High Performance Photodetectors

Joint NRL-UnivTexas Project

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Program Objective

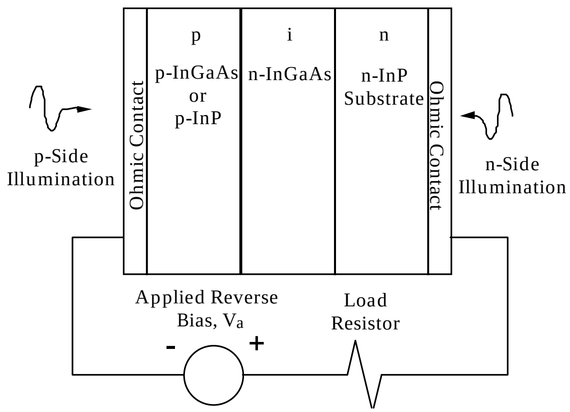
- **Milestones**
  - Linear Photodetectors for PADC, 1-20 GHz, 60 -72 dB DR at I_{op}
  - High Current 100-500 mA, 0.5 to 20 GHz PDs

- **Involvement**
  - Naval Research Laboratory (NRL)
    - Design, Modeling, Testing, Analysis, System Needs & Insertion
  - University of Texas, Austin (UT)
    - Design, Prototype Fabrication, Basic Testing & Resonant Cavity Designs
- **Plan**
  - Linear PDs
    - Leverage existing NRL PD model to handle space-charge and structure effects. Determine limiting NL mechanisms and investigate material limitations.
  - High Current PDs
    - Investigate alternative absorber types, structures resonant cavity designs, and alternative material systems.

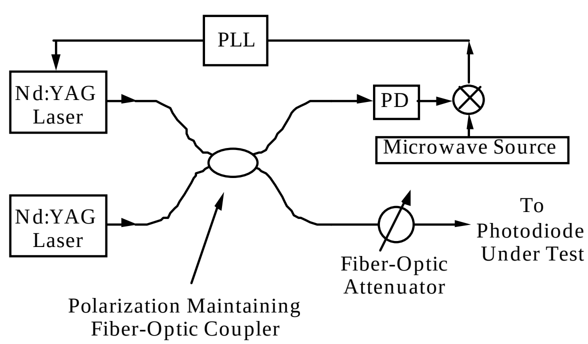
Nonlinearity Characterization and Modeling

NRL MICROWAVE PHOTONICS

p-i-n Structure



Measurement System

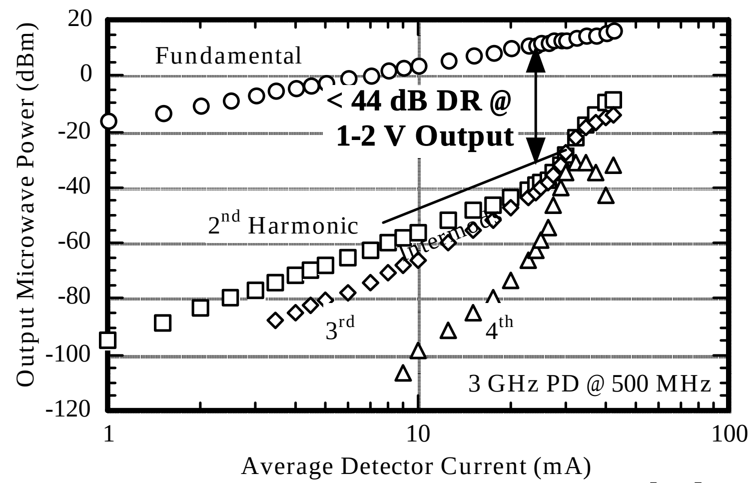


• 100 GHz, > 150 dB Dynamic Range

Numerical Model

- All 3 (p-i-n) Regions
- Includes Diffusion
- Space-Charge Electric Fields
- Scattering - Lower Carrier Mobilities
- Loading in the External Circuit
- Generation in Undepleted Regions
- Heterojunctions

Nonlinearity Measurements



• Best PDs to date still 16-31 dB below 10-12 bit PADC requirements.

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Saturation Current Progress

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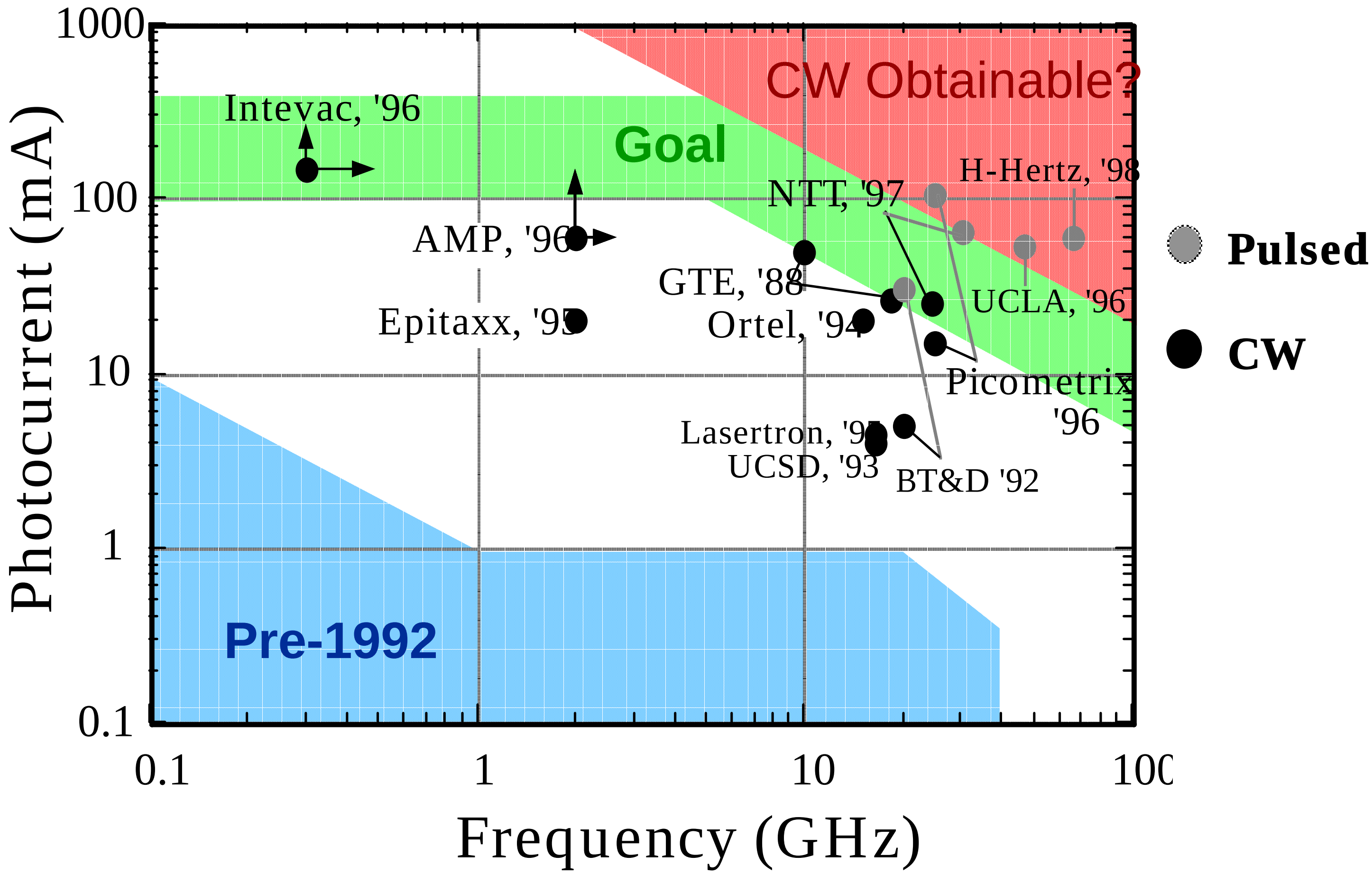

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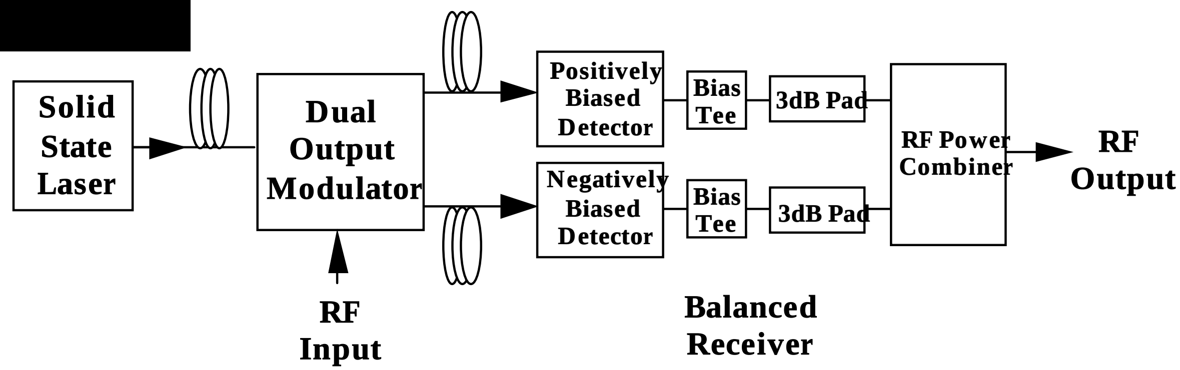
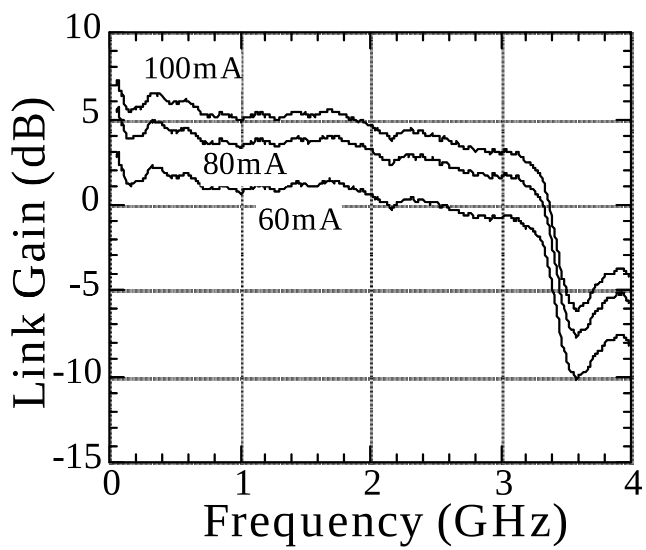
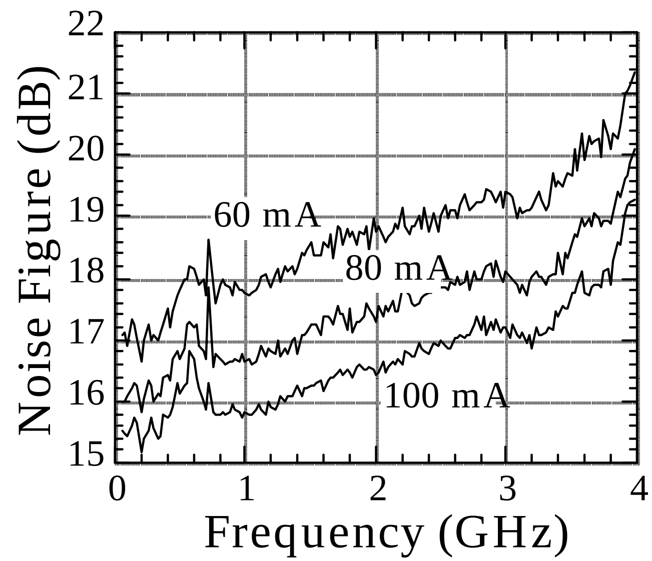
High Current PD Applications

- Analog RF Photonics
- Photonic A / D Converters
- CATV
- Ultra High Speed Digital Receivers
- High Power RF Distribution
- n-Element Low-Power Arrays (n>1000)

High-Performance Photonic Links

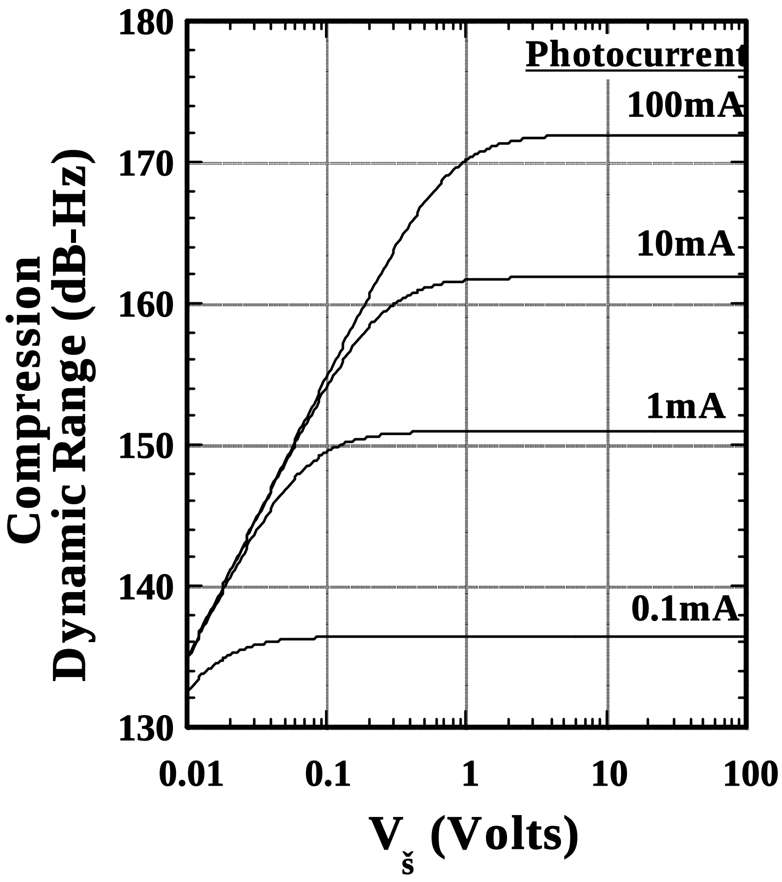


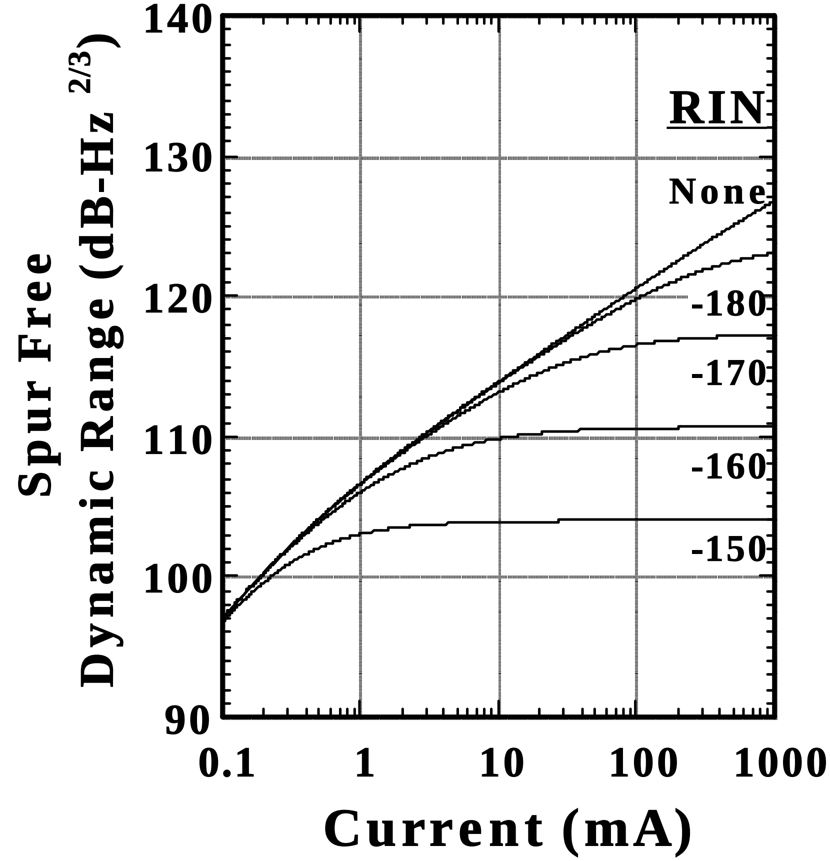




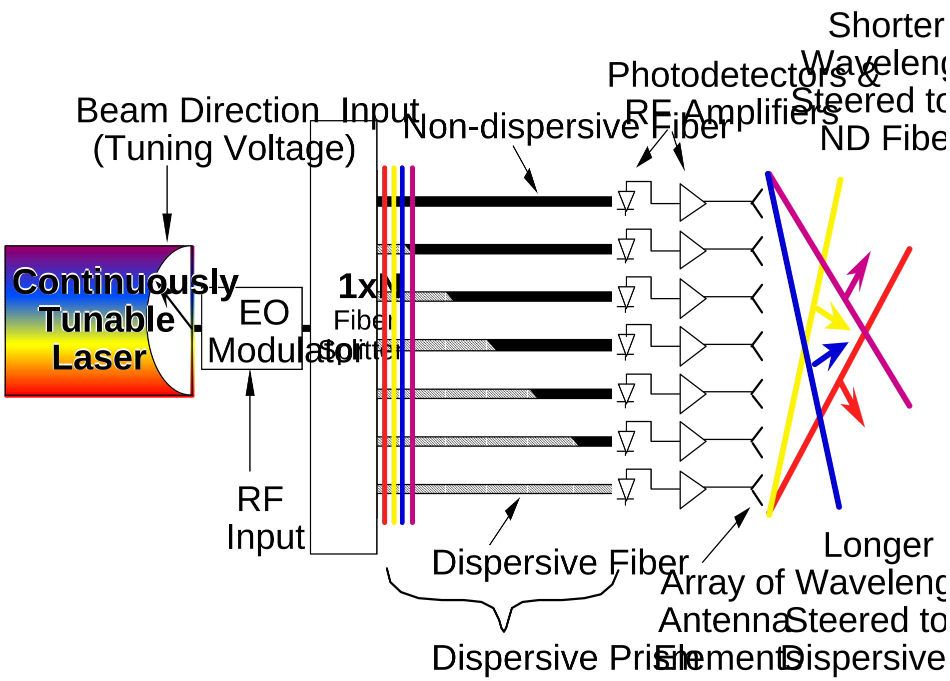
- 3 GHz Instantaneous Bandwidth
- 5 dB gain
- Noise figure ≅ 16~17 dB
- True spur-free dynamic range ≅ 116~119 dB·Hz

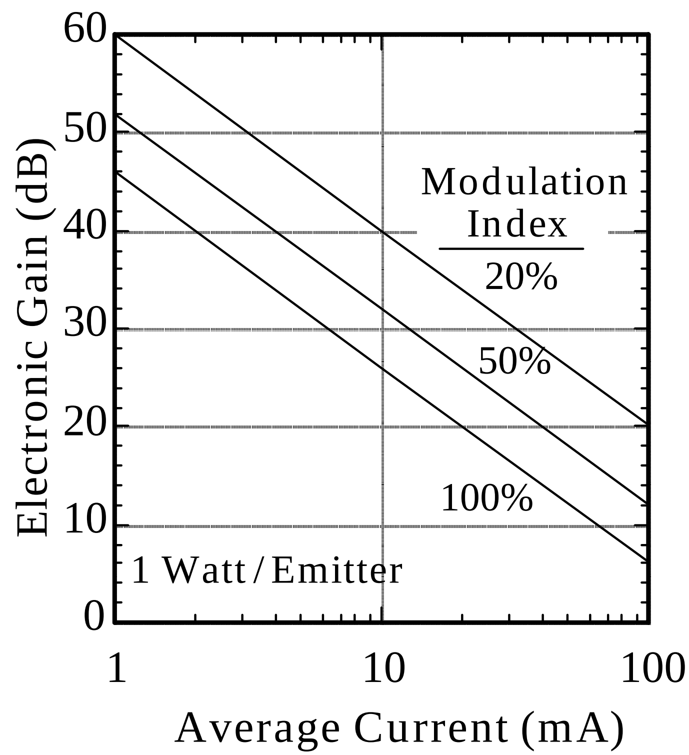
Dynamic Range Limitations





Minimizing Phase-Matched Electronic Gain





High Speed Digital Receivers

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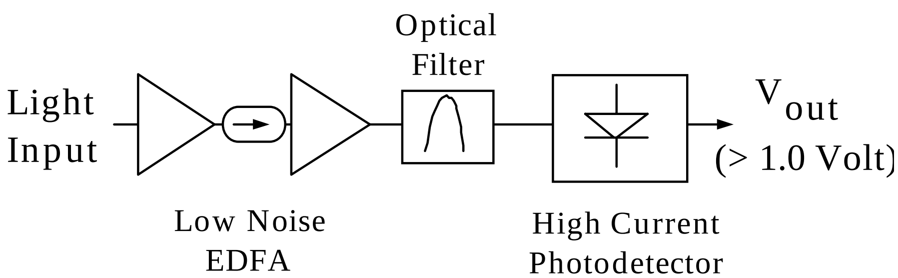
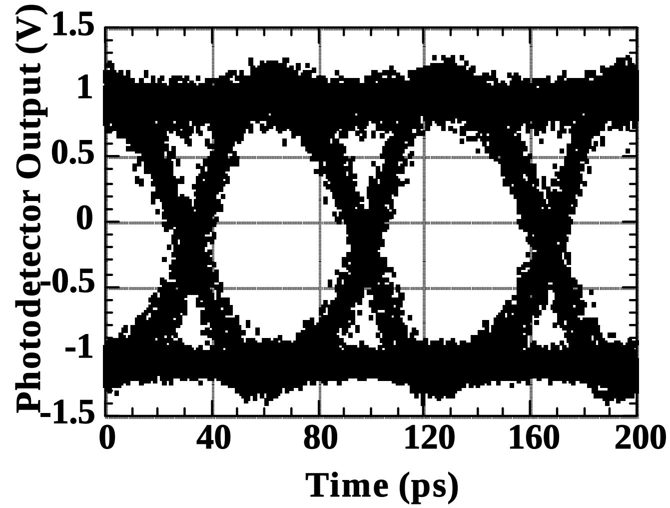
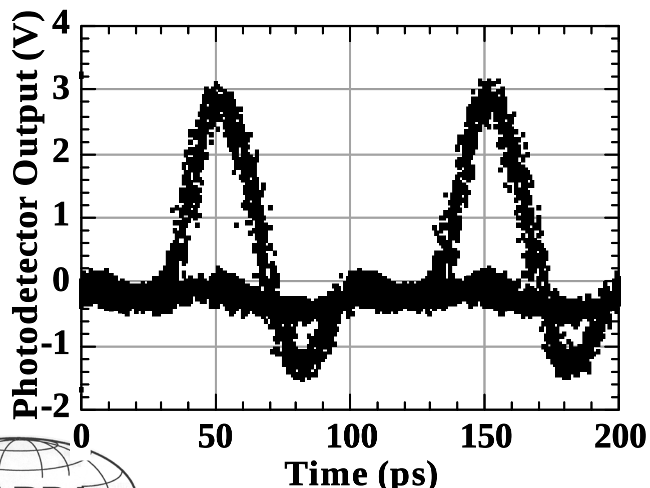


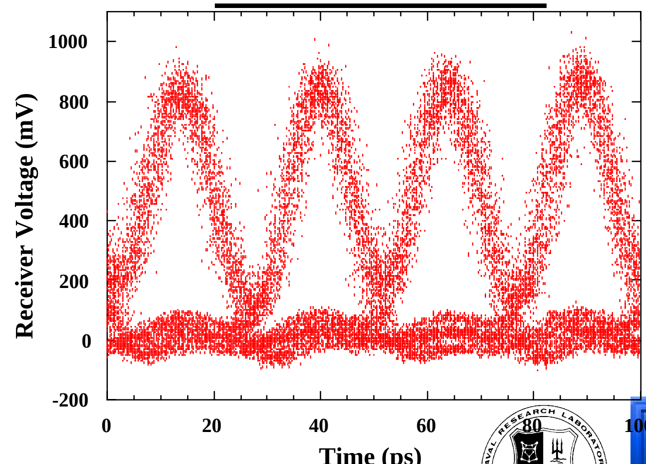
15 Gb/s NRZ



10 Gb/s RZ



40 Gb/s RZ



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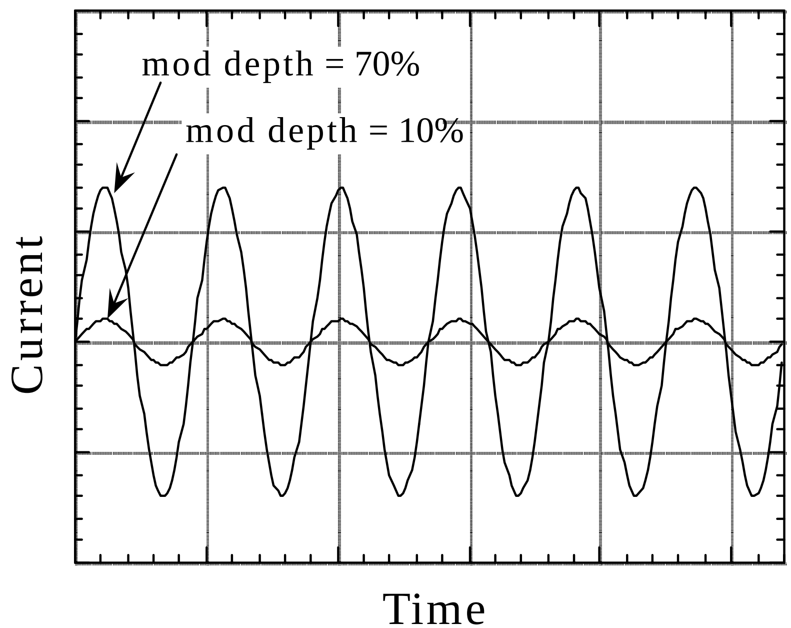
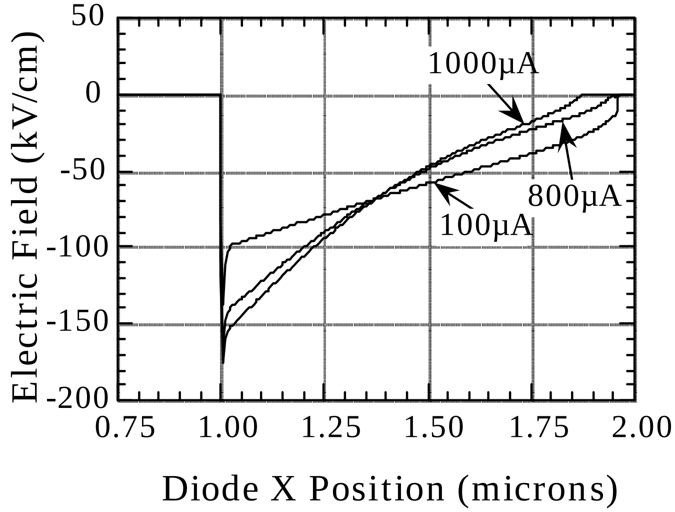
High Current Photodetector Design

Photodiode Compression

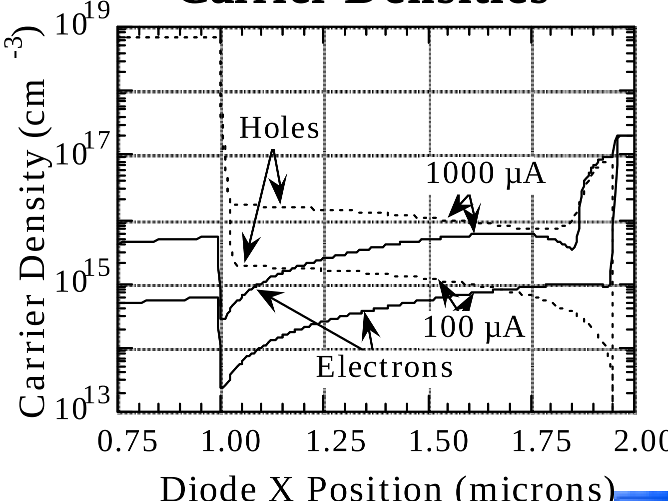
Large-Signal vs Small-Signal Modulation Conditions



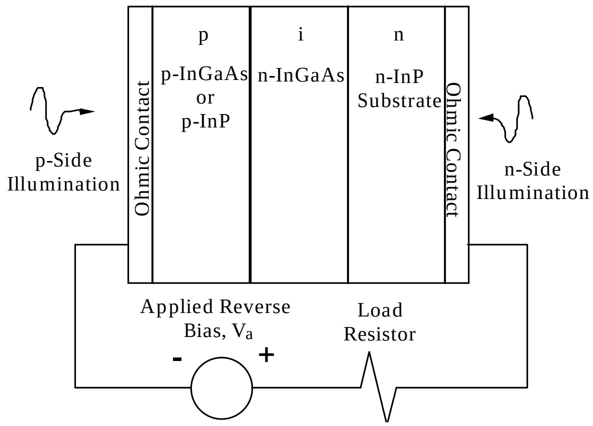
Electric Field



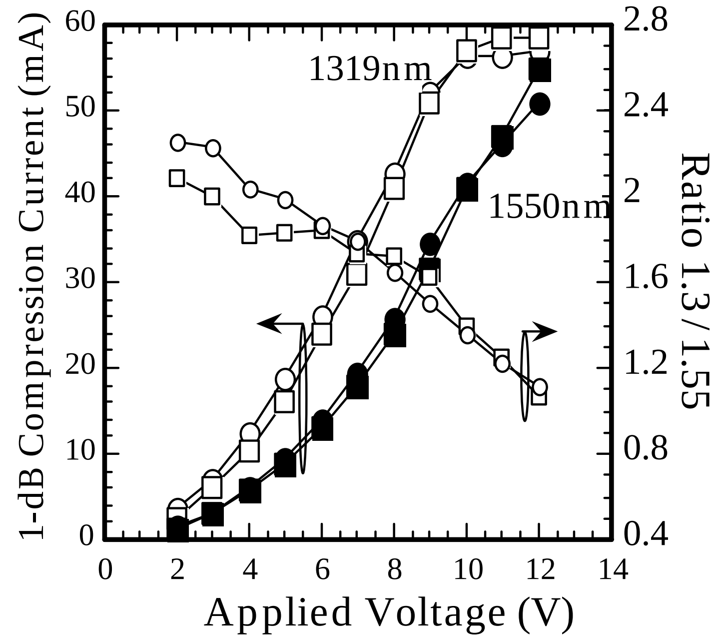
Carrier Densities



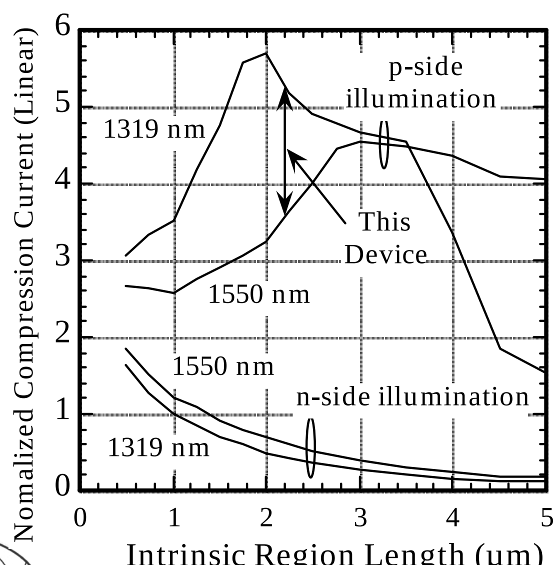
p-side vs n-side Illumination



Measurements



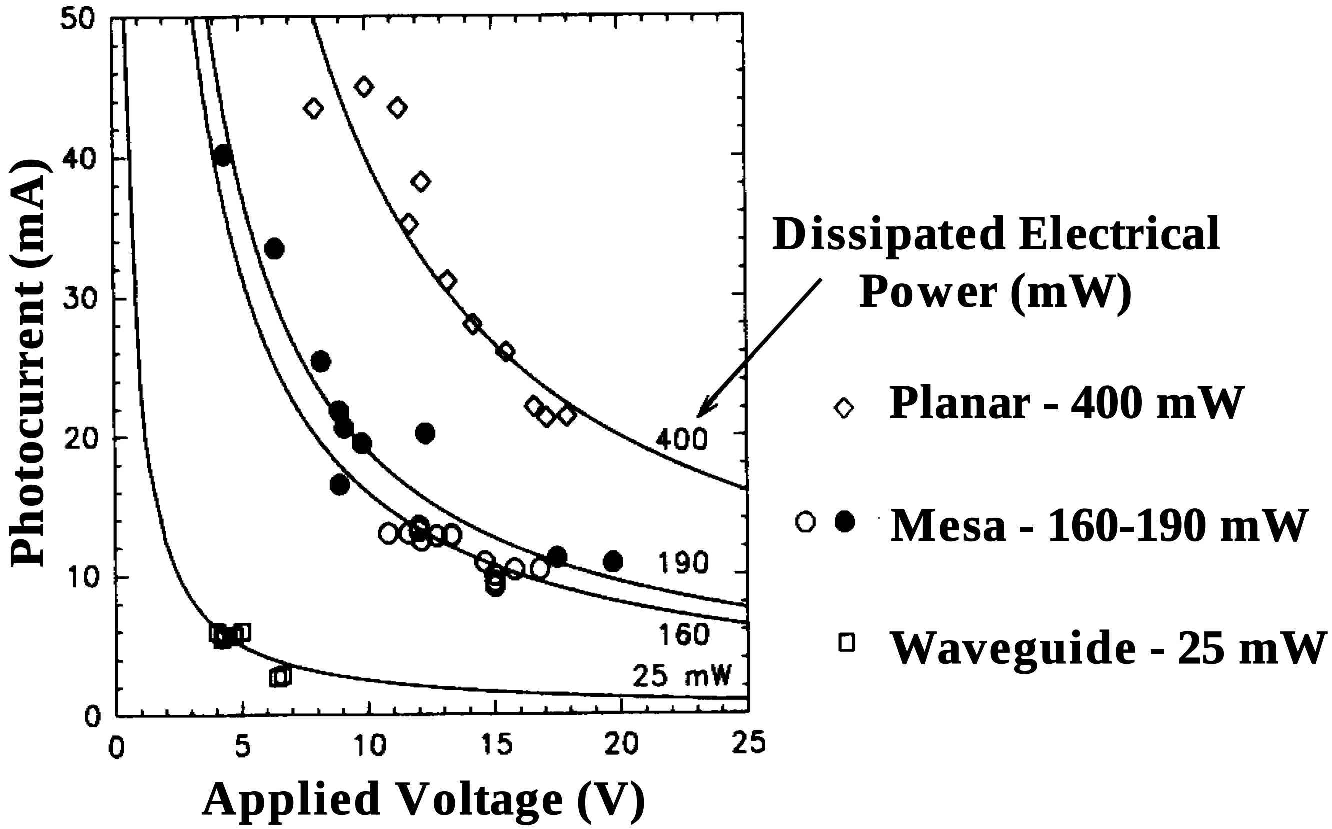
Simulations



-> p-side Illumination is Best

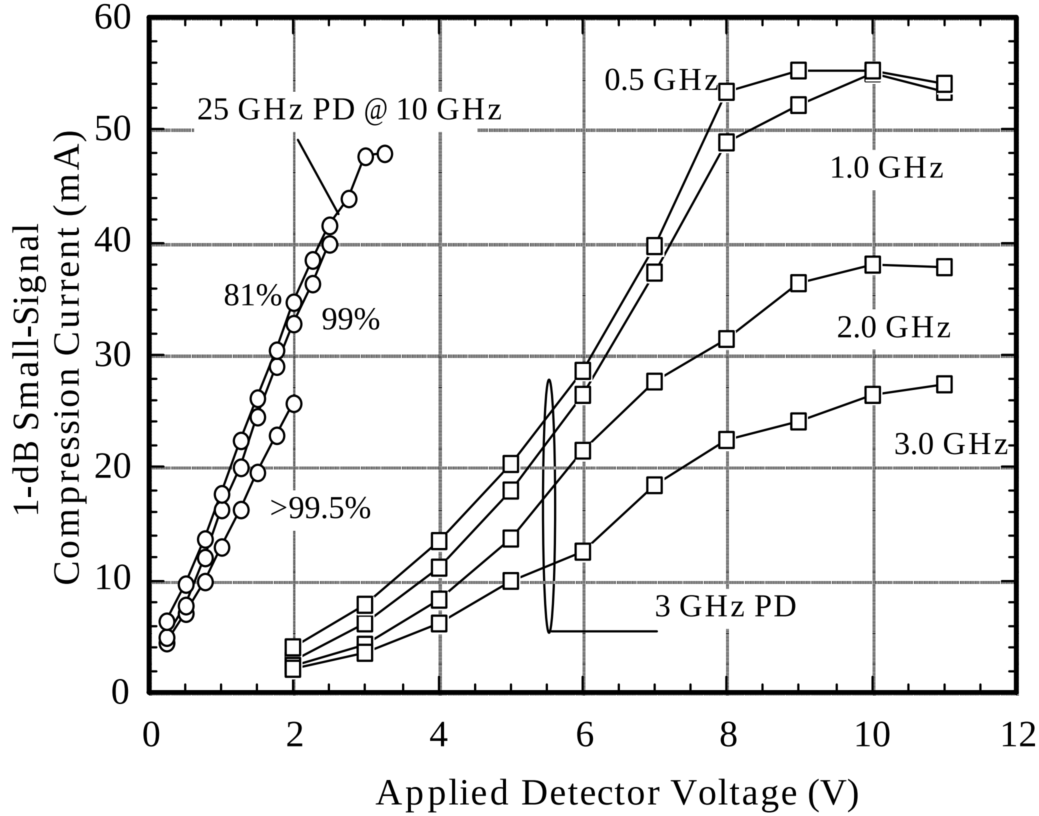
-> 2 to 10 Times More Current

Thermal Failure



* J. Paslaski, “High Power Microwave Photodiode for ...” OFC’94, Paper ThG5

State-of-the-Art Devices

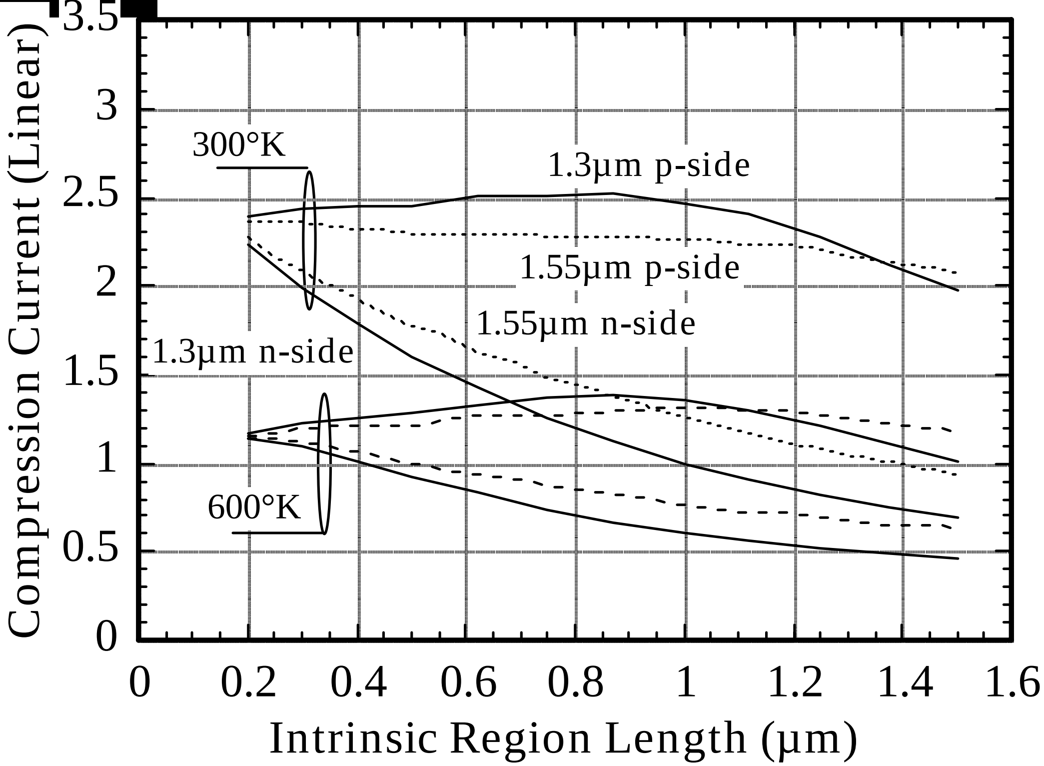


* Quantum Efficiency of 25 GHz PD is only 0.35 A / W

High Current Photodetector Design Issues

- **Minimize Space-Charge Effects**
  - minimize power density
  - internal design (i-region + illumination conditions)
- **Minimize Thermal Effects - A Failure Mechanism**
  - minimize thermal impedance
  - minimize voltage required to maintain response
- **Minimize Nonlinear Recombination**
  - device structure
- **Other Structures**
  - traveling-wave structures (Waveguide, Discrete)
  - devices w/ doped absorbers & nonabsorbing drift layers

Space-Charge Effects - 20 GHz PDs

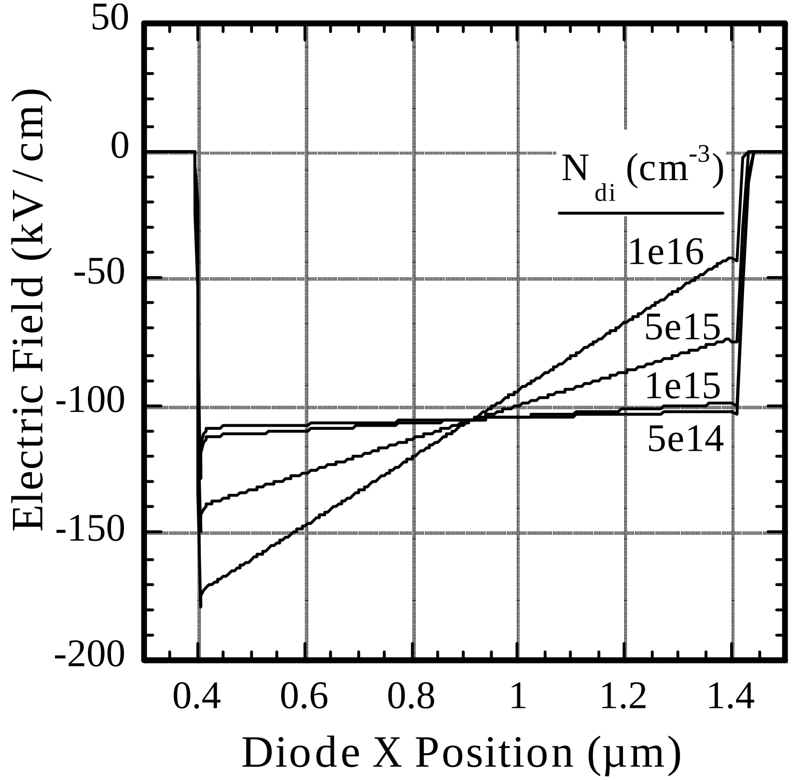


- Assumes Constant Electric Field Strength & Capacitively-Limited Bandwidth

Electric Field ∝ Voltage/Length -> The 0.2 μm PD operates at 1/5 the Voltage (and Power) of the 1.0 μm PD

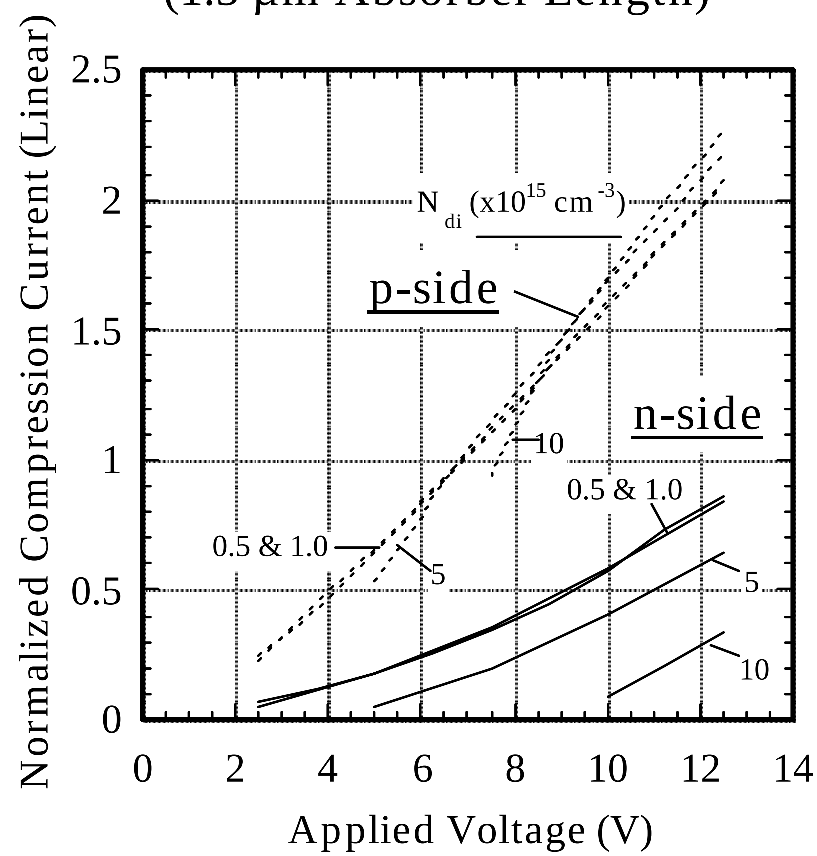
Intrinsic Region Quality

Dark Electric Field

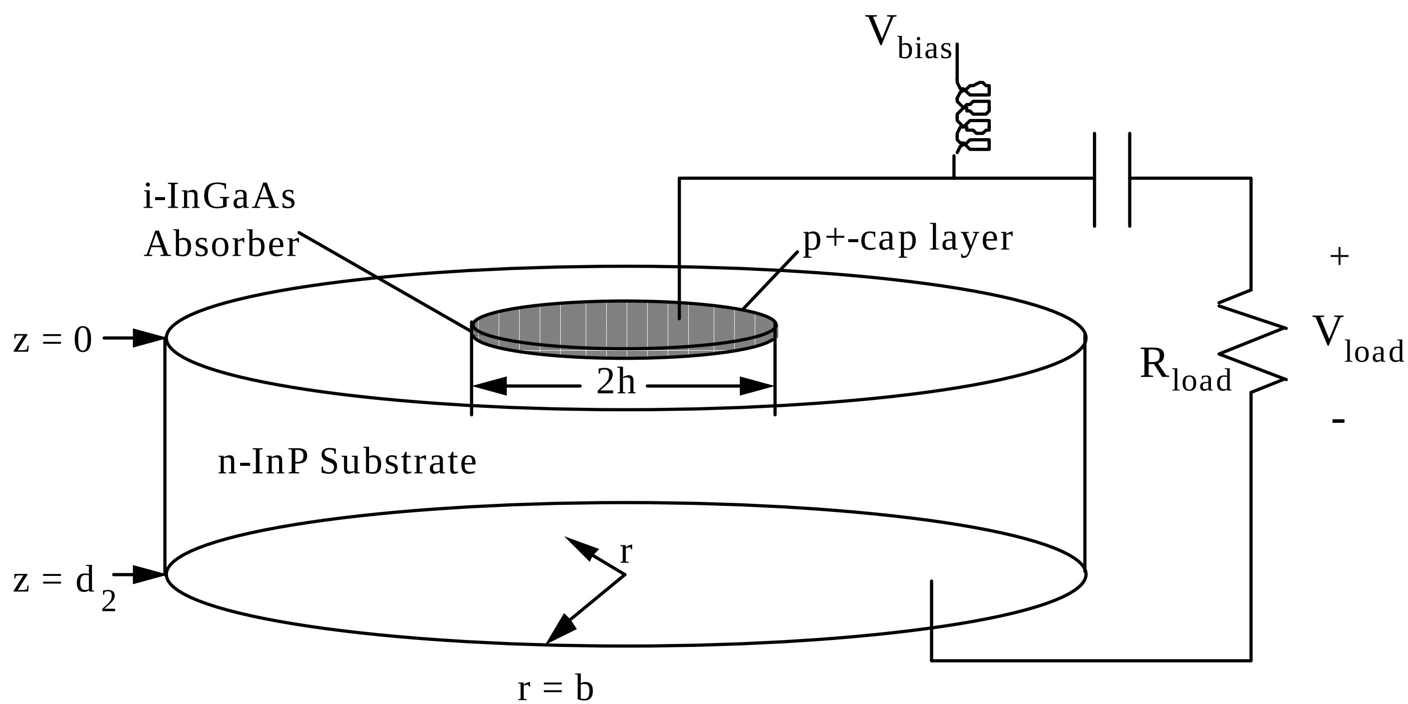


Compression Current

(1.5 µm Absorber Length)



Photodetector Thermal Model



Photodetector Thermal Impedance

Absorber-Only Thermal Impedance:

$$\theta_{abs} = \frac{d_1/2}{k_1 \pi h^2}$$

Temperature Dependent Thermal Conductivity:

$$\theta_o P = \frac{1}{k(T_o)} \int_{T_o}^{T} k(T)\,dT$$

Substrate-Only Thermal Impedance:

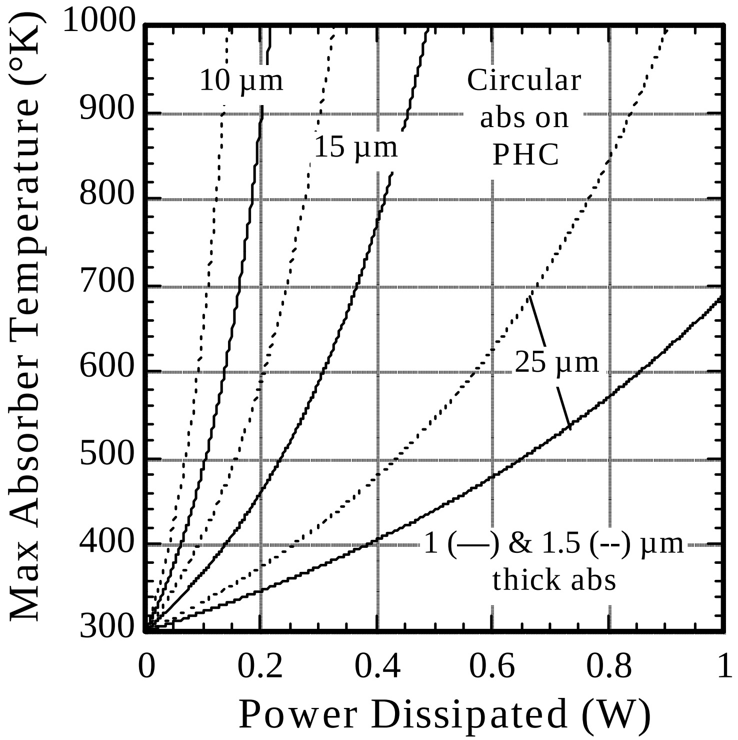
$$\theta_{sub}(r,z) = \frac{d_2}{k_2 \pi b^2} + \frac{2}{k_2 \pi h b^2} \sum_{l=1}^{\infty} \frac{\sinh(\varphi_l (d_2 - z))}{\varphi_l^2 \cosh(\varphi_l d_2)} \frac{J_1(\varphi_l h) J_0(\varphi_l r)}{J_0^2(\varphi_l b)}$$

d_1 = Absorber Thickness
k_1 = Absorber Thermal Conductivity
h = Radius of Absorber (Incident Beam)
d_2 = Substrate Thickness

k_2 = Substrate Thermal Conductivity
b = Substrate Radius
$J_1(\varphi_j b) = 0$

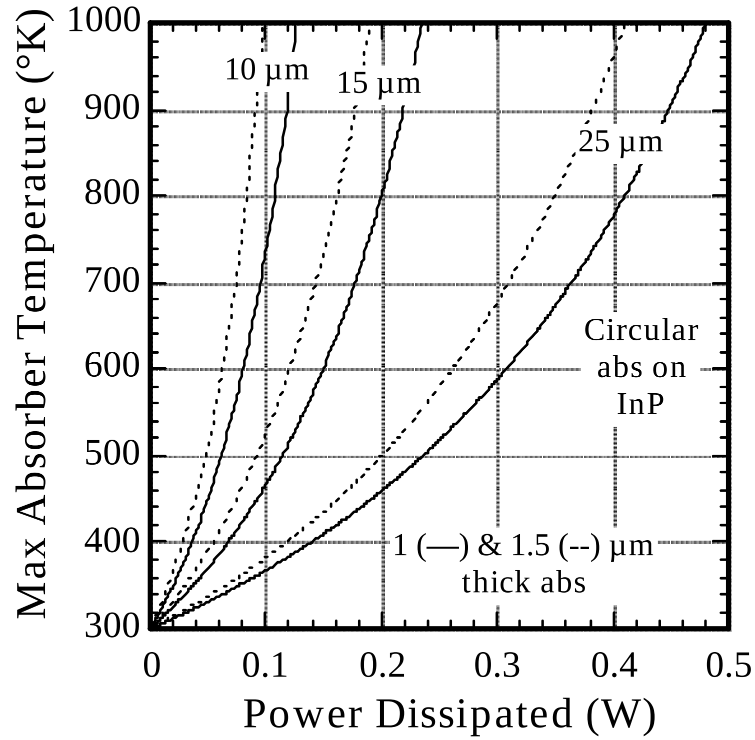
Maximum Possible Power Dissipation

InGaAs Absorber Only



• Thermal Impedance ~ D/kA

InGaAs Absorber on InP



• Thermal Impedance ~ D/kA +1/kA

Geometry Optimization

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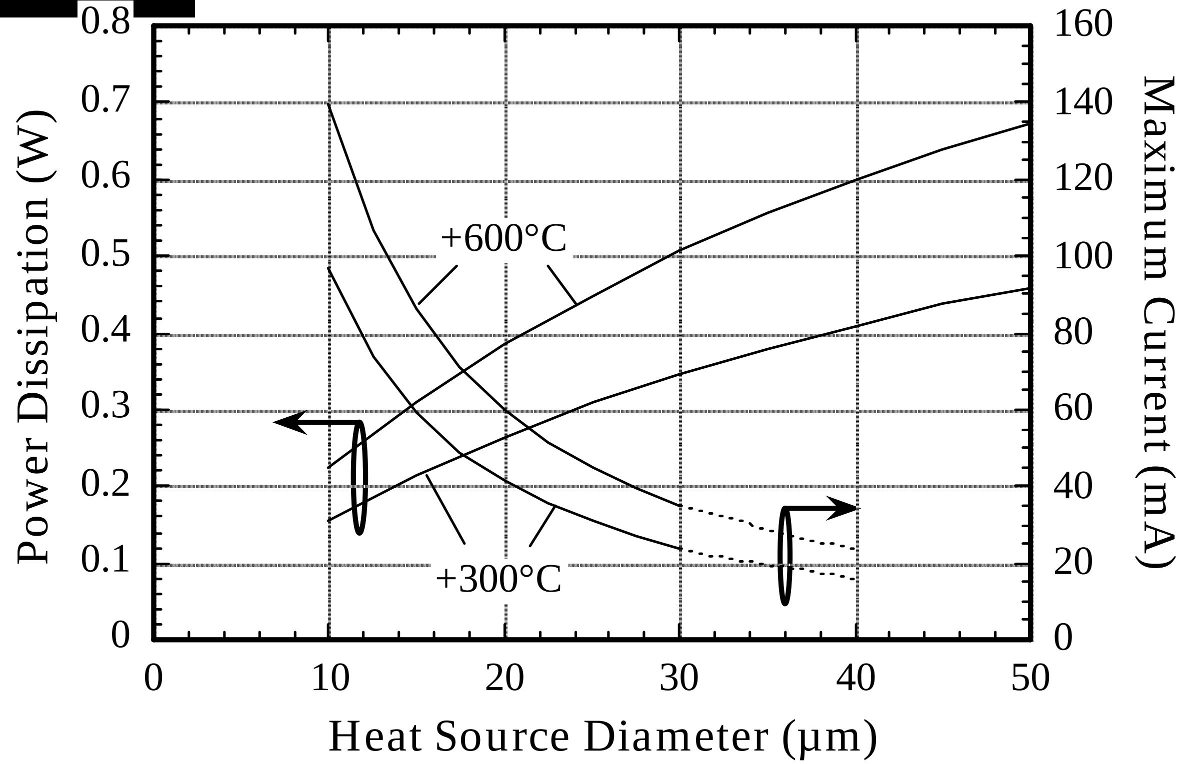

- Thinner, Thinner, Thinner
- Lower Quantum Efficiency
- Double- or Multi-Pass Absorbers

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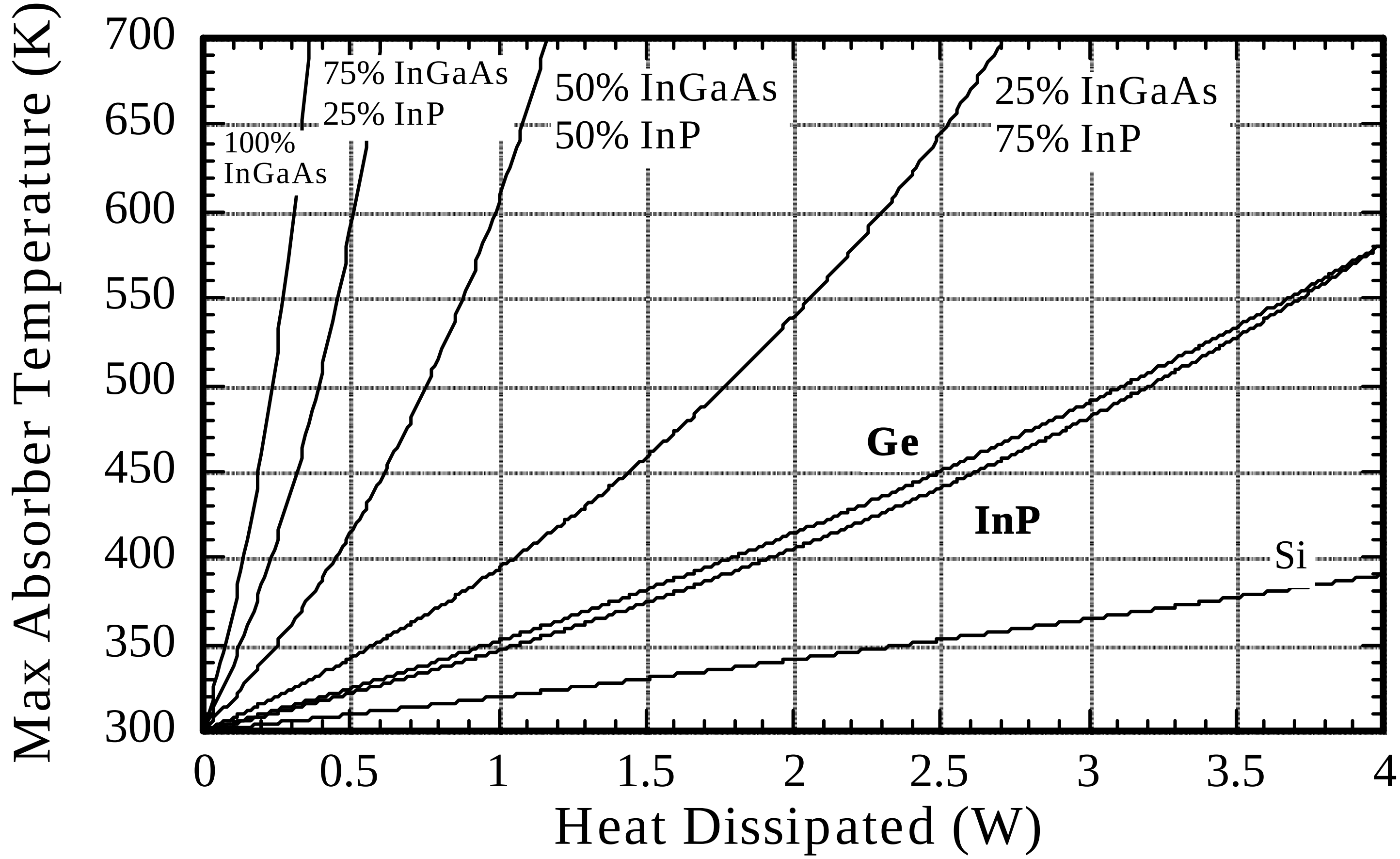
Other p-i-n Structures



Relevant Material Characteristics

Properties	InGaAs	Ge	InP	Si	GaAs
Electron Mobility (cm^2 / Vsec)	8000	3900	4000		
Hole Mobility (cm^2 / Vsec)	300	1900			
Electron Velocity @ E=20kV / cm (cm / s)	10 X 10^6	6 X 10^6	15 X 10^6		
Hole Velocity @ E=20kV / cm (cm / s)	3 X 10^6	6 X 10^6			
Electron Velocity @ E=100 kV / cm (cm / s)	6 X 10^6	6 X 10^6	8 X 10^6		
Hole Velocity @ E=100 kV / cm (cm / s)	5 X 10^6	9 X 10^6			
Thermal Conductivity (°C-cm / W)	21	1.67	1.47	0.67	2.17
Maximum Electric Field (kV / cm)	200	125	>300		
Absorption Coefficient @ 1.32 µm (μm^{-1})	1.15	0.74			
Absorption Coefficient @ 1.55 µm (μm^{-1})	0.68	0.046			

Transport Equations

$$\frac{\partial p}{\partial t} = G - R - \frac{1}{q}\nabla \cdot \left(J_{p\,drift} + J_{p\,diff}\right)$$

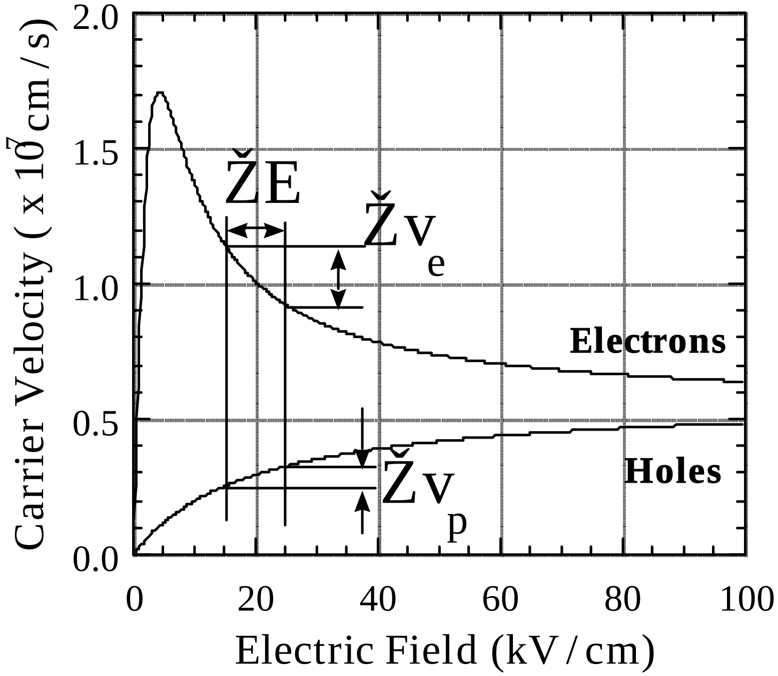
$$\frac{\partial n}{\partial t} = G - R - \frac{1}{q}\left[v_n \frac{\partial n}{\partial x} + n\frac{\partial v_n}{\partial x} + q\frac{\partial D_n}{\partial x}\frac{\partial n}{\partial x} + qD_n \frac{\partial^2 n}{\partial x^2}\right]$$

$$\nabla \cdot E = \frac{q}{\varepsilon}\left(p - n + N_d - N_a\right)$$

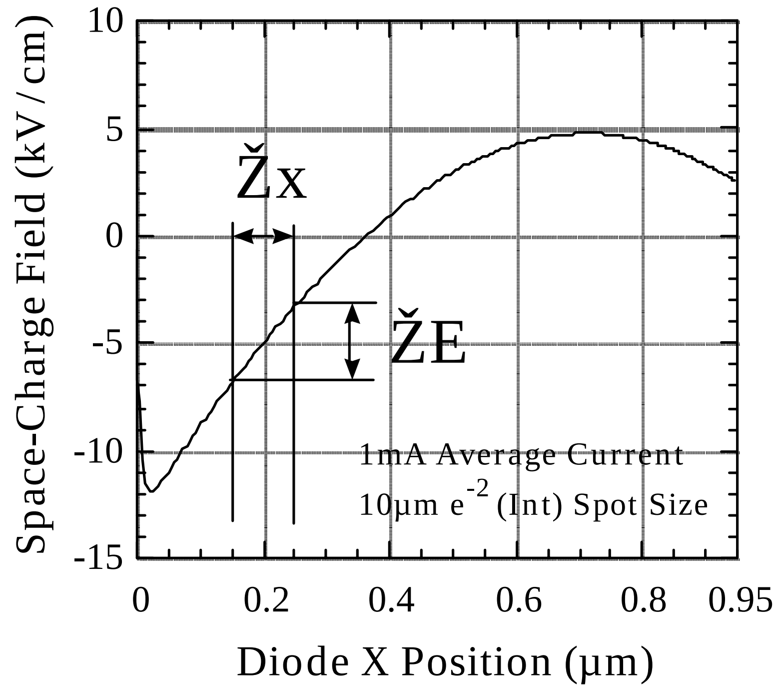
Carrier Velocity Nonlinearities

$$n \frac{\partial v_n}{\partial x} = n \frac{\partial v_n}{\partial E} \frac{\partial \left(E_{dark} + E_{sc}\right)}{\partial x} \quad , \quad E_{sc} \propto \left(p' - n'\right)$$

Carrier Velocities



Space-Charge Electric Field



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Improvements to 1-D Model

	Present Model
• Space-Charge Electric Fields	1-D
• Scattering - Lower Carrier Mobilities	X
• Loading in the External Circuit	X
• Generation in Undepleted Regions	X
• Diffusion	Partial
• Trapping	No
• Heterojunctions	Partial
• Finite Carrier Acceleration Time	No
• Bleaching	No

FY 00-01 Plans

High Current Photodetectors

- **Trade Study to Determine Best Approach to High Current**
- **Fabricate and Characterize High Current Devices**
- **Refine Model if Necessary**

High Linearity Photodetectors

- **Analyze, Model and Quantify NL Mechanisms**
- **Reconcile Model with Experiments on Latest PDs**
- **Design and Model High Linearity Structure**
- **Fabricate and Measure Improved Device**