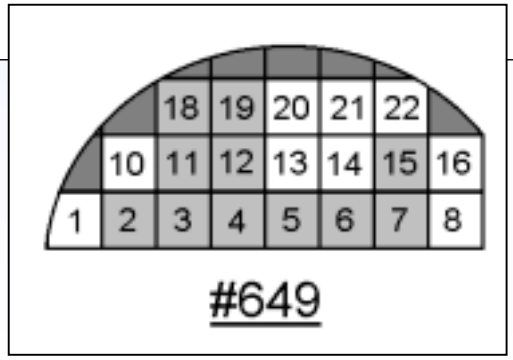

N-Contact Character

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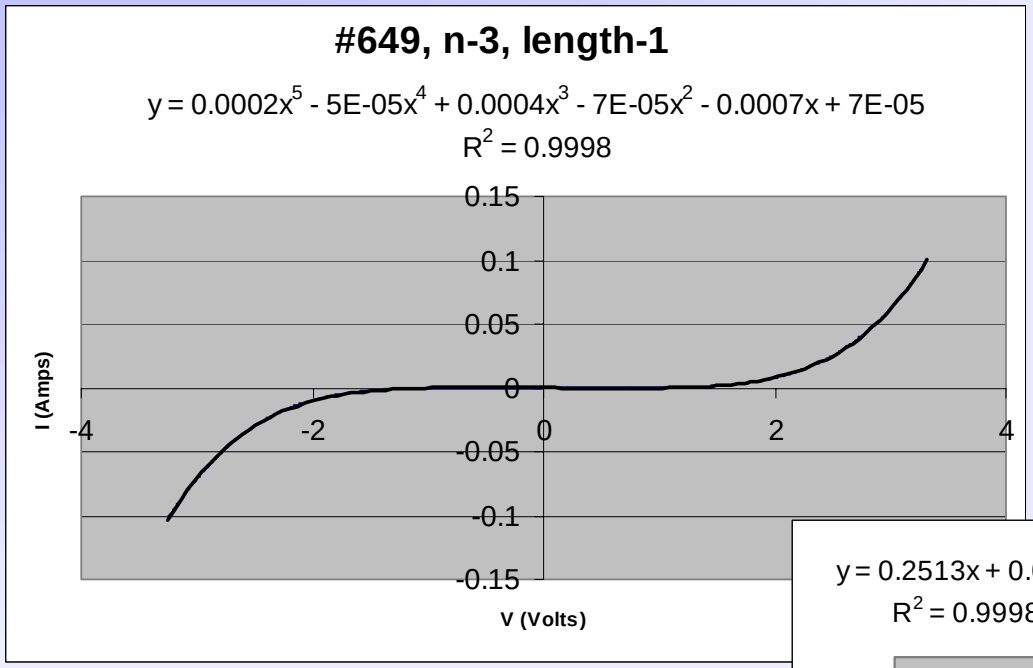
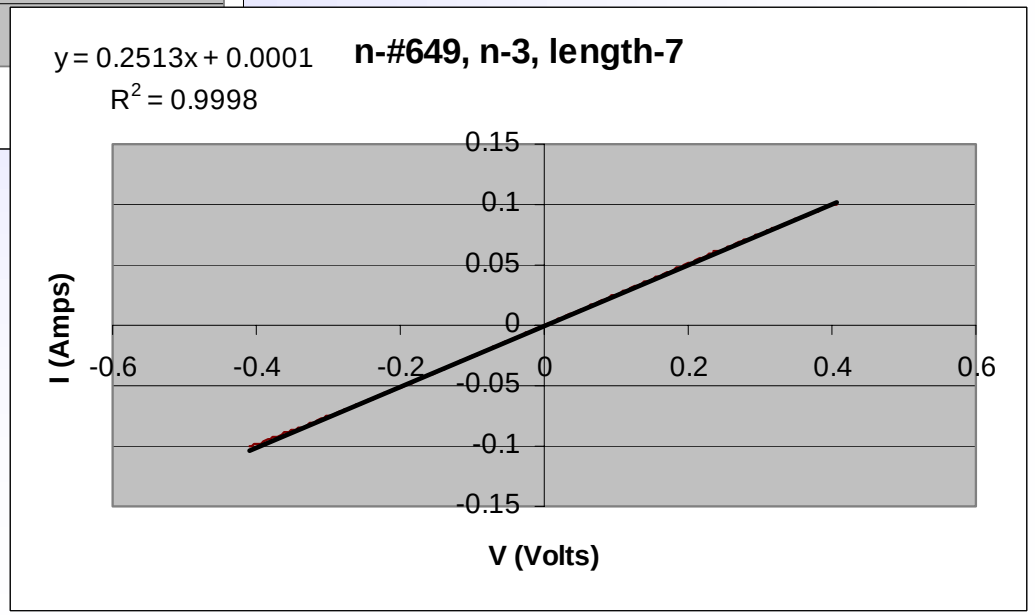


Before Annealing:

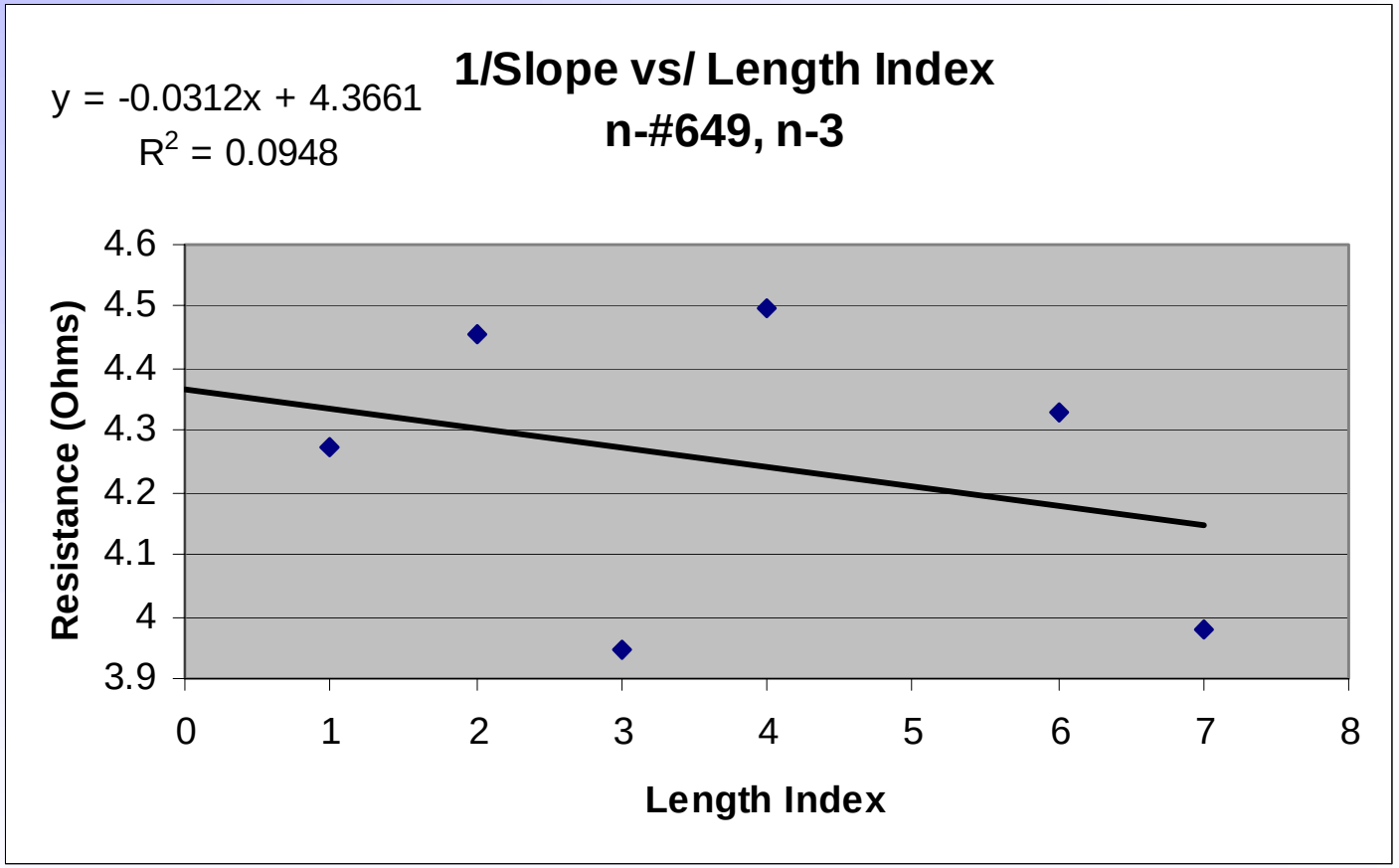
→ Not Ohmic (Schottky)



After Annealing:

→ Ohmic

N-Contact Resistance (After Anneal)



→Not very linear!

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N- and P- Contact Resistance

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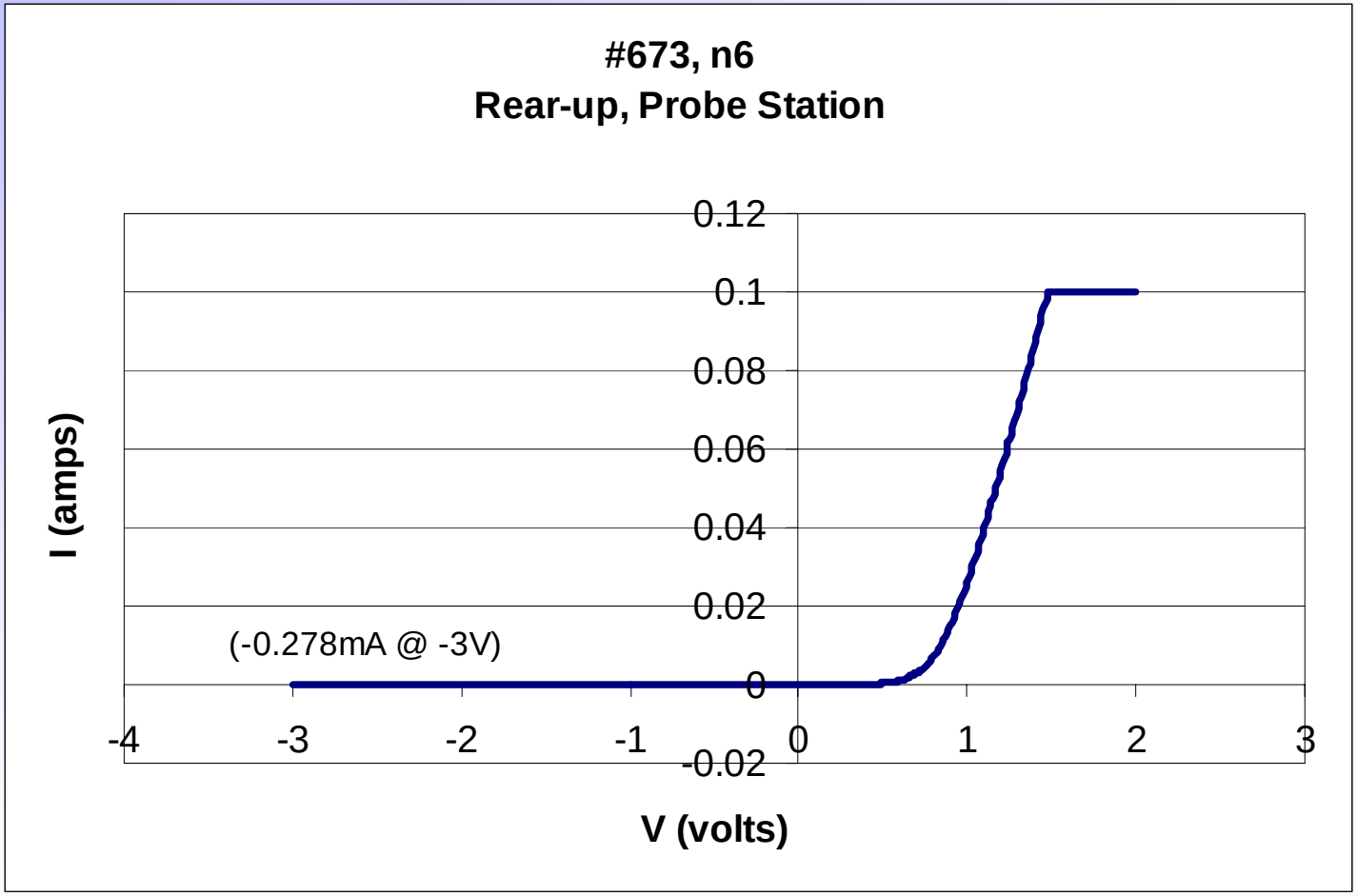
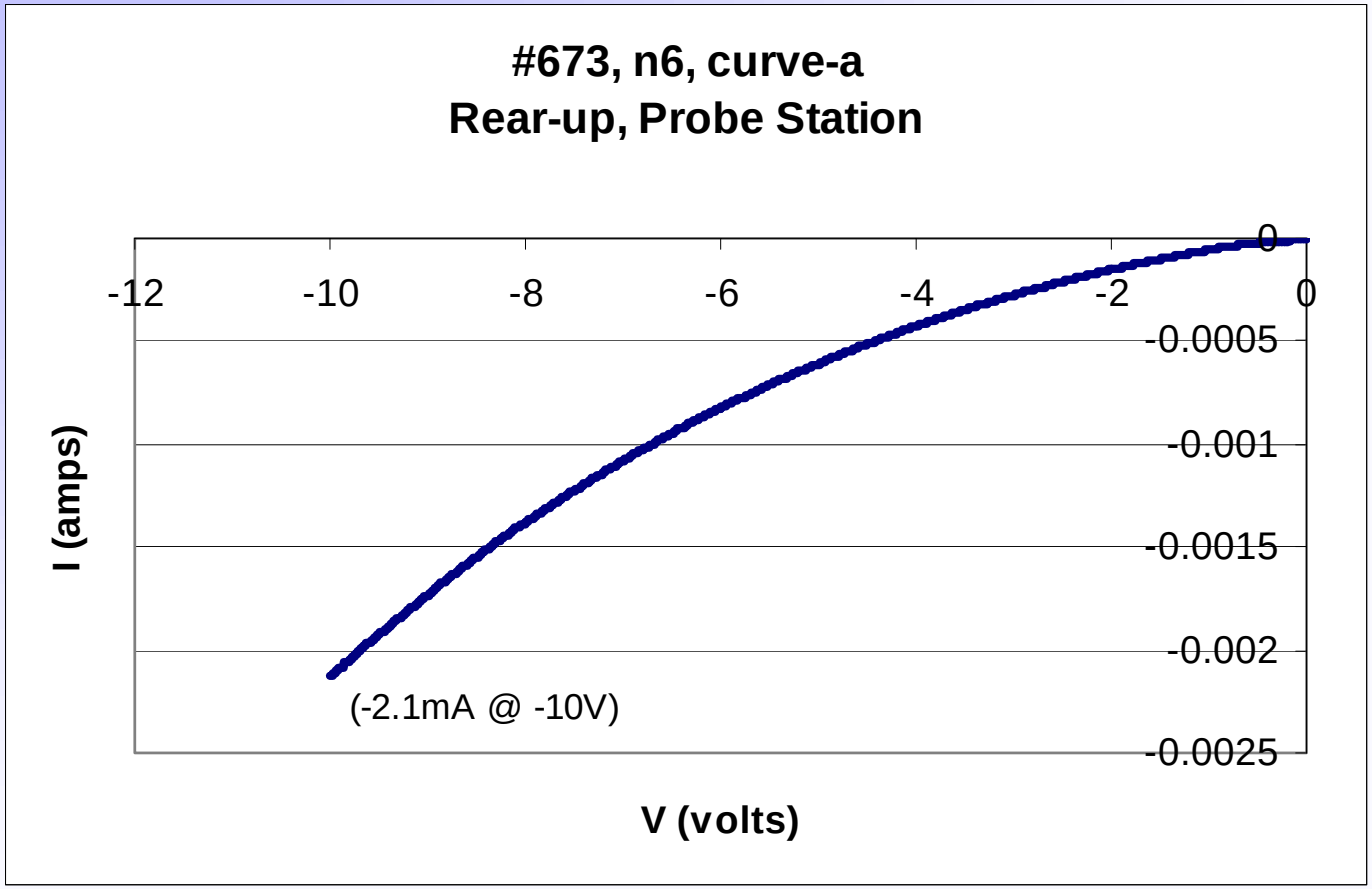
	Resistance: Test Pad (1200 μm^2)	Resistance: Actual Contacts	Resistivity
N - Contact	2.1 Ω	0.36 mΩ	0.00175 $\Omega/\mu m^2$
P – Contact	4.5 Ω	2.8 mΩ	0.00375 $\Omega/\mu m^2$

I-V Characteristics



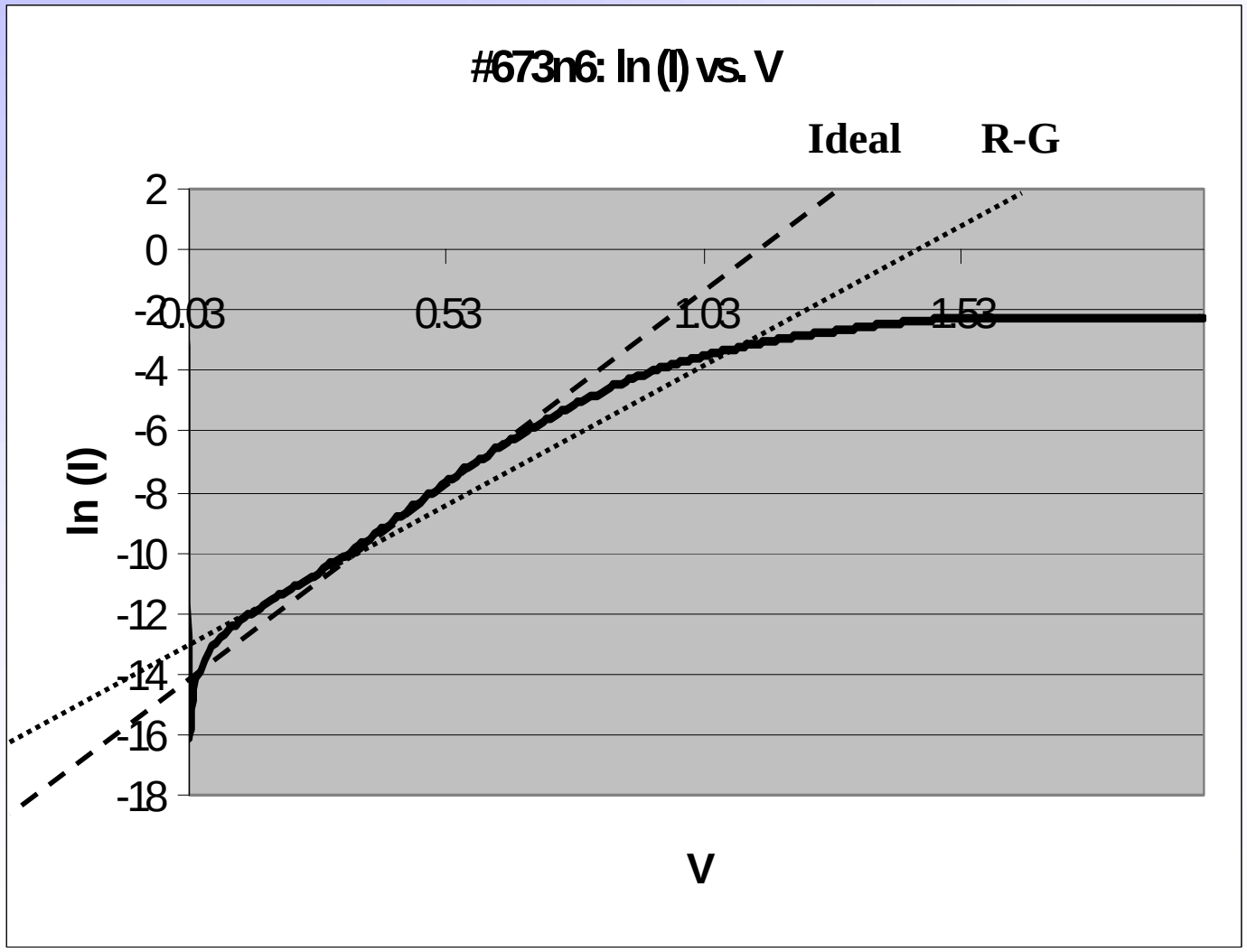
(#673 Rectified, #649 Did not…)

I-V Characteristics: Reverse Bias



- **Wrong shape (defects?)**
- **Large Current Values**

I-V Characteristics: Semi-Log Plot



Ideal:

Slope = 11.4

q/kT = 38.6

n1 = 3.39

I_{01} = 0.83μA

R-G:

Slope = 10.13

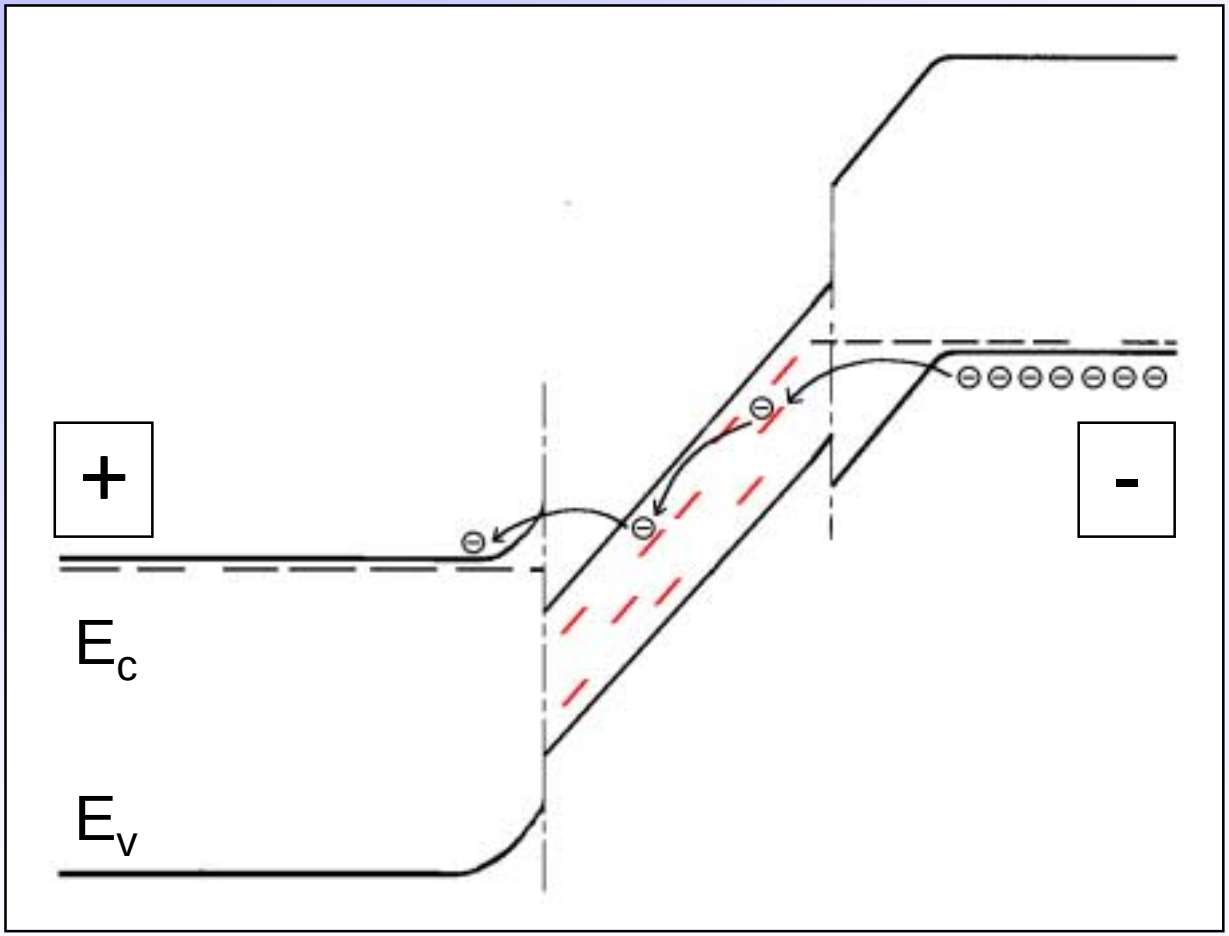
q/2kT = 19.3

n2 = 3.82

I_{02} = 2.26μA

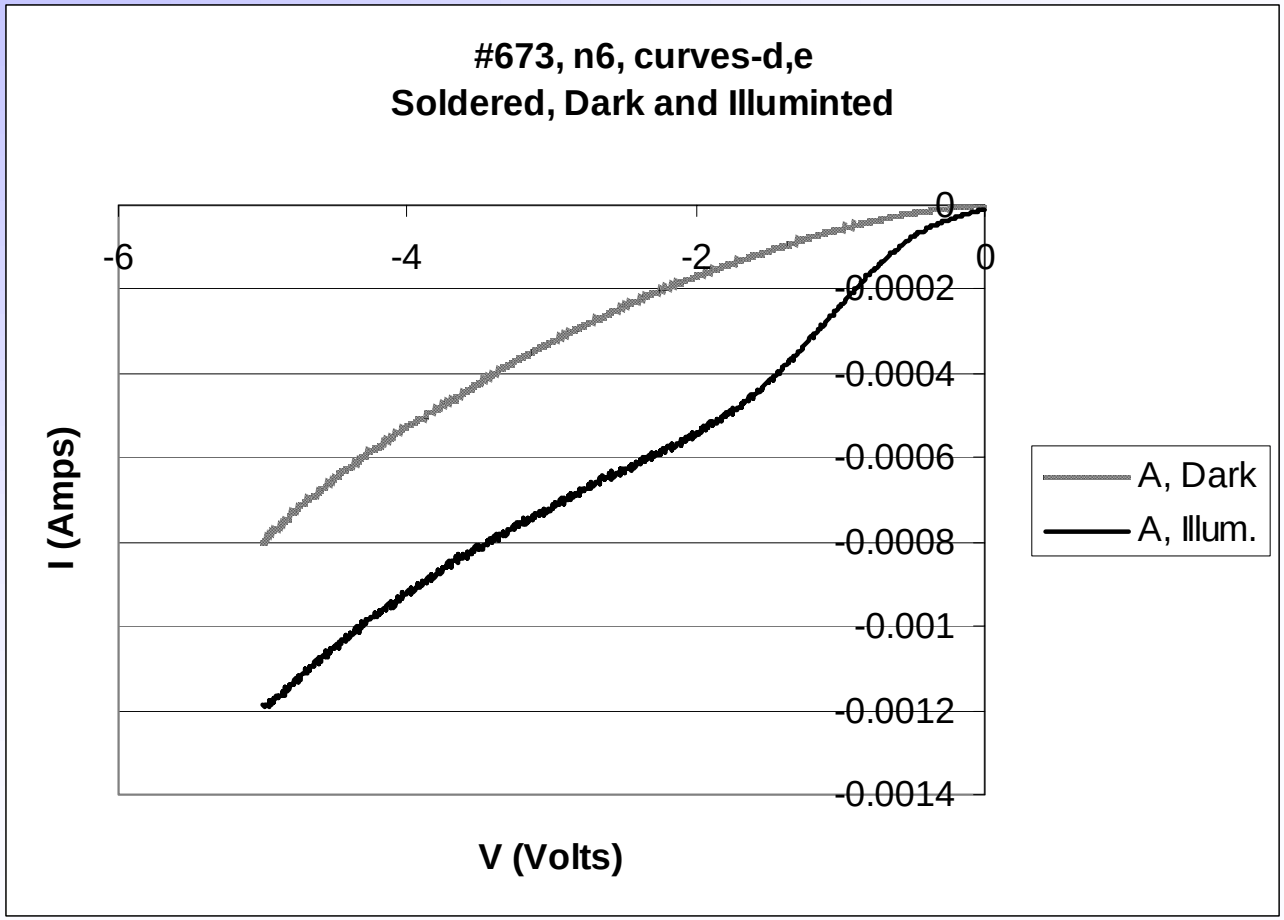
I_0 = 3.09 μA

Possible Explanation: Carrier Hopping



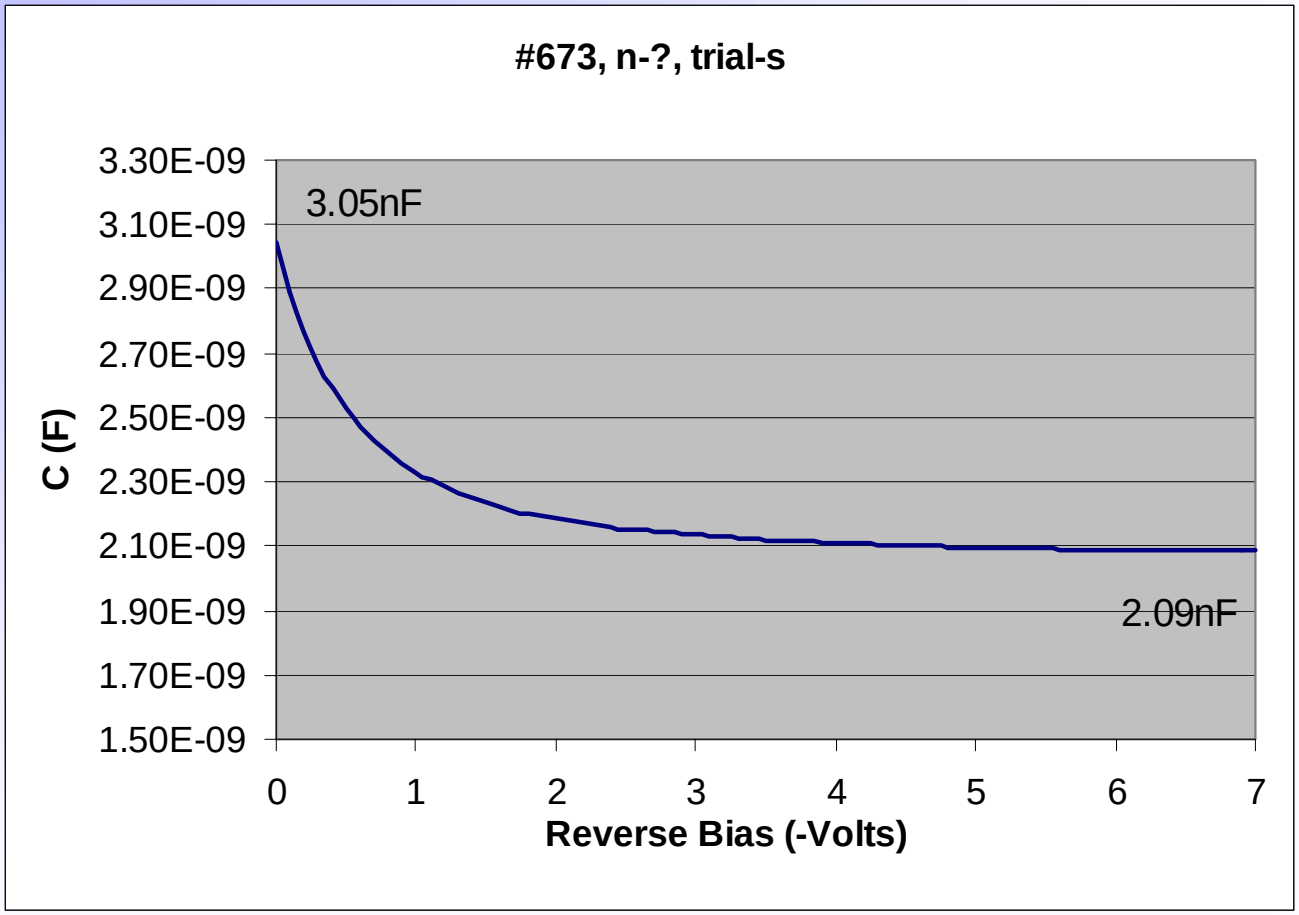
- **Defects in the I-layer**
- **Alternative Transport Mechanism**

I-V Characteristics: Light vs. Dark



→I-layer not fully depleted at zero bias…

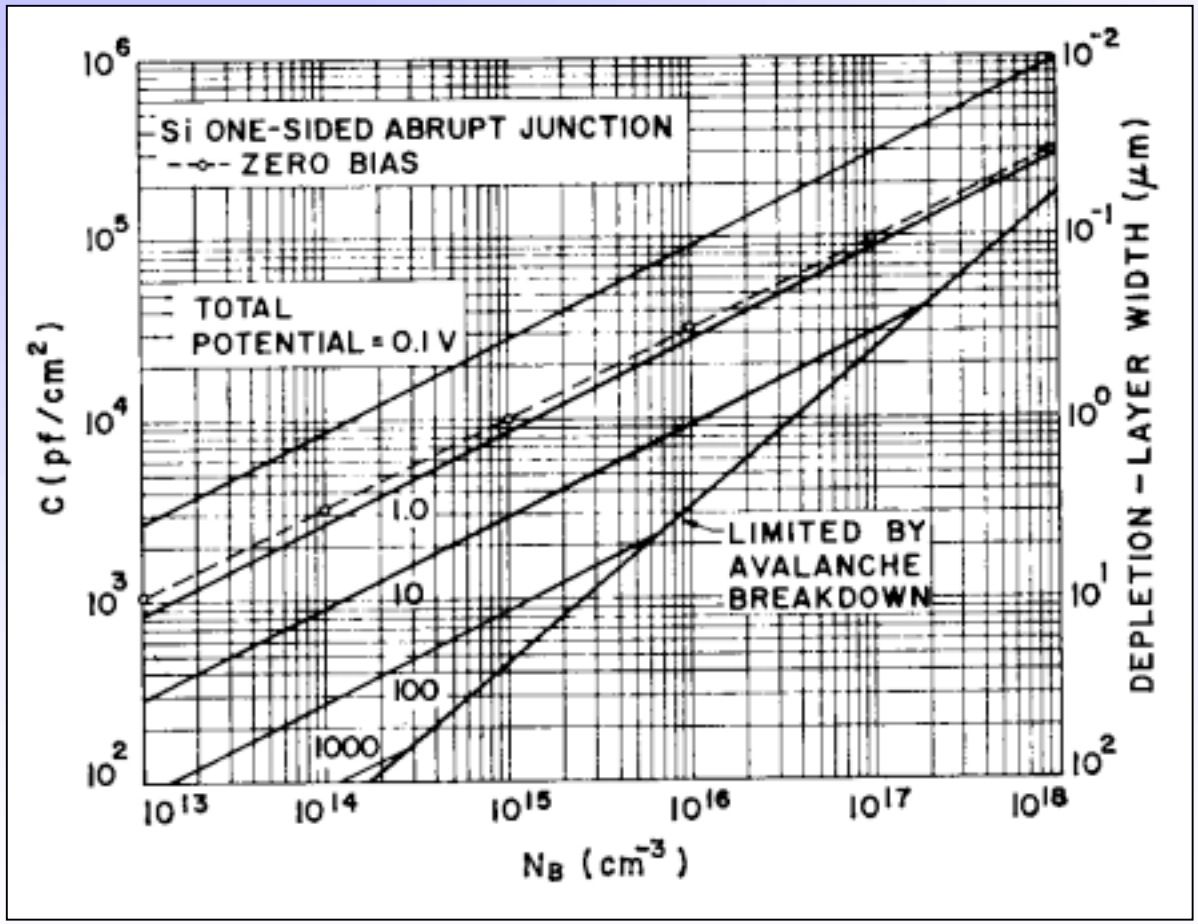
C-V Characteristics (#673)



Theoretical C ≈ 0.40nF

→ depletion width ≈ 0.39μm

Capacitance, W_D, and N_D



$W_D \approx 0.5\mu m$

$N_D \approx 10^{16} cm^{-3}$

(@ 10V bias)

$W_D \approx 2.0\mu m$

$N_D \approx 10^{15} cm^{-3}$

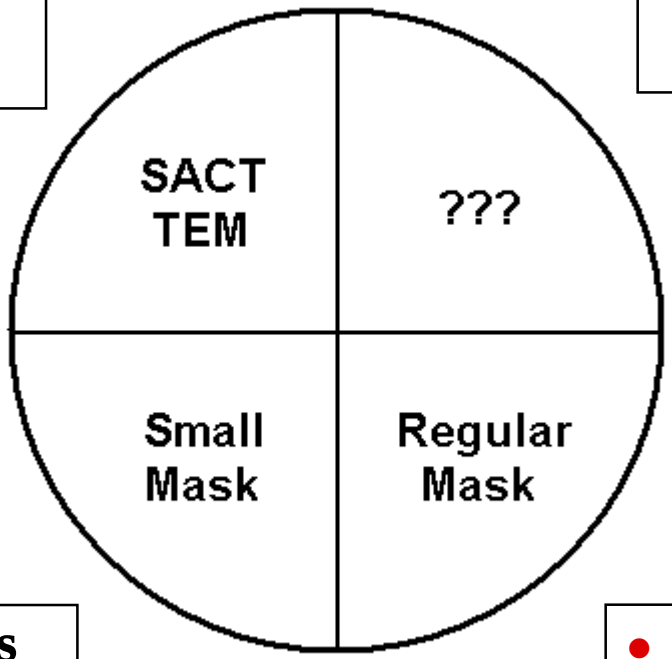
(@ 5V bias)

(Sze, S. M., Physics of Semiconductor Devices, 1969)

Future Plans: InGaAs/InAlAs

- Buffer Layers
- Defects
- Materials Analysis

- Front Illum.
- Thin Substrate



- Less defects
- Test QE

- Bandwidth
- TLM
- Test QE

Future Plans: Nd:YAG & Nitrides

- **Nd:YAG LASER Testing**
  - **Set-up at Stanford (w/ help from Mike Z.)**
  - **Compliment Faster Device Turn-Around**

- **Nitride System: InGaNAs**
  - **Quaternary**
  - **No Graded Buffer**
  - **But, Still Rear-Illuminated**