Advanced LIGO Photodiodes

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LSC Meeting – LHO
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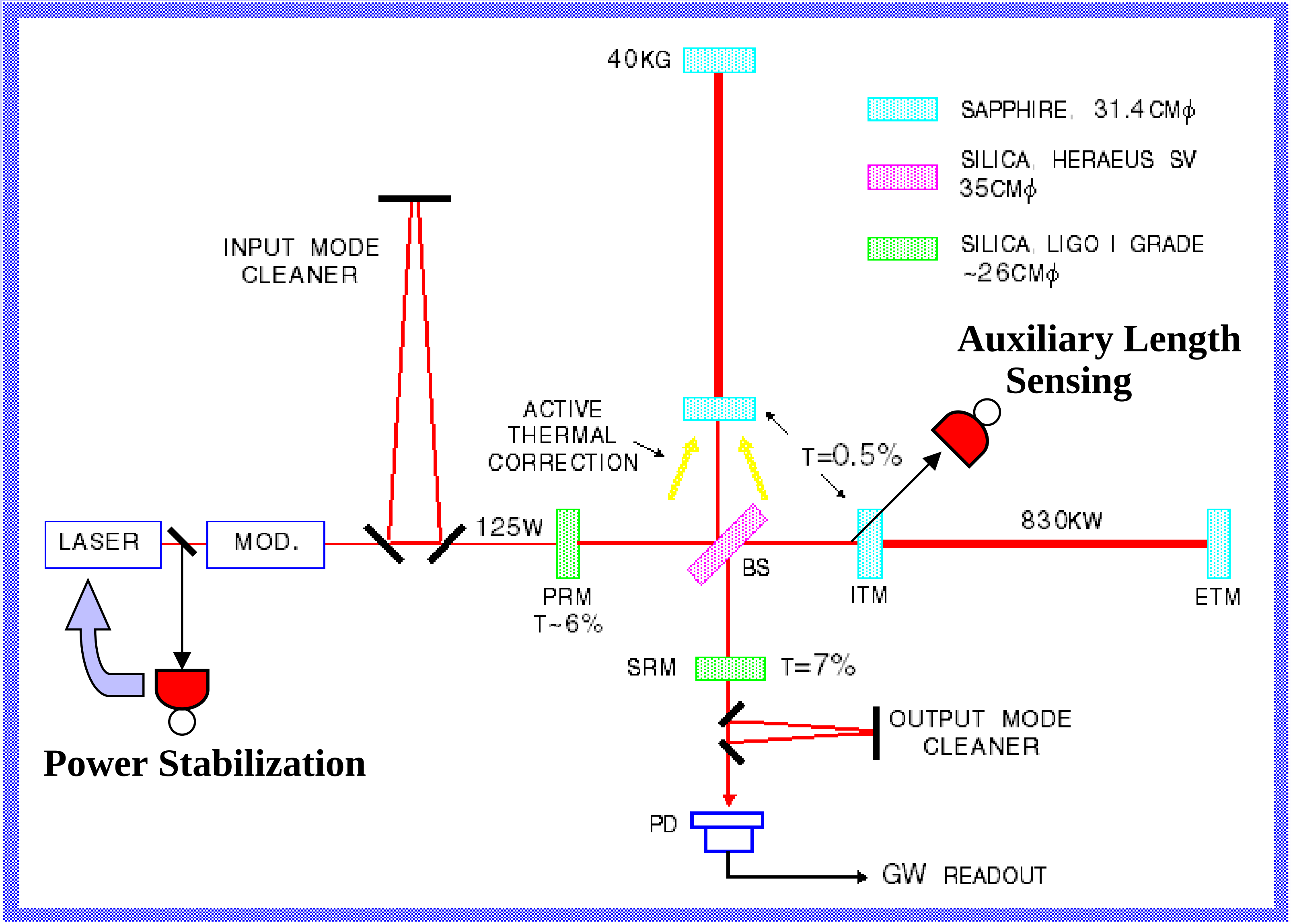
Outline

- Introduction
  - AdLIGO Photodiode Specifications
  - Device Materials & Structures
- Optoelectronic Device Results
  - I-V Character
  - Quantum Efficiency
- AdLIGO Devices

Advanced LIGO Schematic



Auxiliary Length Sensing

Power Stabilization

Photodiode Specifications

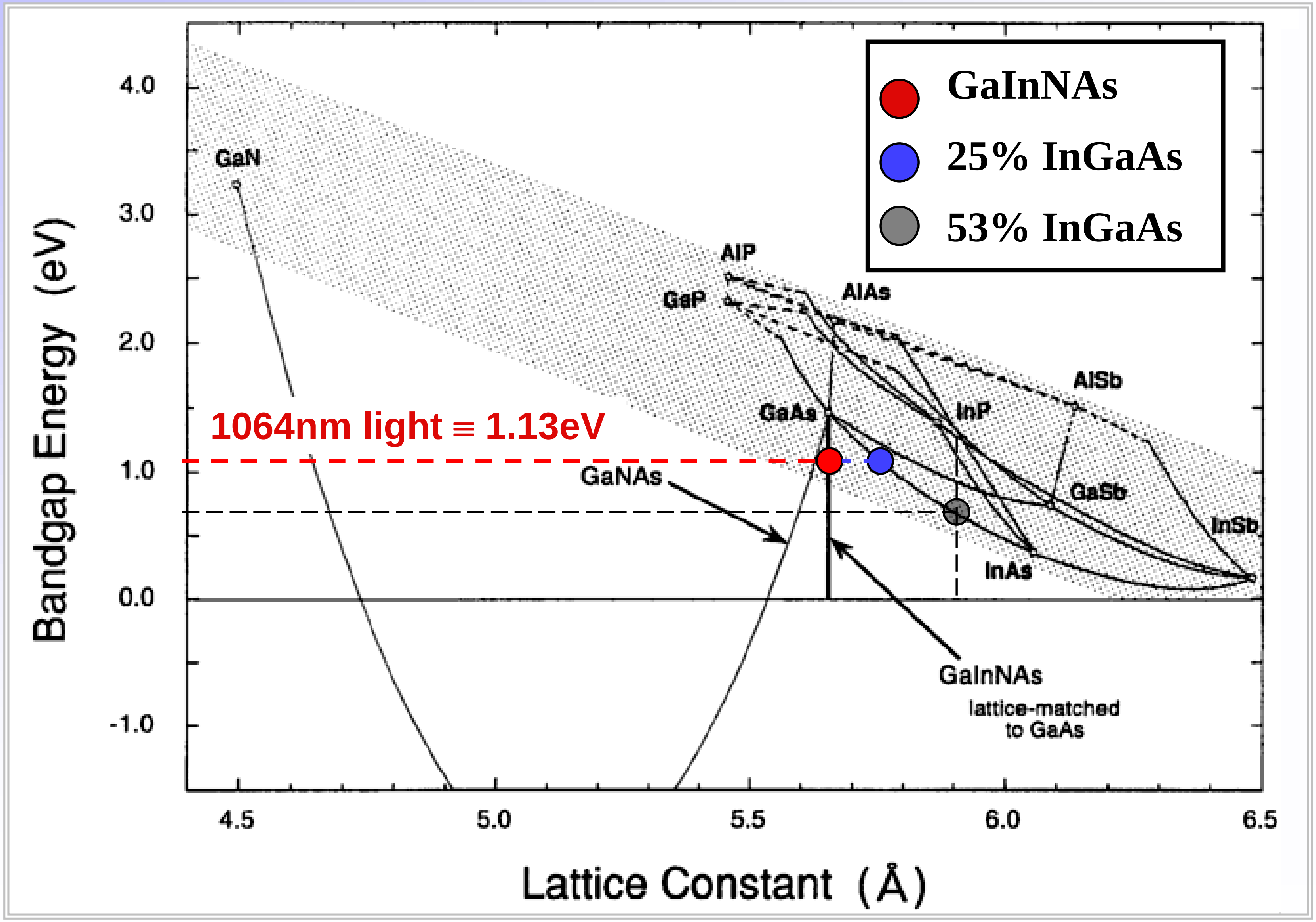
	LIGO I		Advanced LIGO	
Detector	Bank of 6PDs	Power Stabilization	Aux. Length (RF) Detection	GW Channel
Steady-State "Power"	0.6 W	~ 300 mA	10 – 100 mW	30 mW
Operating Frequency	~29 MHz	100 kHz	200 MHz	100 kHz
Quantum Efficiency	> 80%	η	> 80%	> 90%

(300mA)/(0.868A/W * 0.90 QE) = 385mW

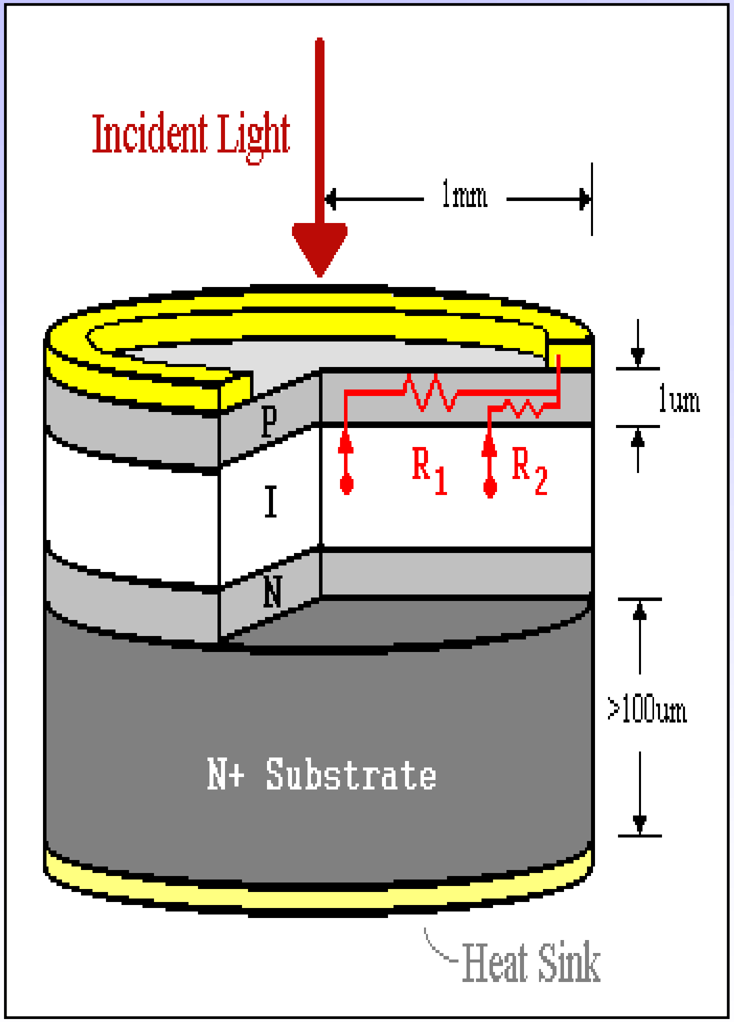
Resonating Tank Circuit

Trades w/ Sensitivity

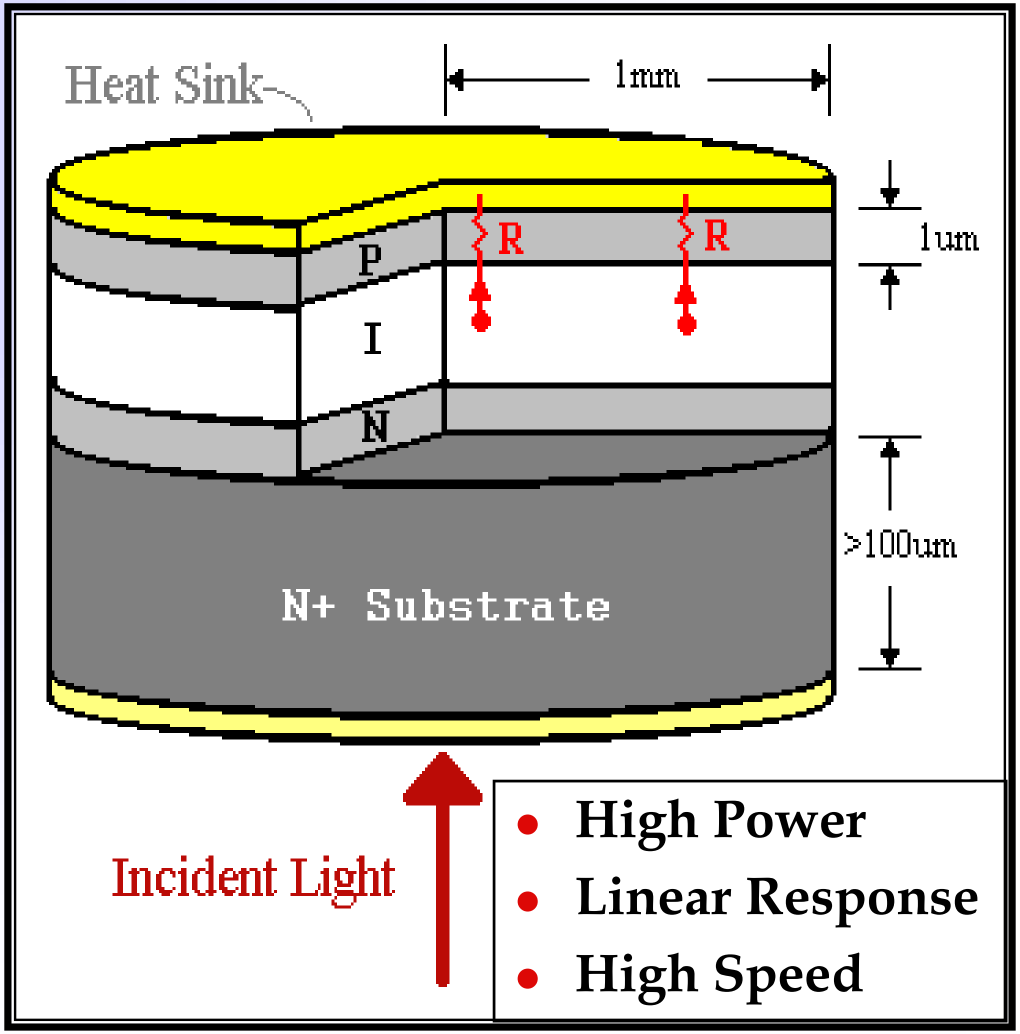
GaInNAs vs. InGaAs



Rear-Illuminated PD Advantages



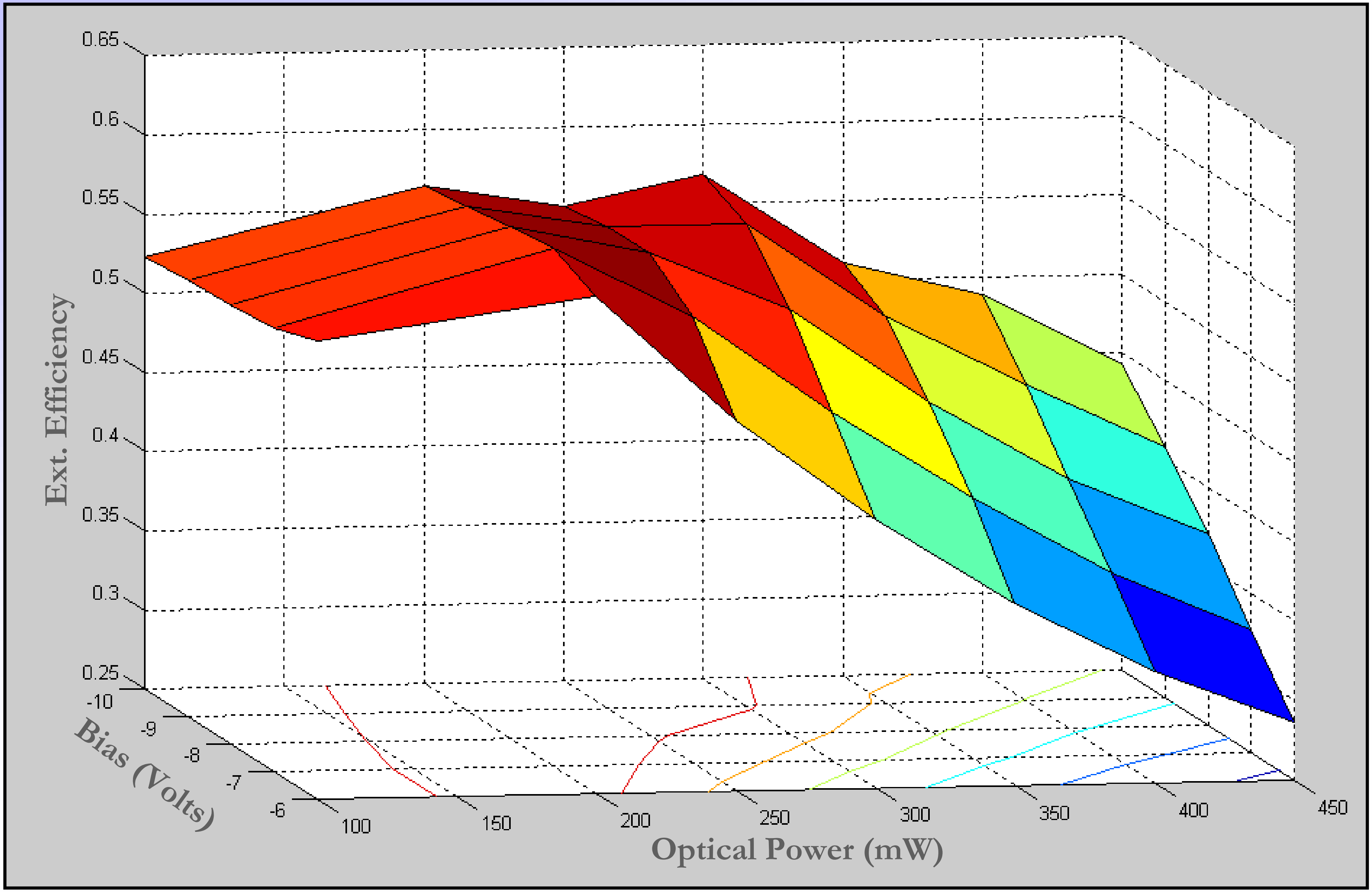
Conventional PD



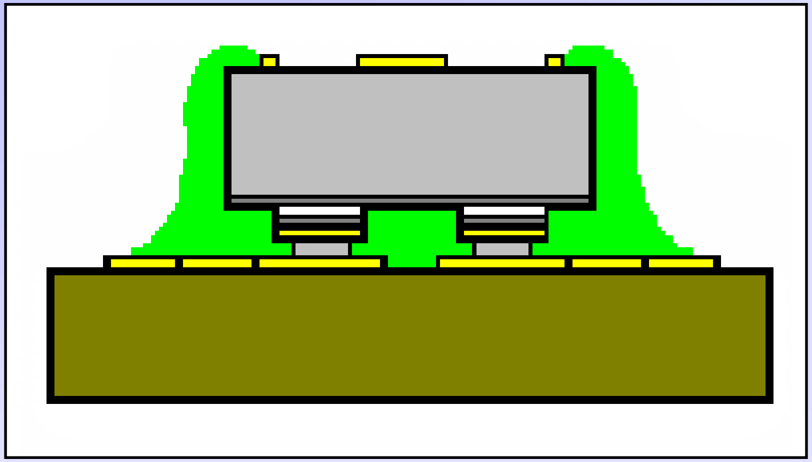
- High Power
- Linear Response
- High Speed

Adv. LIGO Rear-Illuminated PD

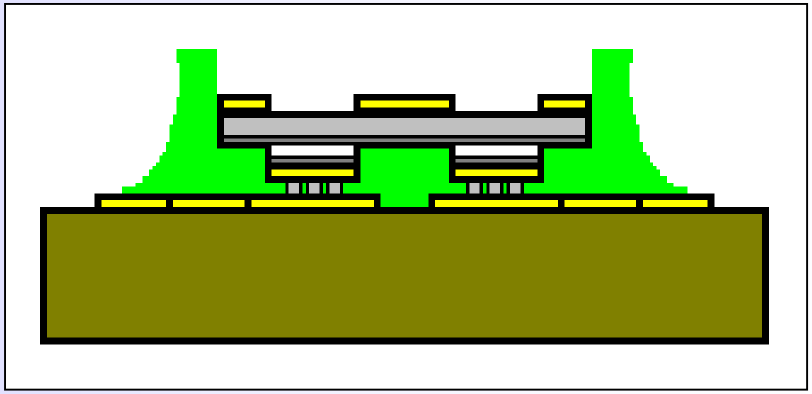
Quantum Efficiency – Thick Sub.



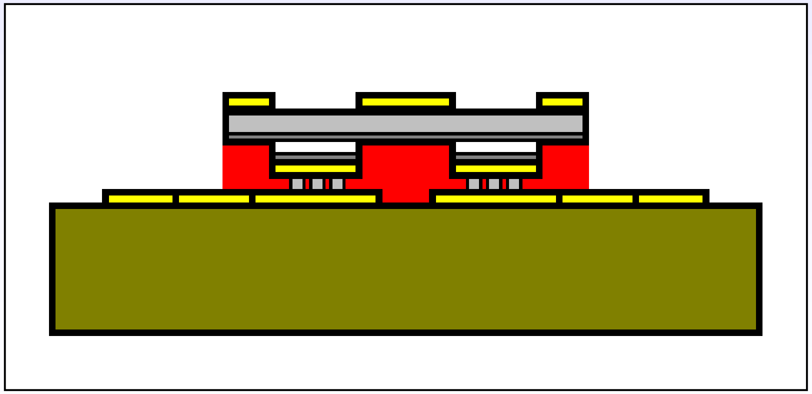
'Thick' and *'Thinned'* Structures



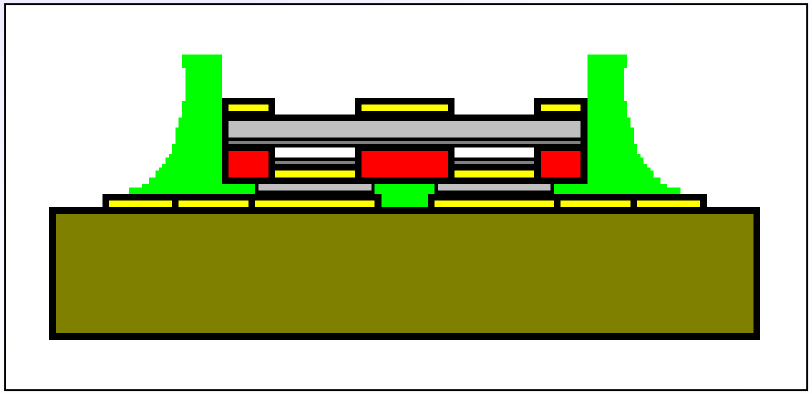
0.) Thick Substrate –
Mounted w/ Conducting Epoxy



1.) Epoxy (or BCB) Underfill –
Mounted w/ Flip-Chip Bonder

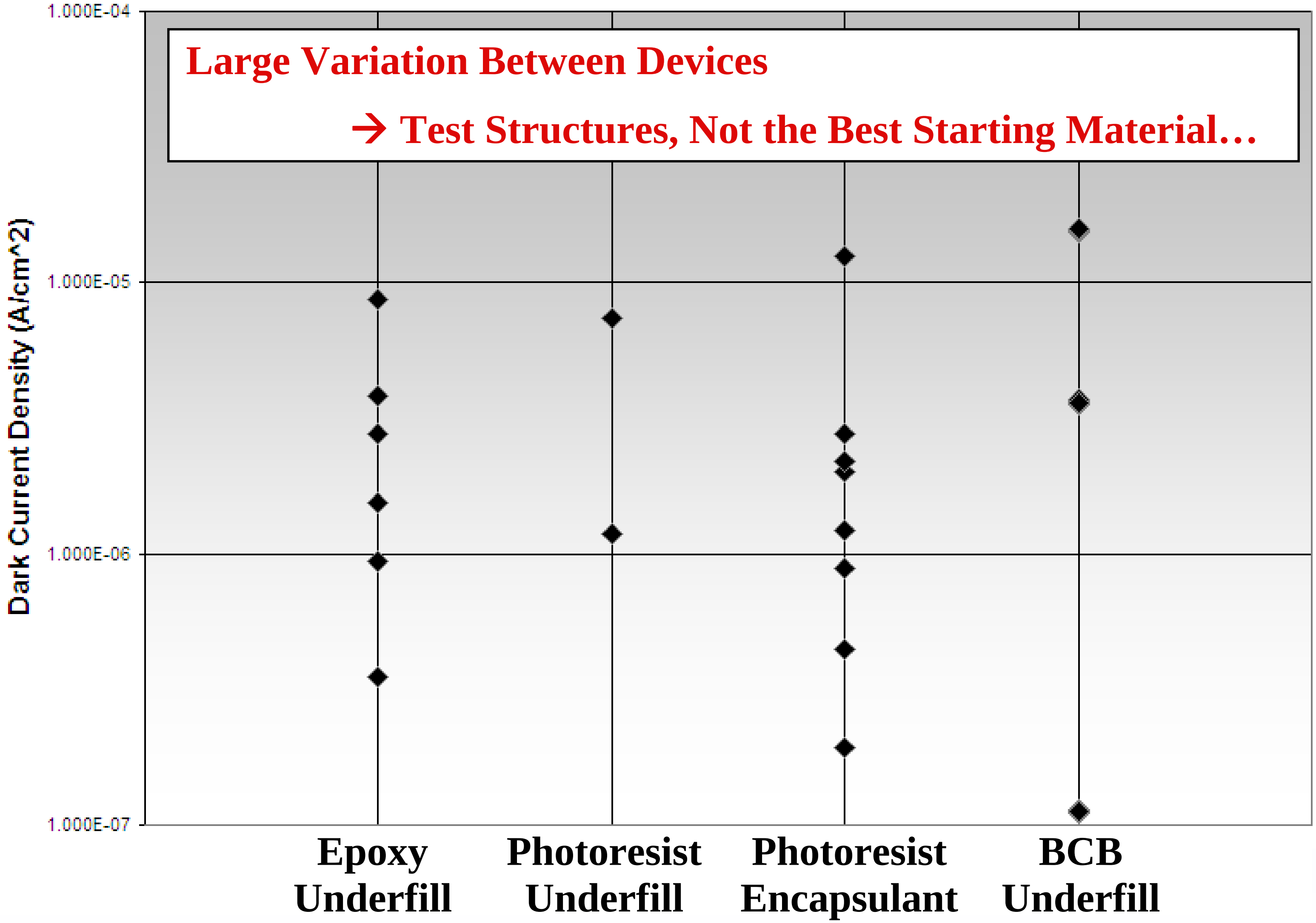


2.) Photoresist Underfill –
Mounted w/ Flip-Chip Bonder



3.) Photoresist Encapsulant –
Mounted w/ Conducting Epoxy

Dark Current: Various Encapsulants



(@ – 0.1 V)

Large Variation Between Devices

→ Test Structures, Not the Best Starting Material…

Thinned Device Quantum Efficiency

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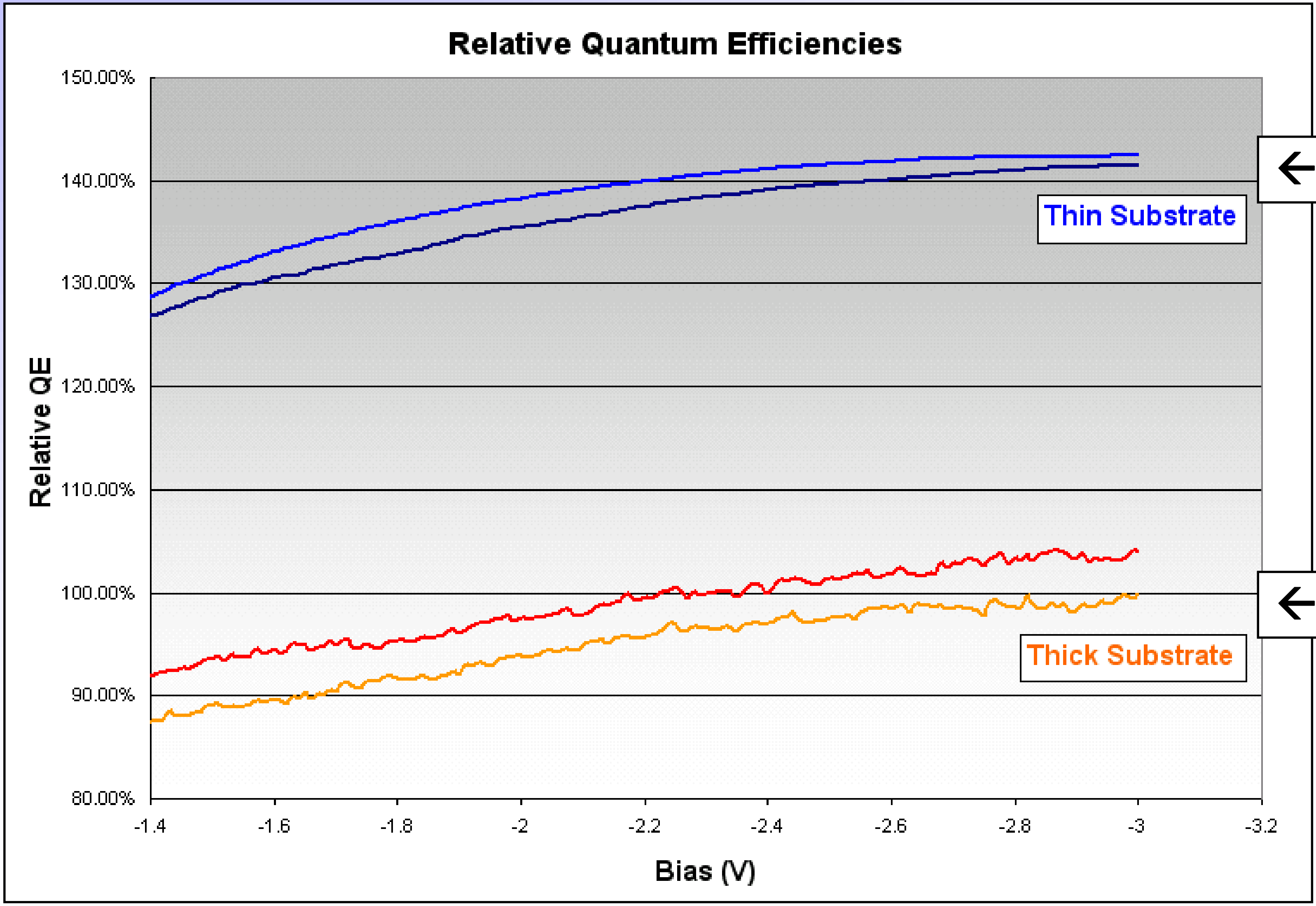


← ~ 85%

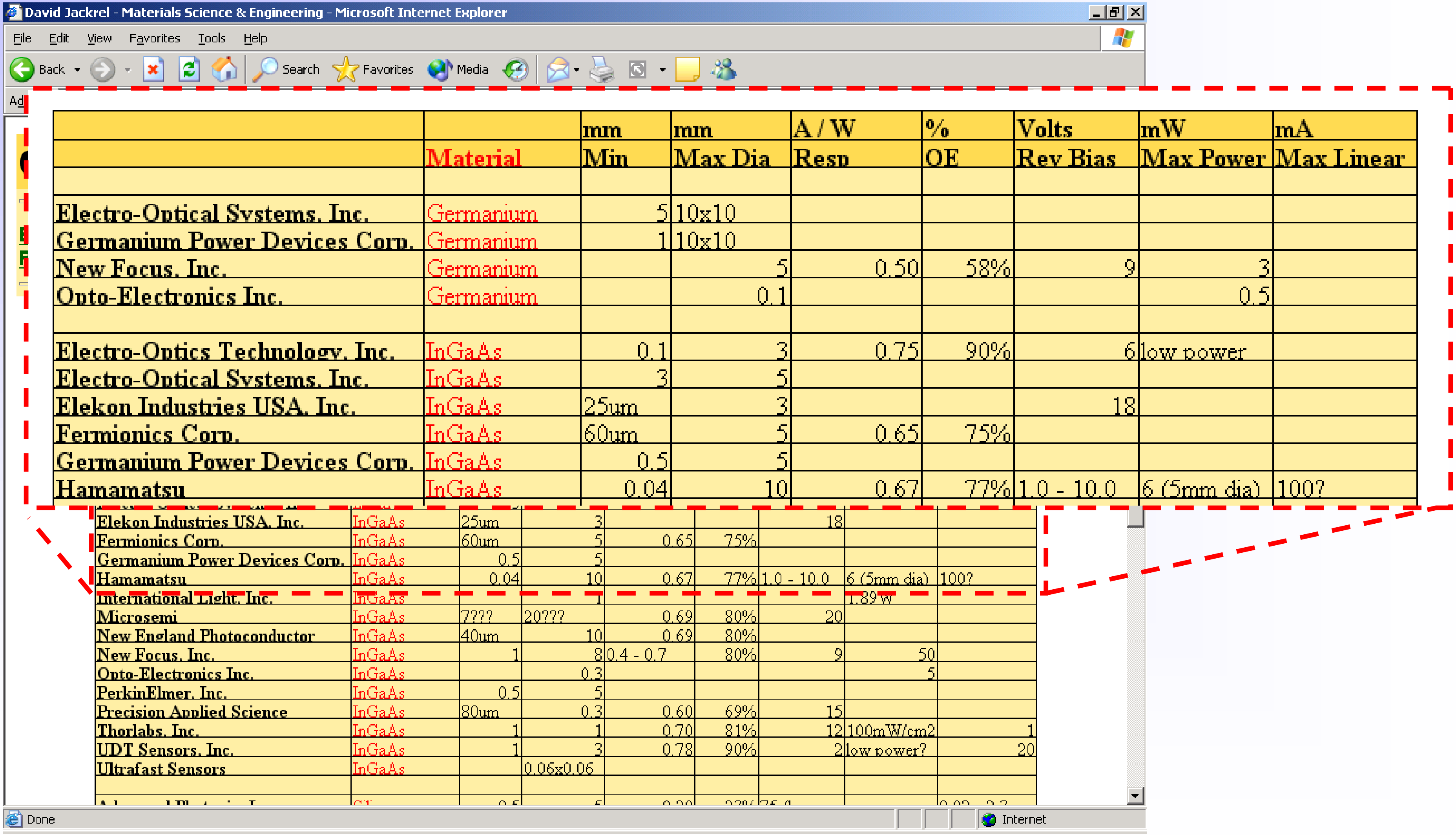
← ~ 60%

AdLIGO Devices

Detector	**Power Stabilization**	**RF Detection**	**GW Channel**
Diameter	3 - 5 mm	1.5 mm	1 mm (or larger?)
Steady-State Power	400 mW	100 mW	50 mW
3-dB 1/RC Bandwidth	1 - 3 MHz	30 MHz (→ 180 MHz)	60 MHz
Quantum Efficiency	–	> 80 %	> 90 %
Damage Threshold	–	*?*	*Important?!*

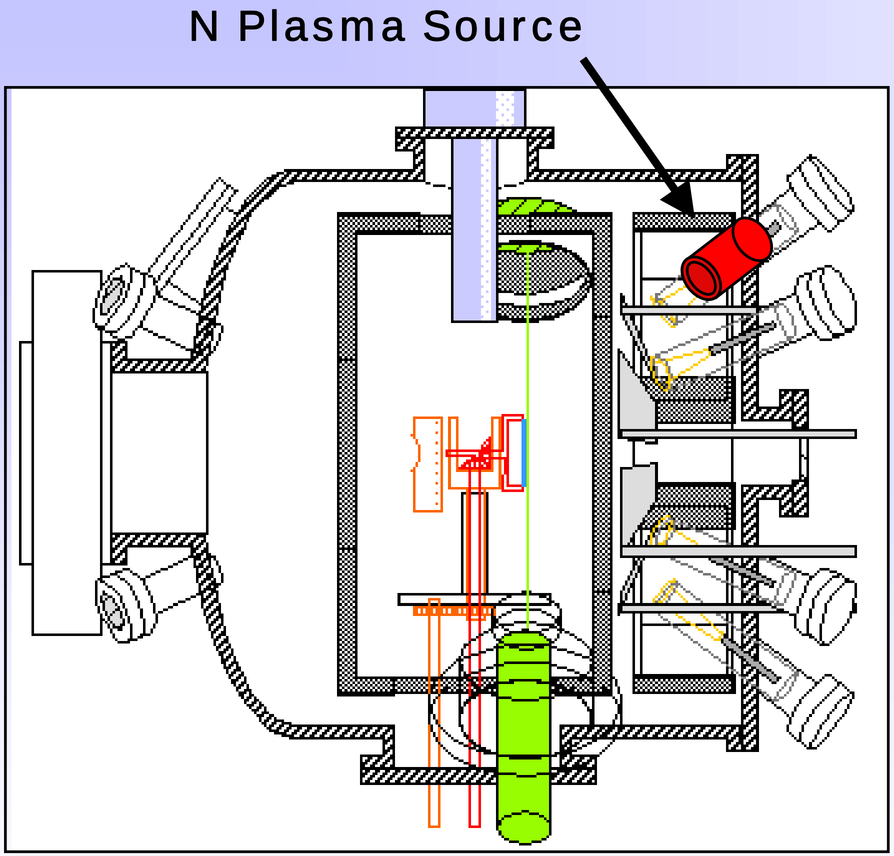
AdLIGO Devices: Commercial Vendors

http://www.stanford.edu/~djackrel



		mm	mm	A / W	%	Volts	mW	mA
	Material	Min	Max Dia	Resp	QE	Rev Bias	Max Power	Max Linear
Electro-Optical Systems, Inc.	Germanium	5	10x10					
Germanium Power Devices Corp.	Germanium	1	10x10					
New Focus, Inc.	Germanium		5	0.50	58%	9	3	
Opto-Electronics Inc.	Germanium		0.1				0.5	
Electro-Optics Technology, Inc.	InGaAs	0.1	3	0.75	90%	6	low power	
Electro-Optical Systems, Inc.	InGaAs	3	5					
Elekon Industries USA, Inc.	InGaAs	25um	3			18		
Fermionics Corp.	InGaAs	60um	5	0.65	75%			
Germanium Power Devices Corp.	InGaAs	0.5	5					
Hamamatsu	InGaAs	0.04	10	0.67	77%	1.0 - 10.0	6 (5mm dia)	100?
International Light, Inc.	InGaAs		1				1.89 W	
Microsemi	InGaAs	????	20???	0.69	80%	20		
New England Photoconductor	InGaAs	40um	10	0.69	80%			
New Focus, Inc.	InGaAs	1	8	0.4 - 0.7	80%	9	50	
Opto-Electronics Inc.	InGaAs		0.3				5	
PerkinElmer, Inc.	InGaAs	0.5	5					
Precision Applied Science	InGaAs	80um	0.3	0.60	69%	15		
Thorlabs, Inc.	InGaAs	1	1	0.70	81%	12	100mW/cm2	1
UDT Sensors, Inc.	InGaAs	1	3	0.78	90%	2	low power?	20
Ultrafast Sensors	InGaAs		0.06x0.06					

MBE Crystal Growth



- **Effusion cells for In, Ga, Al**
- **Cracking cell for As**
- **Abrupt interfaces**
- **Chamber is under UHV conditions to avoid incorporating contaminants**
- **RHEED can be used to analyze crystal growth *in situ* due to UHV environment**
- **T=450-600°C**

Atomic source of nitrogen needed

→ Plasma Source!

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InGaAs vs. GaInNAs PD Designs

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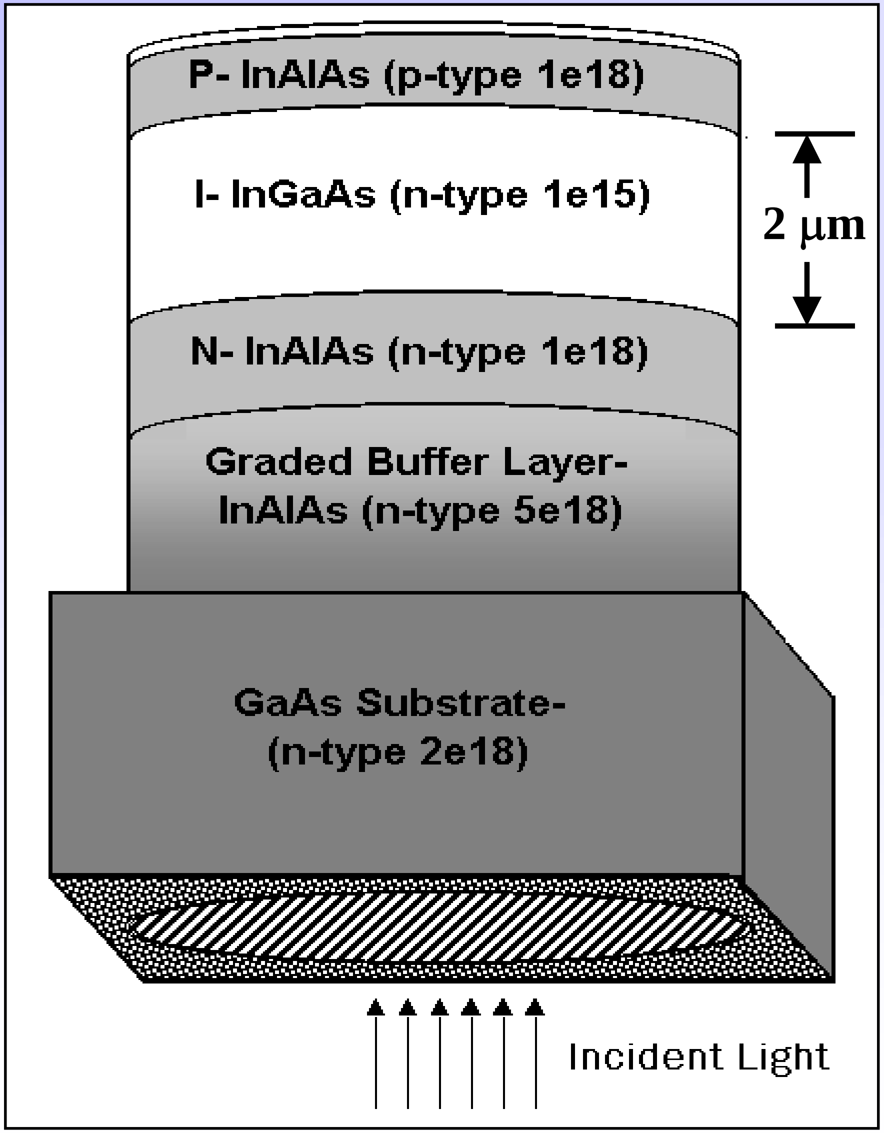

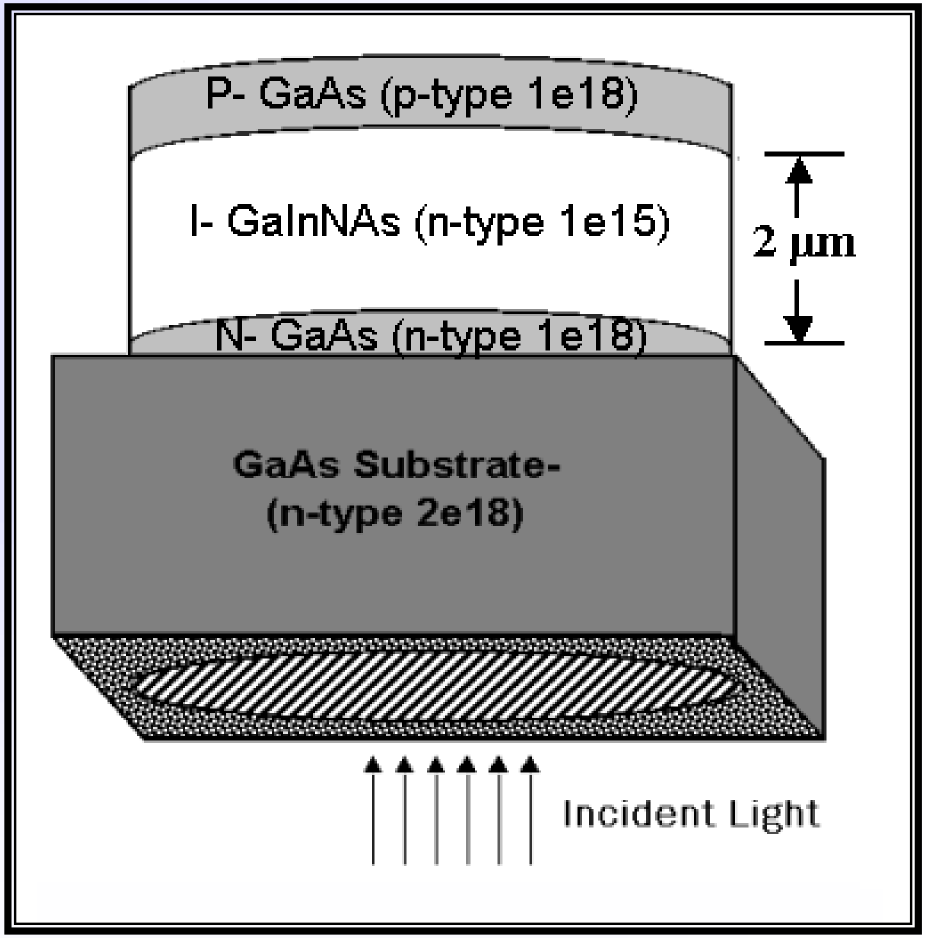

GaInNAs lattice-matched to GaAs!

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Full Structure Simulated by ATLAS

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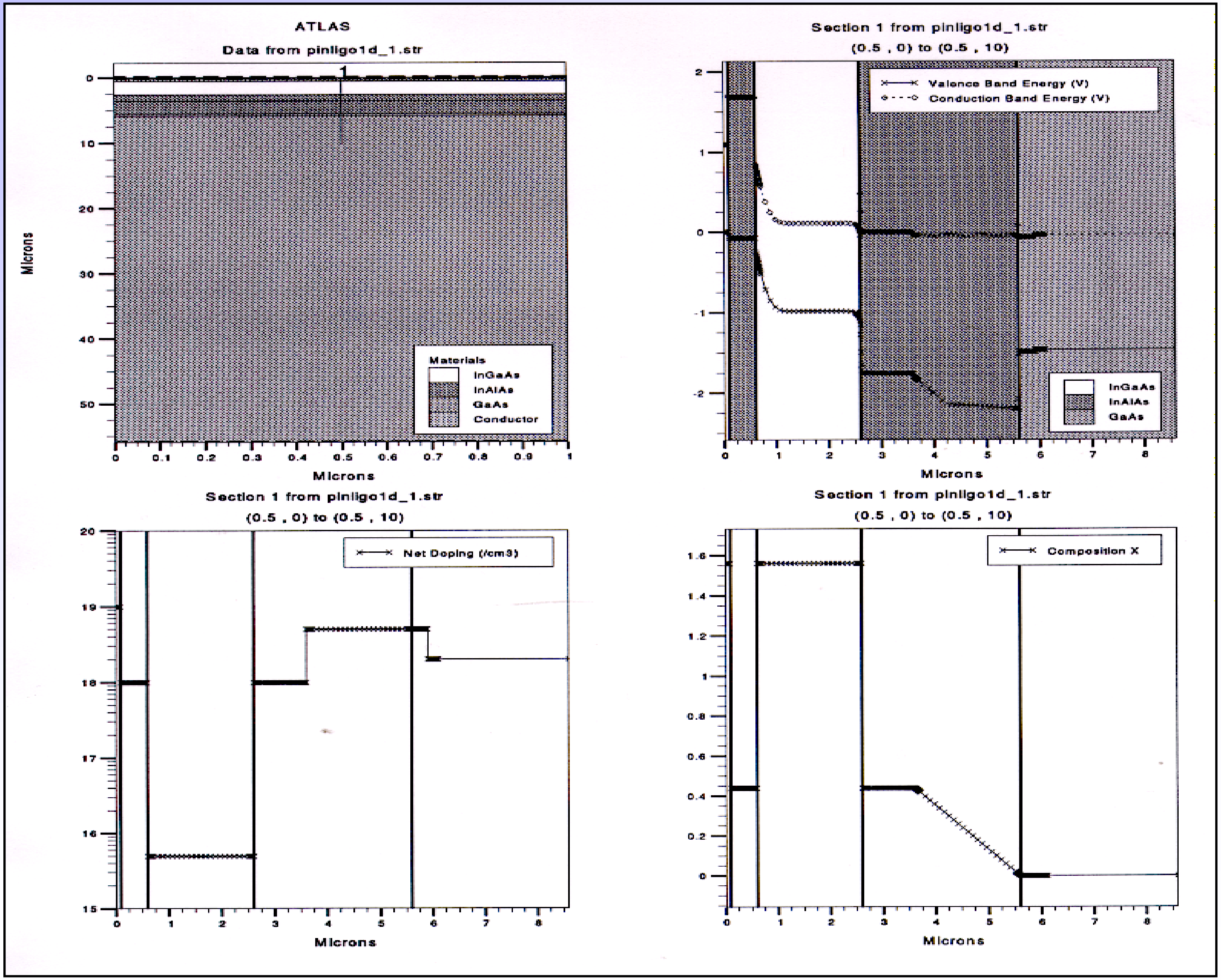
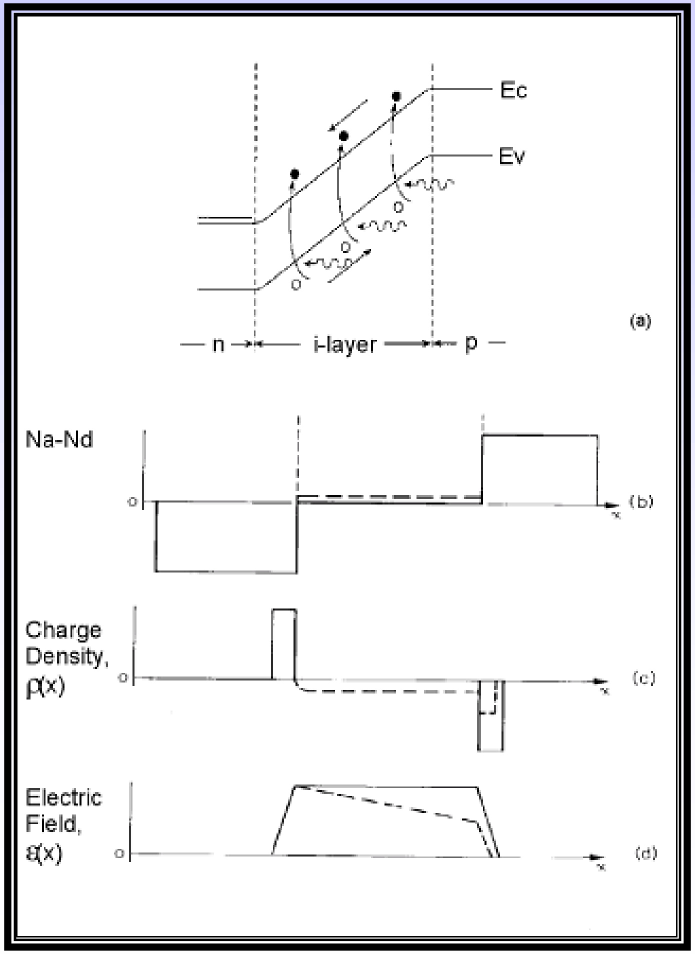
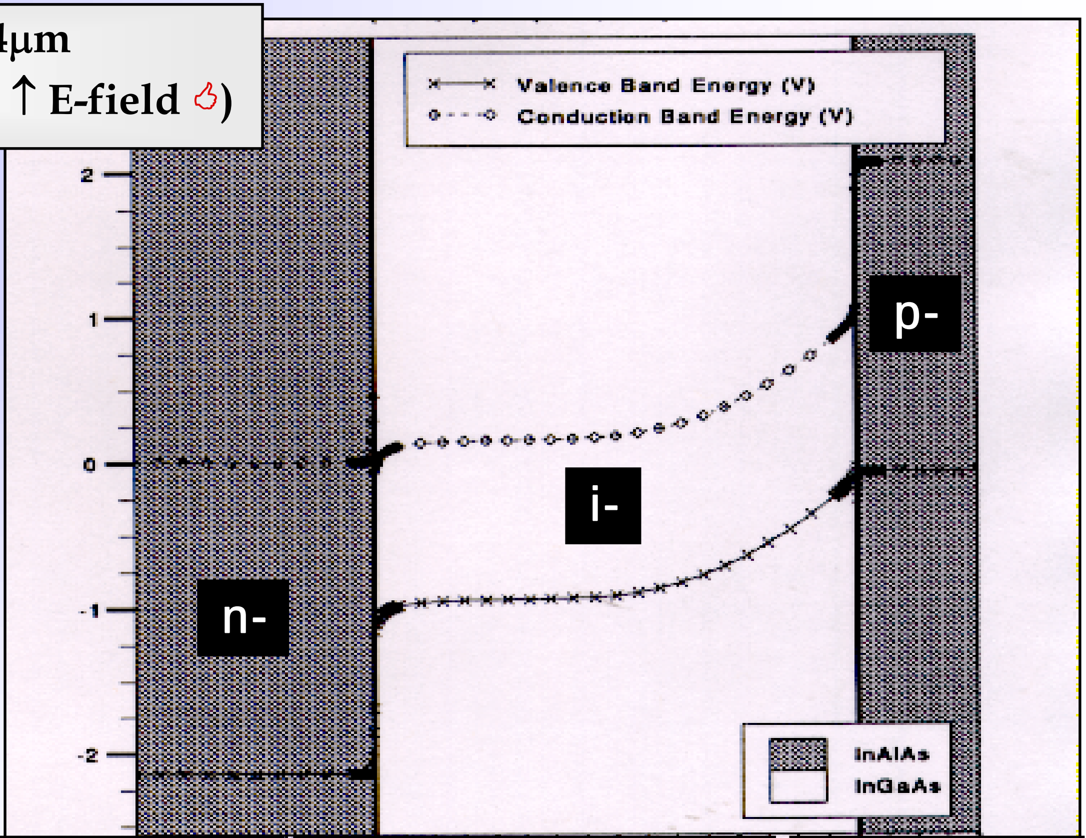


Heterojunction Band Gap Diagram

InAlAs and GaAs transparent at 1.064μm
→ Absorption occurs in I-region (in ↑ E-field ☝)





N-layer:

$In_{.25}Al_{.75}As$ or GaAs

$E_{g2} = 2.0–1.4eV$

I-layer:

$In_{.25}Ga_{.75}As$, or $Ga_{.88}In_{.12}N_{.01}As_{.99}$

$E_{g1} = 1.1eV$

P-layer:

$In_{.25}Al_{.75}As$ or GaAs

$E_{g2} = 2.0–1.4eV$

Fabrication Procedure

1. P-Contact

Lift-Off Process

2. Mesa Etch

H2SO4:H2O2:H2O
(1:1:20)

Etch Rate ~ 0.75
micron/min

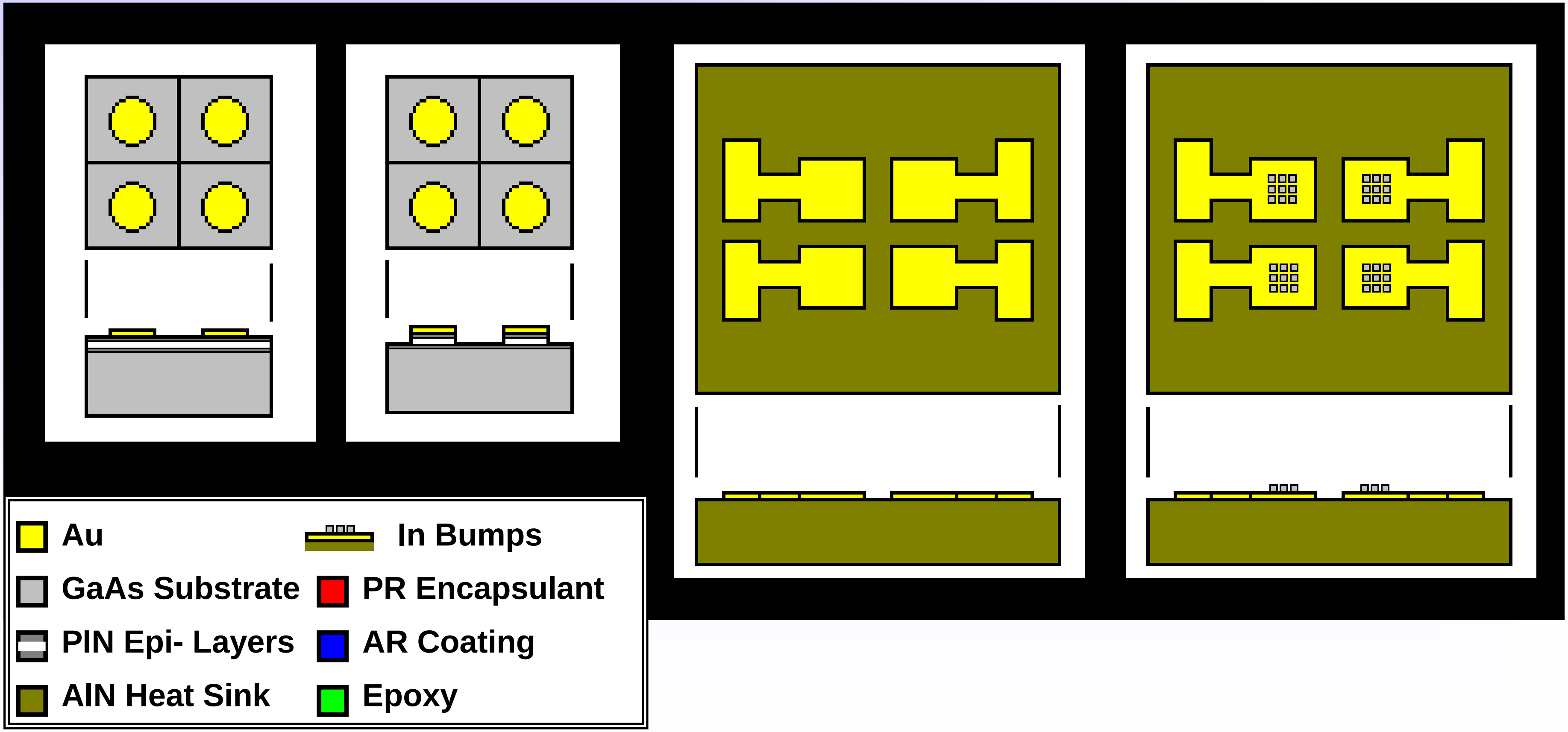
3. Au on Heat Sink

Lift-Off Process

4. In Bumps

Lift-Off Process

~3um In



- 🟨 Au
- ▨ GaAs Substrate
- ▤ PIN Epi- Layers
- 🟫 AlN Heat Sink
- ▦ In Bumps
- 🟥 PR Encapsulant
- 🟦 AR Coating
- 🟩 Epoxy

Standard Epoxy Procedure

5. Flip-Chip Bond & Under-fill w/ Epoxy

Low viscosity – Fills all of the voids

Makes chip mechanically stable

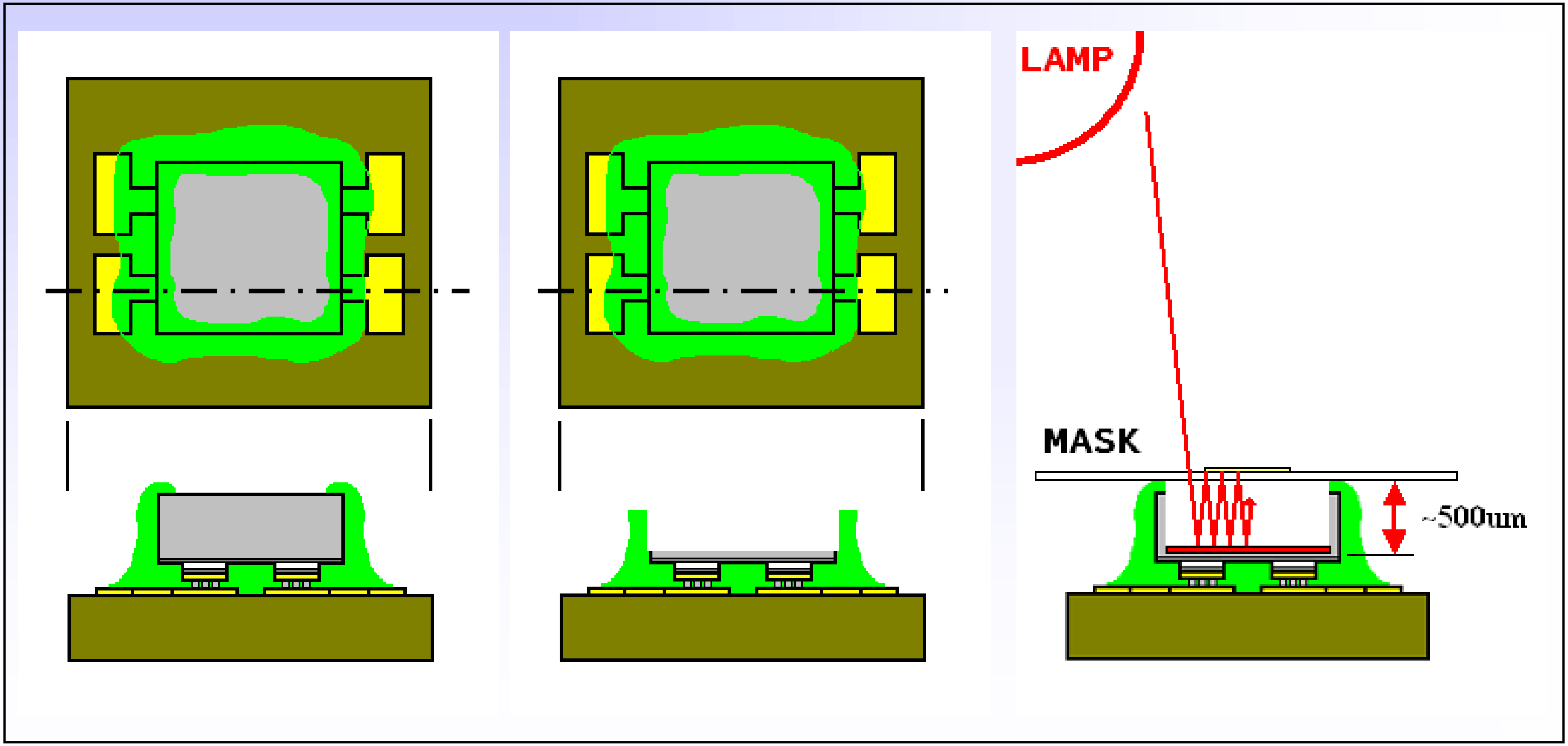
6. Thin GaAs Substrate

Piranha - $H_2SO_4:H_2O_2:H_2O$ (1:8:1)

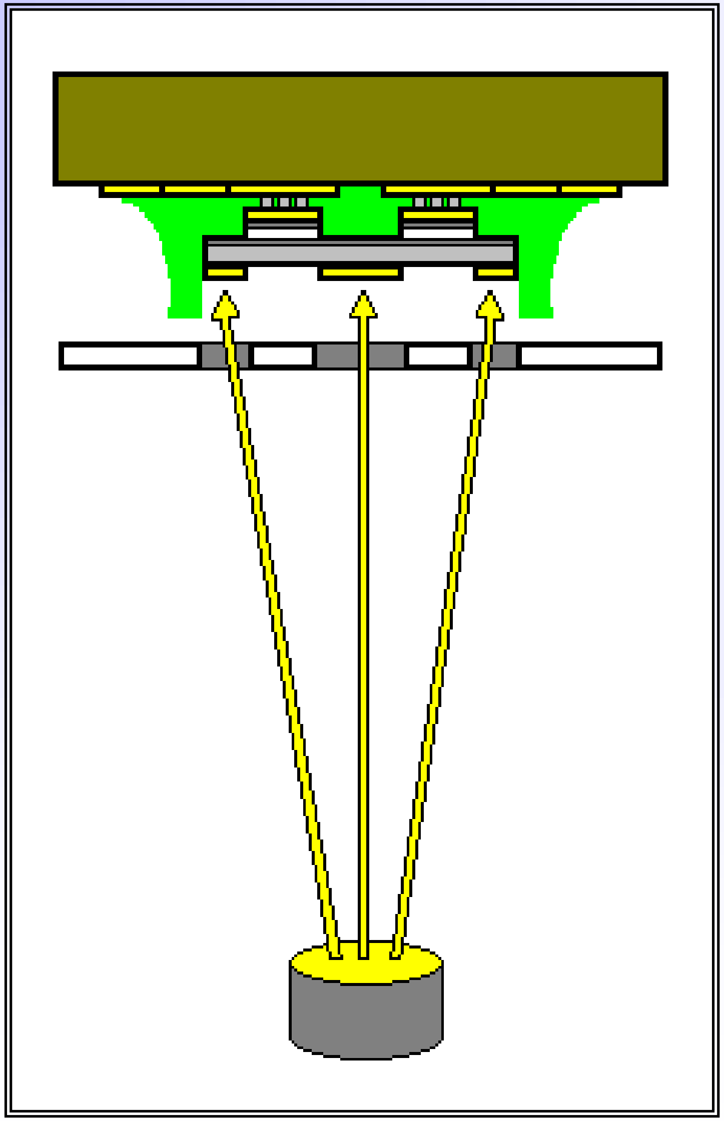
Doesn’t affect epoxy!

Now you can’t pattern the top contact (or the ARC) w/ standard processing...

But, shadow masks might work...



Shadow Masking



Photoresist Underfill Technique

5. Flip-Chip Bond

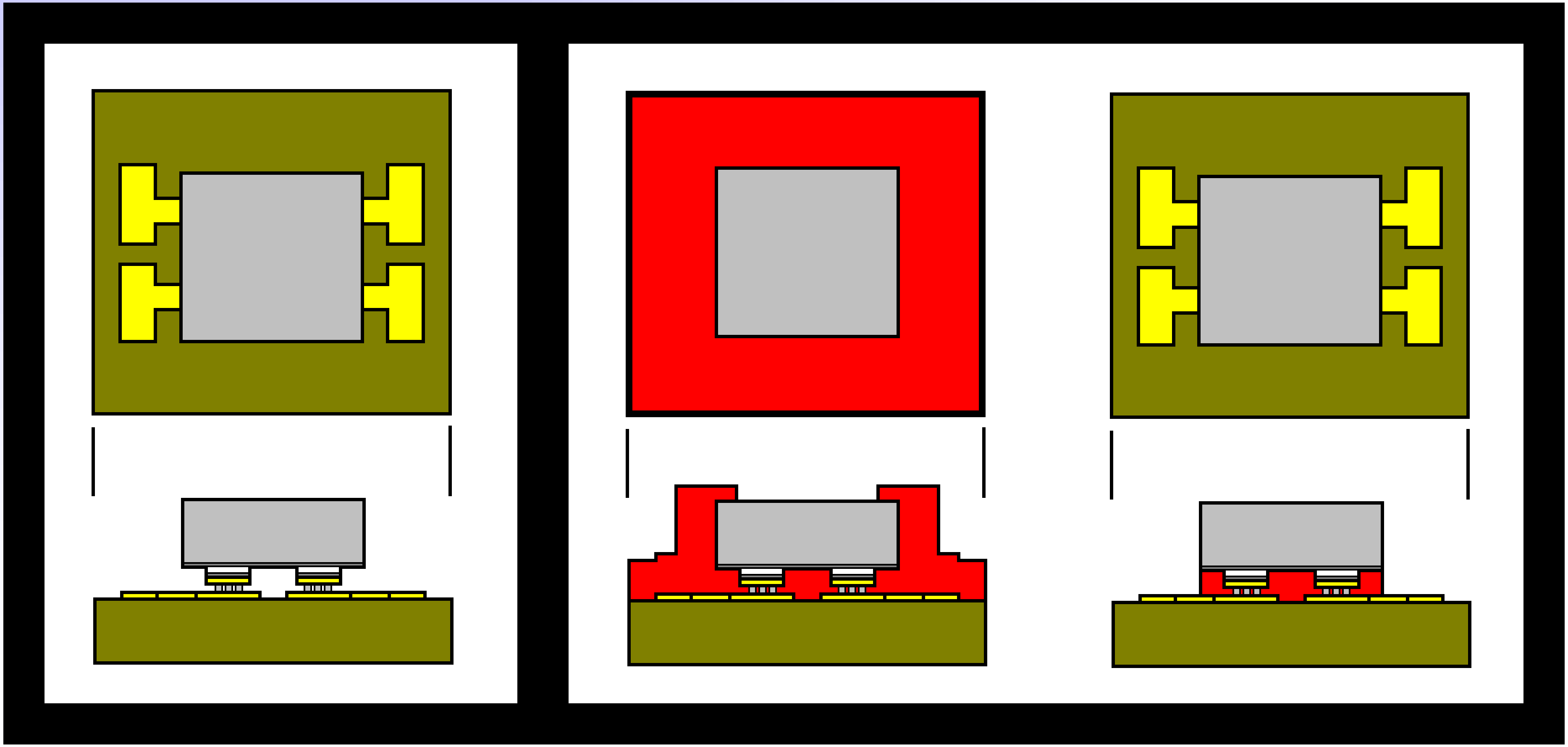
1 g / 100 sq. micron, 140°C

6A. Apply Photoresist

SPR 3612 Positive PR

6B. Blanket Exposure

Long exposure, Hard Bake > 240°C



Photoresist Underfill Technique (2)

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7. Thin GaAs Substrate

Piranha - $H_2SO_4:H_2O_2:H_2O$ (1:8:1)

Etch Rate ~10 microns / min

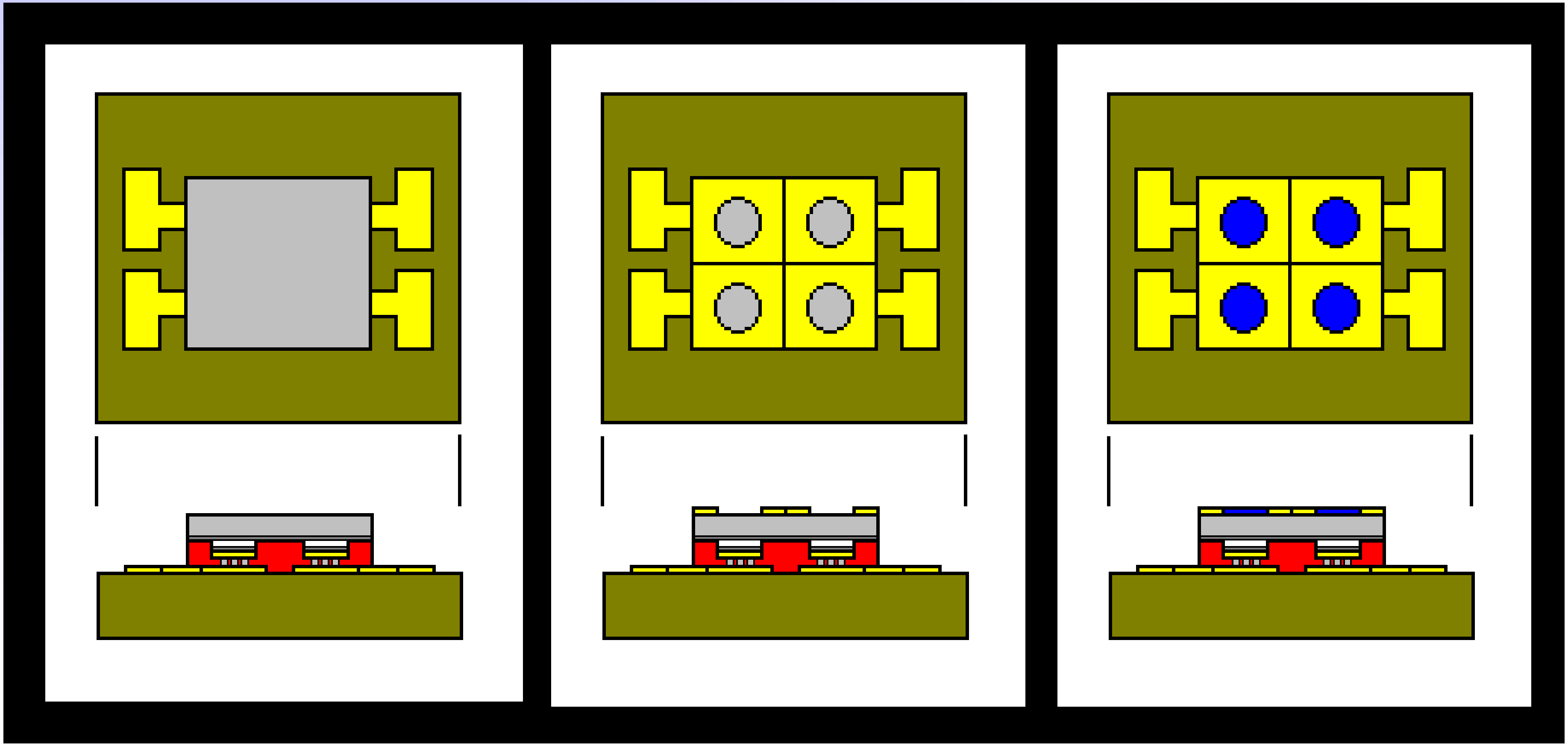
8. N-Contact

Lift-off Process

9. Evaporate AR Coating

Etch Process

(SiNx, HfO, …depends where done)



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Dimensions

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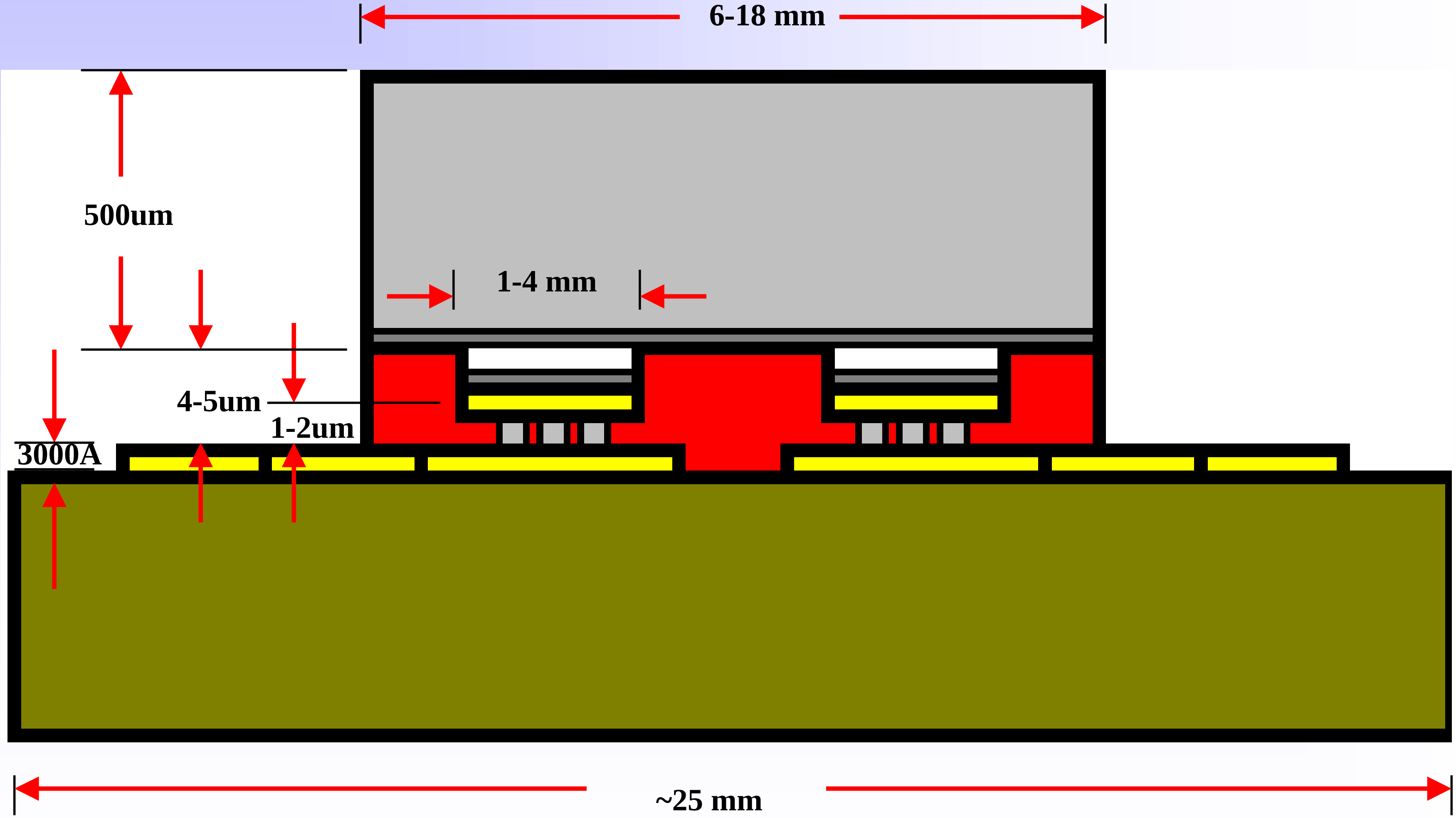

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Dark Current: Various Encapsulants

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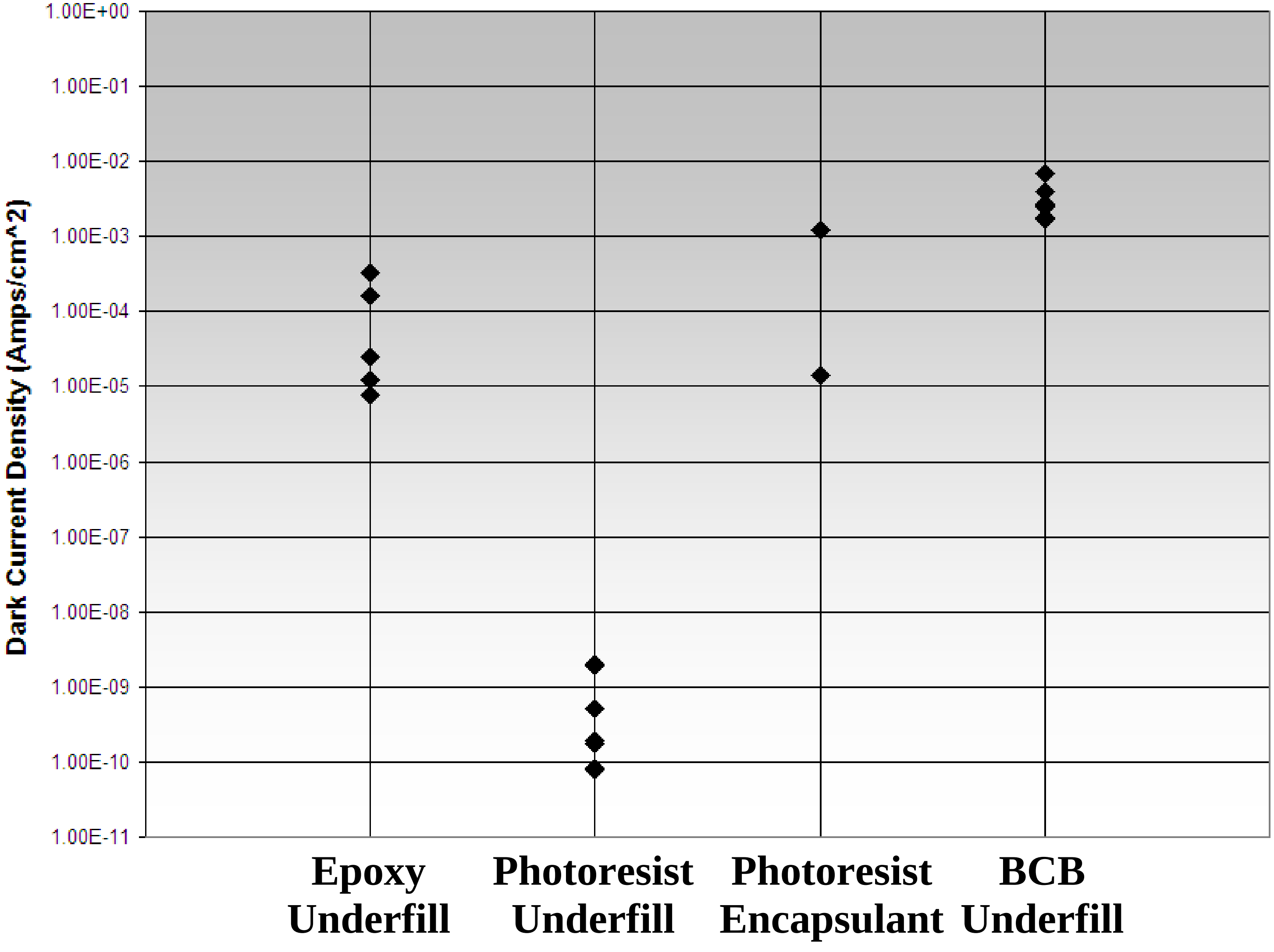
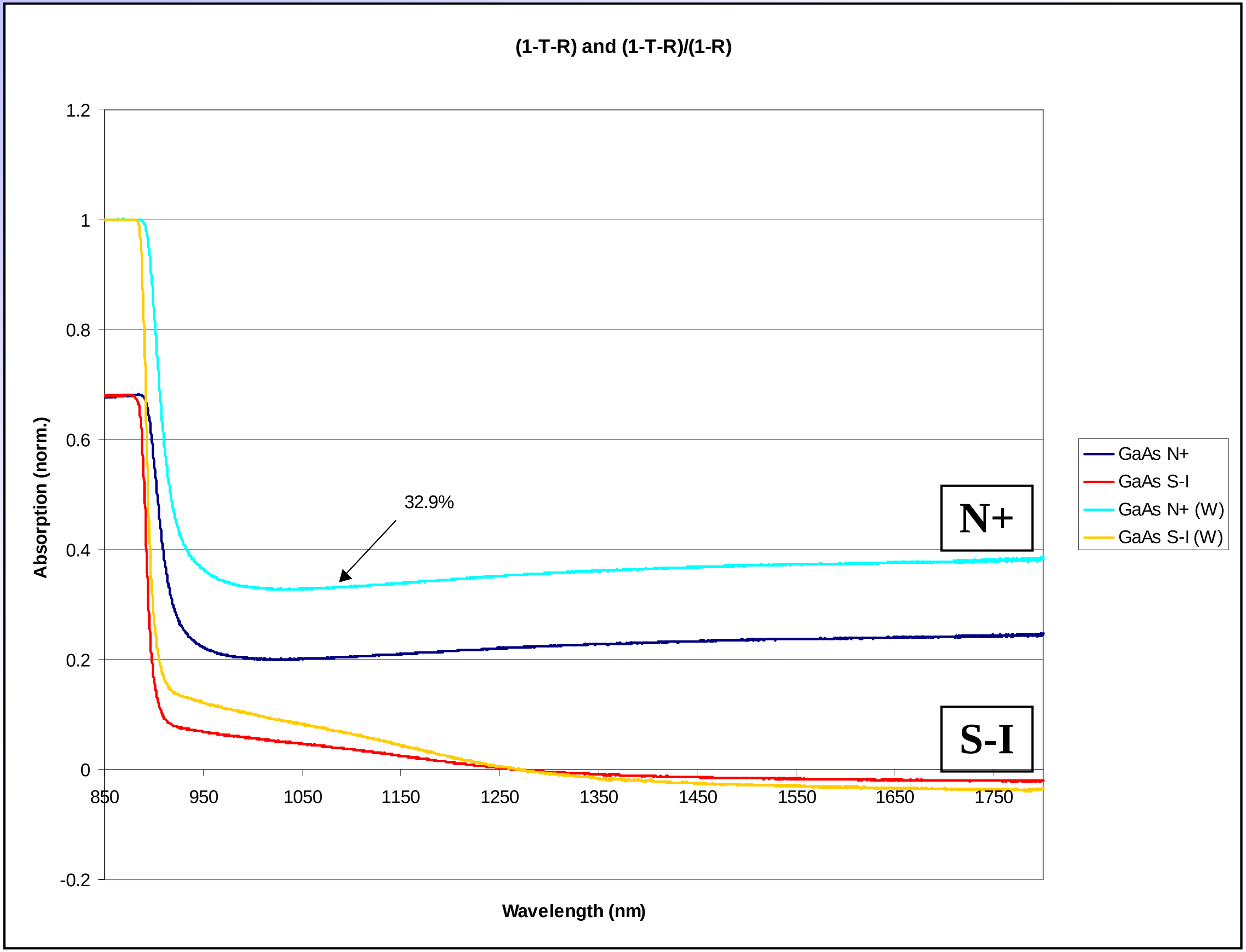
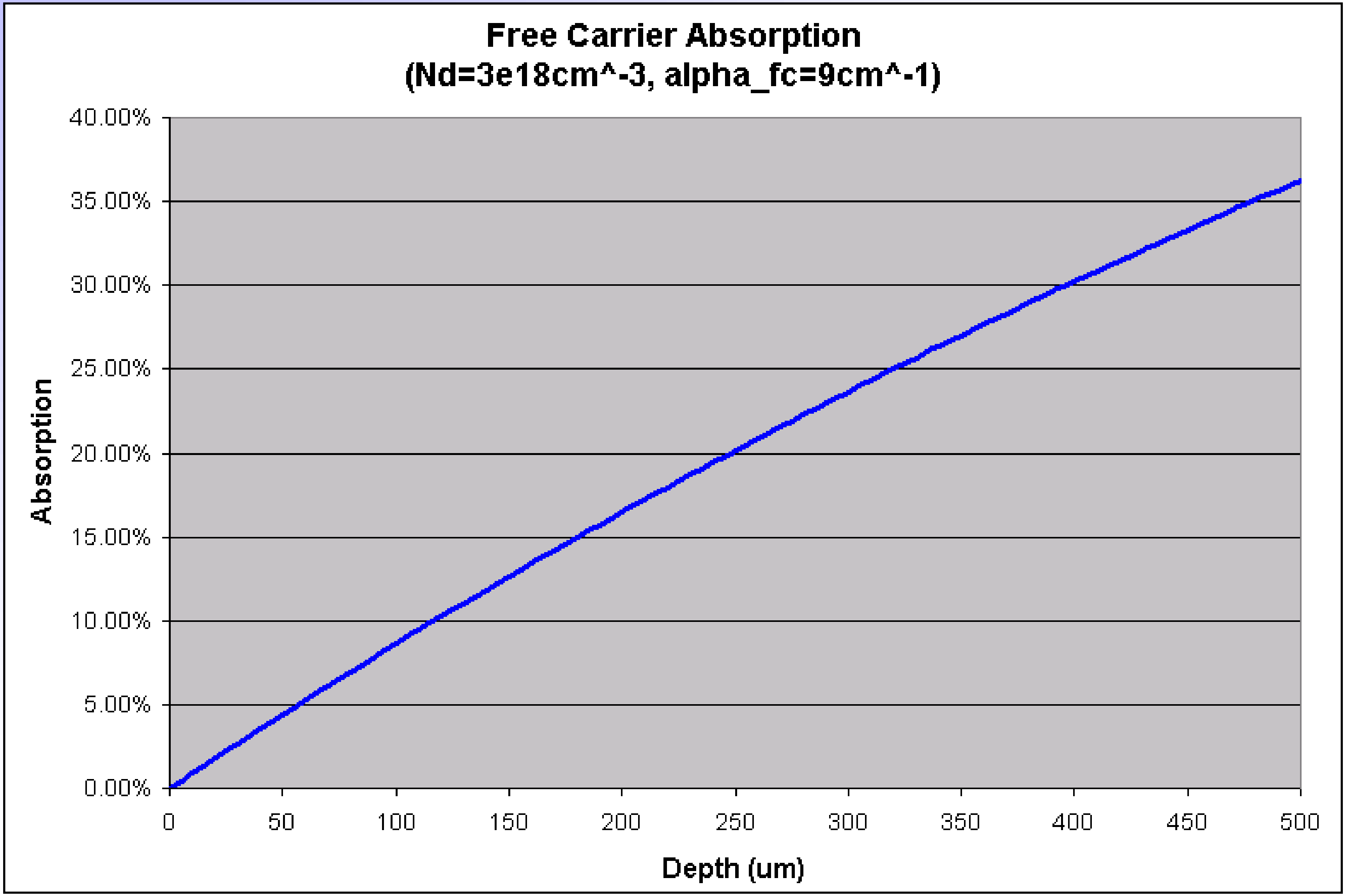
(@ – 3 V)



Free-Carrier Absorption



Free-Carrier Absorption



Free-Carrier Absorption

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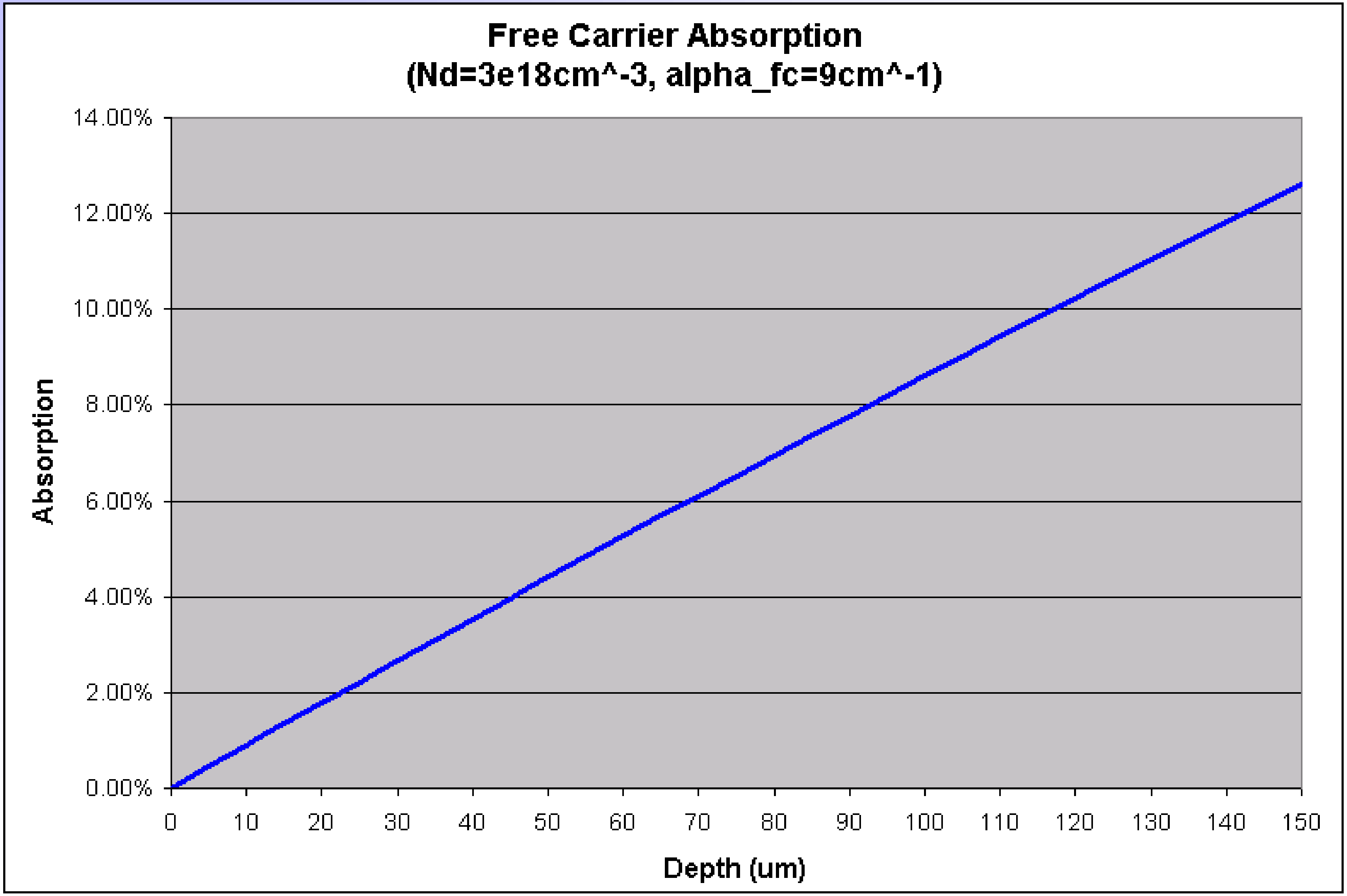
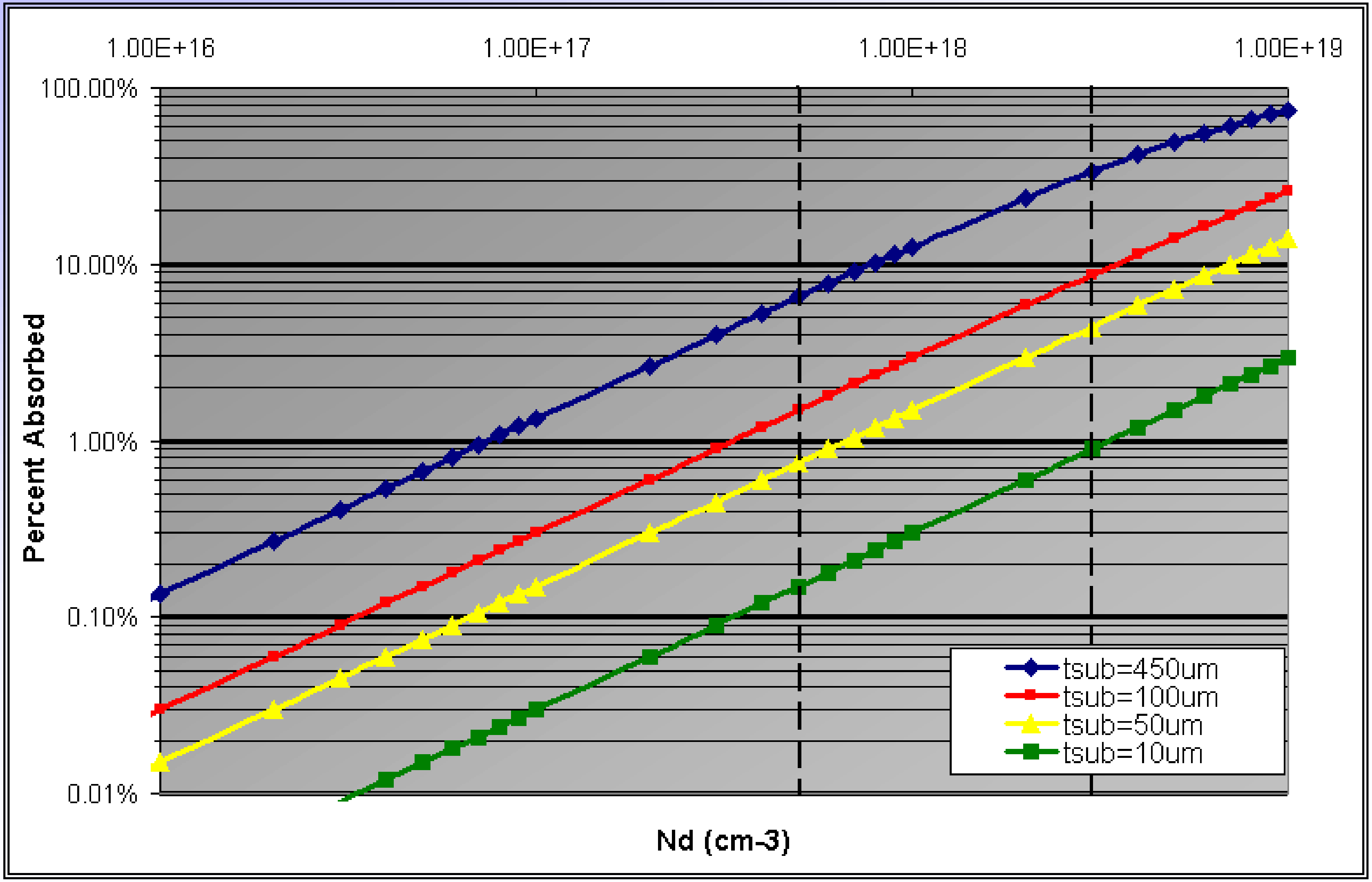


Free-Carrier Absorption



$$A = 1 - \exp(-t_{sub} \bullet \alpha_{fc}) , \alpha_{fc} = N_d * 3e\text{-}18$$

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Thinned Device Photocurrent

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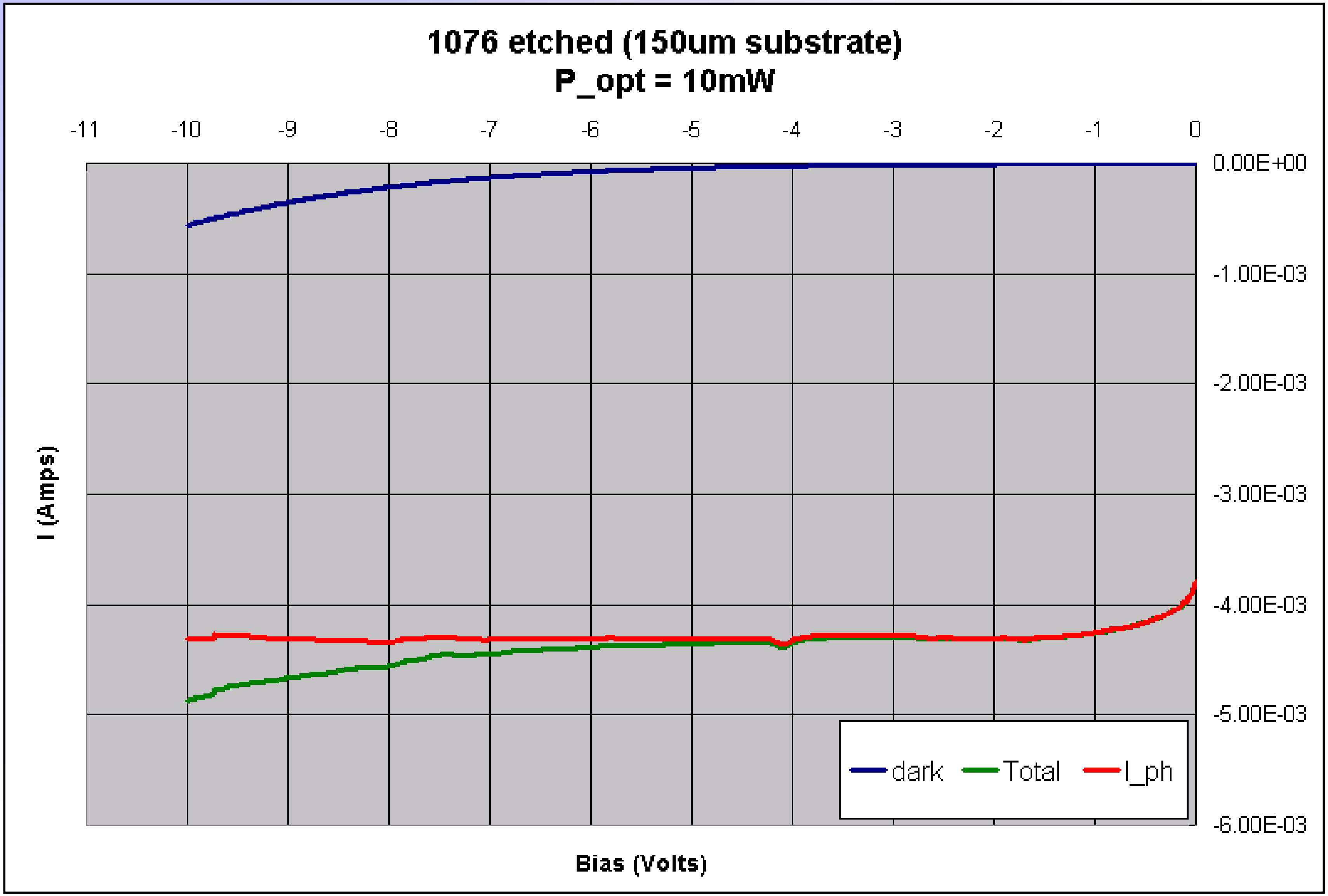

Thinned Device QE

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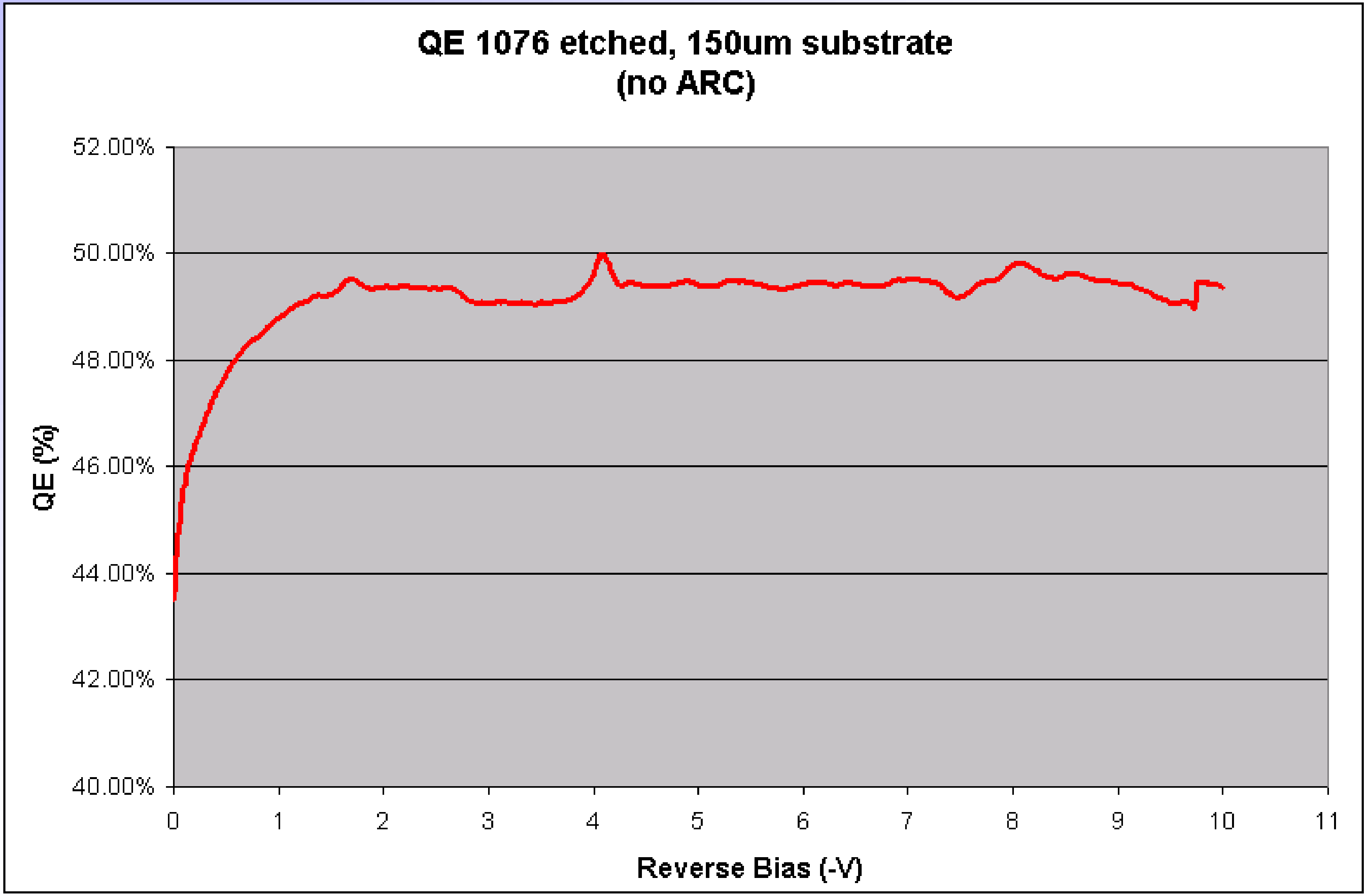
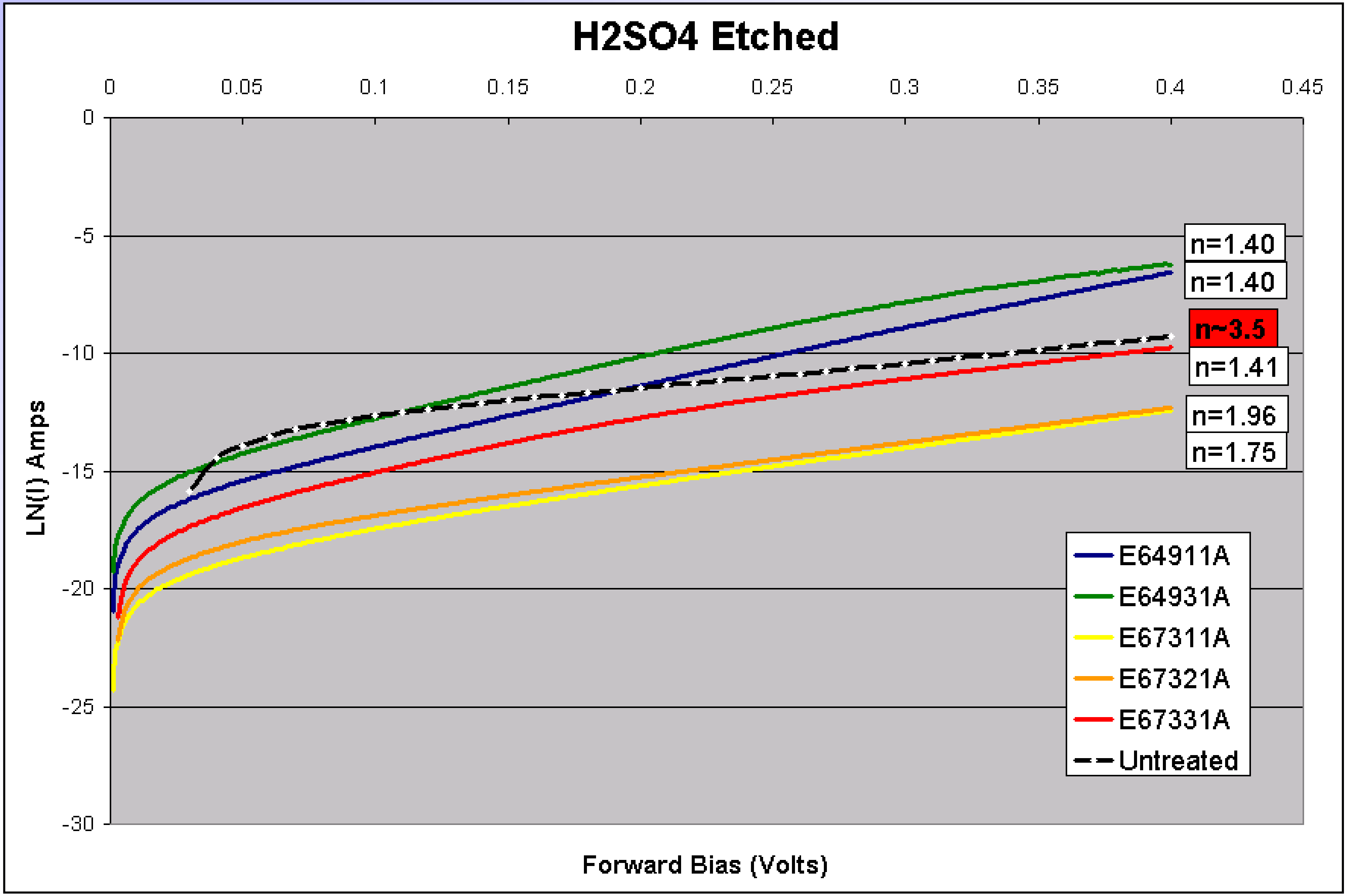
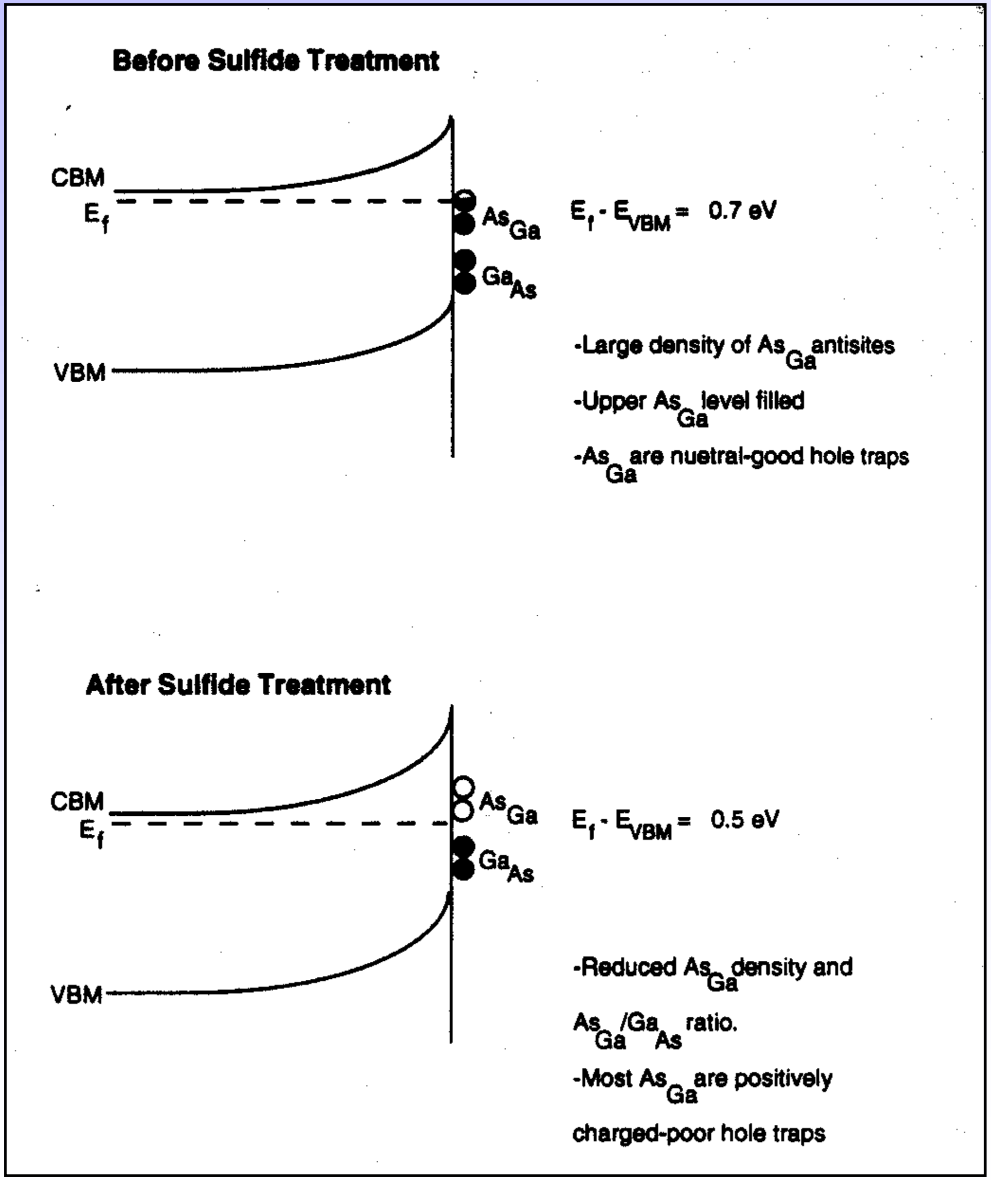


Surface Passivation Results (2)



$(NH_4)_2S$+ Surface States



Before Sulfide Treatment

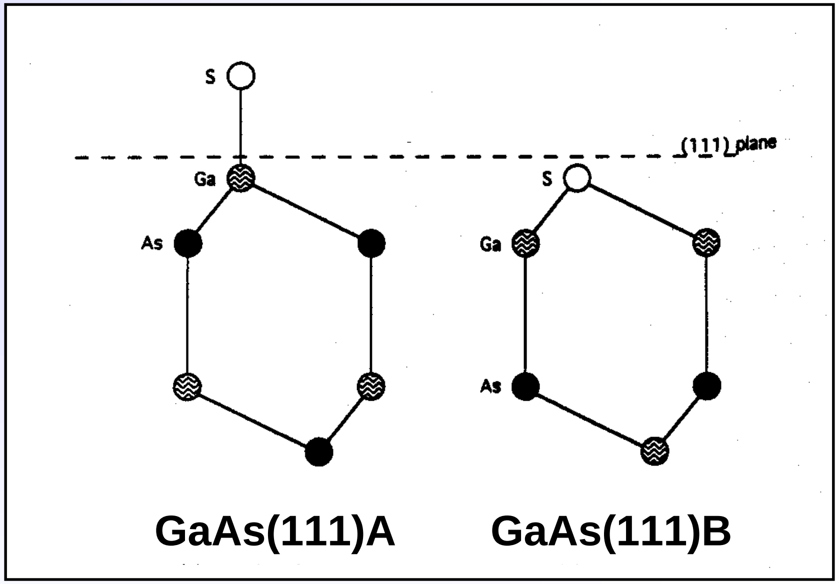
$E_f - E_{VBM} = 0.7$ eV

- Large density of As_{Ga} antisites
- Upper As_{Ga} level filled
- As_{Ga} are nuetral-good hole traps

After Sulfide Treatment

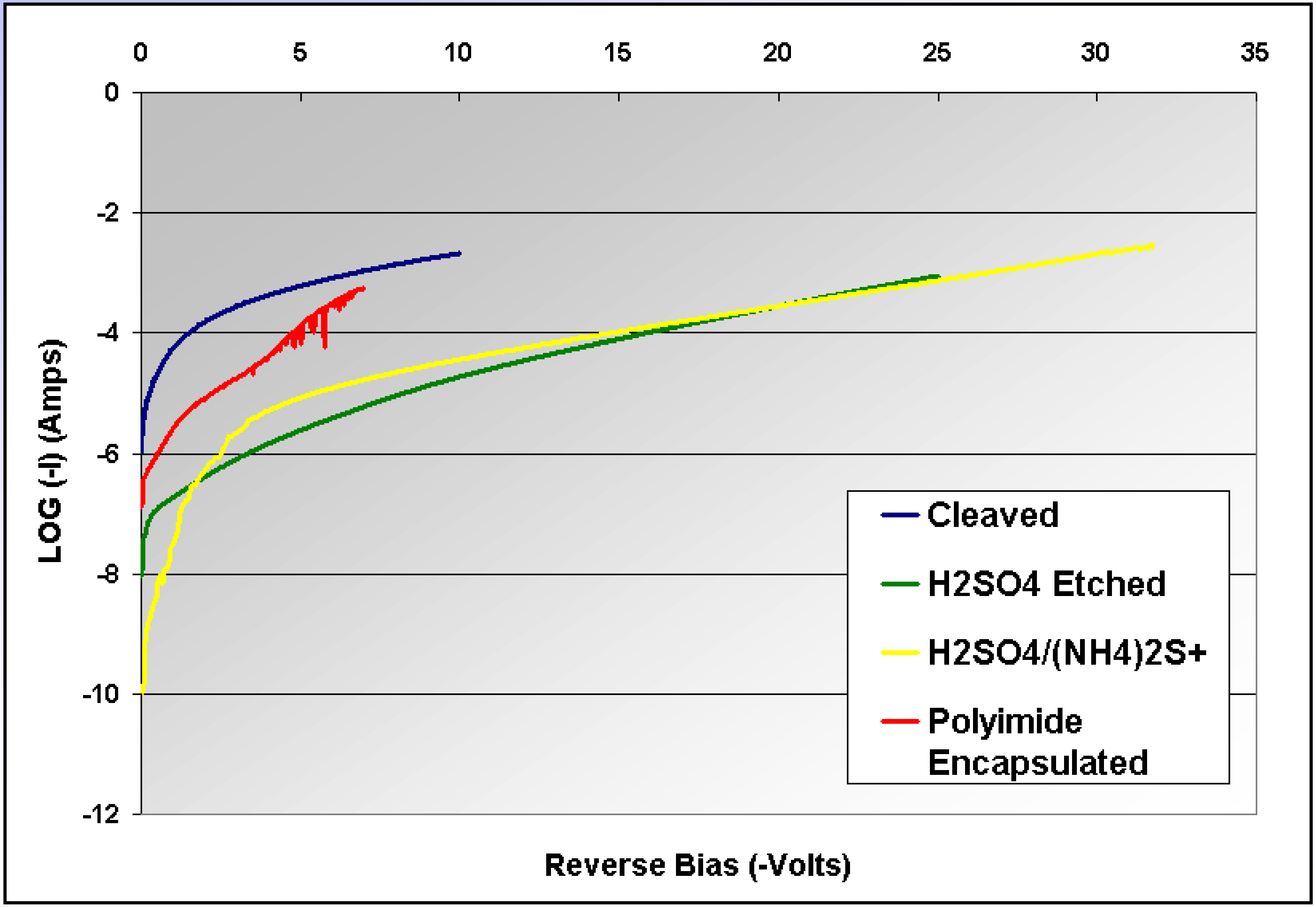
$E_f - E_{VBM} = 0.5$ eV

- Reduced As_{Ga} density and As_{Ga}/Ga_{As} ratio.
- Most As_{Ga} are positively charged-poor hole traps

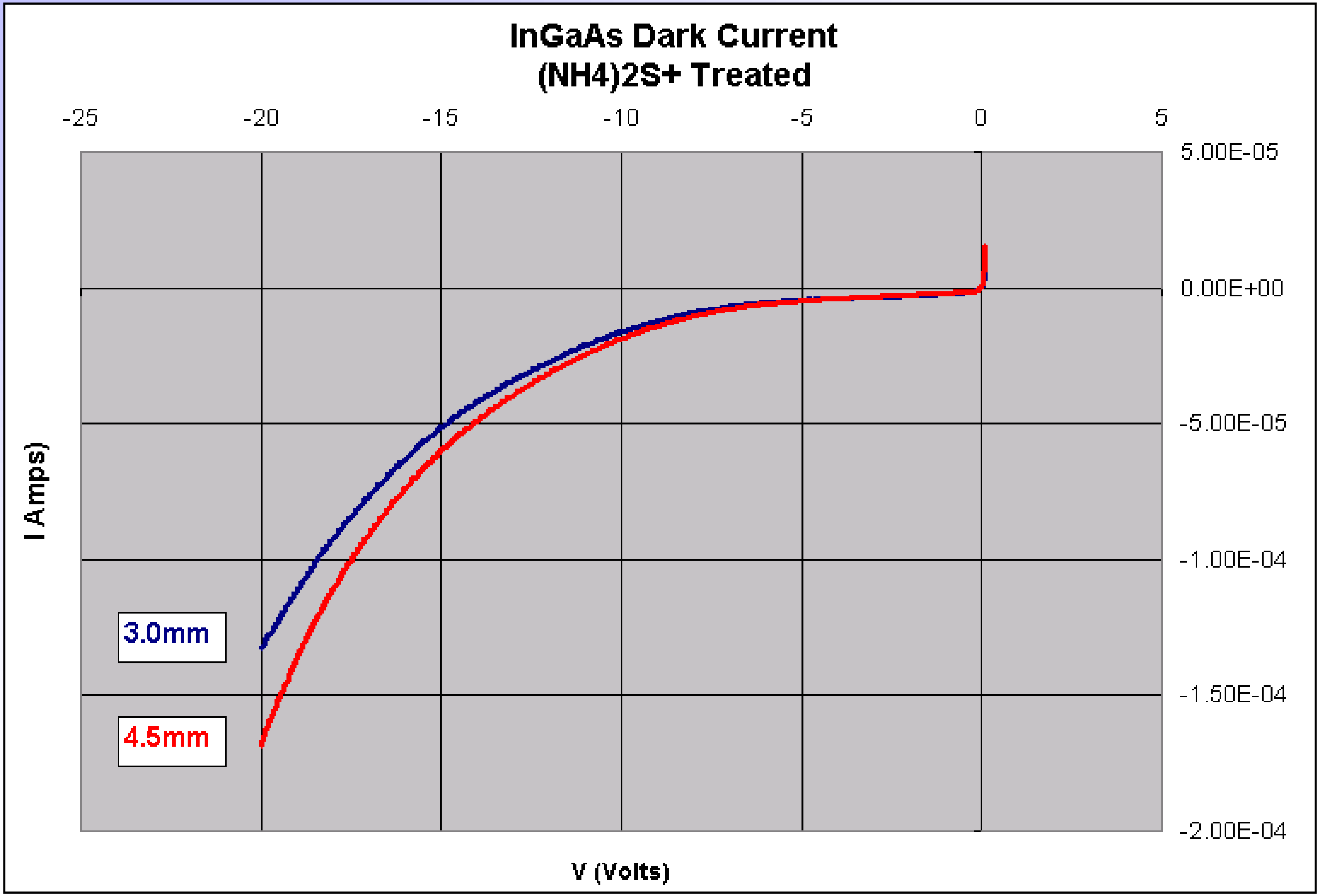


(Green and Spicer, 1993)

Surface Passivation Results



Large InGaAs Devices, –20V Bias



InGaAs vs. GaInNAs Dark Current

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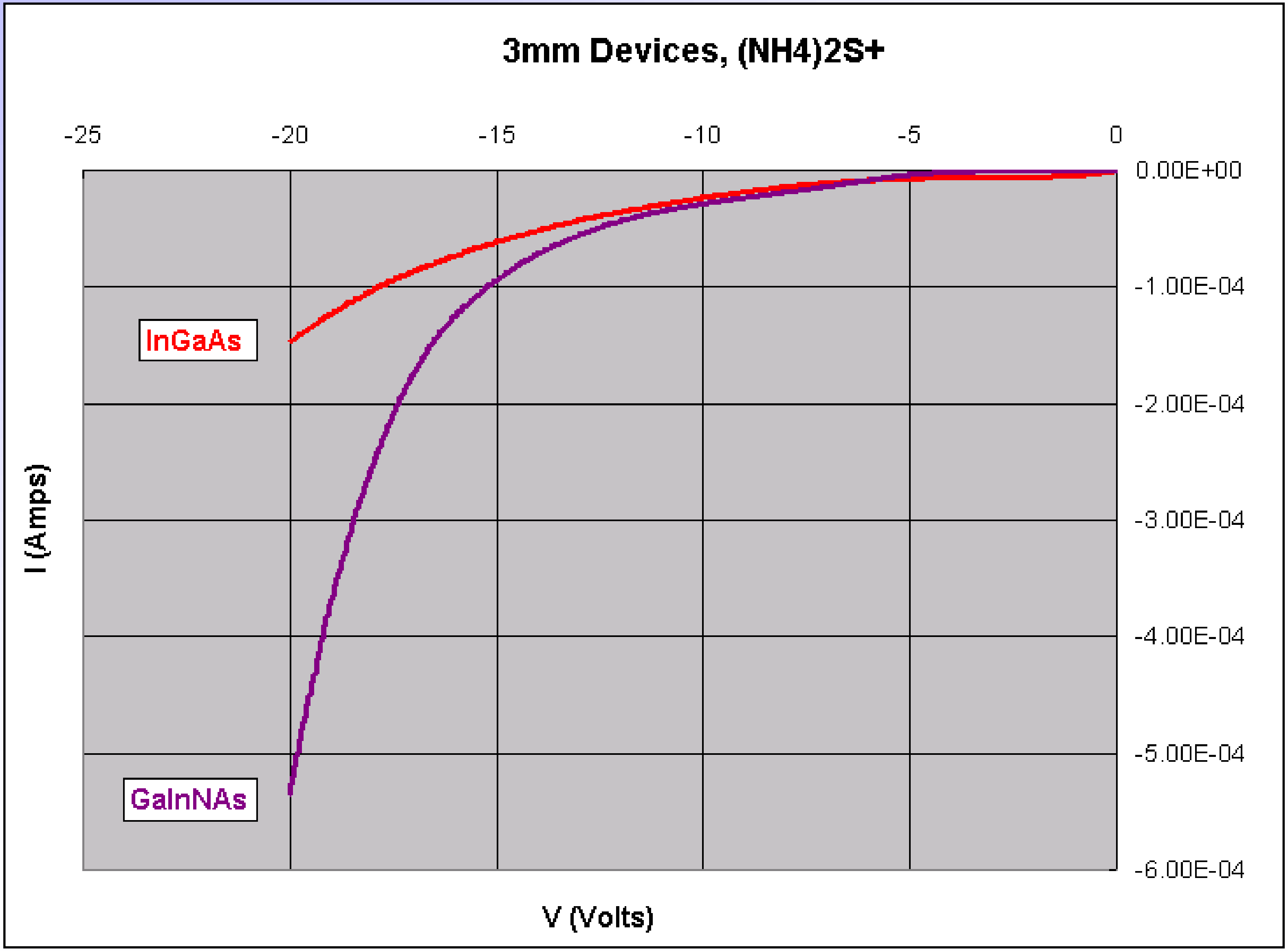

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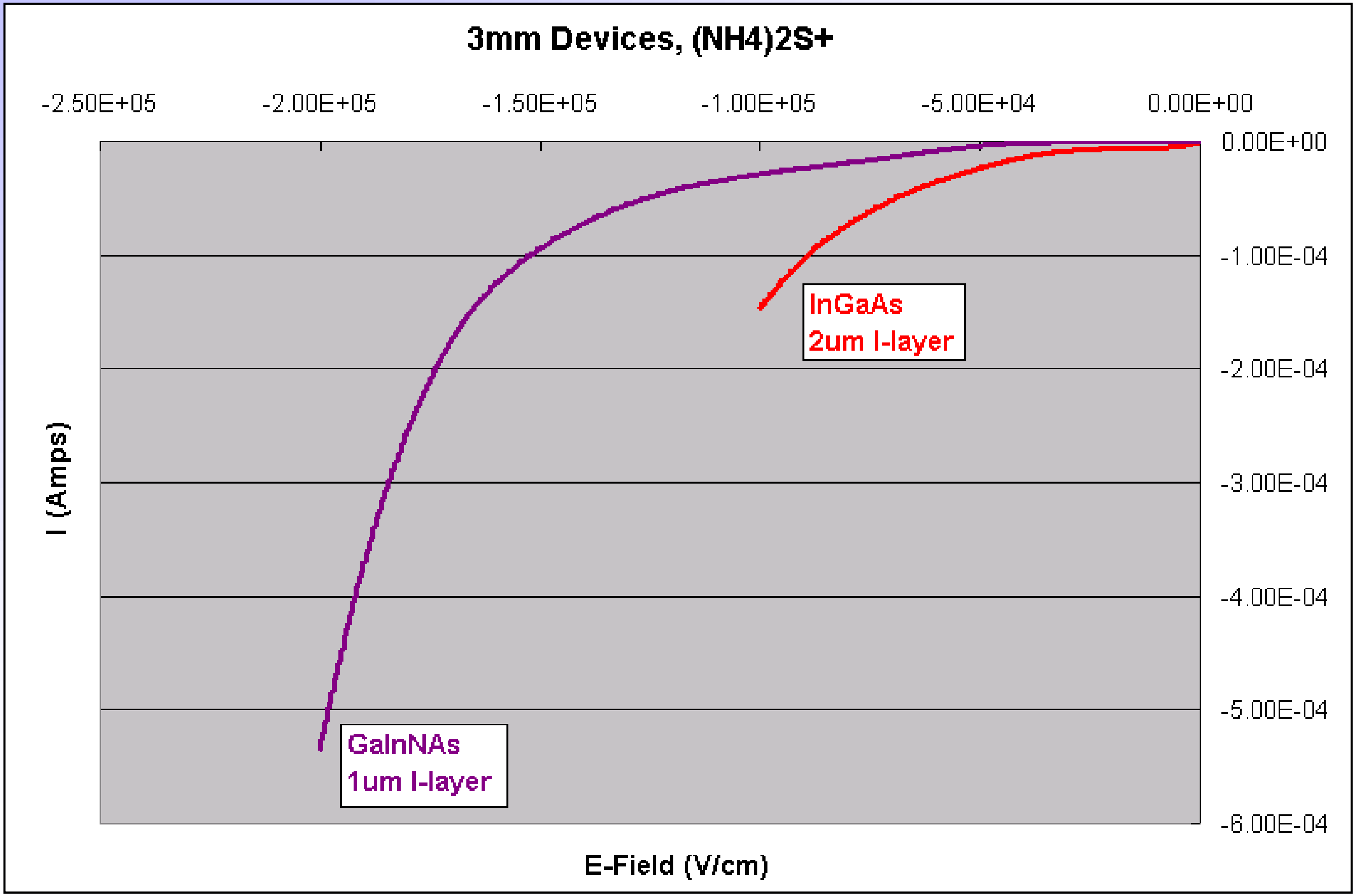

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GaInNAs Dark Current

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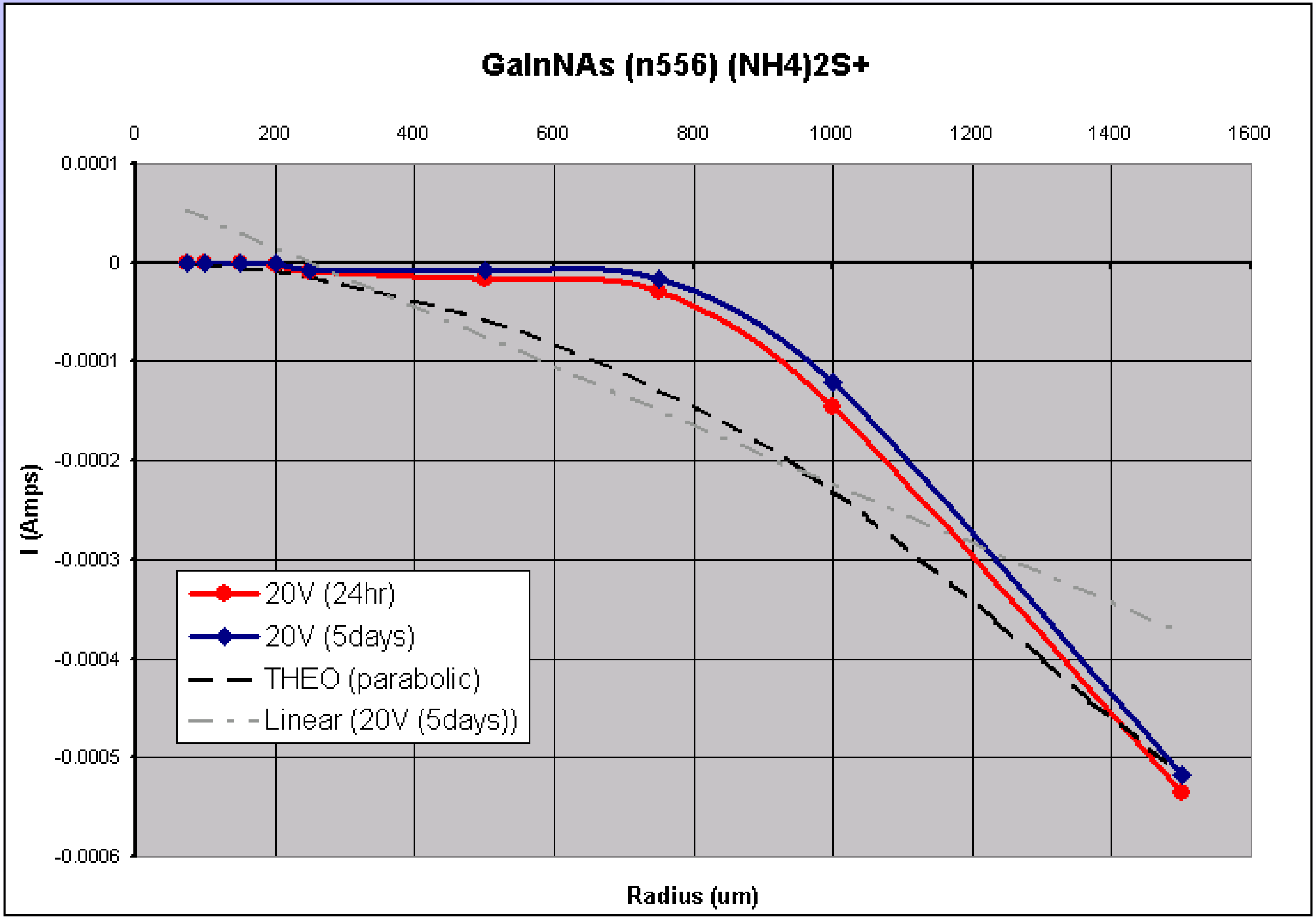

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InGaAs Dark Current

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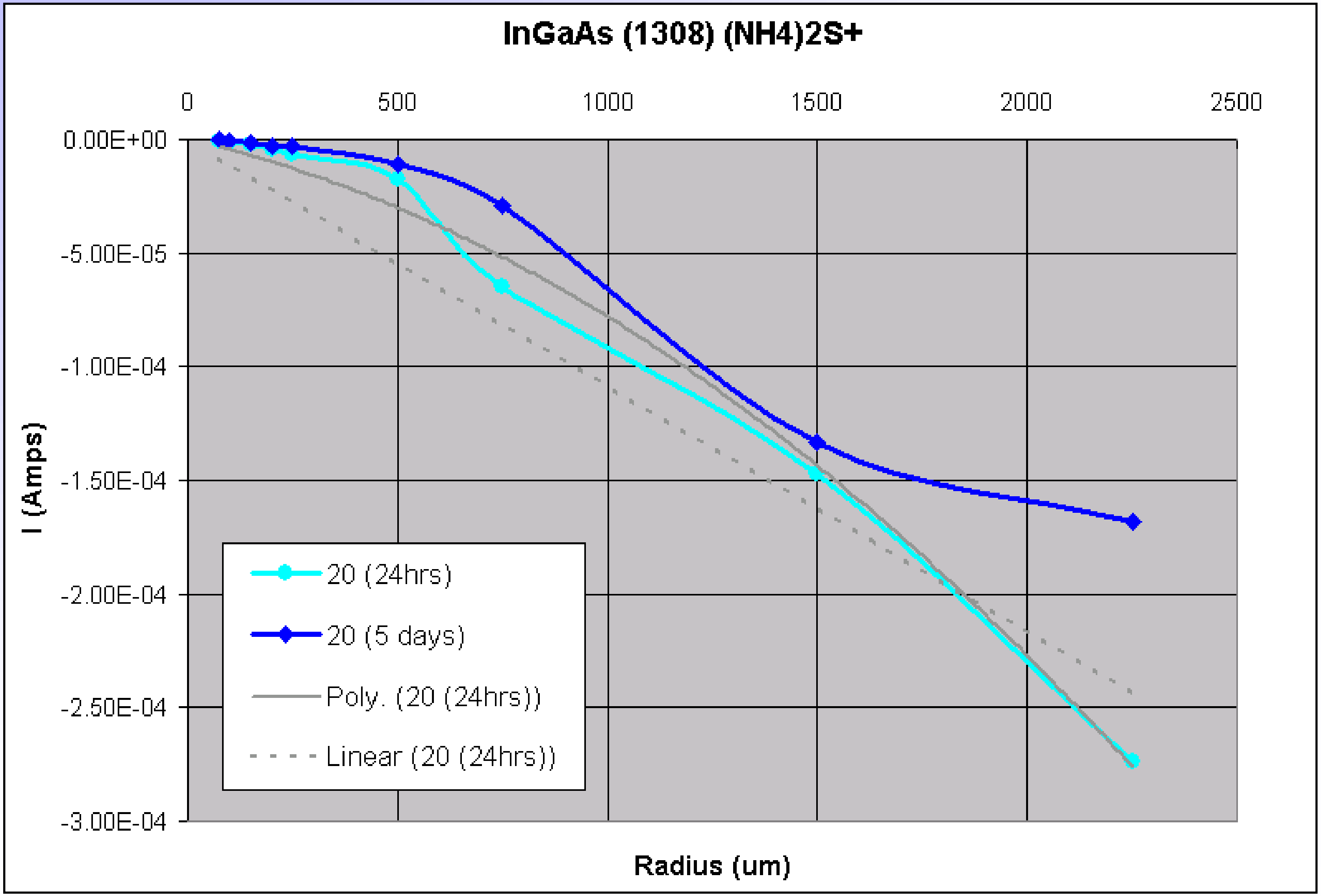

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GaInNAs H2SO4 vs. (NH4)2S+

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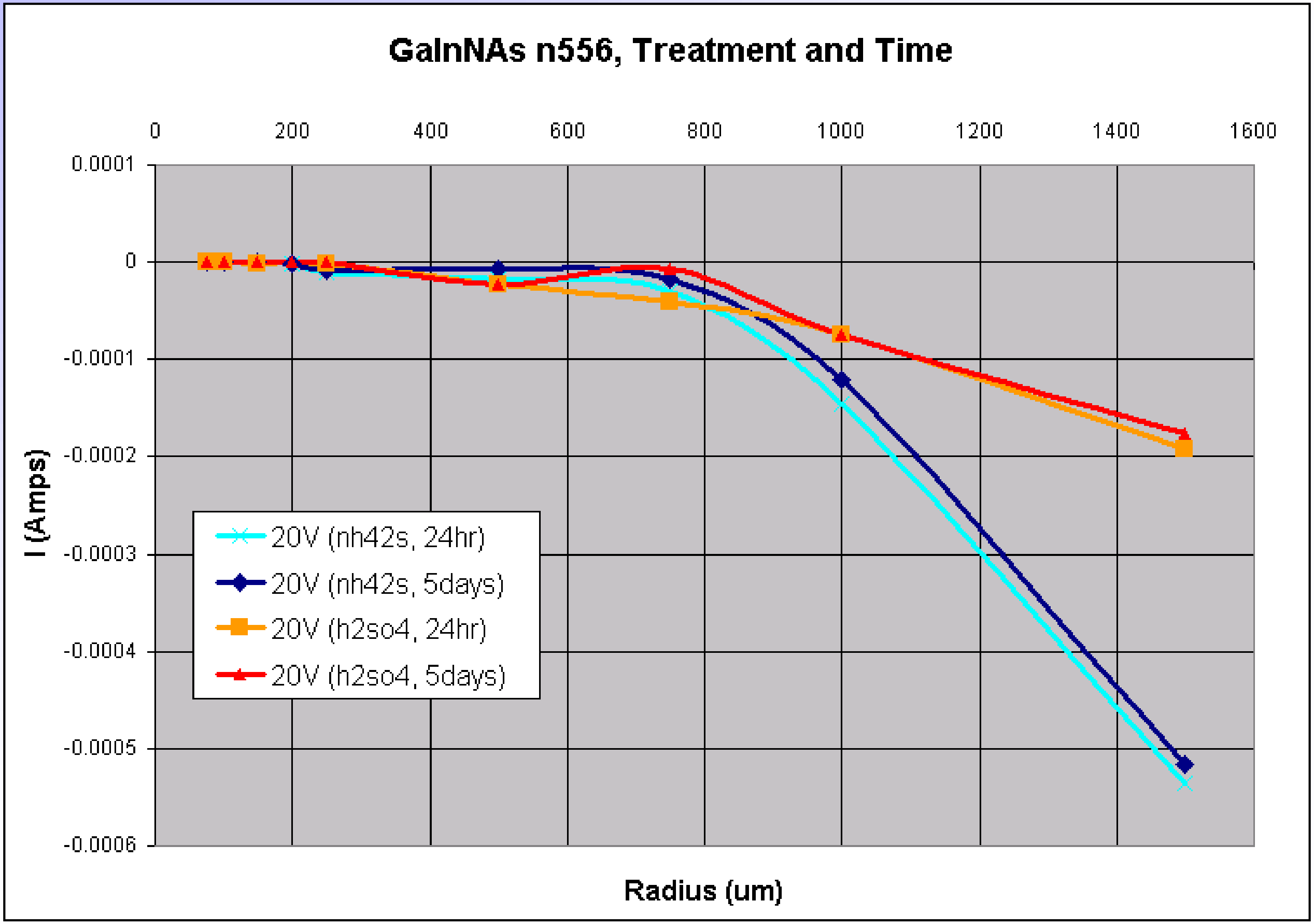
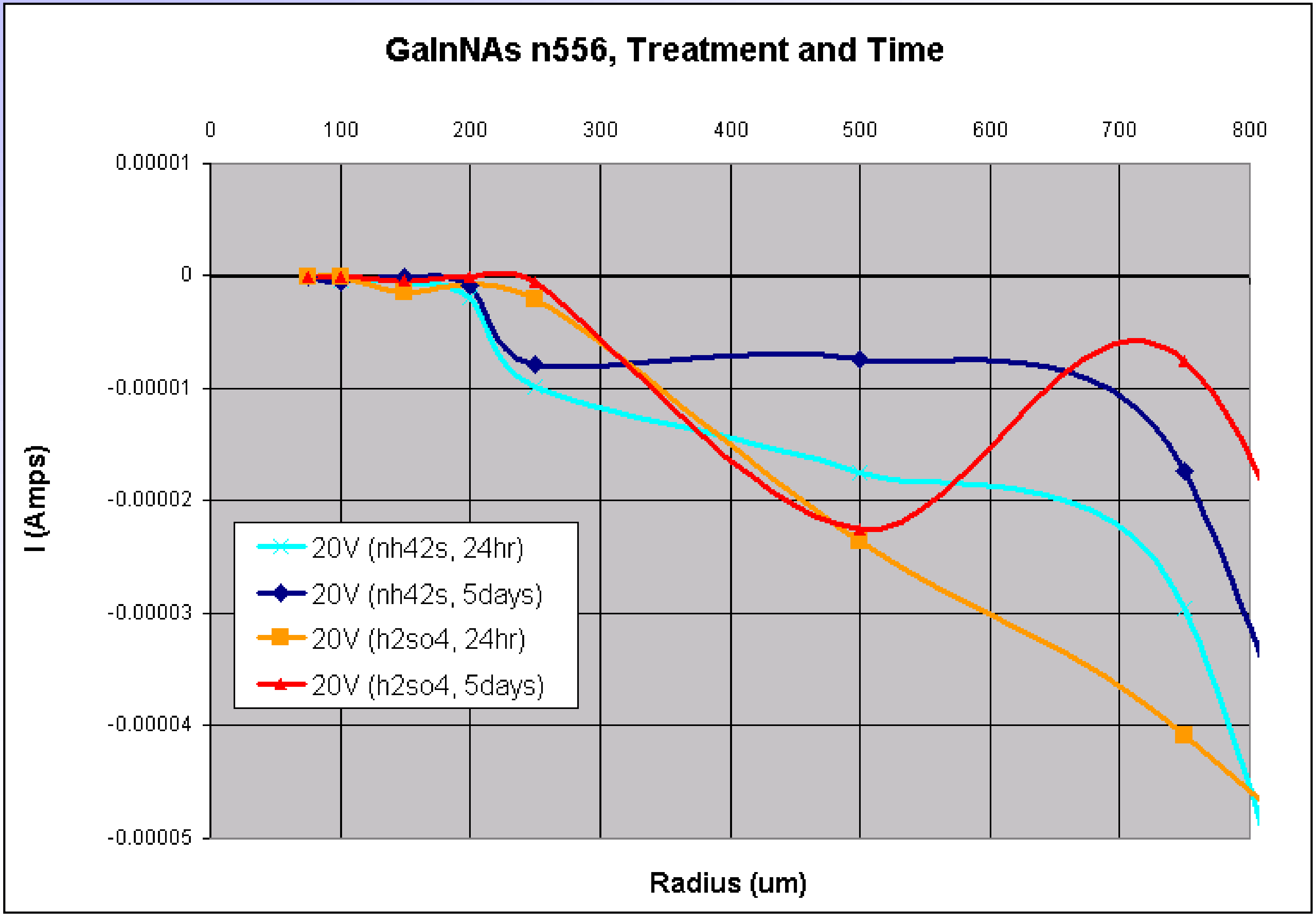
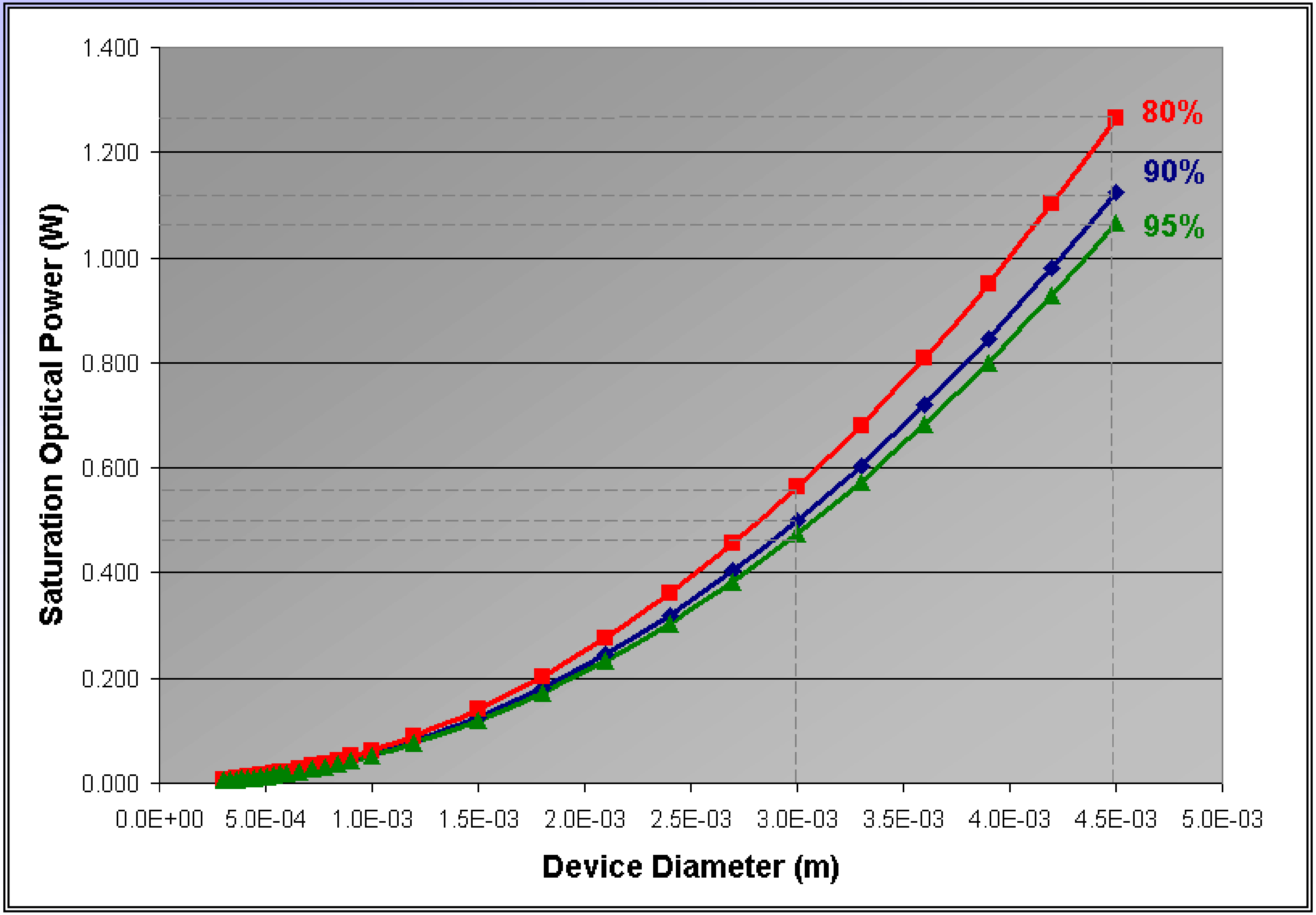


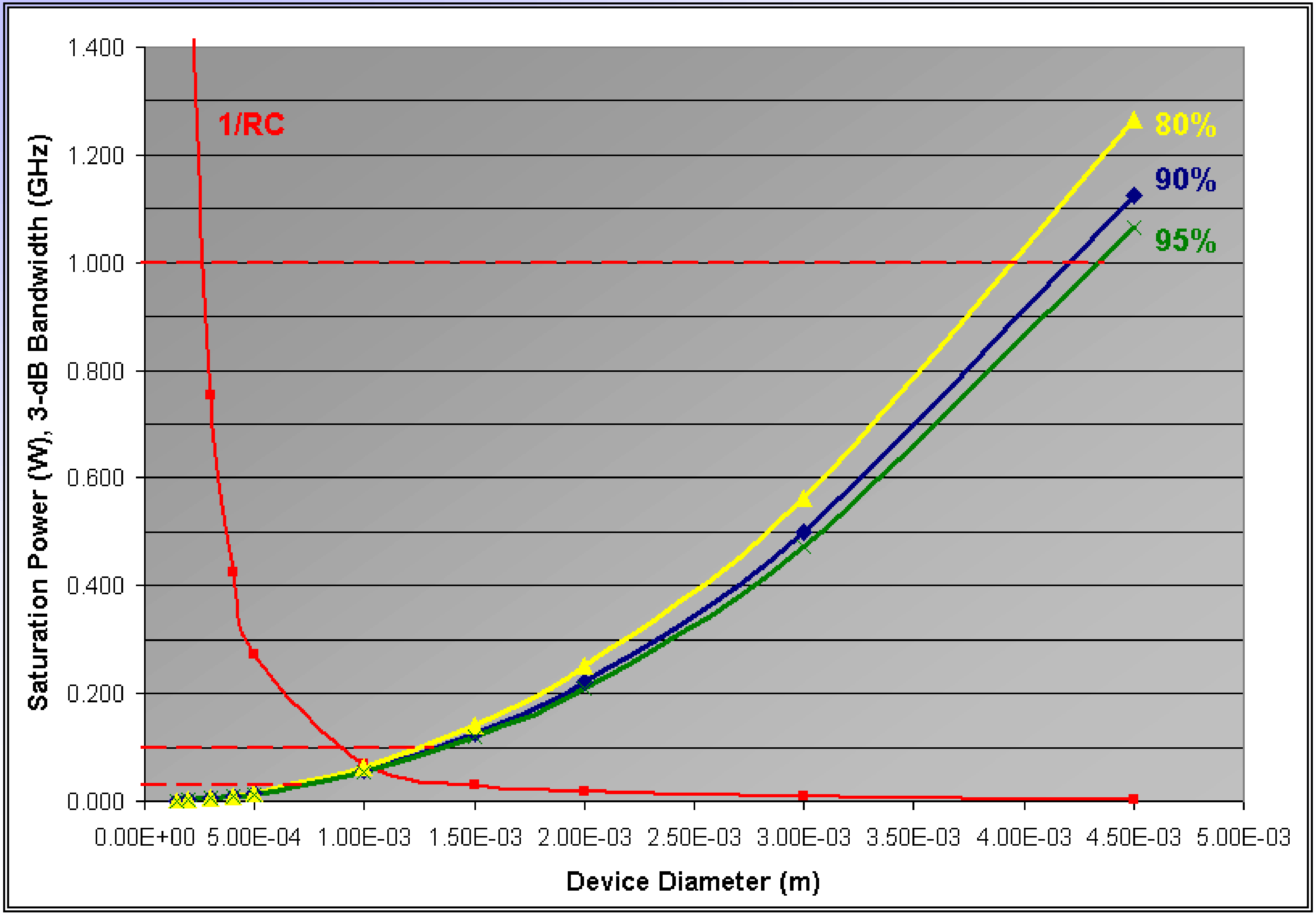
GaInNAs H2SO4 vs. (NH4)2S+



Theoretical Saturation Powers



Theoretical Saturation Powers



RC-Circuit Bode Plot

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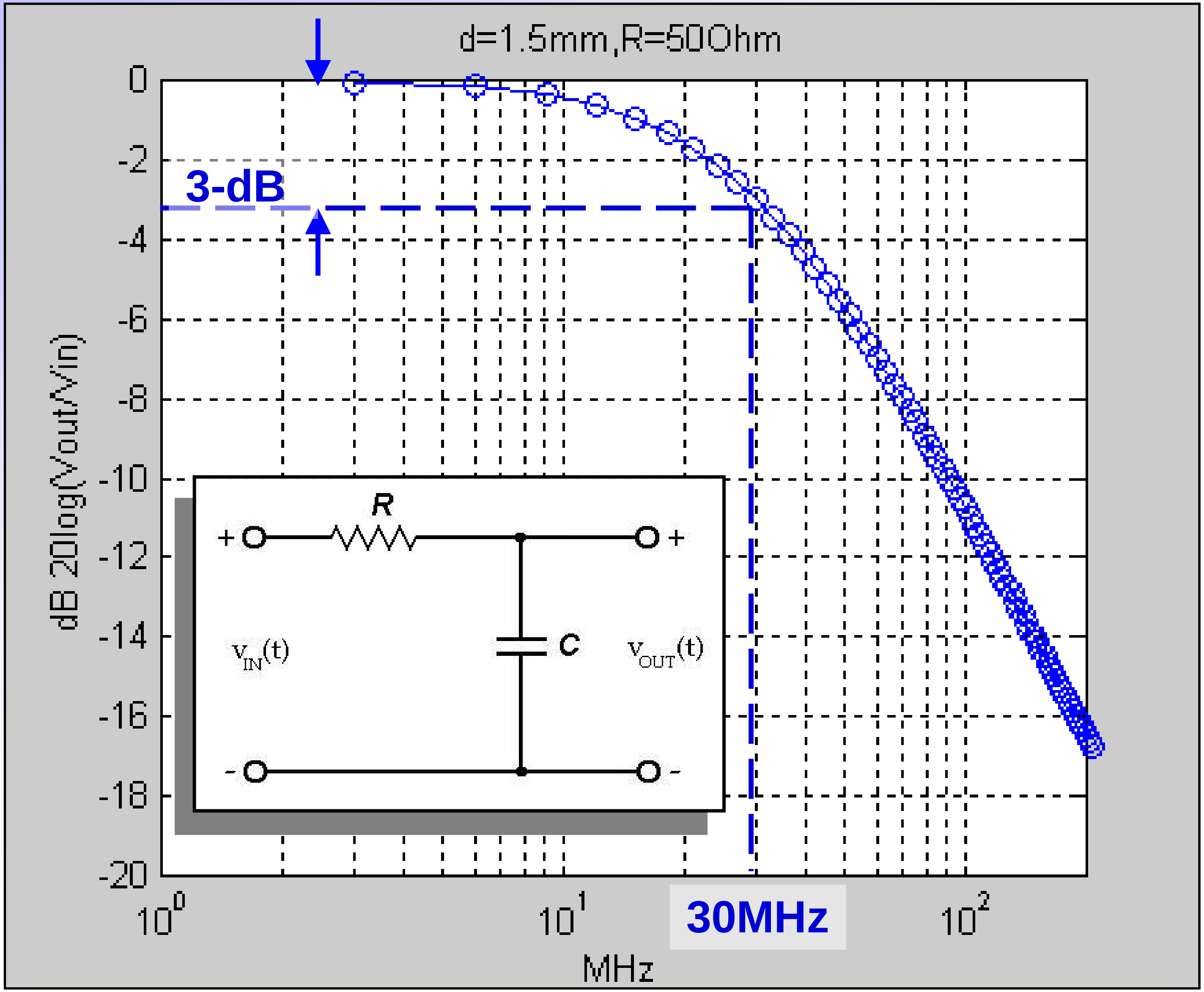
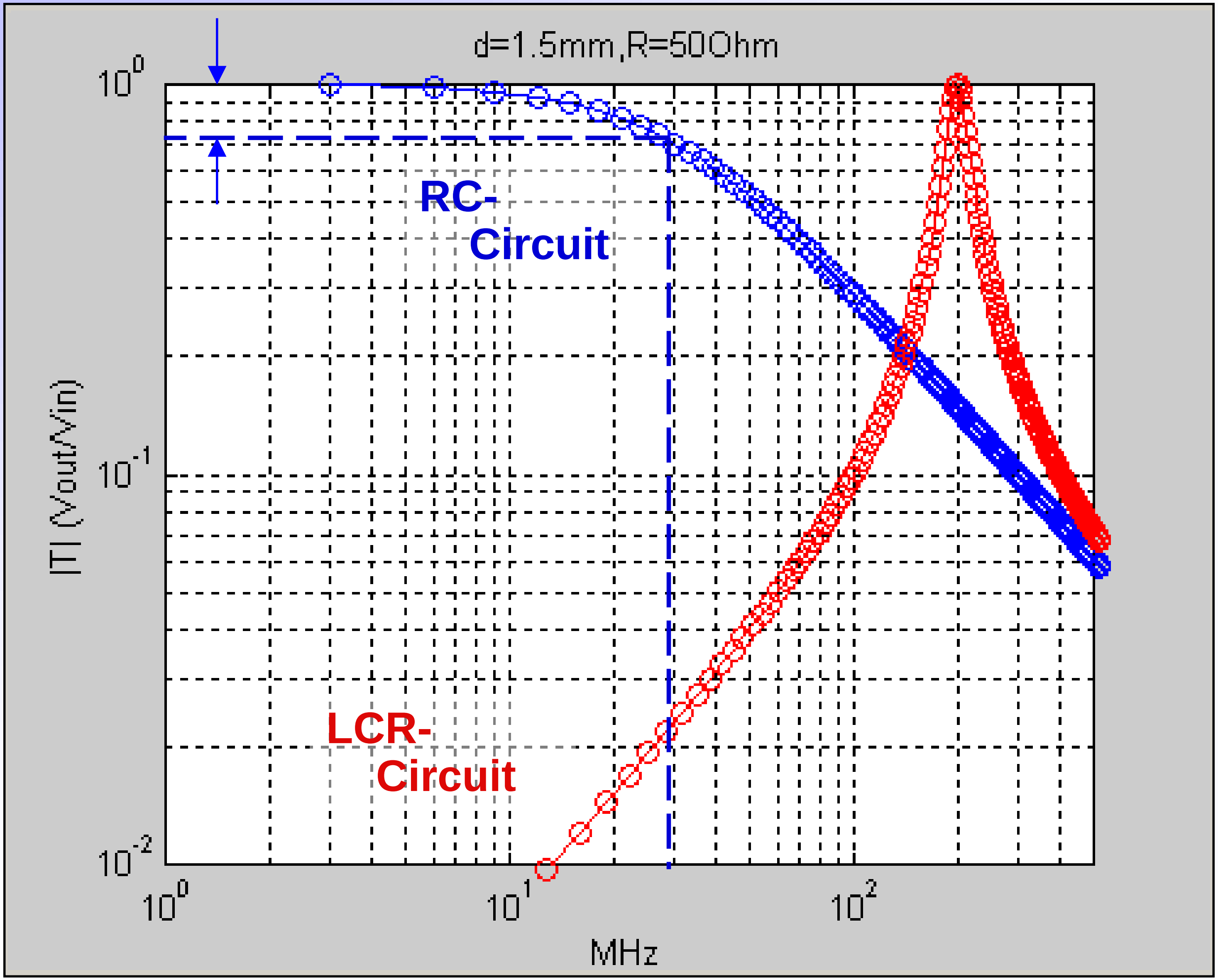
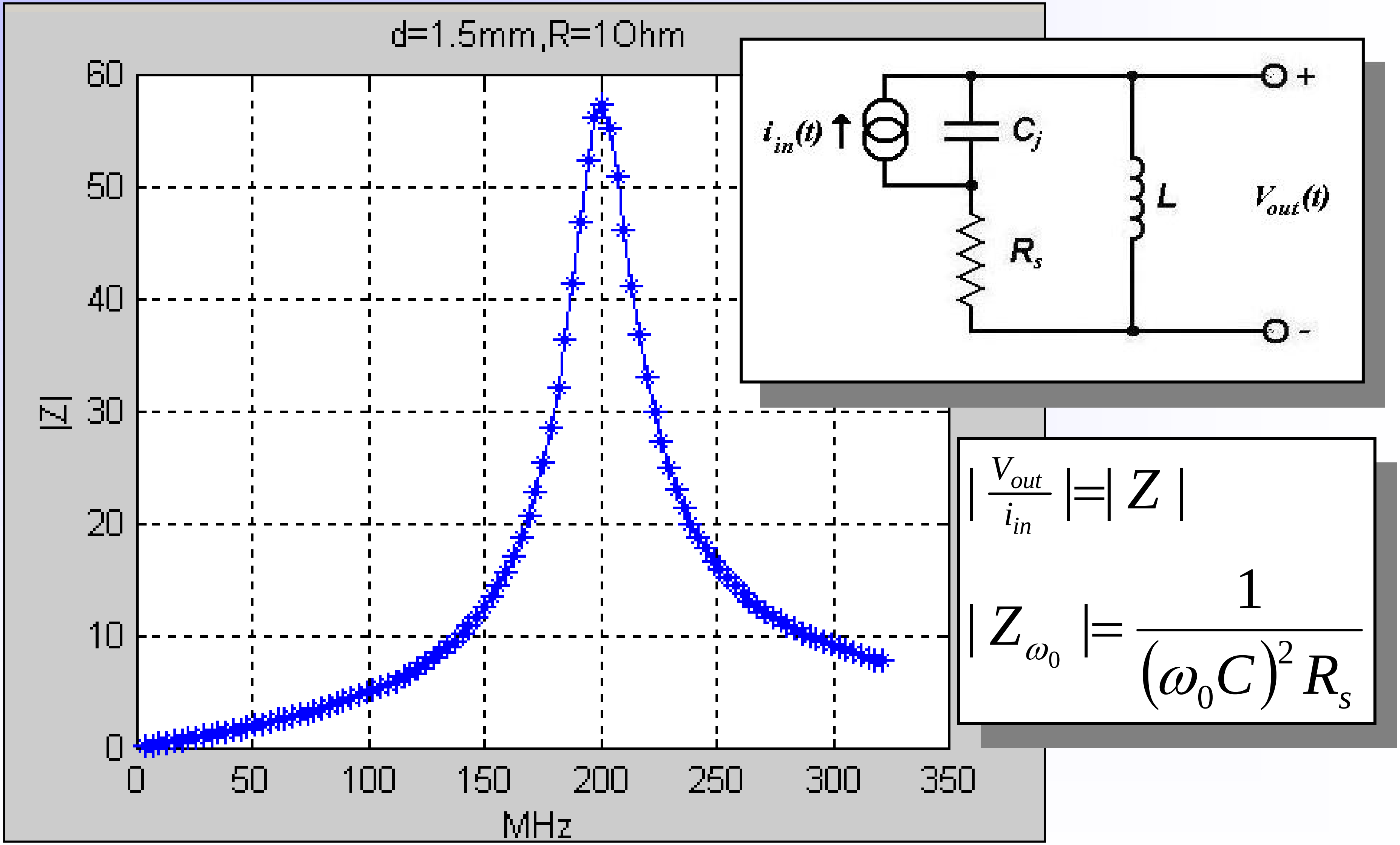


RC- and LCR- Transmittance



LCR- Circuit Impedance



$$\left|\frac{V_{out}}{i_{in}}\right| = |Z|$$

$$|Z_{\omega_0}| = \frac{1}{(\omega_0 C)^2 R_s}$$