Advanced LIGO
Photodiode Development

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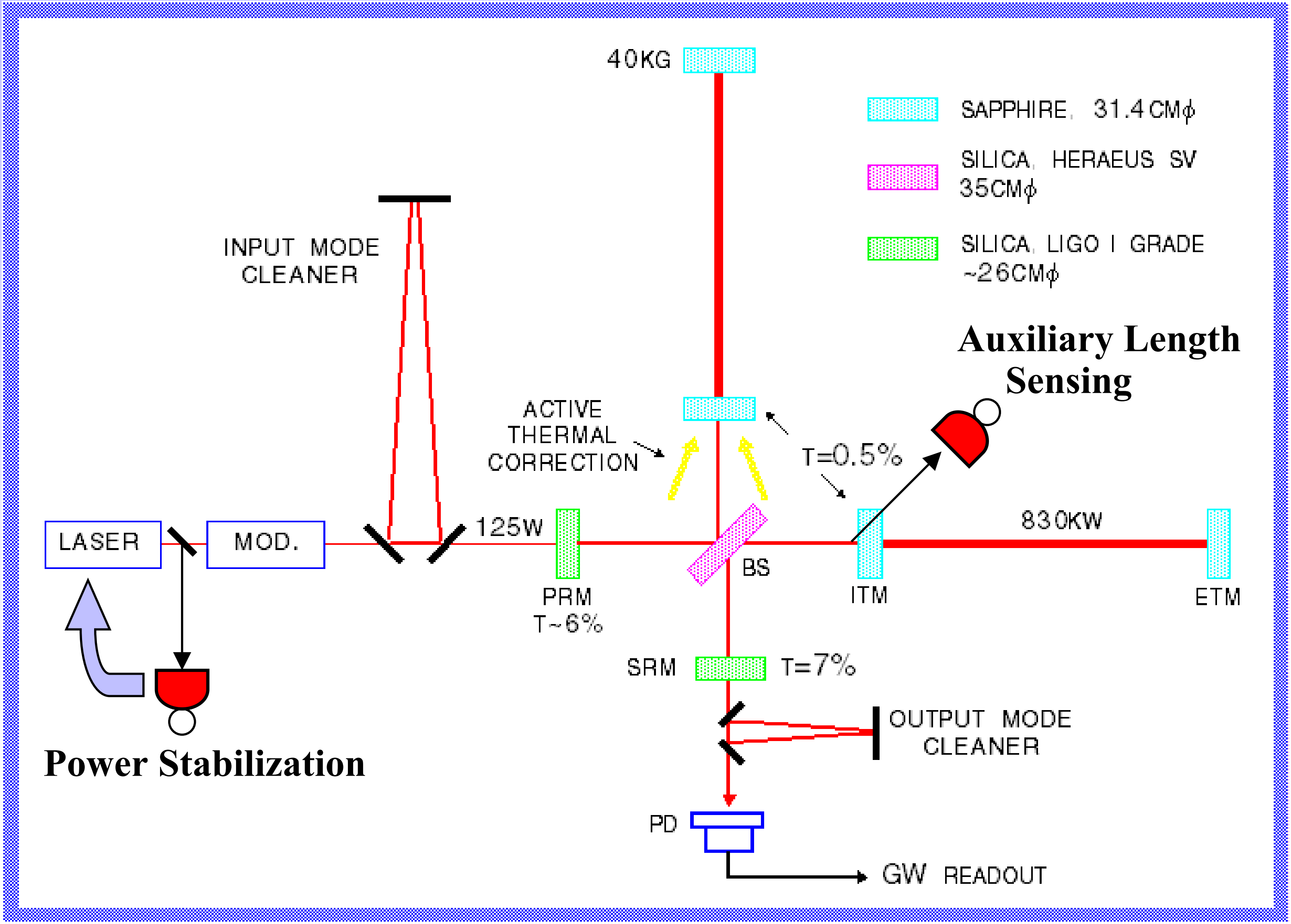
Hannover, Germany
August 20th, 2003
LIGO-G030495-00-Z

Outline

- Motivation & Introduction
  - AdLIGO PD Specifications
  - Device Materials and Design
    - → InGaAs vs. GaInNAs
- Device Results
  - Thinned Device QE
  - InGaAs & GaInNAs I-V
  - 2μm Thick GaInNAs Absorption
- Predictions

Advanced LIGO Schematic



Auxiliary Length Sensing

Power Stabilization

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Photodiode Specifications

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	LIGO I		Advanced LIGO	
Detector	**Bank of 6PDs**	**Power Stabilization**	**RF Detection**	**GW Channel**
Steady-State Power	0.6 W	1W/η	10 – 100mW	30mW
Operating Frequency	~29 MHz	100 kHz	200MHz	100 kHz
Quantum Efficiency	> 80%	η	> 80%	> 95%

e.g. 1W/0.70=1.43W

Resonating Tank Circuit

Thinned Substrate

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GaInNAs vs. InGaAs

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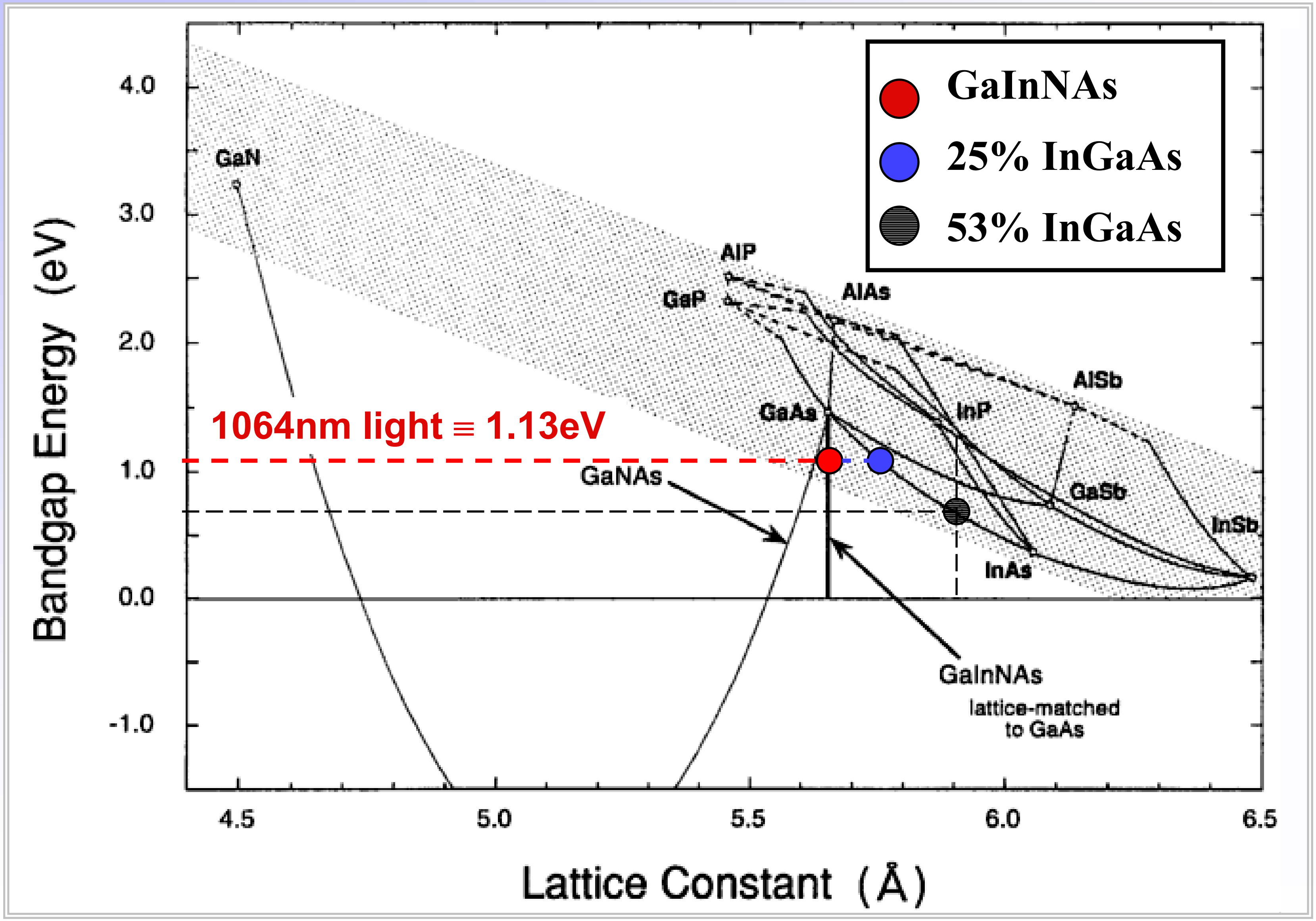
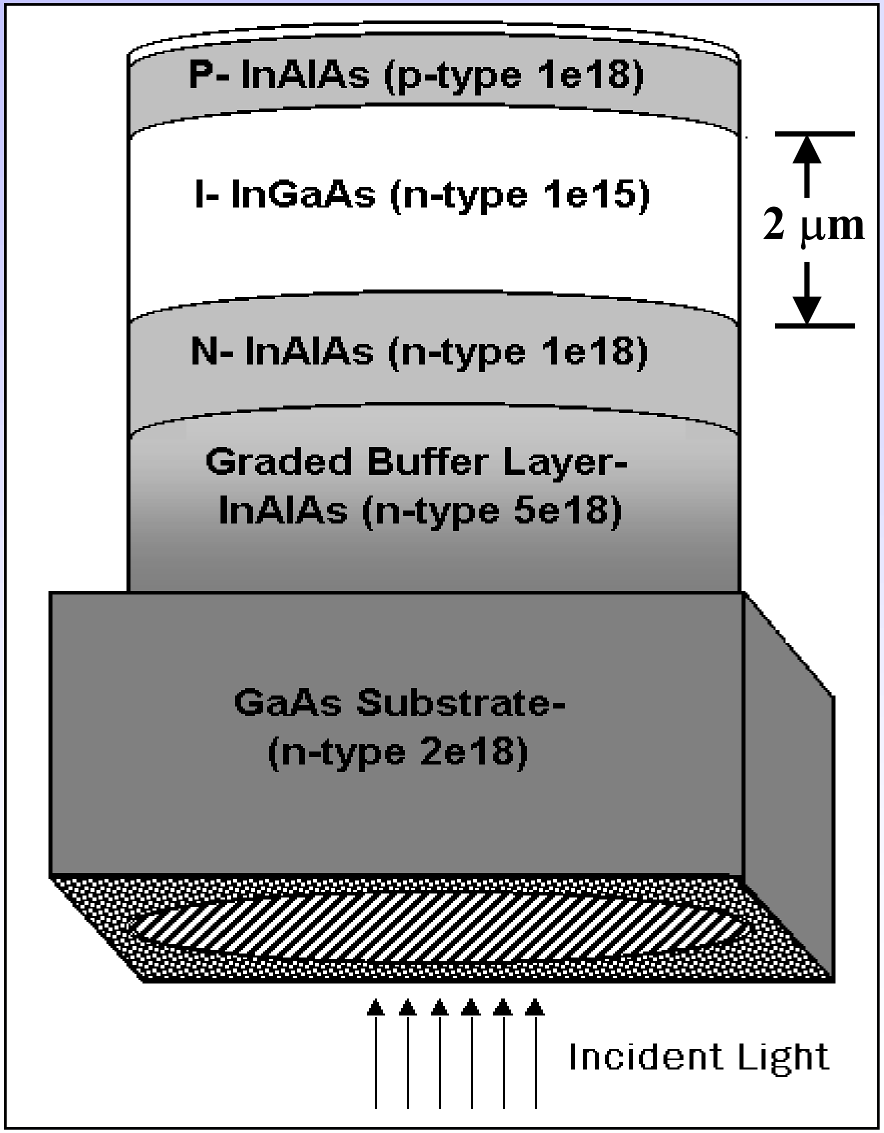
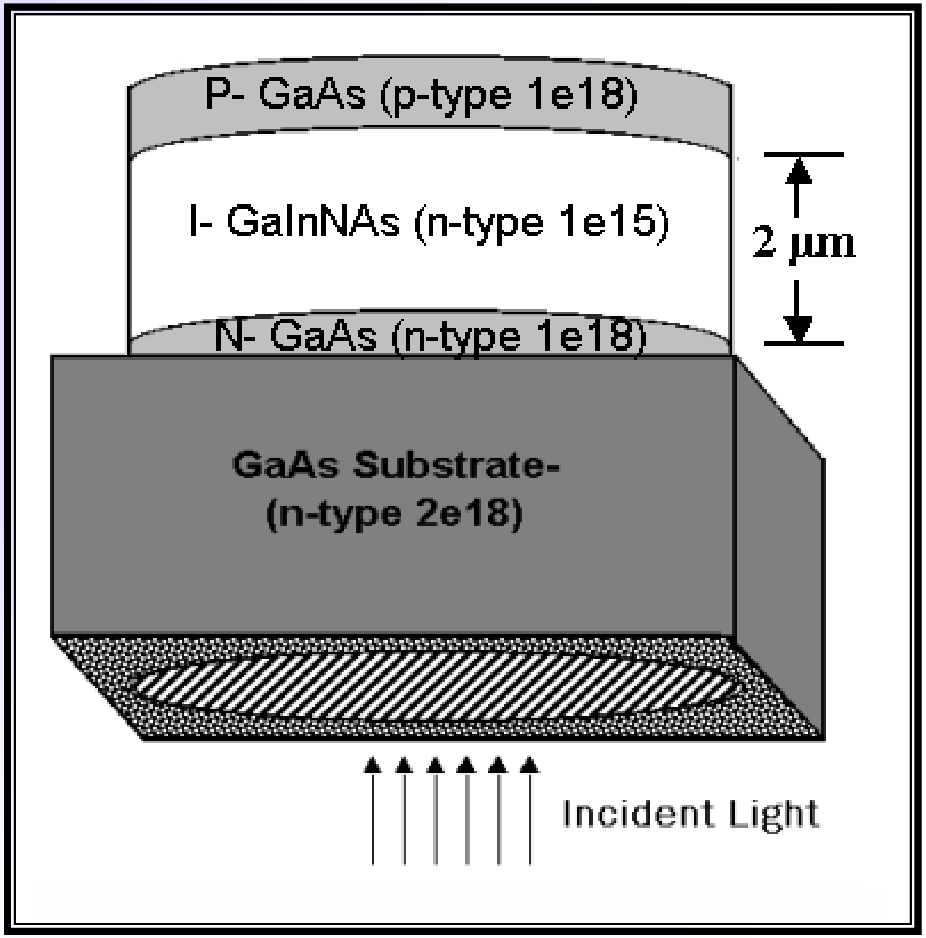


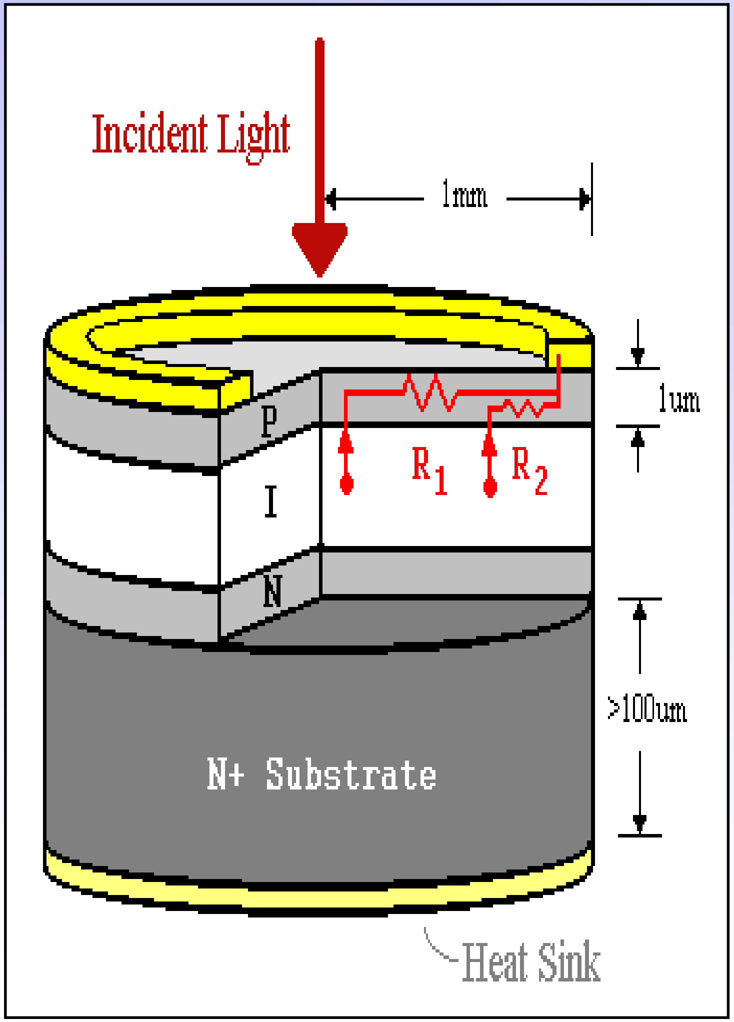
InGaAs vs. GaInNAs PD Designs



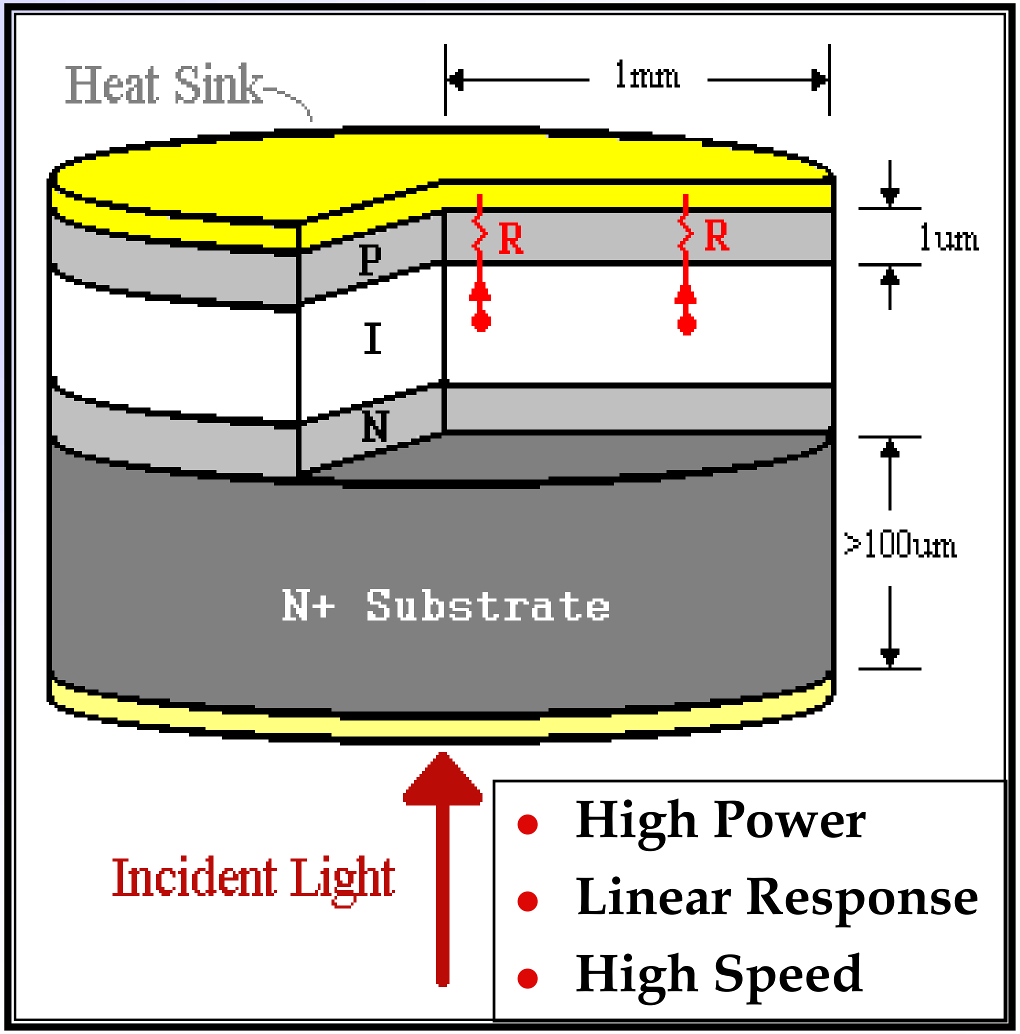


GaInNAs lattice-matched to GaAs!

Rear-Illuminated PD Advantages



Conventional PD



- High Power
- Linear Response
- High Speed

Adv. LIGO Rear-Illuminated PD

Development Flow-Chart

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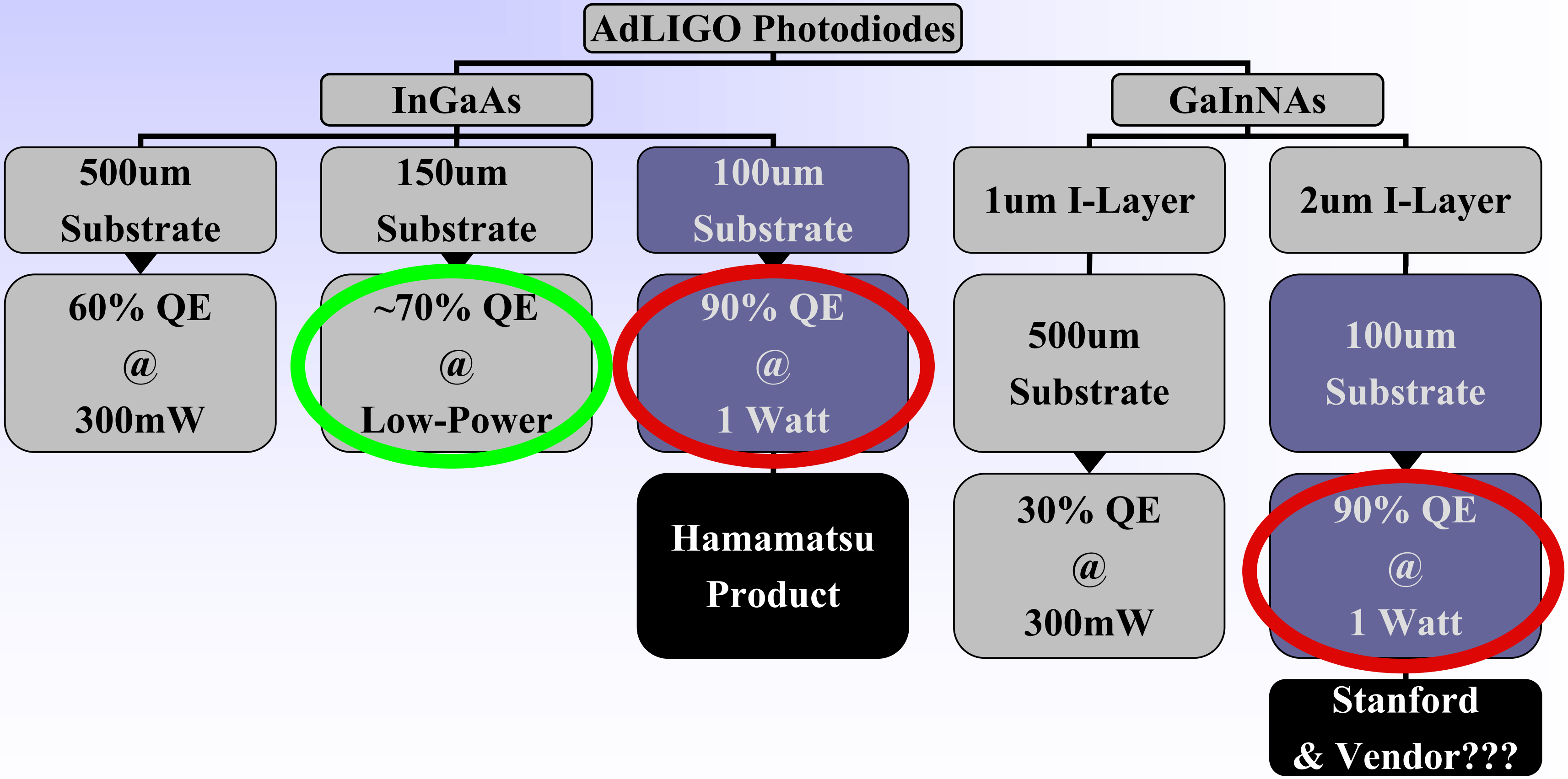


AdLIGO Photodiodes

InGaAs

500um Substrate

60% QE @ 300mW

150um Substrate

~70% QE @ Low-Power

100um Substrate

90% QE @ 1 Watt

Hamamatsu Product

GaInNAs

1um I-Layer

500um Substrate

30% QE @ 300mW

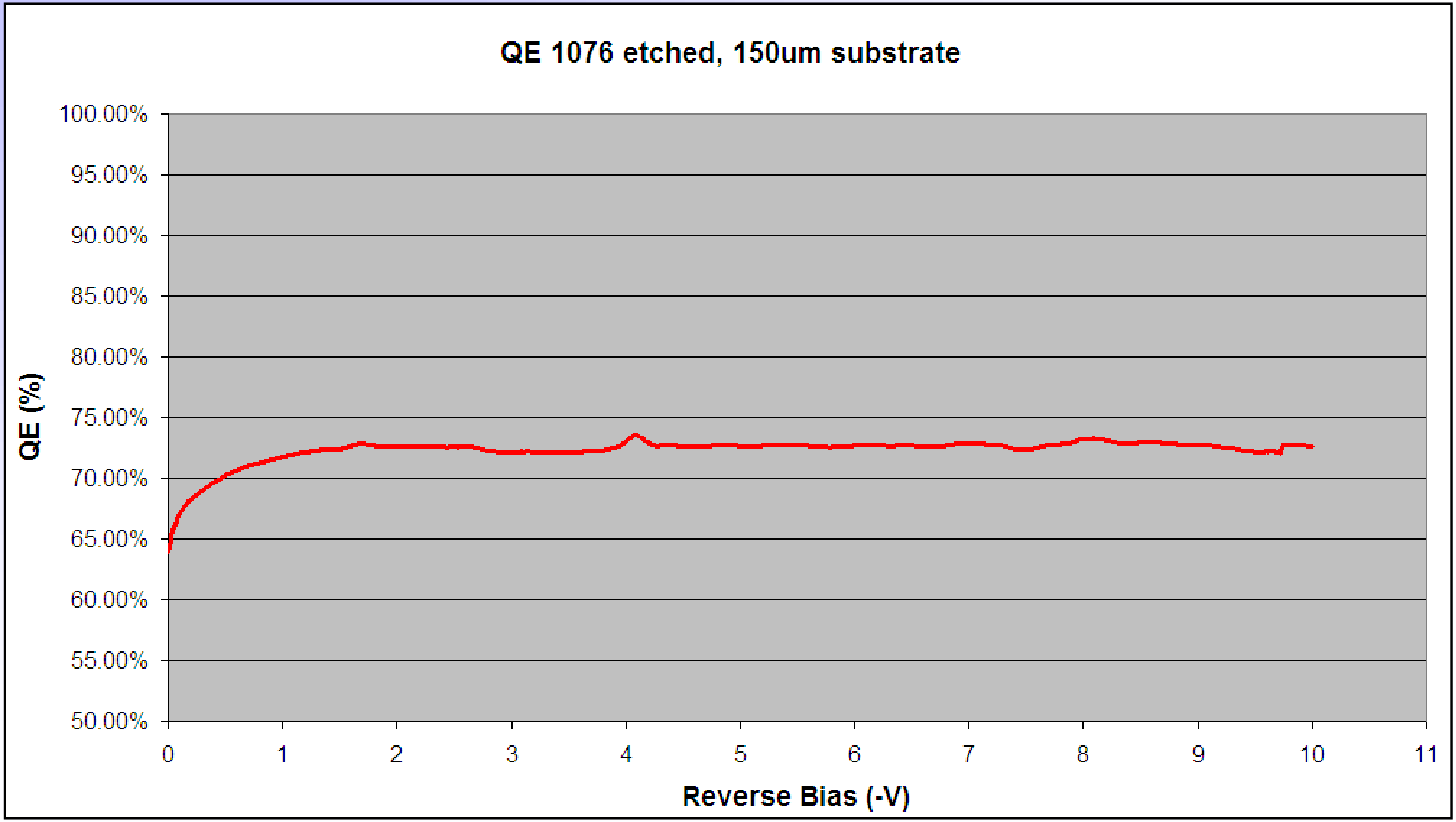
2um I-Layer

100um Substrate

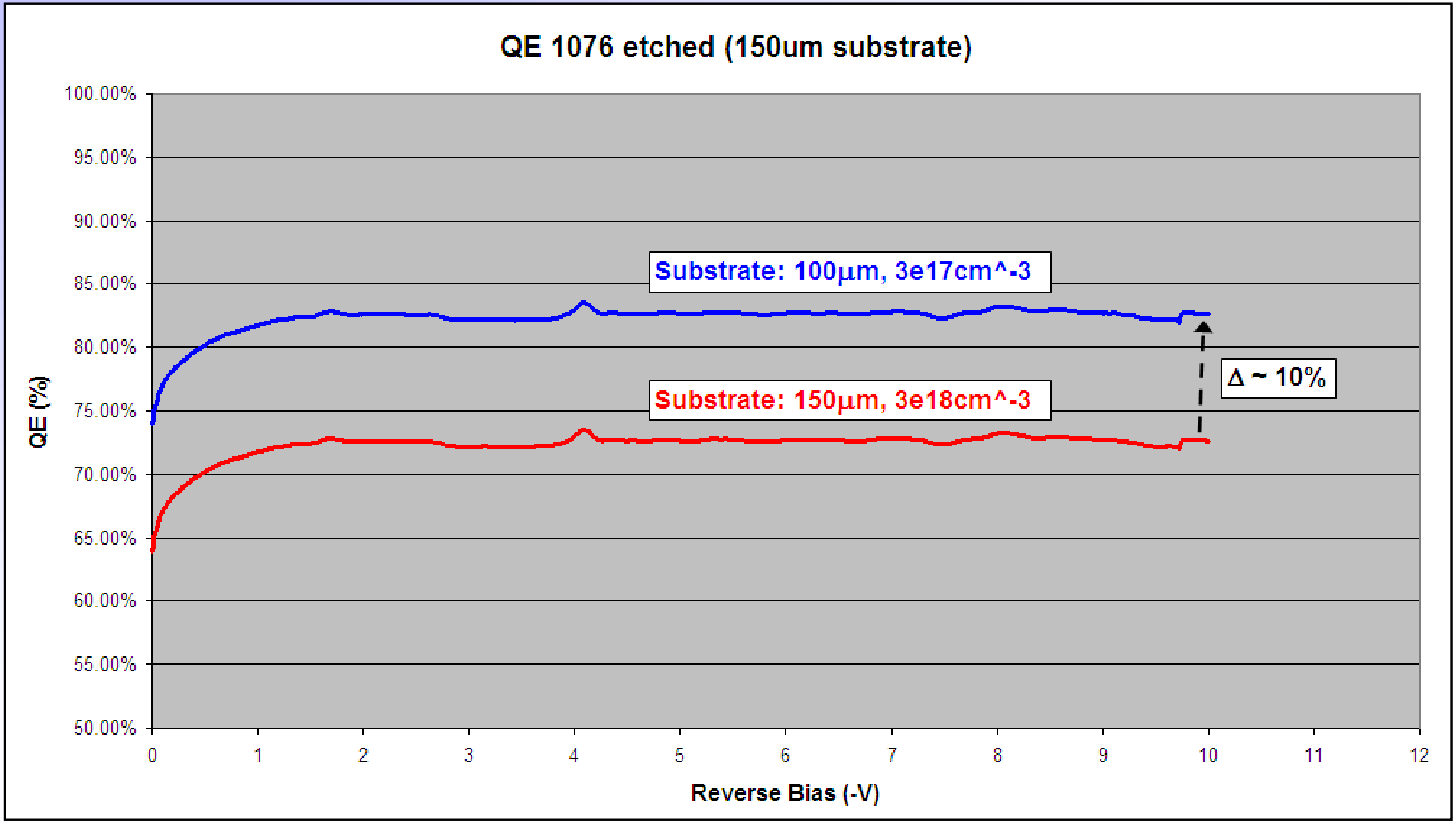
90% QE @ 1 Watt

Stanford & Vendor???

Thinned Device QE (10mW)



Thinned Device QE (w/ 100μm, 3e17cm^{-3} Substrate)



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DC Device Efficiency (w/ ARC)

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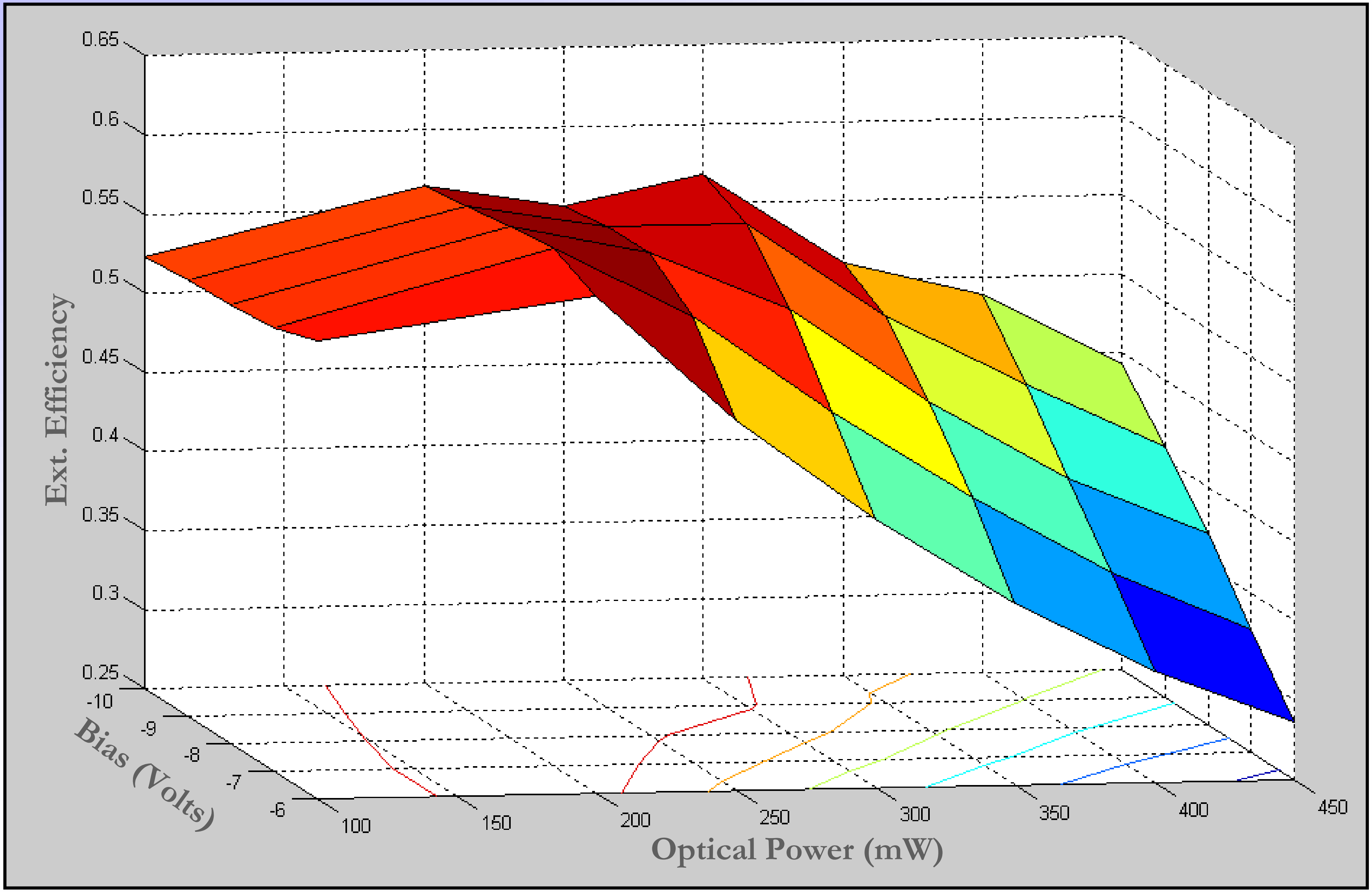
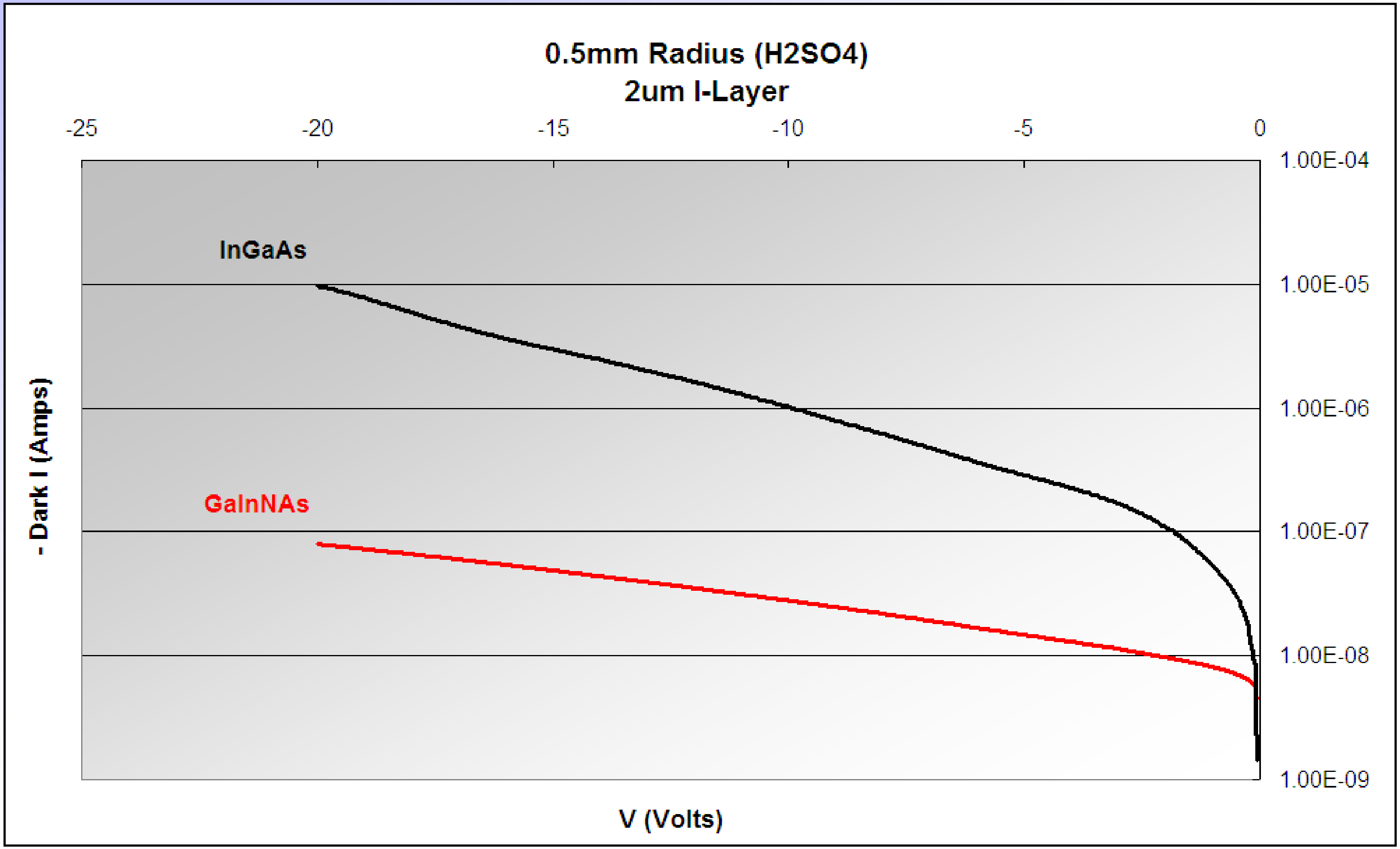
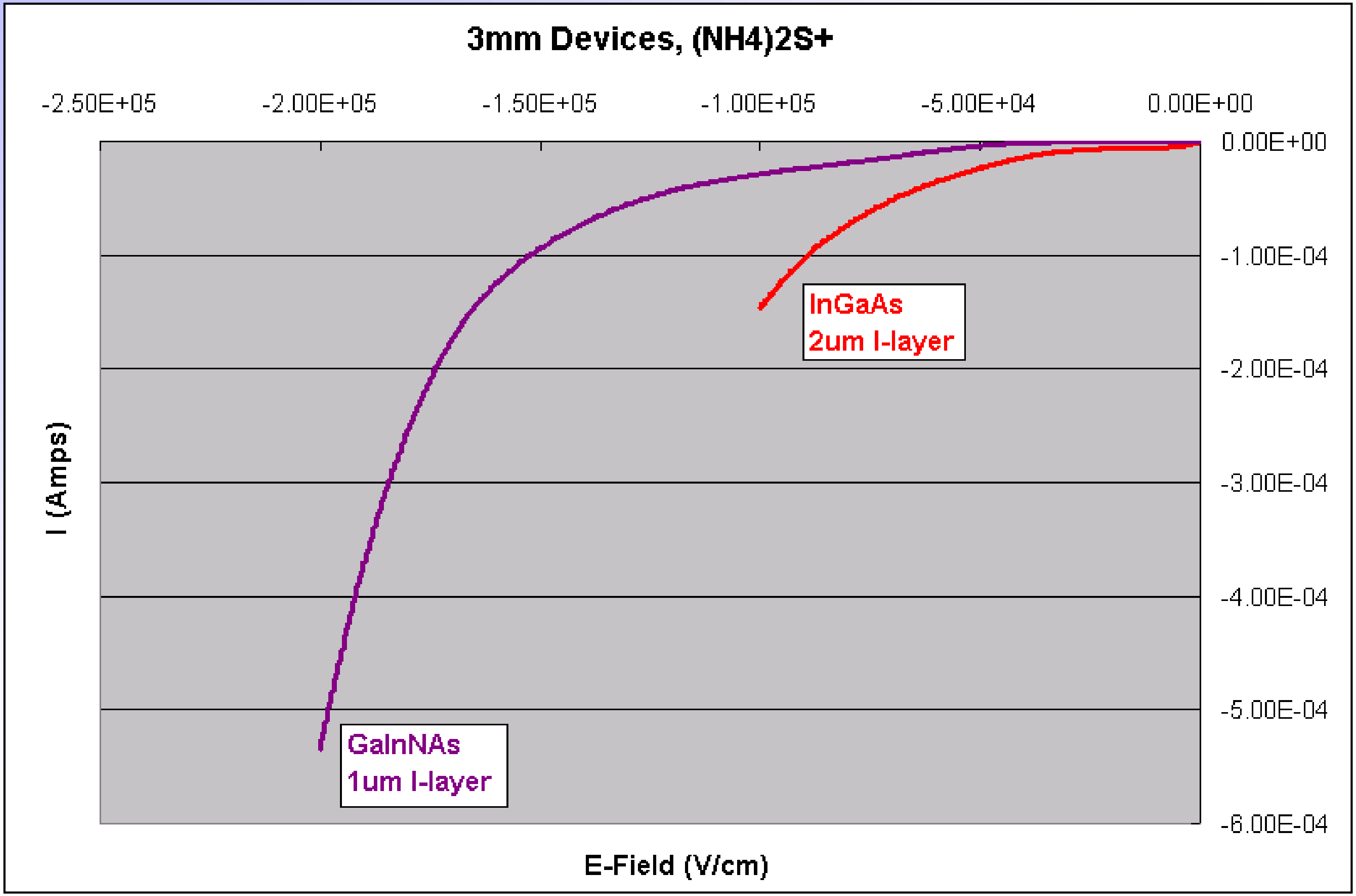


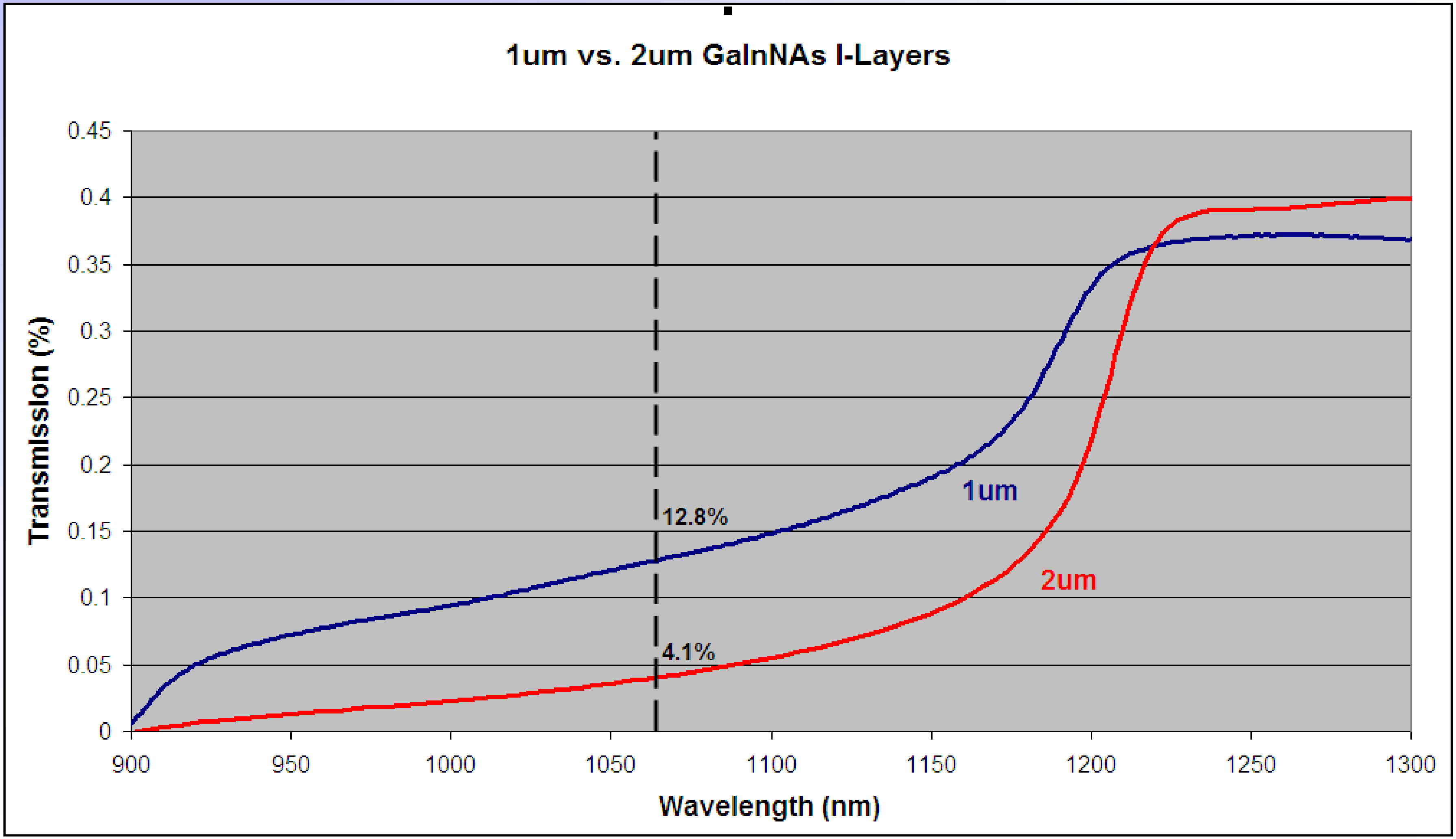
InGaAs vs. GaInNAs Dark Current



InGaAs vs. GaInNAs Dark Current



GaInNAs Device Transmission



Predictions (I think we can do it…)

Detector	Power Stabilization	RF Detection	GW Channel
Diameter	4.5mm	1.5mm	1mm
Bias	-25V	-25V	-25V
Steady-State Power	1130mW	110mW	50mW
3-dB 1/RC Bandwidth	3MHz	30MHz (→ 180MHz)	60MHz
Quantum Efficiency	~ 90%	~ 90%	~ 90%

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Laser Interferometer Gravitational Wave Observatory (LIGO)

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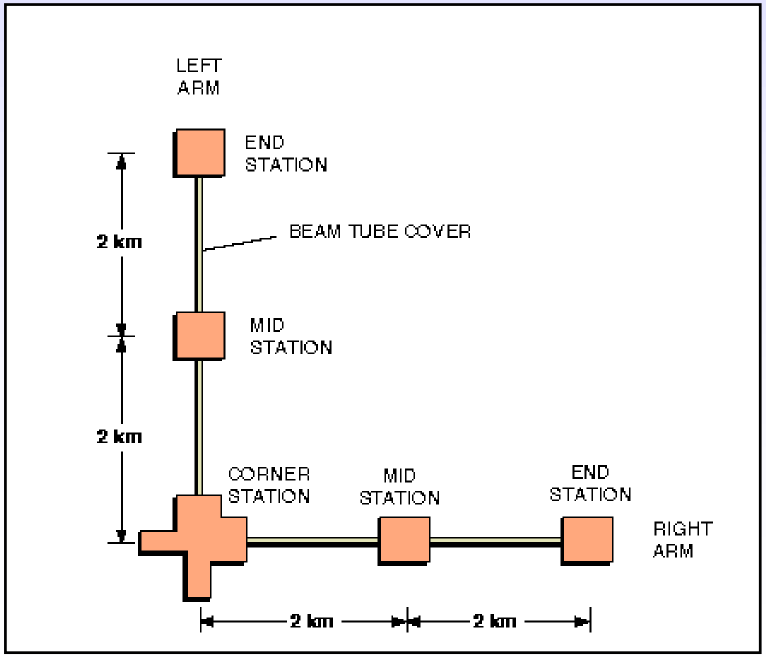
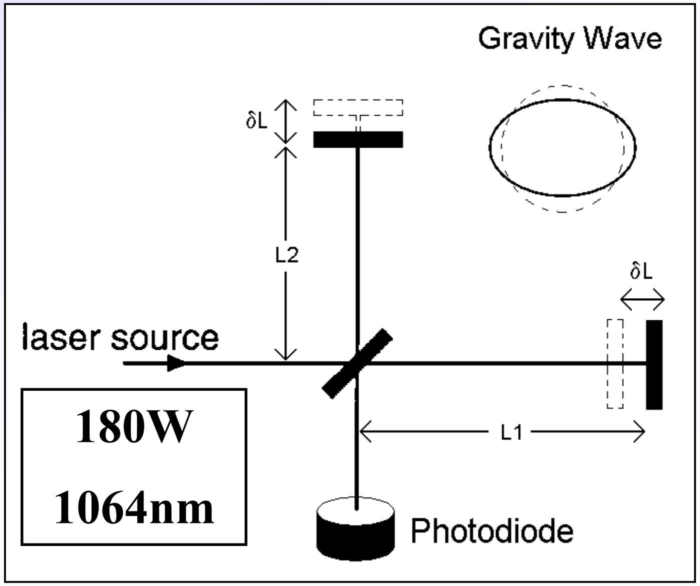
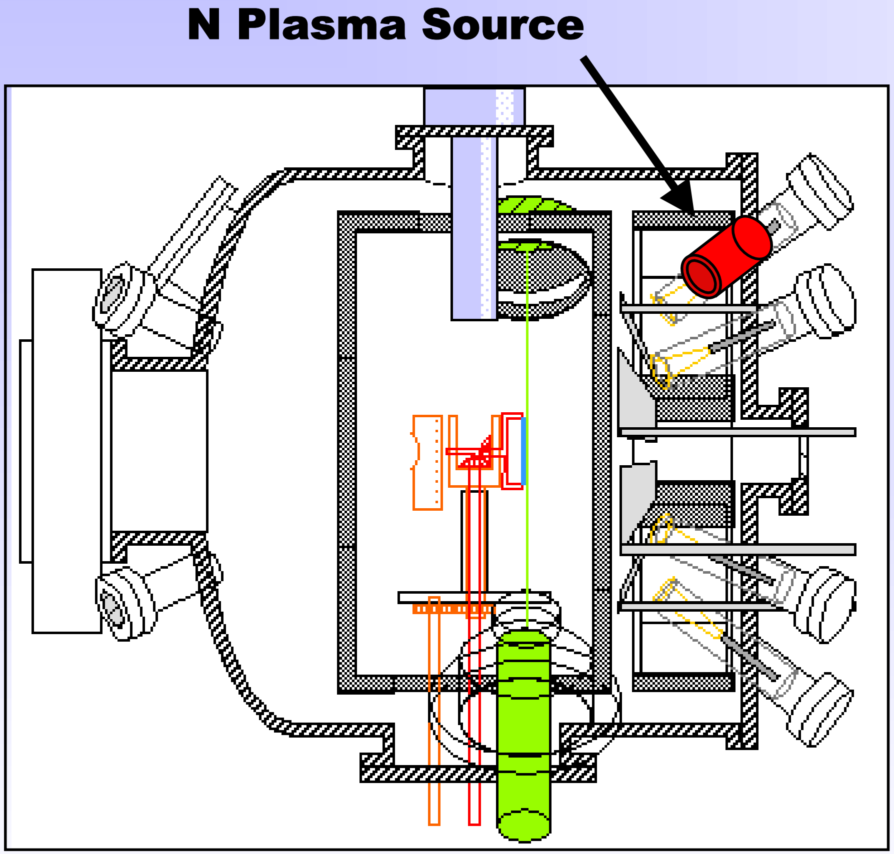
Arm Length	4km
Beam Tube Diameter	4 ft.
Vacuum Pressure	**~10^{-10} atm**
Differential Strain	**~10^{-18} m**





MBE Crystal Growth



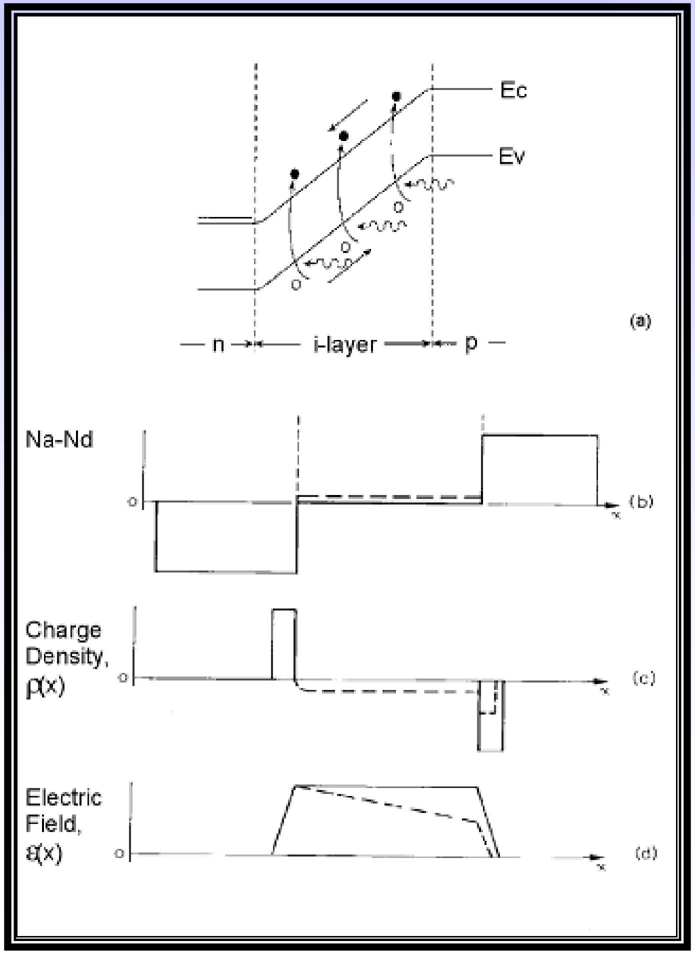
- Effusion cells for In, Ga, Al
- Cracking cell for As
- Abrupt interfaces
- Chamber is under UHV conditions to avoid incorporating contaminants
- RHEED can be used to analyze crystal growth *in situ* due to UHV environment
- T=450-600°C

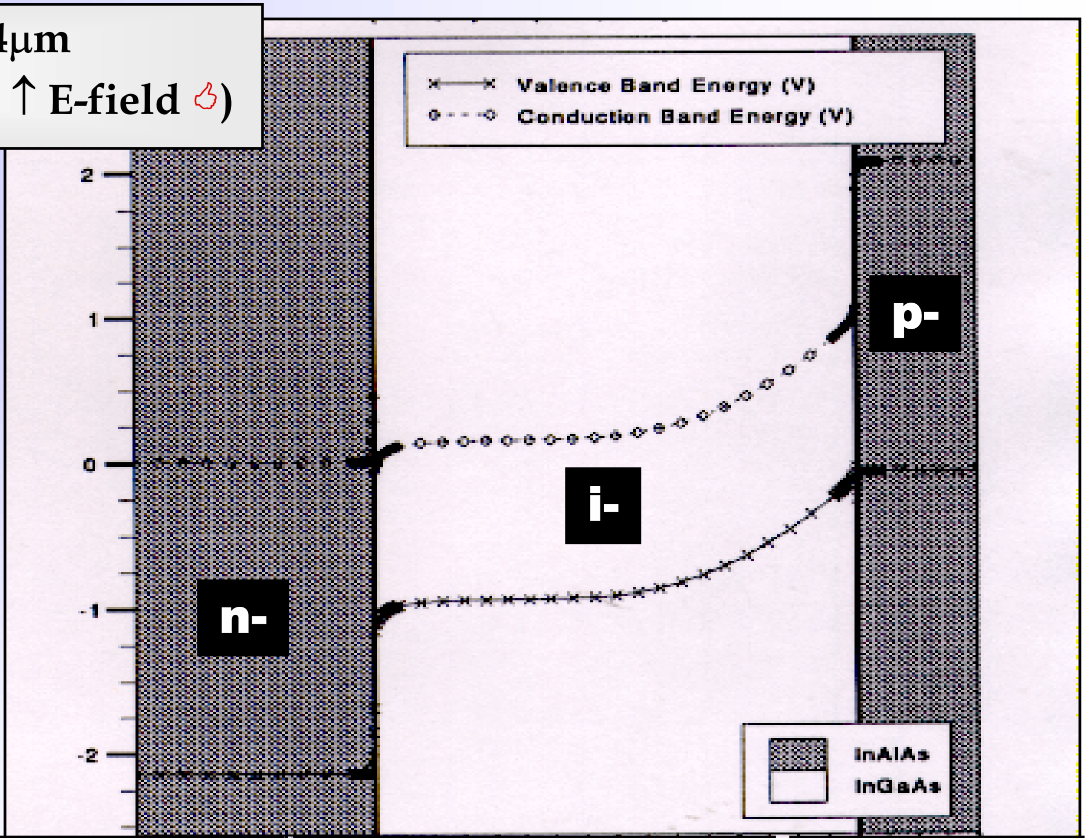
Atomic source of nitrogen needed

→ Plasma Source!

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 $Ga_{.88}In_{.12}N_{.01}As_{.99}$

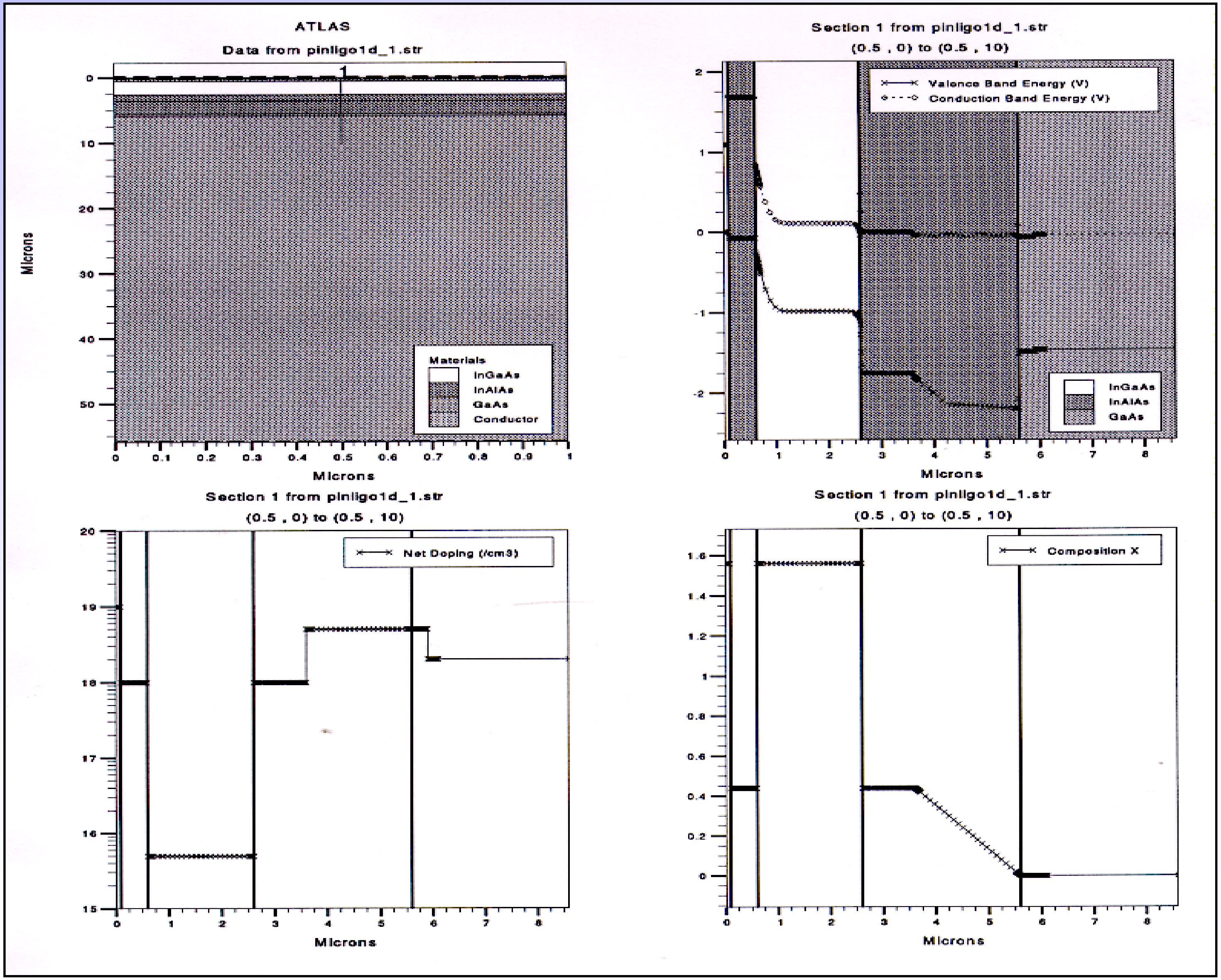
$E_{g1}=1.1$eV

P-layer:

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

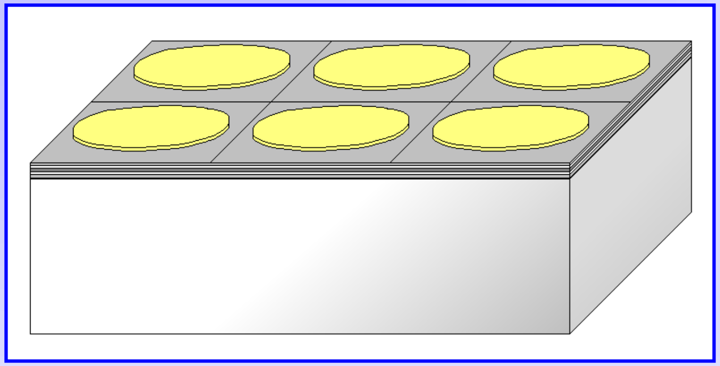
$E_{g2}=2.0$–1.4eV

Full Structure Simulated by ATLAS

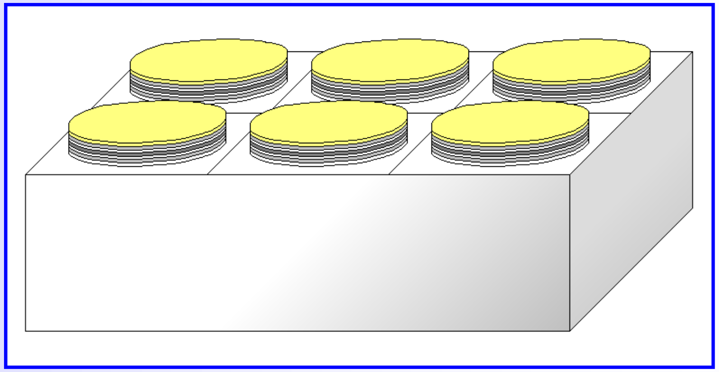


High Efficiency Detector Process (1)

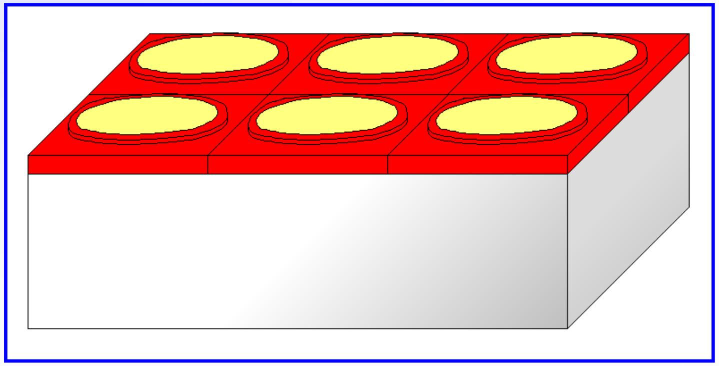
1. Deposit and Pattern P-Contact



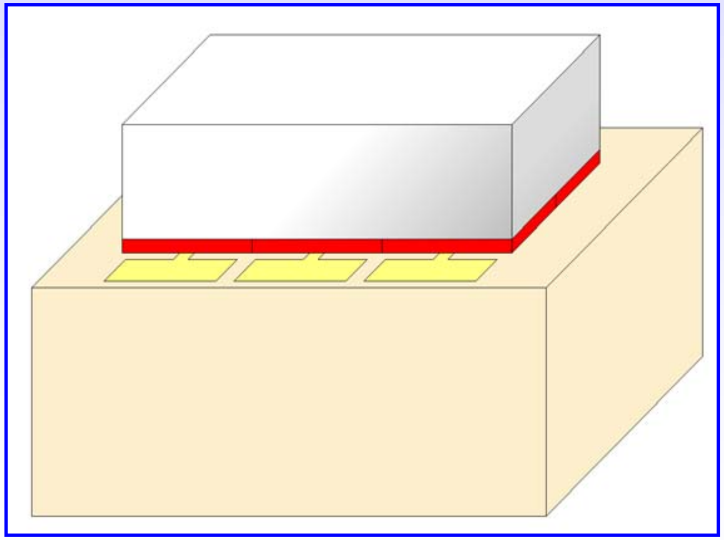
2. Etch Mesa – H_2SO_4:H_2O_2:H_20 and Passivate in $(NH_4)_2S$+



3. Encapsulate Exposed Junction



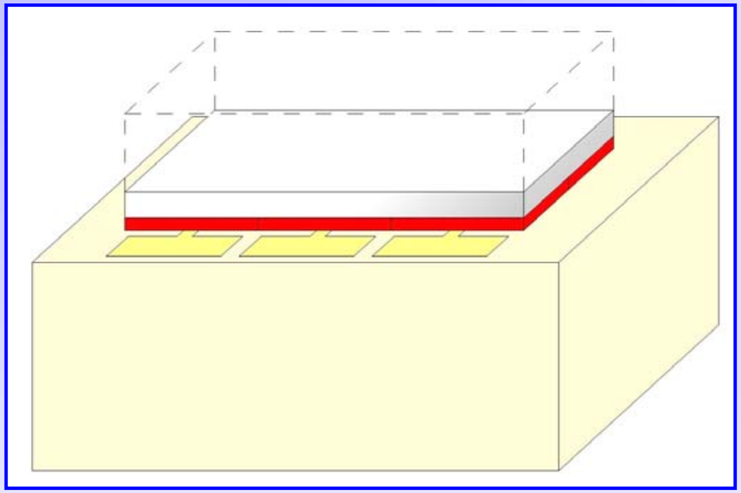
4. Flip-Chip Bond



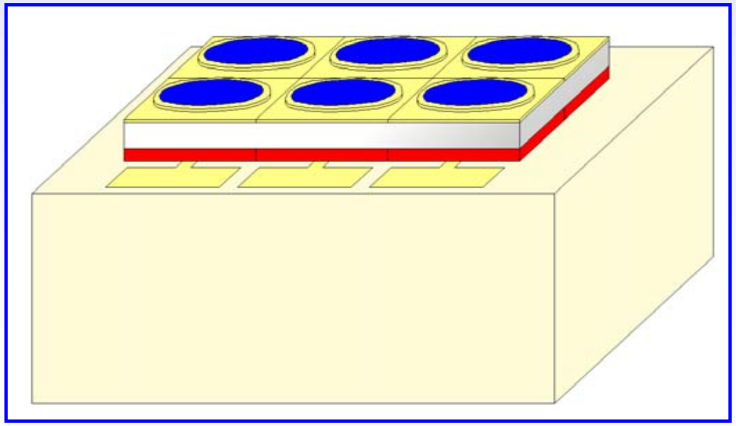
□ - N+ GaAs Substrate
▤ - Epitaxial Layers
🟨 - Au Contacts
🟥 - Polyimide Insulator
🟦 - SiN_x AR Coating
▨ - AlN Ceramic

High Efficiency Detector Process (2)

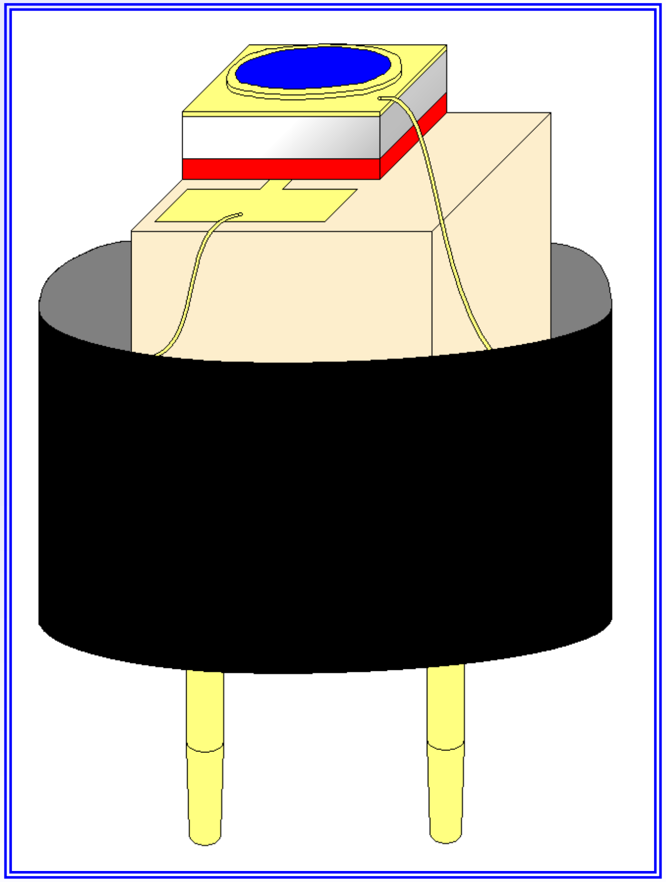
5. Thin N+ GaAs Substrate



6. Deposit AR Coating & N-Contact



7. Saw, Package and Wire-Bond



⬜ - N+ GaAs Substrate
▤ - Epitaxial Layers
🟨 - Au Contacts
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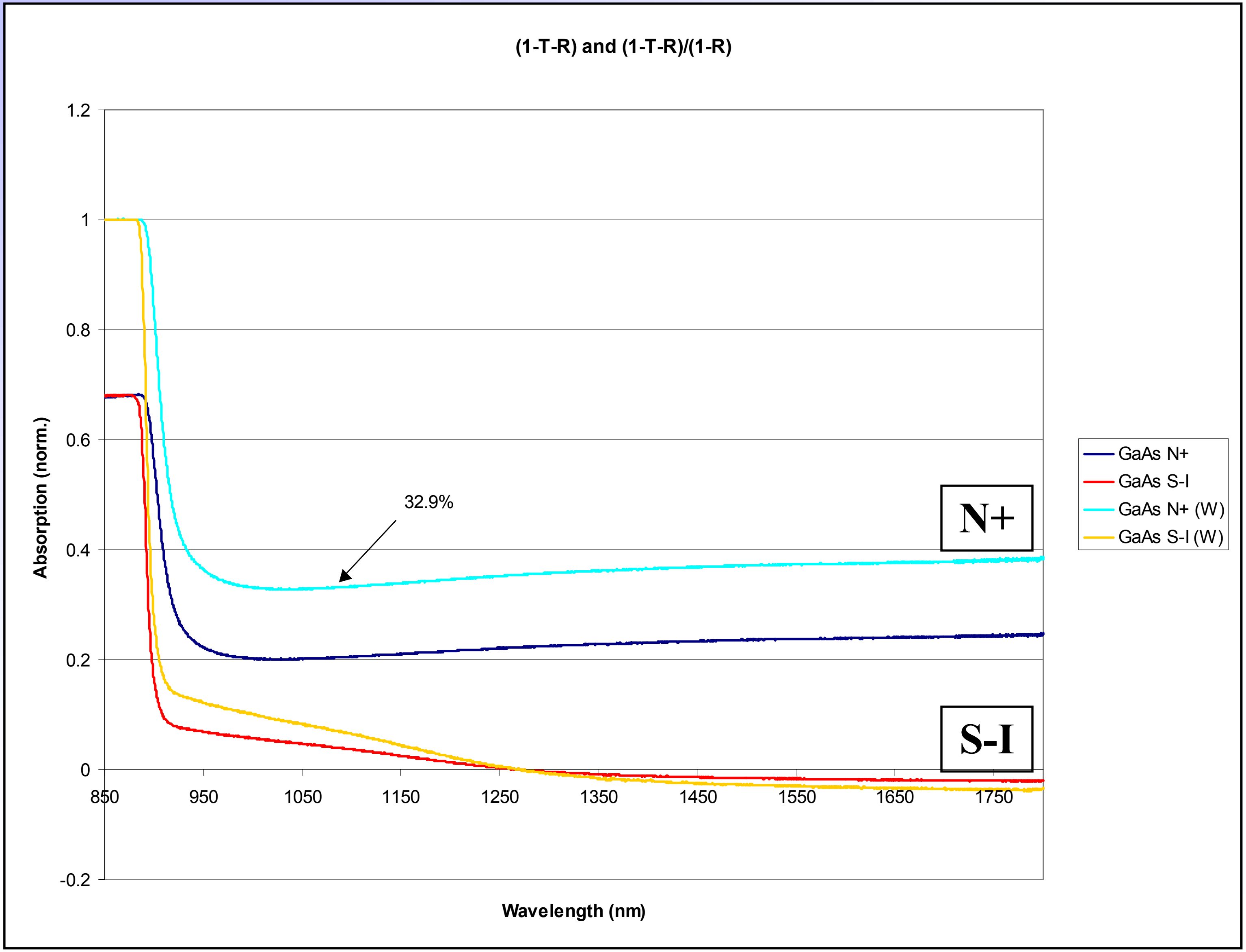
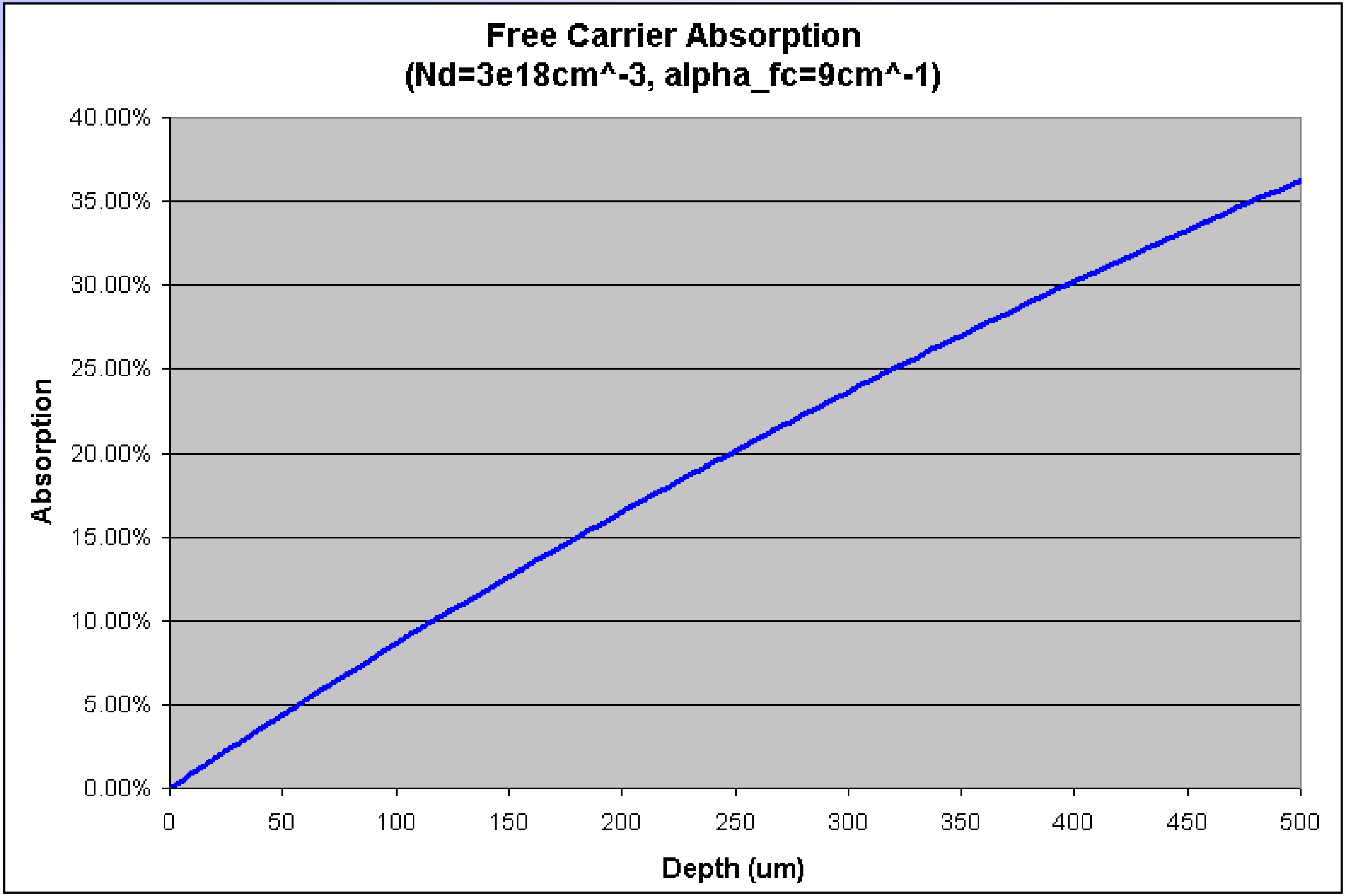
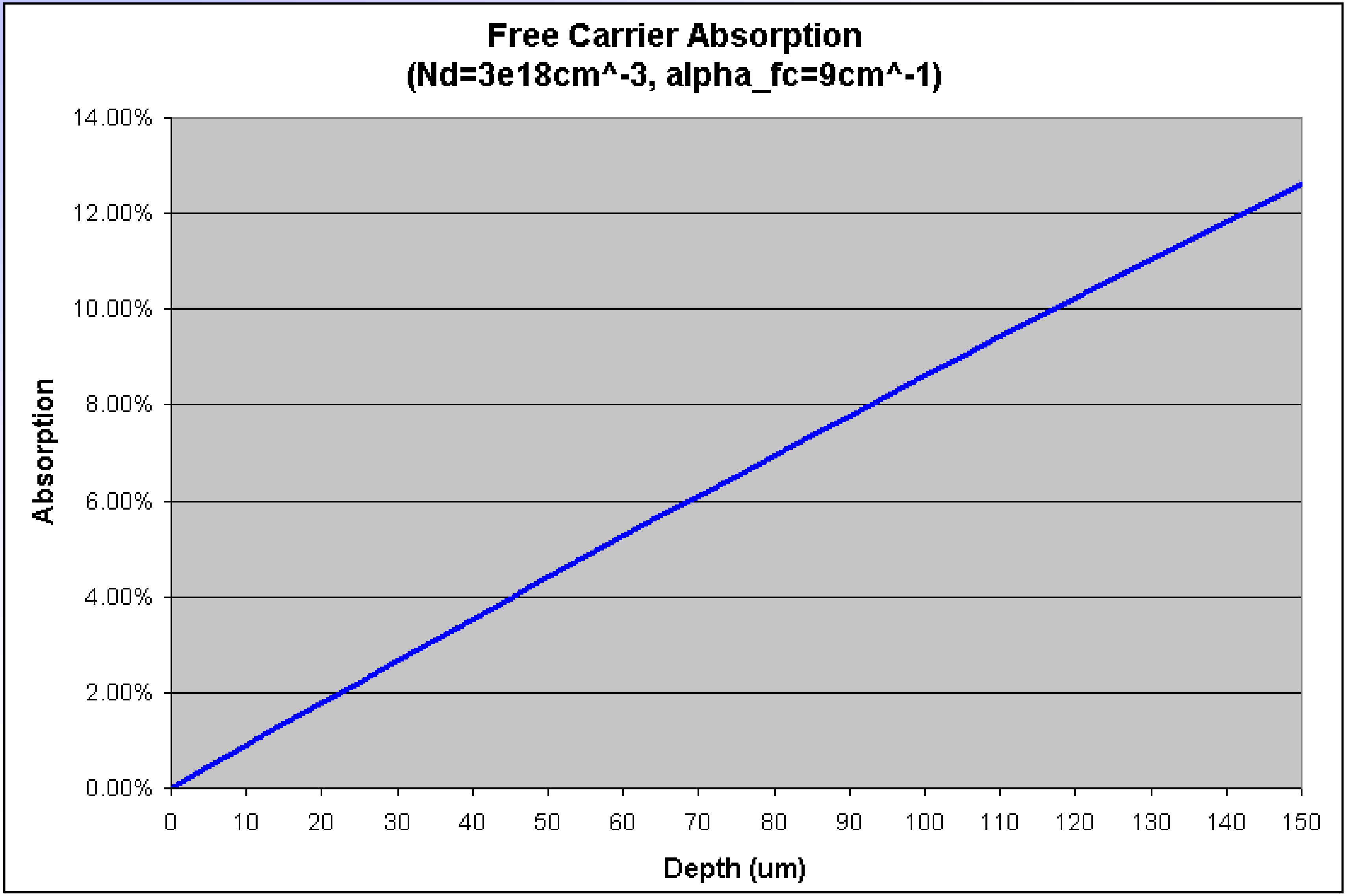
Free-Carrier Absorption



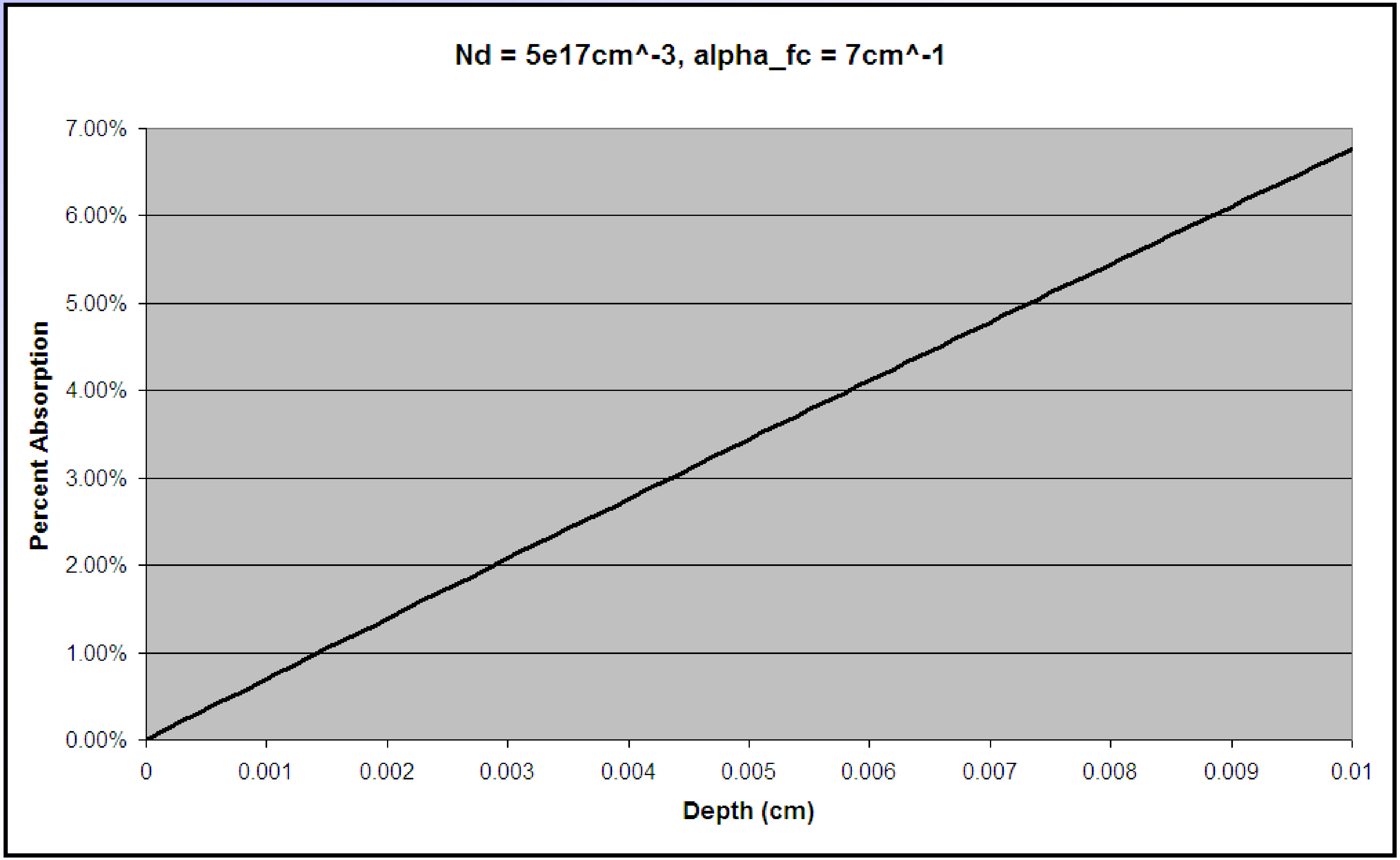
Free-Carrier Absorption



Free-Carrier Absorption



Free-Carrier Absorption 5e17cm^-3



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Thinned Device QE (w/ ARC)

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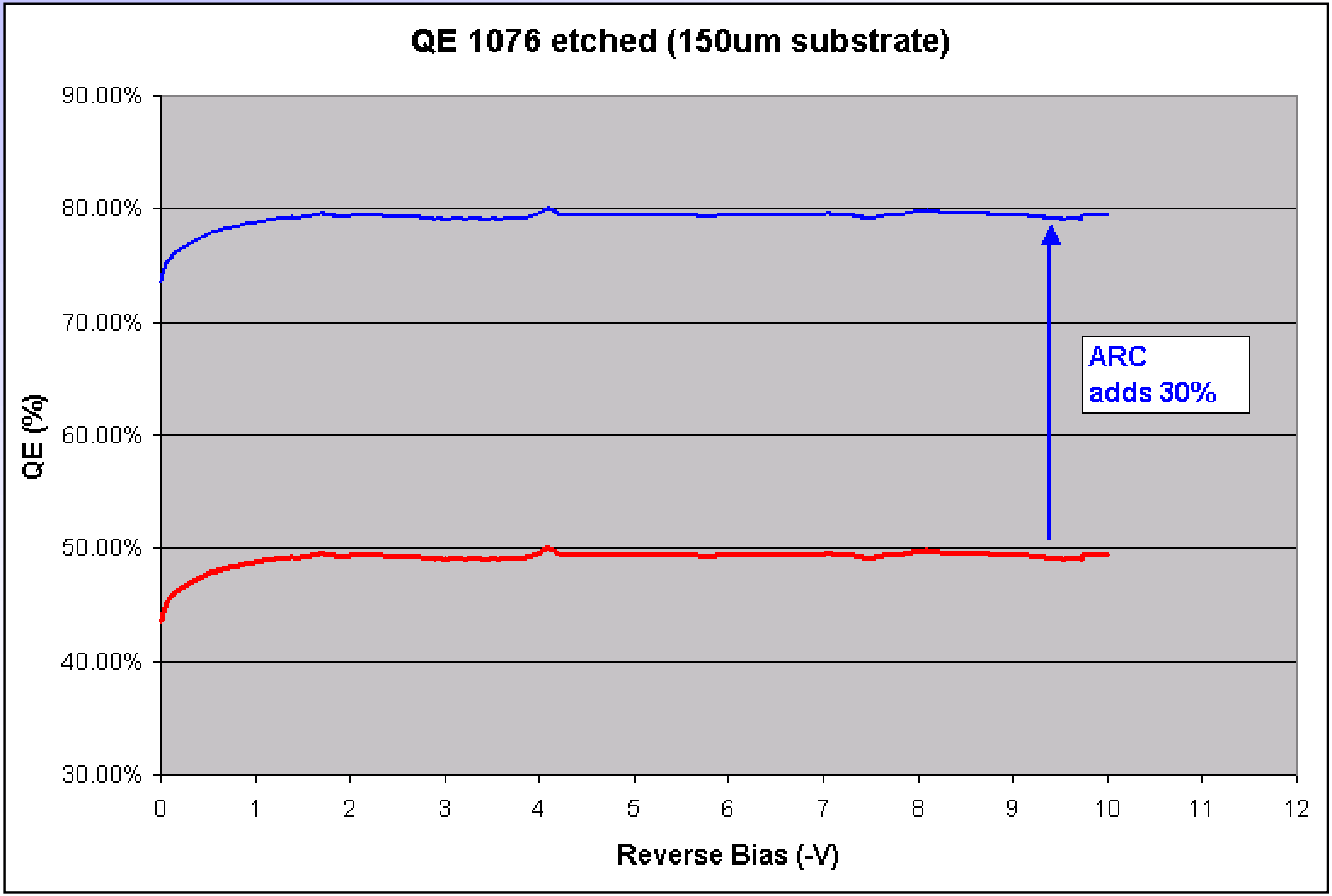

ARC adds 30%

Photodiode Specifications

	LIGO I		Advanced LIGO	
Detector	**Bank of 6PDs**	**Power Stabilization**	**RF Detection**	**GW Channel**
Steady-State Power	0.6 W	1W/η	10 – 100mW	30mW
Operating Frequency	~29 MHz	100 kHz	200MHz	100 kHz
Quantum Efficiency	> 80%	η	> 80%	> 90%-95%

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Thinned Device Photocurrent

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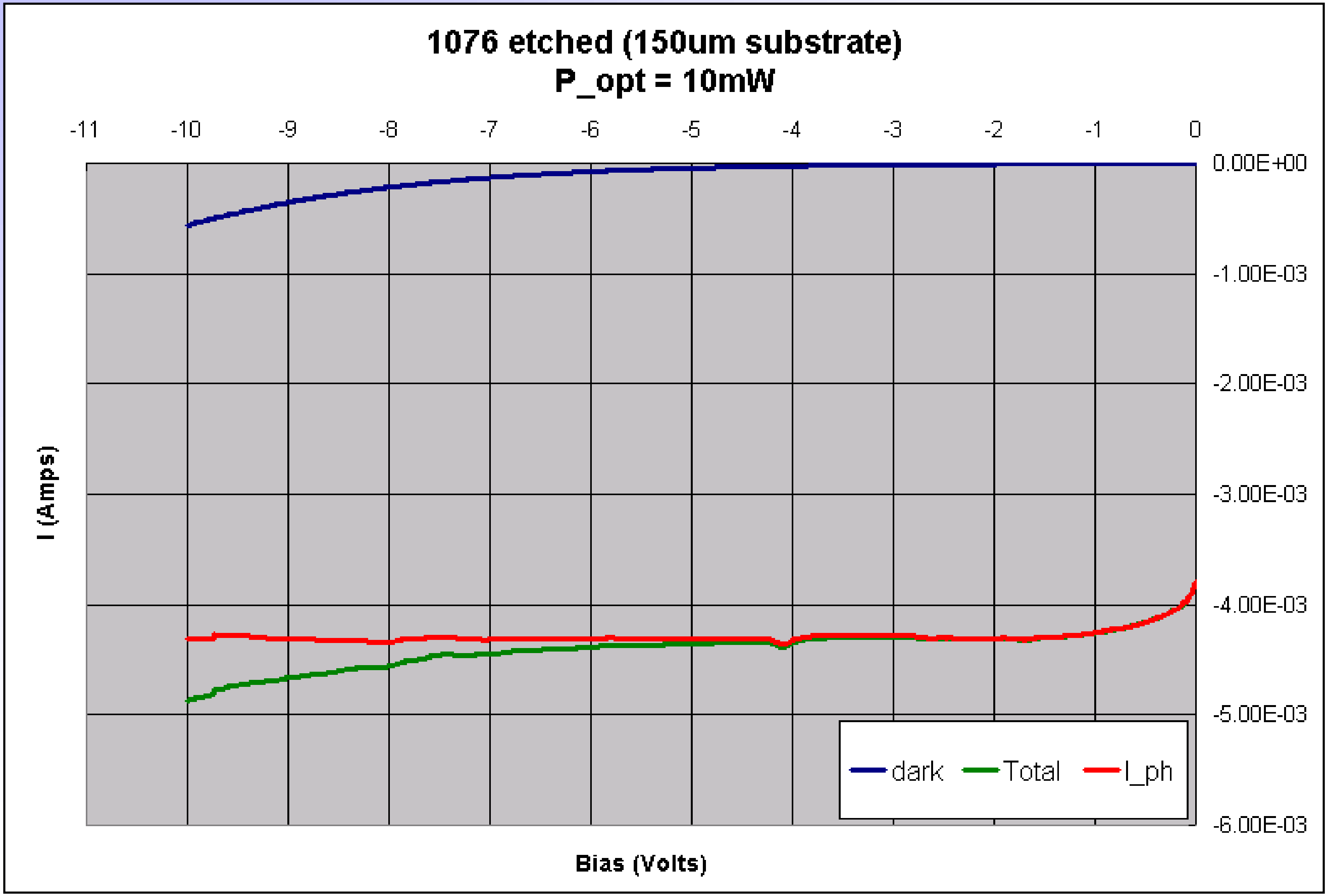

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DC Device Response

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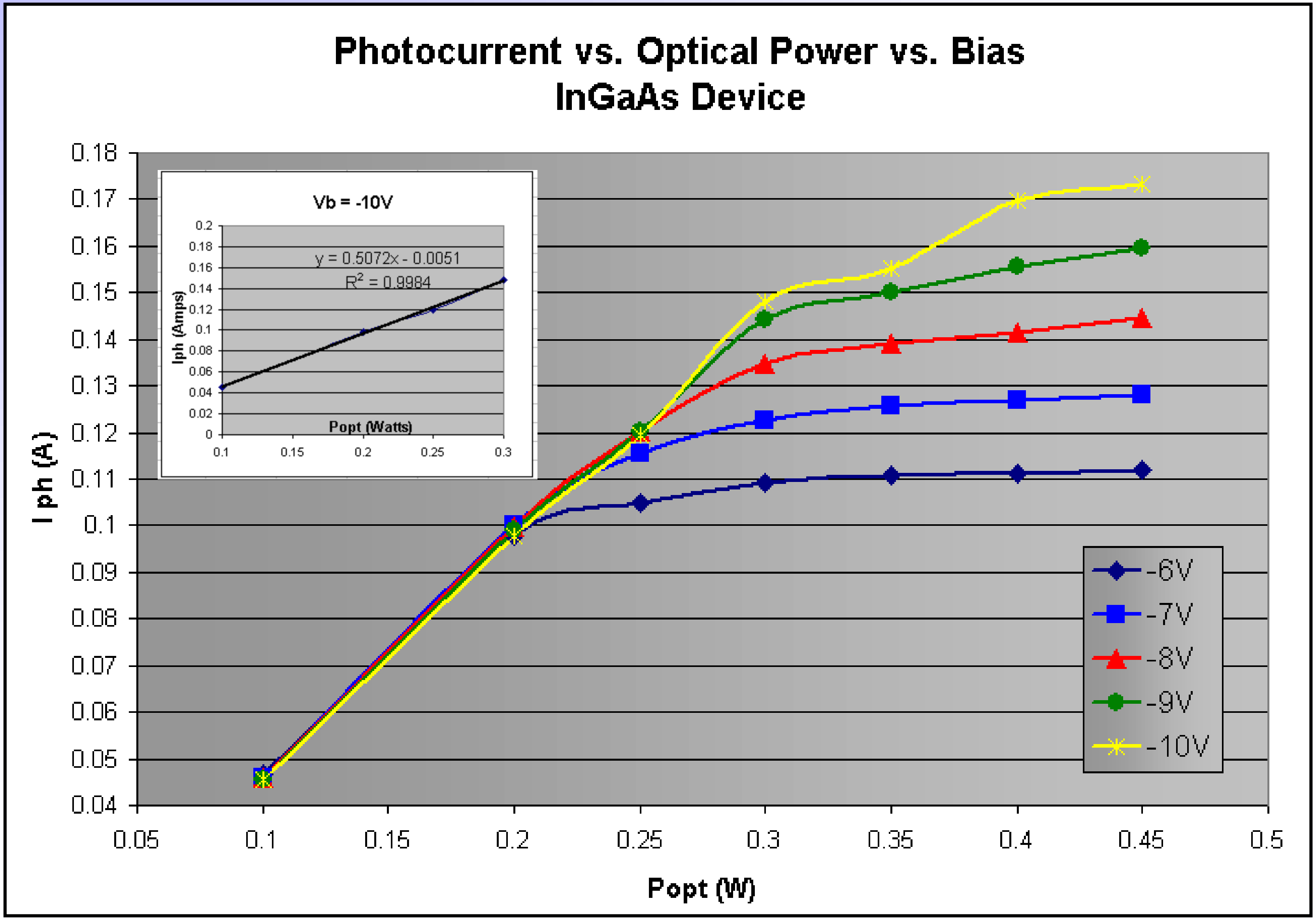

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DC Device Efficiency

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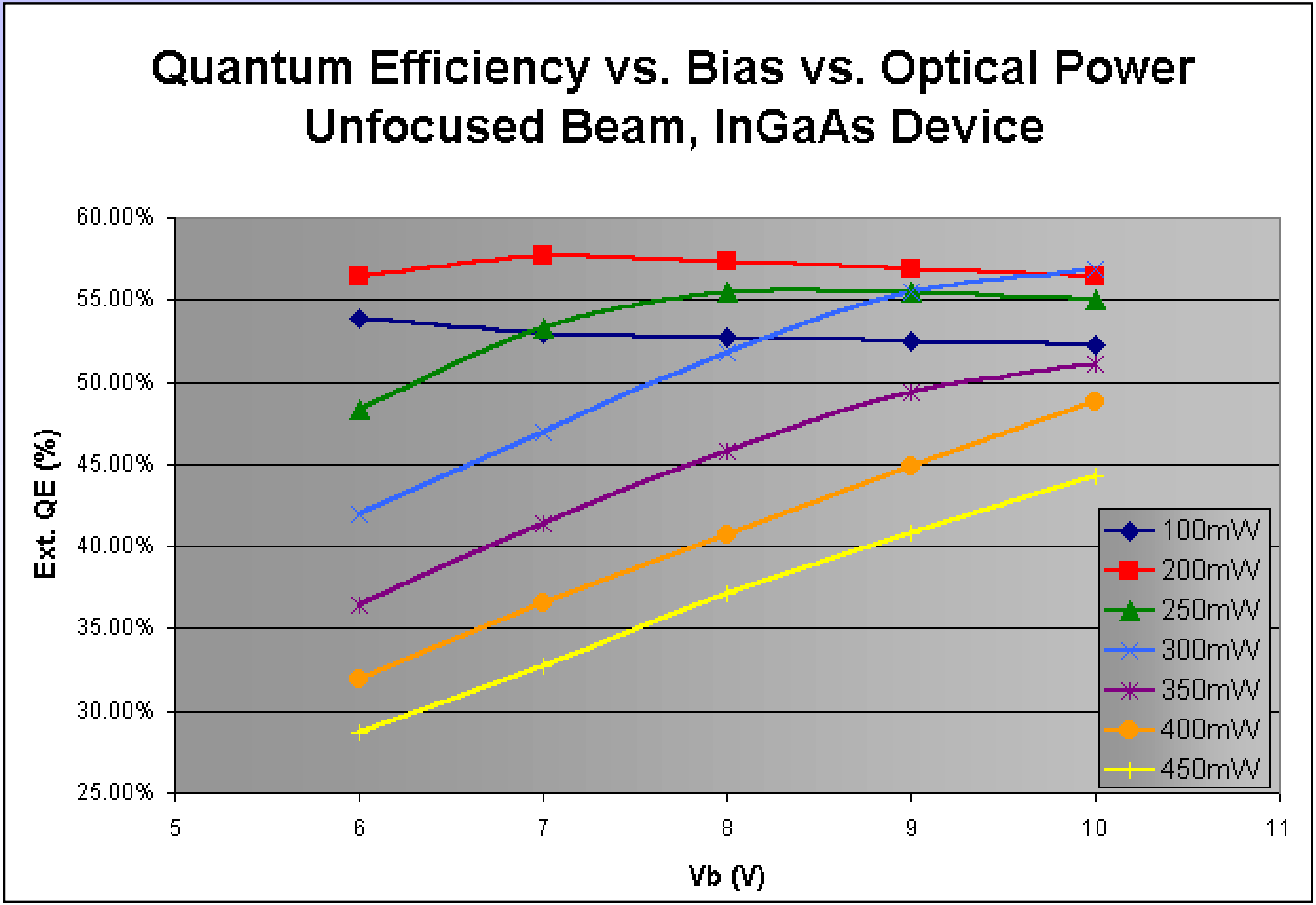
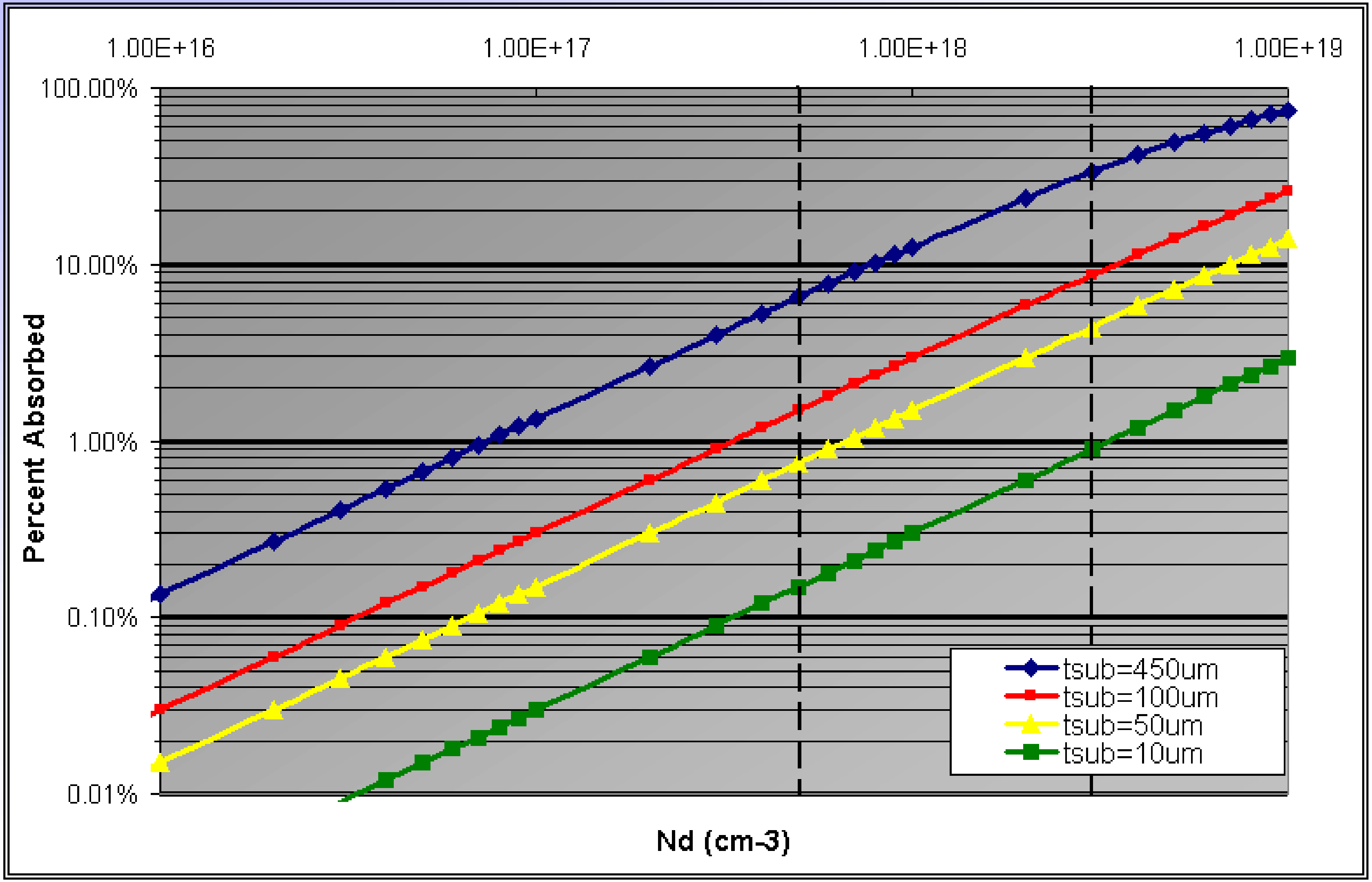


Free-Carrier Absorption



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

Surface Passivation Results (2)

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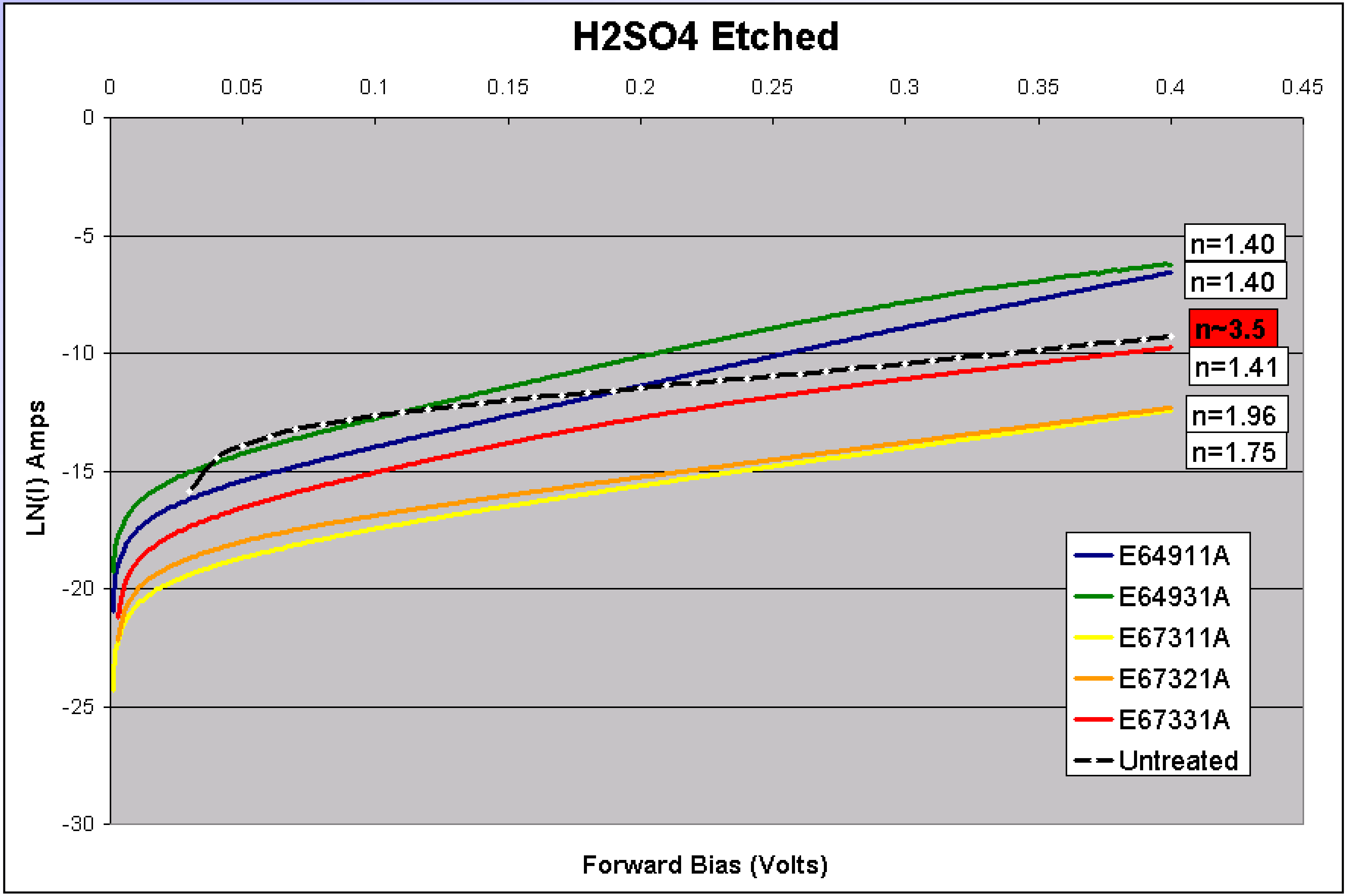
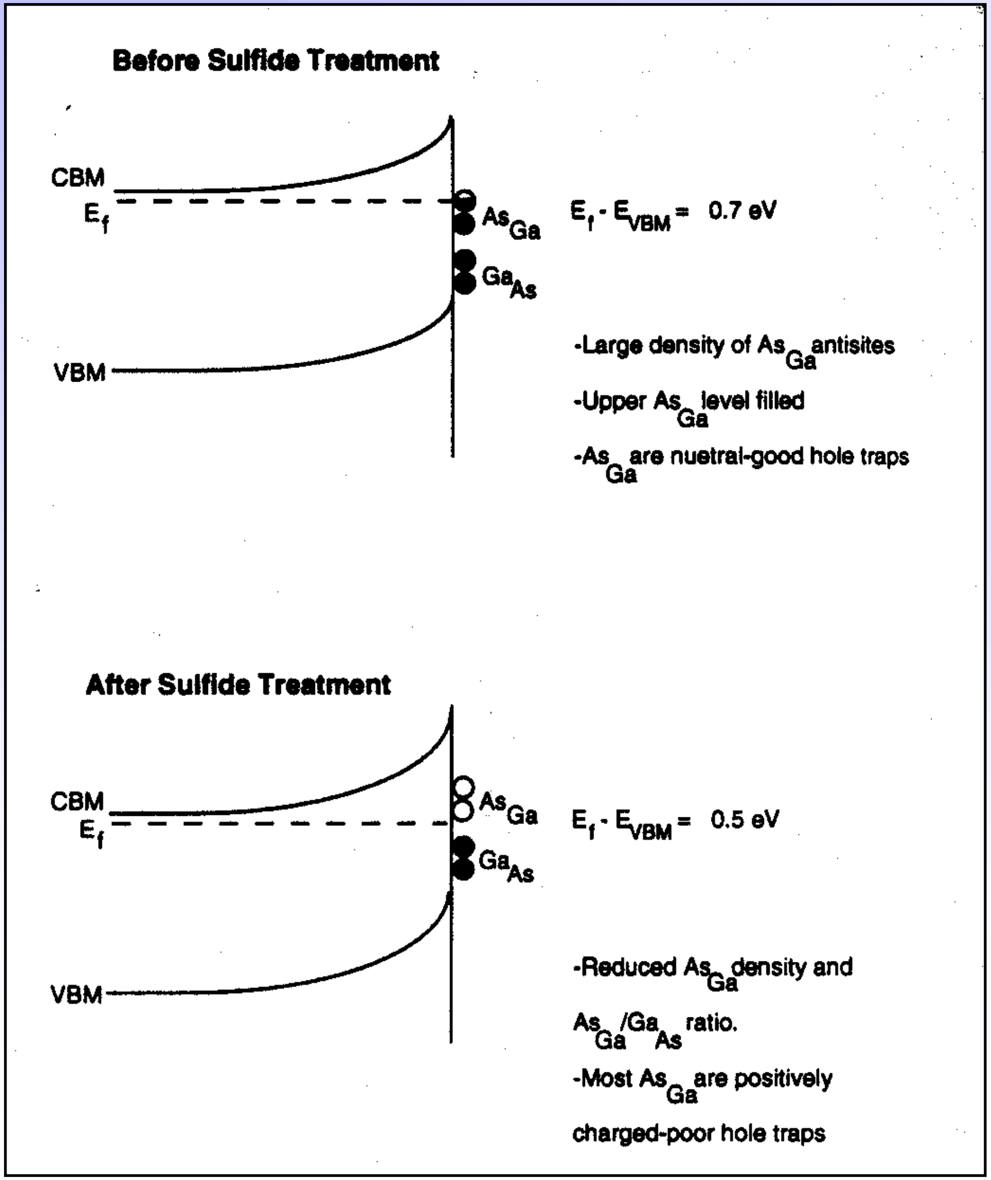


$(NH_4)_2S$+ Surface States



Before Sulfide Treatment

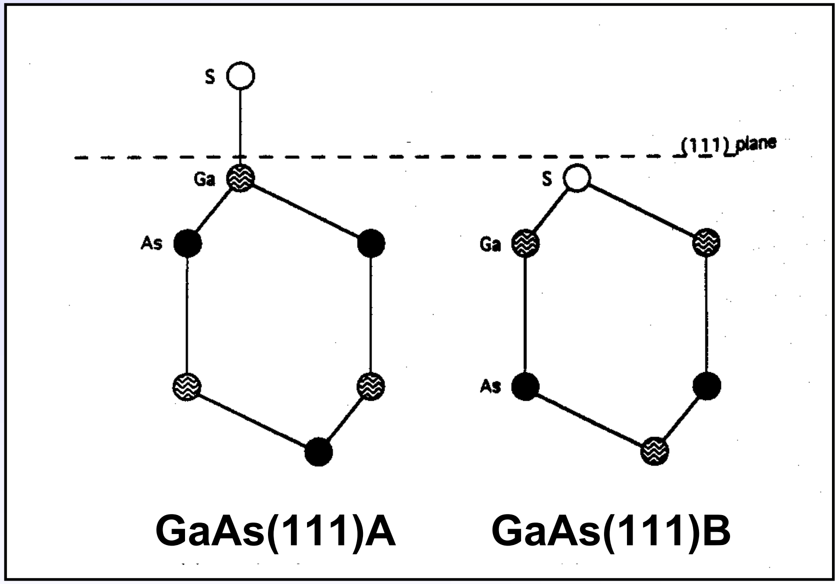
$E_f - E_{VBM} =$ 0.7 eV

- -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



GaAs(111)A GaAs(111)B

(Green and Spicer, 1993)

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Surface Passivation Results

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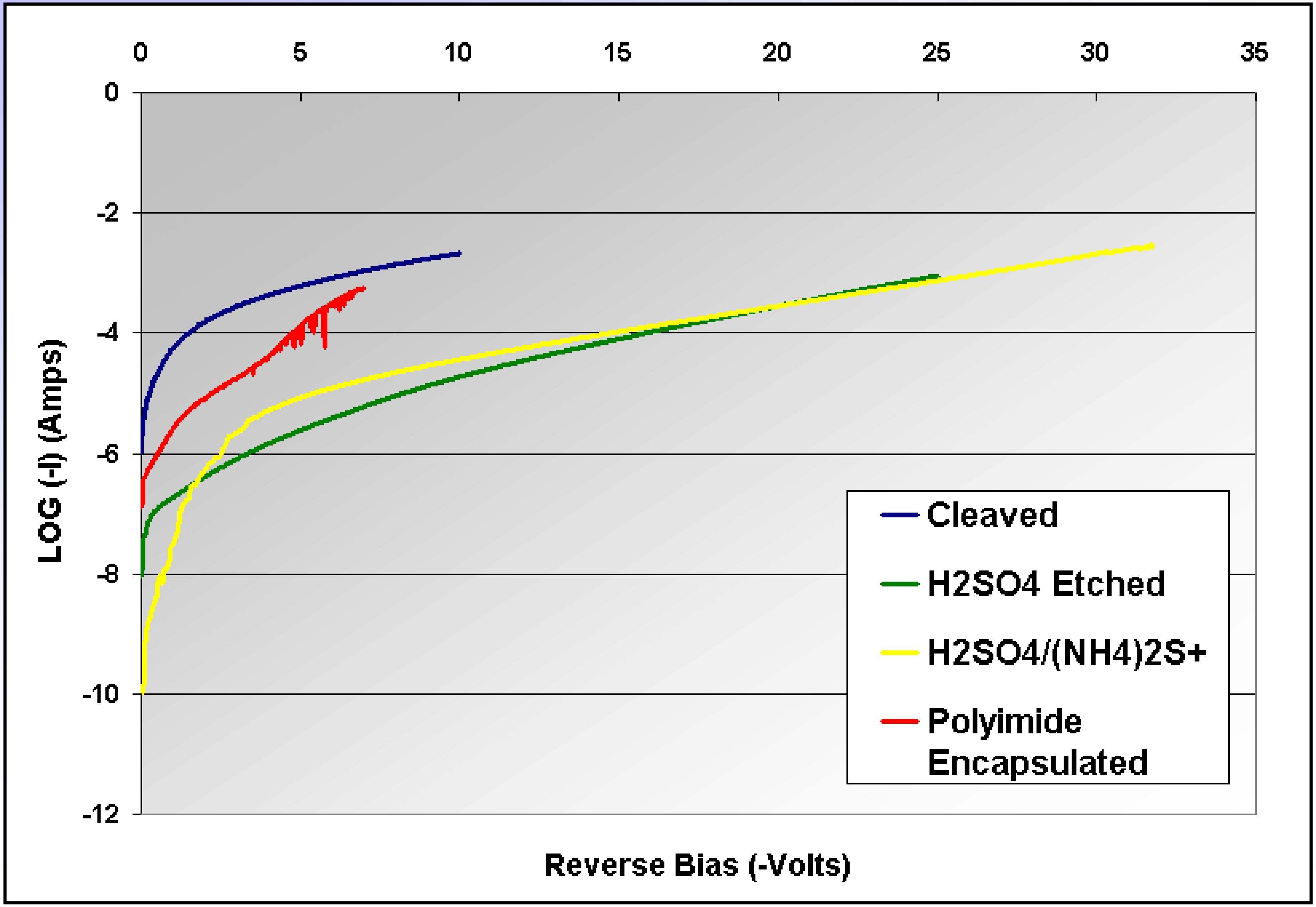

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Large InGaAs Devices, –20V Bias

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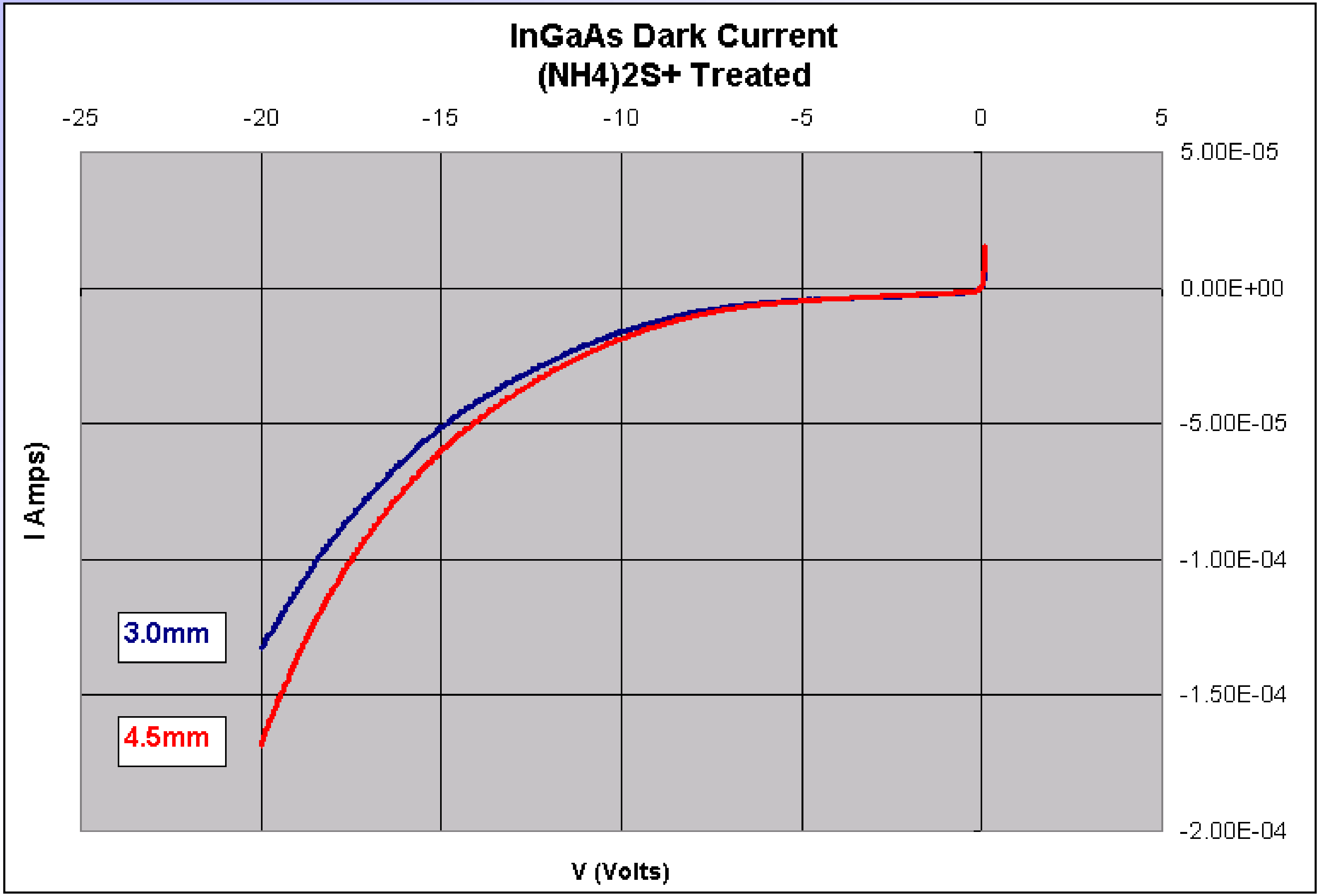
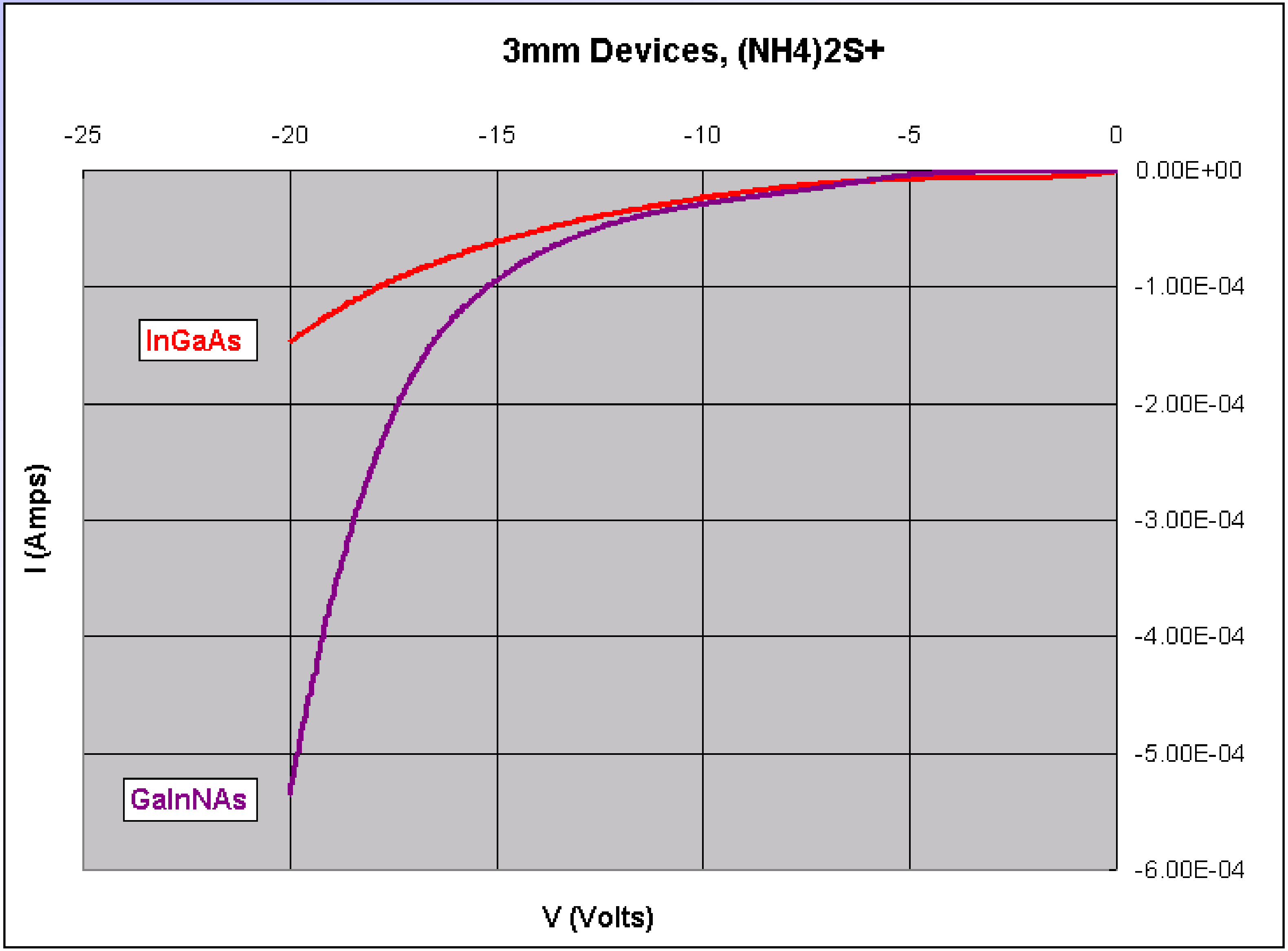


InGaAs vs. GaInNAs Dark Current



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GaInNAs Dark Current

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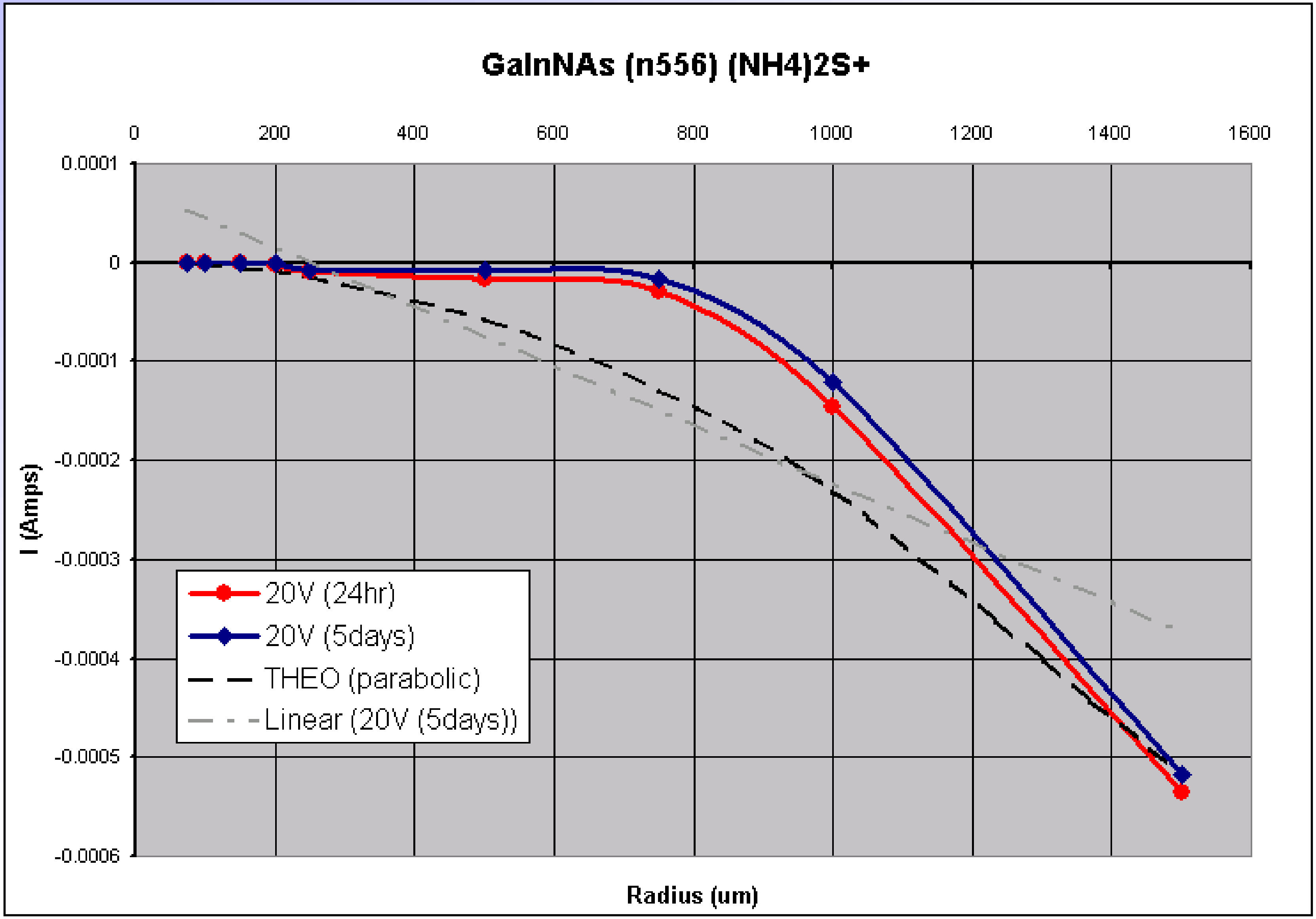

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InGaAs Dark Current

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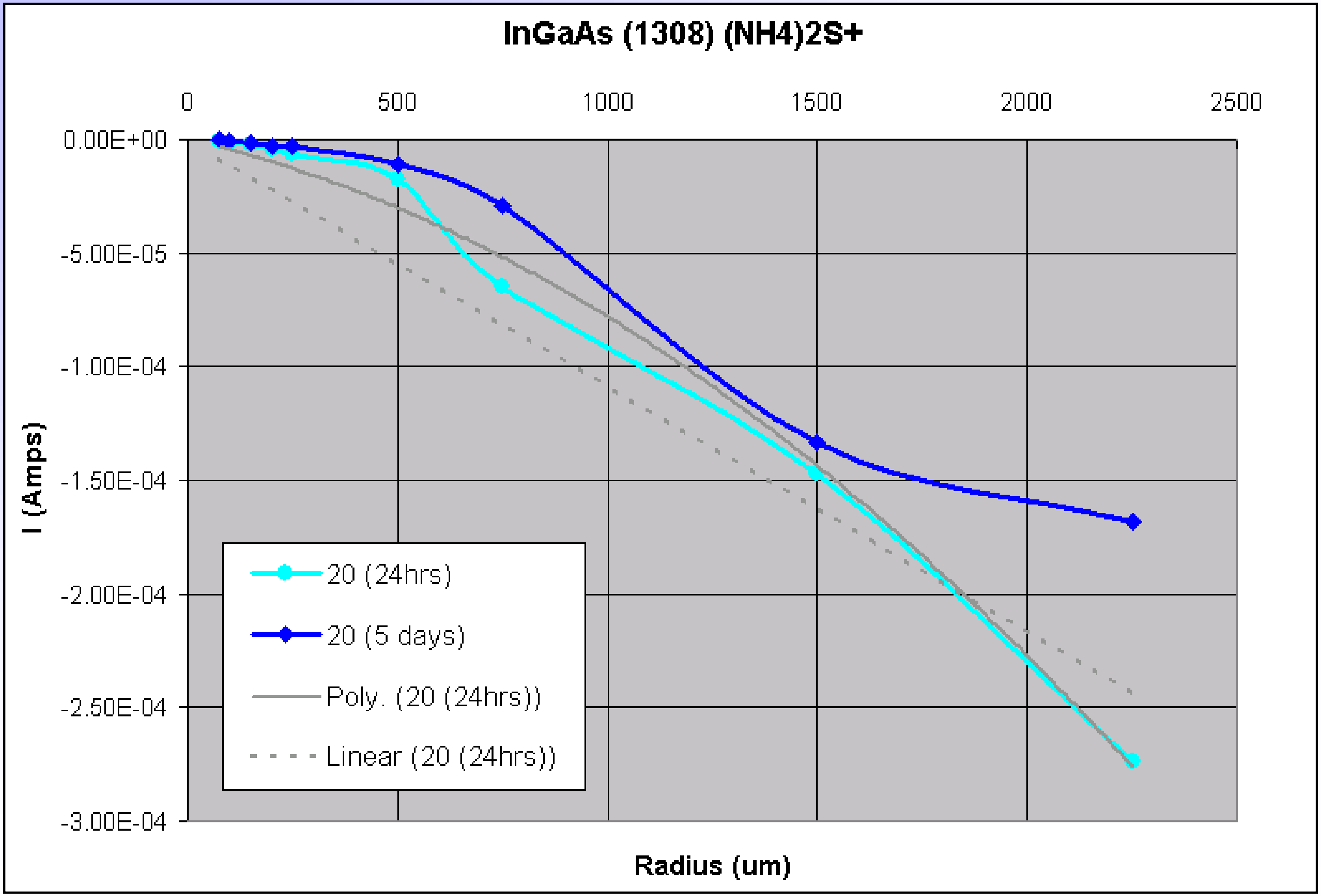

GaInNAs H2SO4 vs. (NH4)2S+

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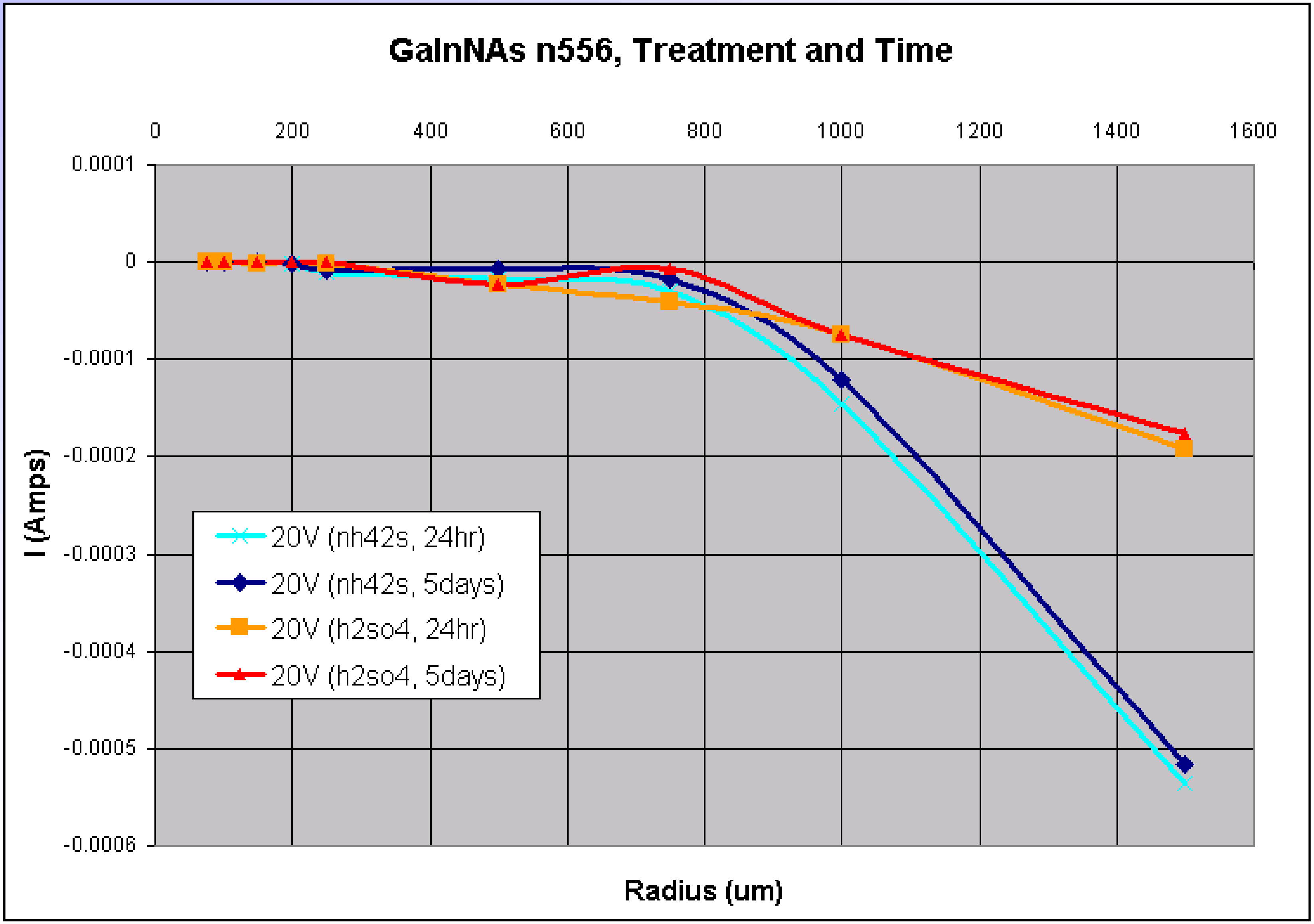
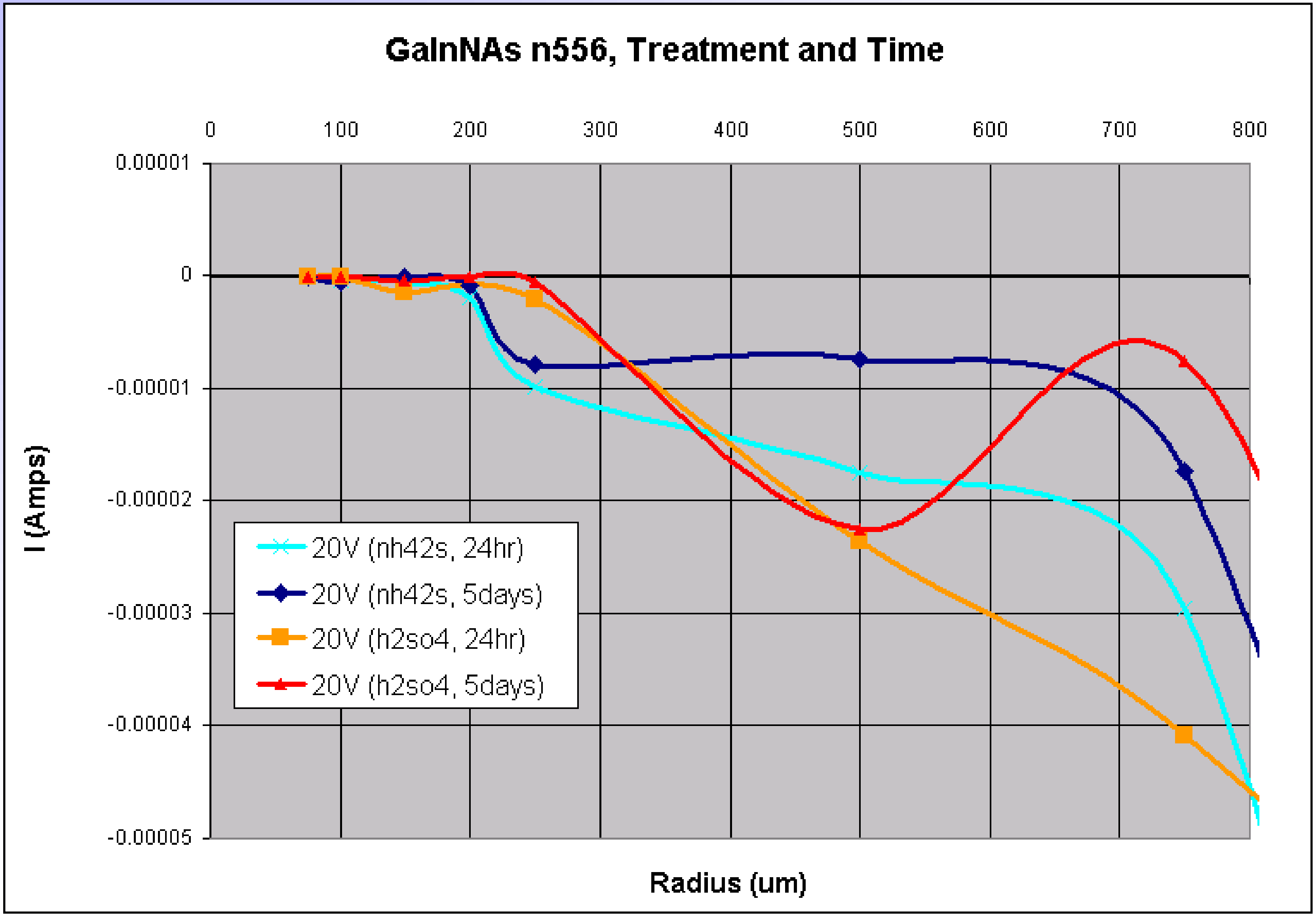


GaInNAs H2SO4 vs. (NH4)2S+



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Theoretical Saturation Powers

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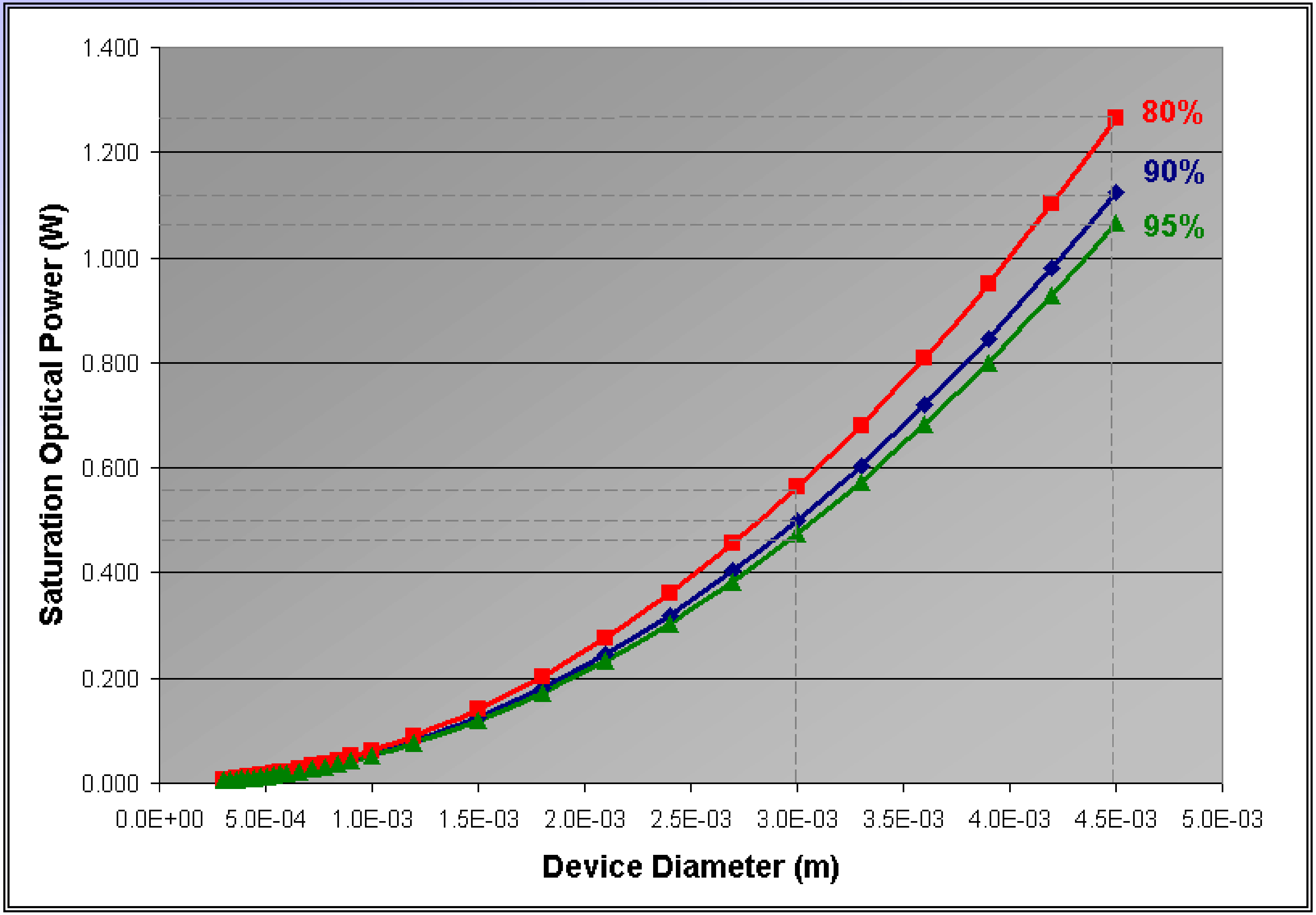

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Theoretical Saturation Powers

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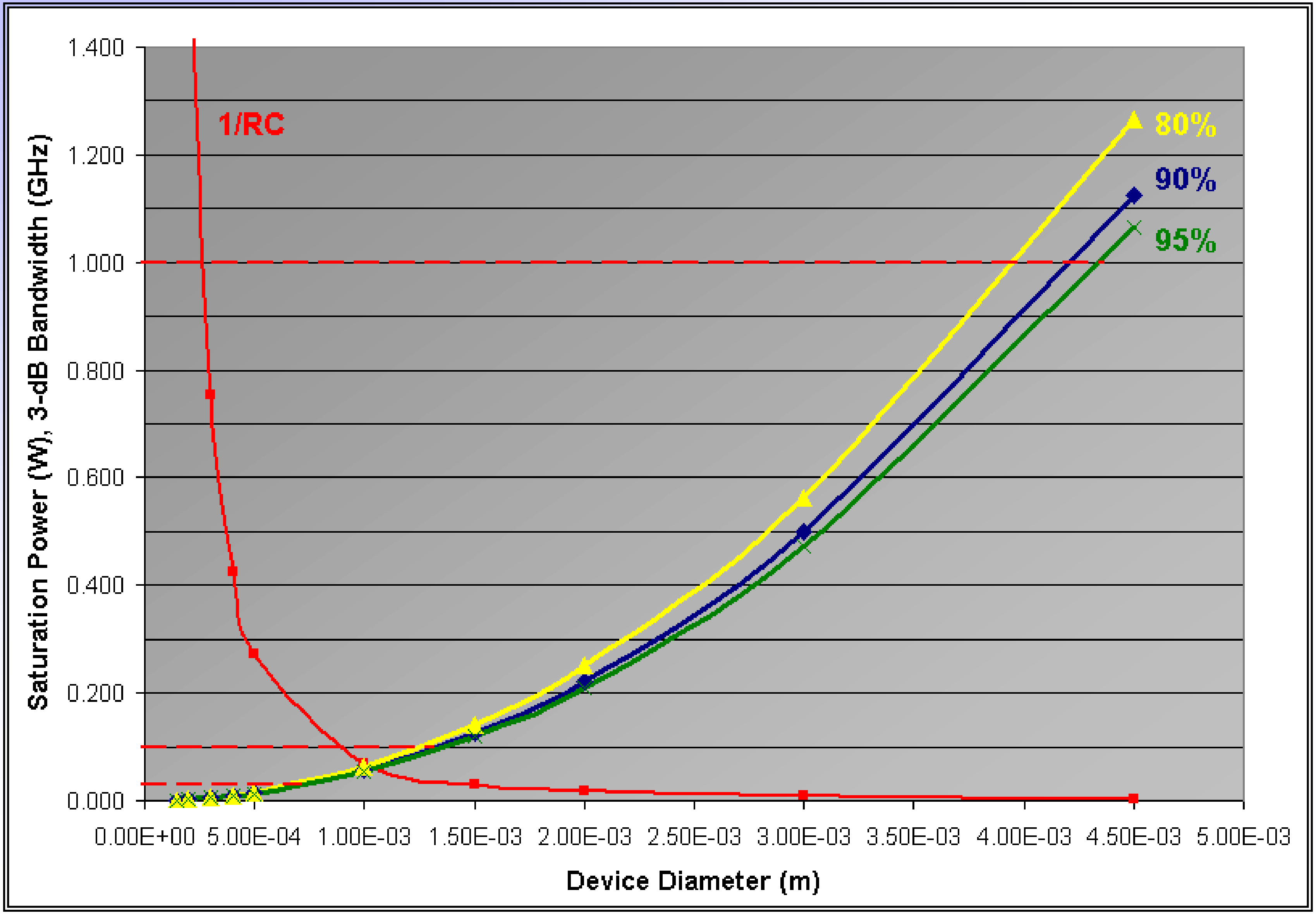
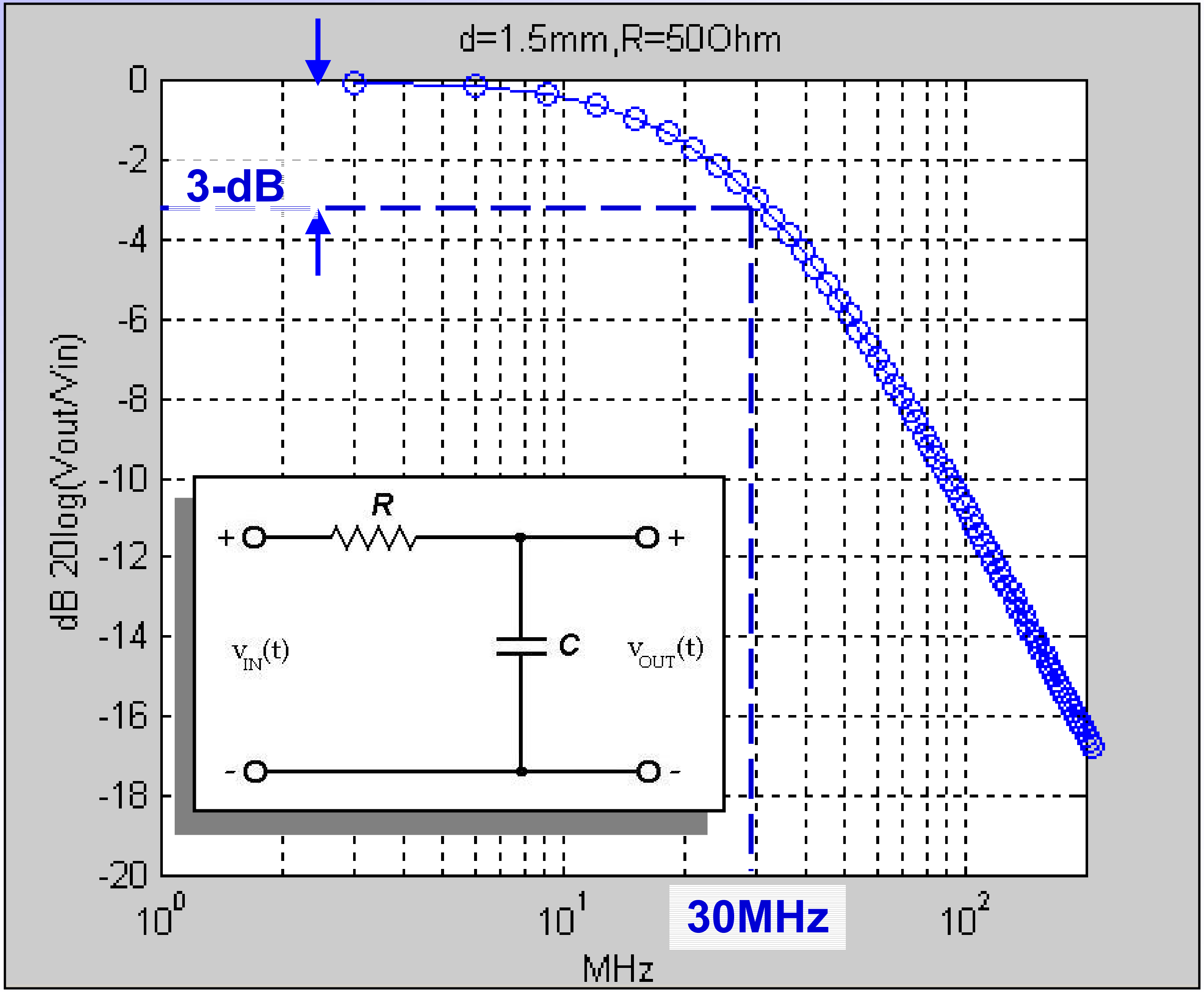


RC-Circuit Bode Plot



3-dB

30MHz

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RC- and LCR- Transmittance

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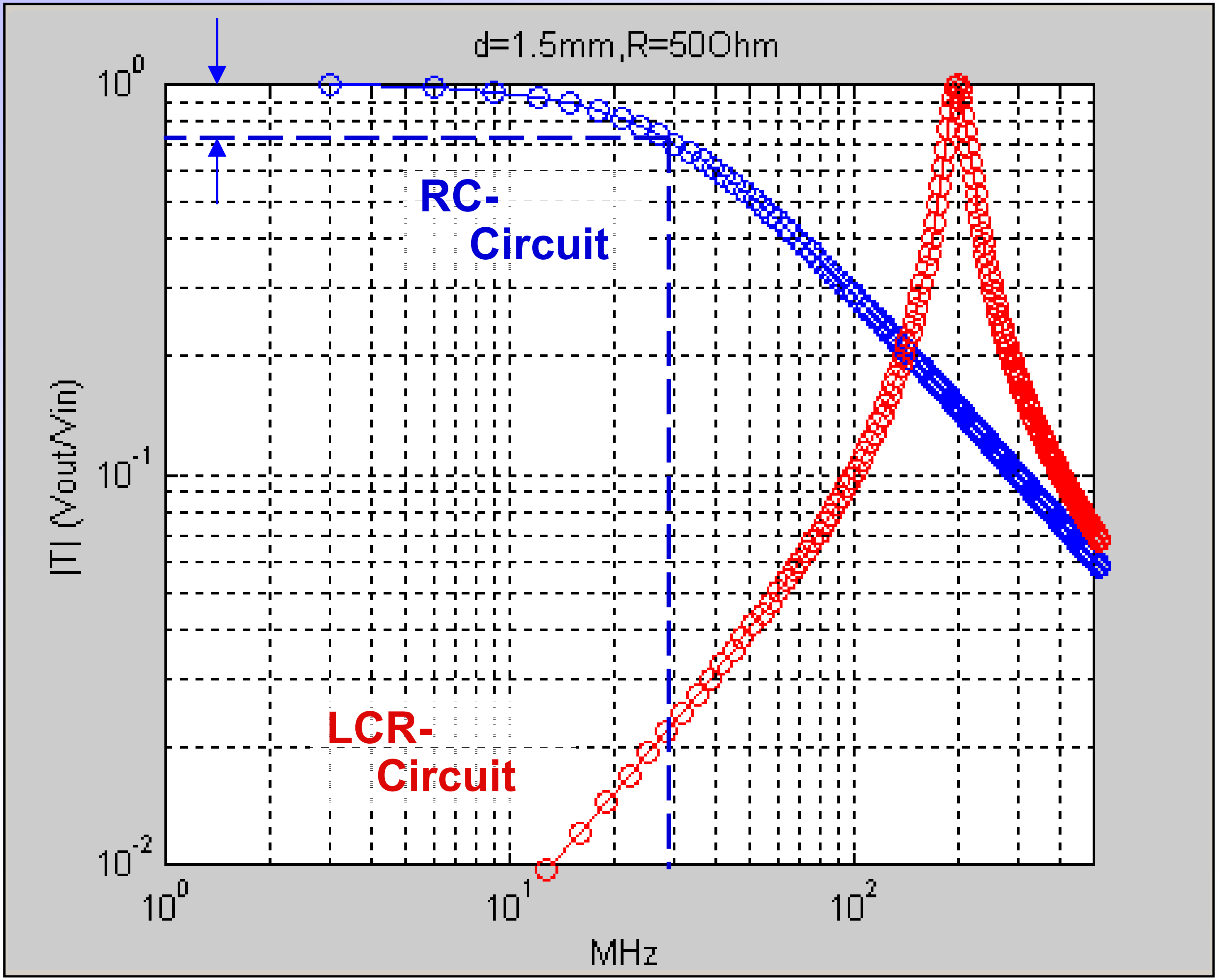
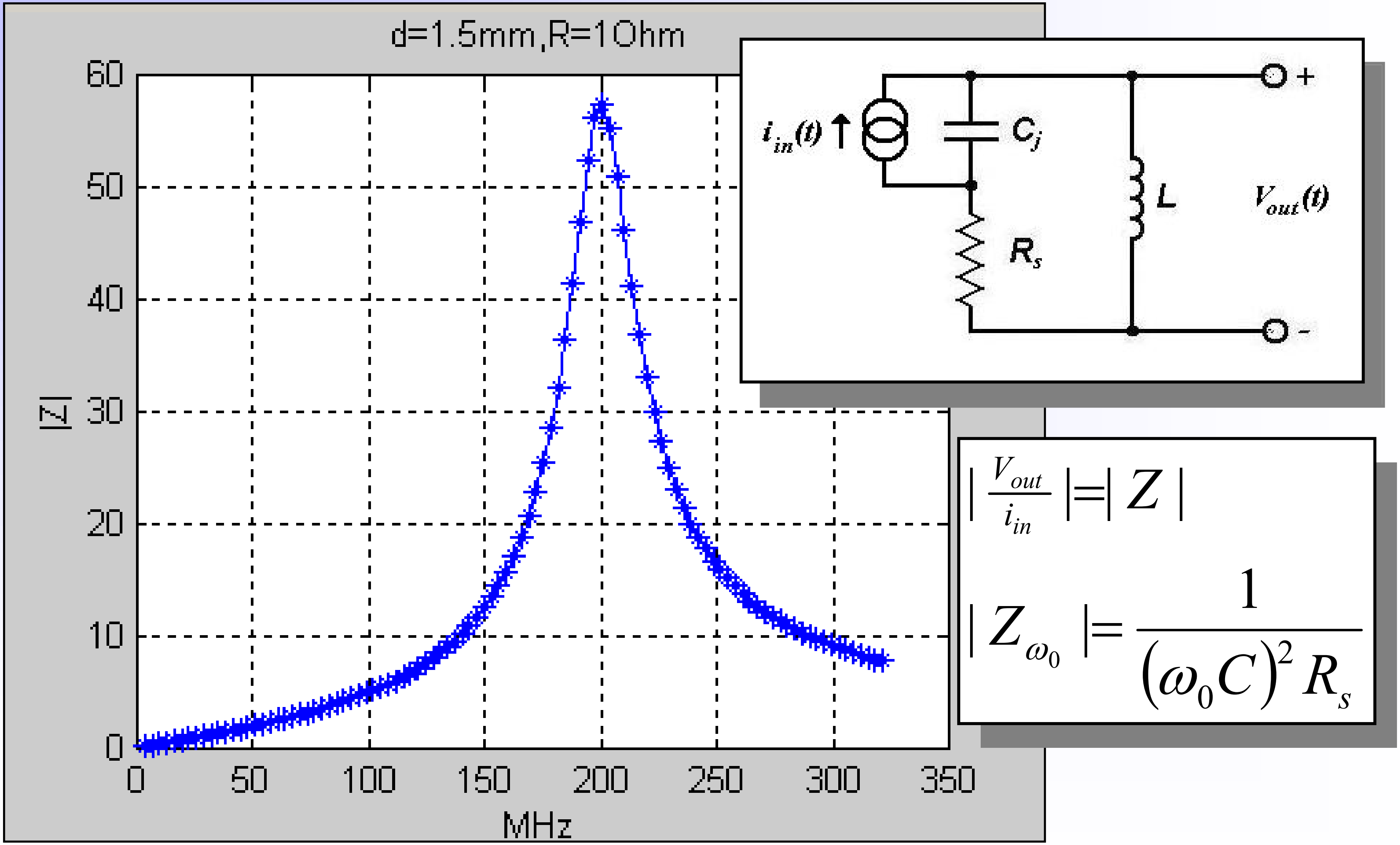


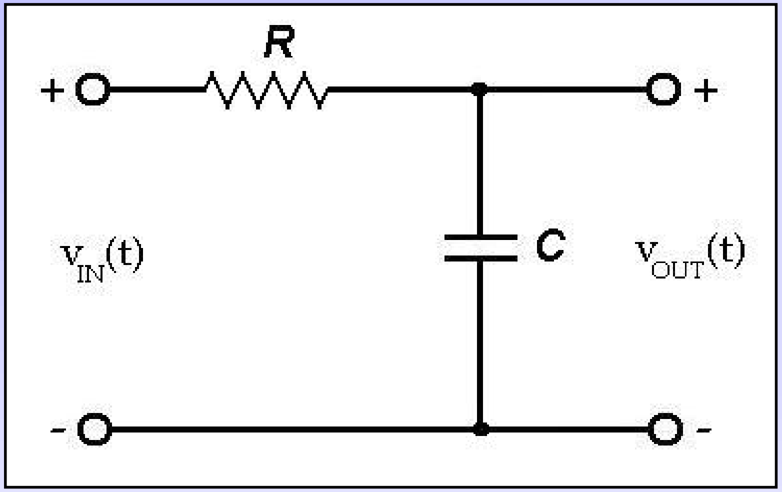
LCR- Circuit Impedance



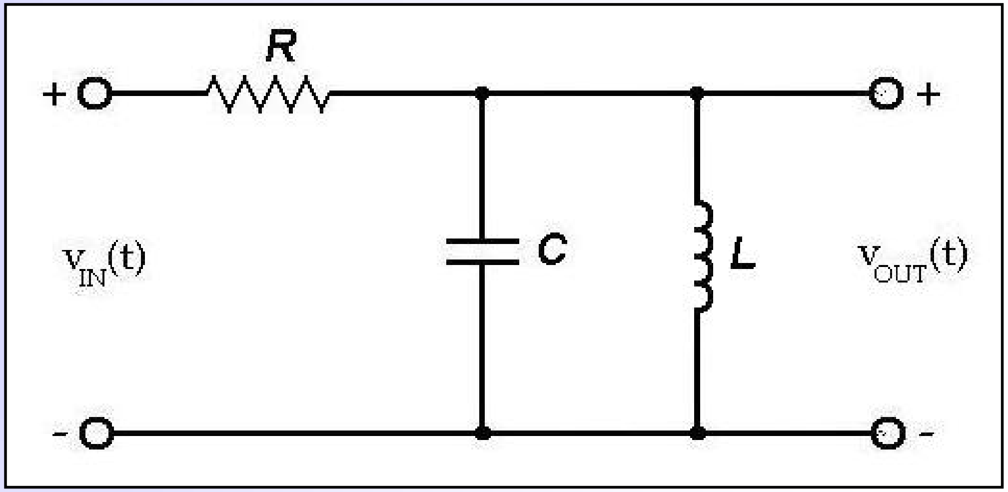
$$\left|\frac{V_{out}}{i_{in}}\right| = |Z|$$

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

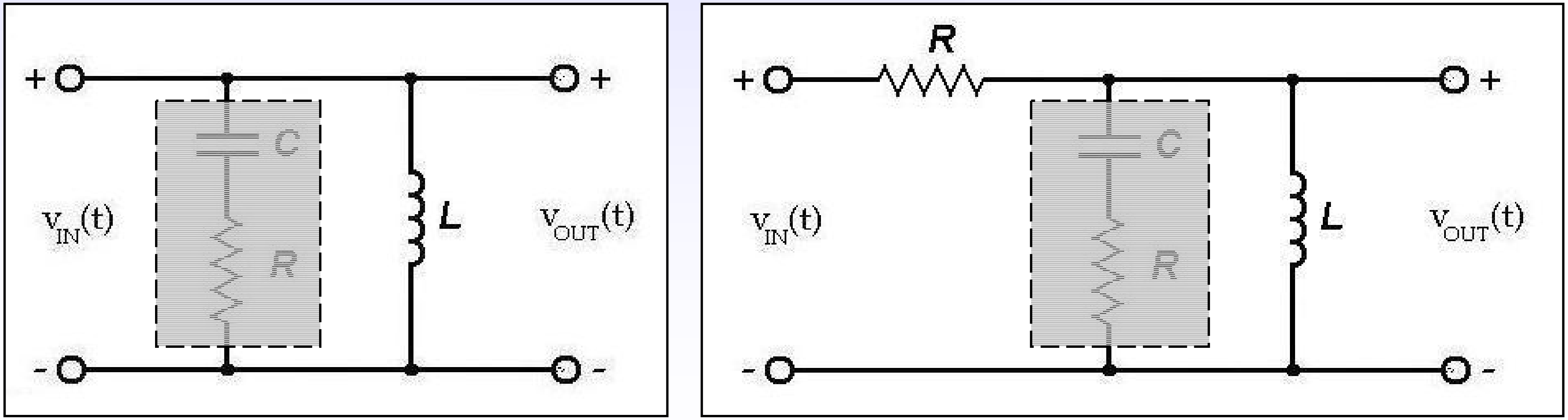
RC- vs. LCR-Circuits



RC- PD acting as a Low-Pass Filter



LCR #1- PD // Inductor as a Tuned Band-Pass Filter (with large R=50Ω)



LCR #2,3- PD // Inductor as a Tuned Band-Pass Filter (R_s=1Ω)

Transfer Function LCR #3