High Performance Photodetectors

DARPA R-FLICs Program Review

Los Angeles CA, July 30 - August 1, 2001

Site Visit?

Joint NRL - Univ. Texas Project

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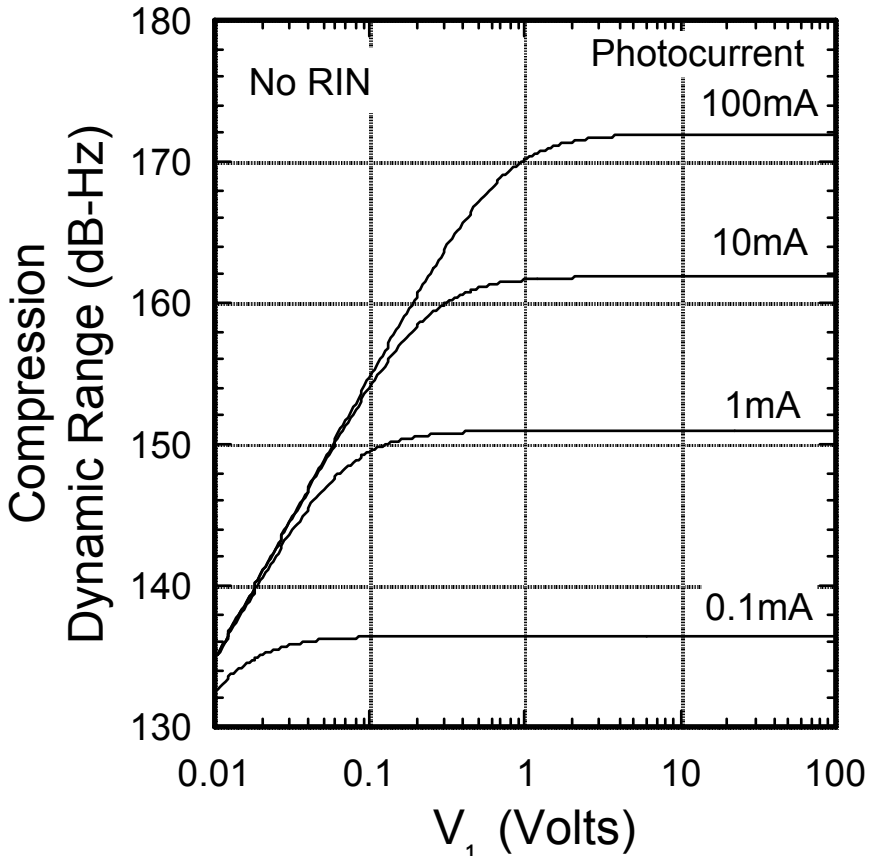
Program Objective

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

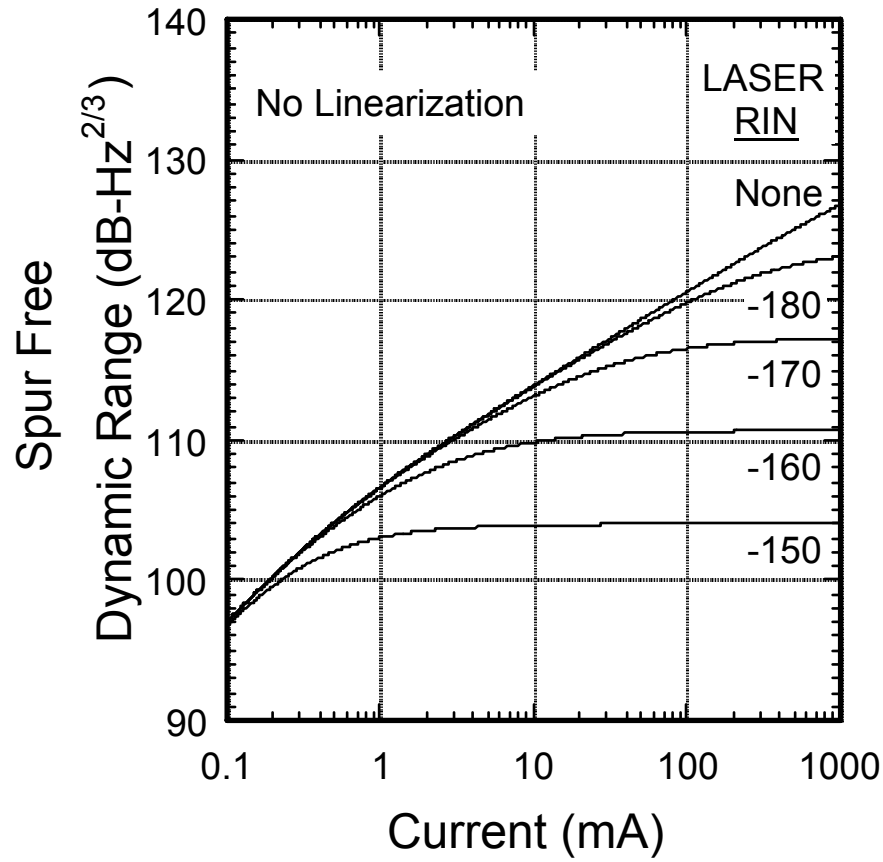
- **Involvement**
  - Naval Research Laboratory (NRL)
    - Design, Modeling, Testing, Analysis, System Needs & Insertion
  - University of Texas, Austin (UT)
    - Design, Prototype Fabrication, Basic Testing & Resonant Cavity Designs
- **Plan**
  - Linear PDs
    - Leverage existing NRL PD model to 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.

Dynamic Range

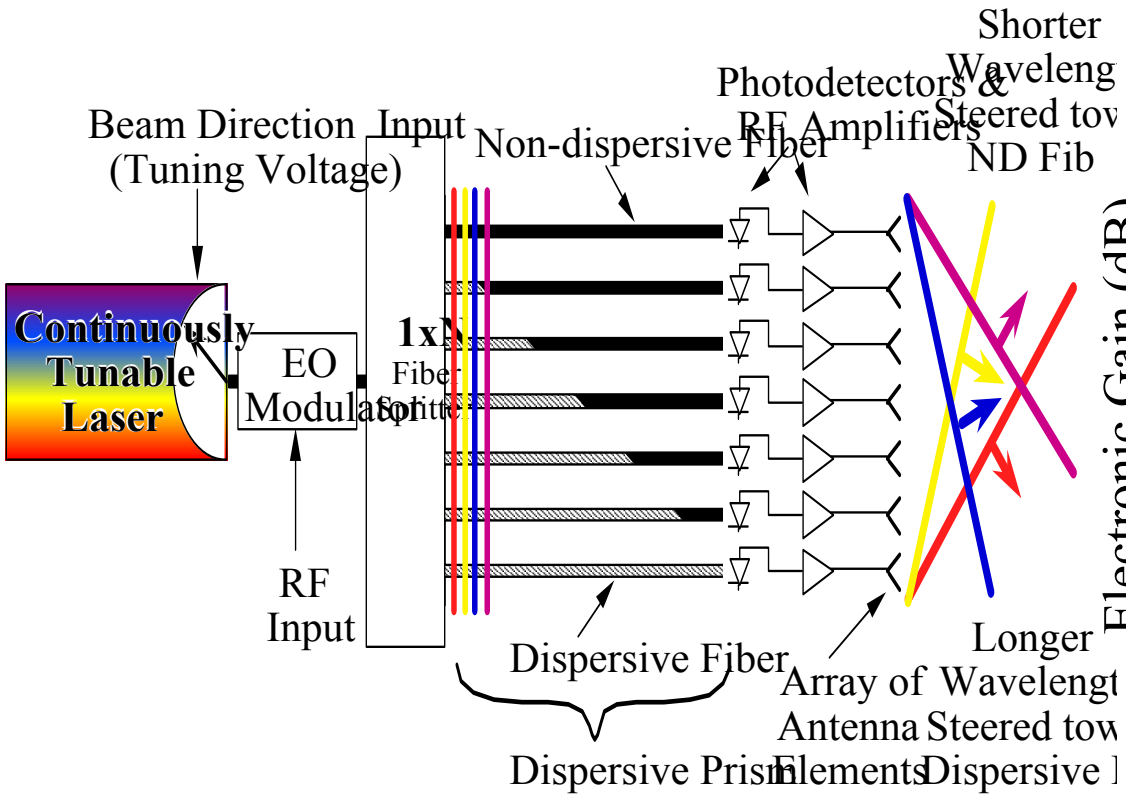
CDR

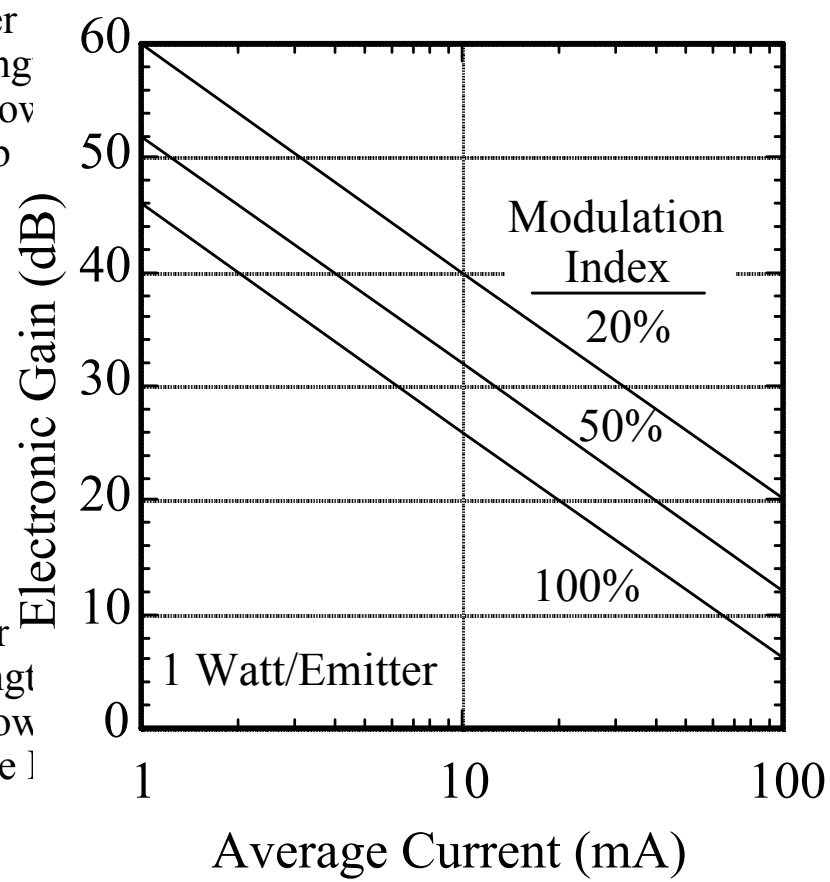


SFDR

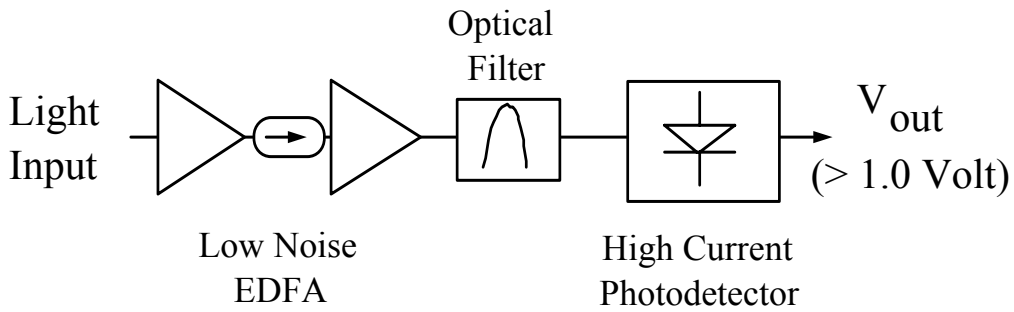


Minimizing Phase-Matched Electronic Gain

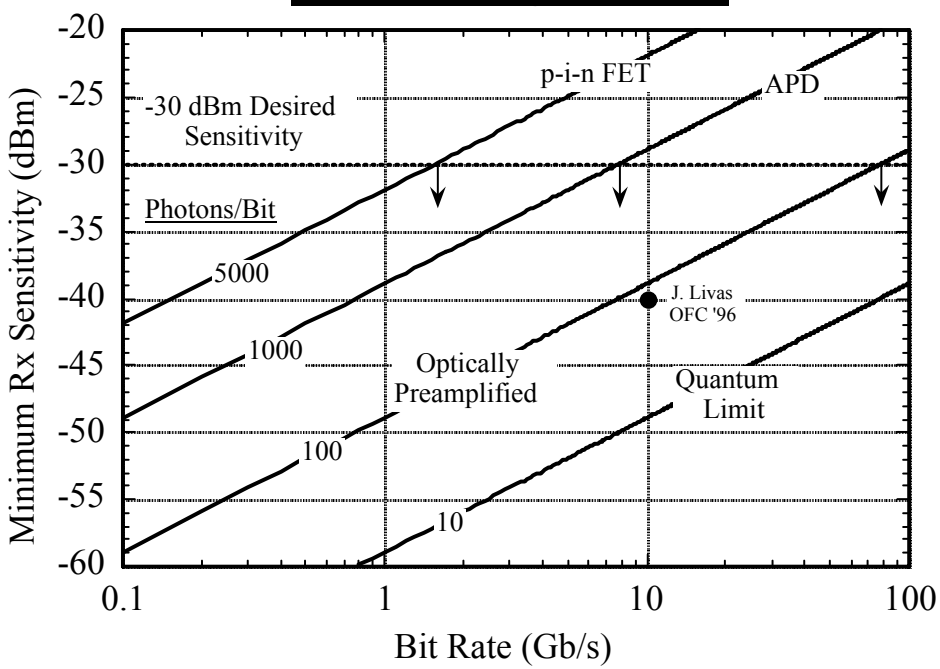




High Speed Digital Receivers

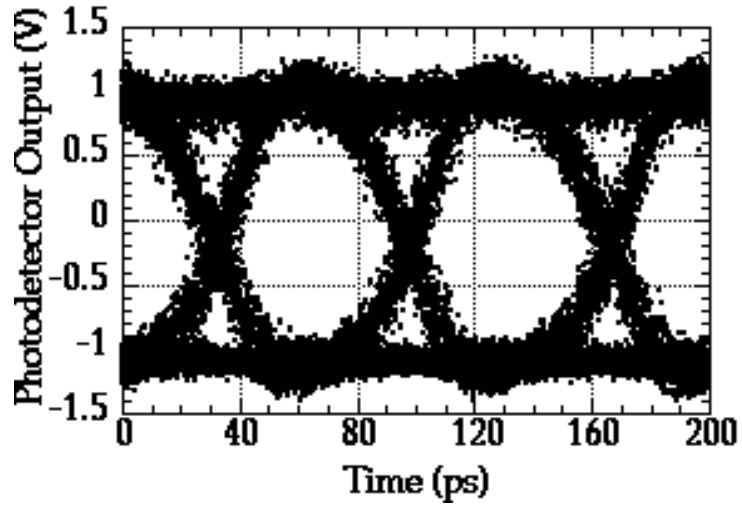


Sensitivity Limits

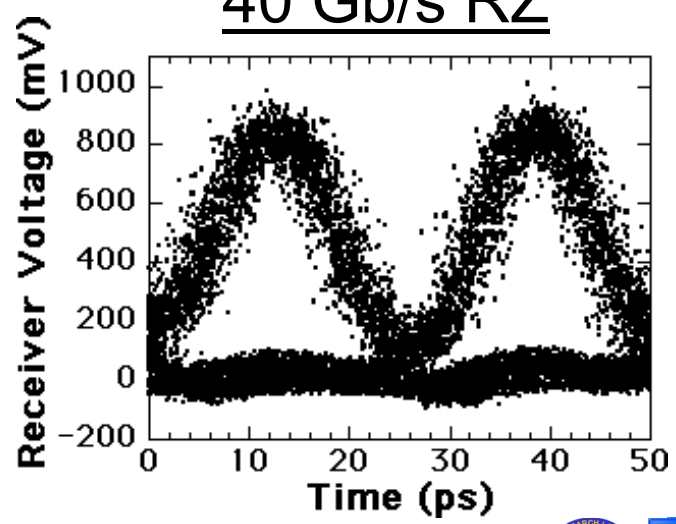


100 photons/bit = -42 dBm @ 10 Gb/s

15 Gb/s NRZ



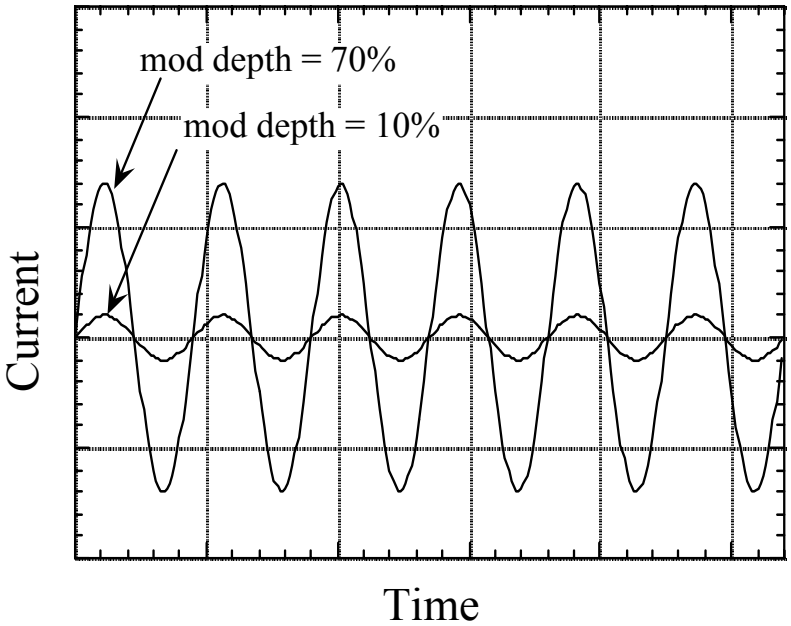
40 Gb/s RZ



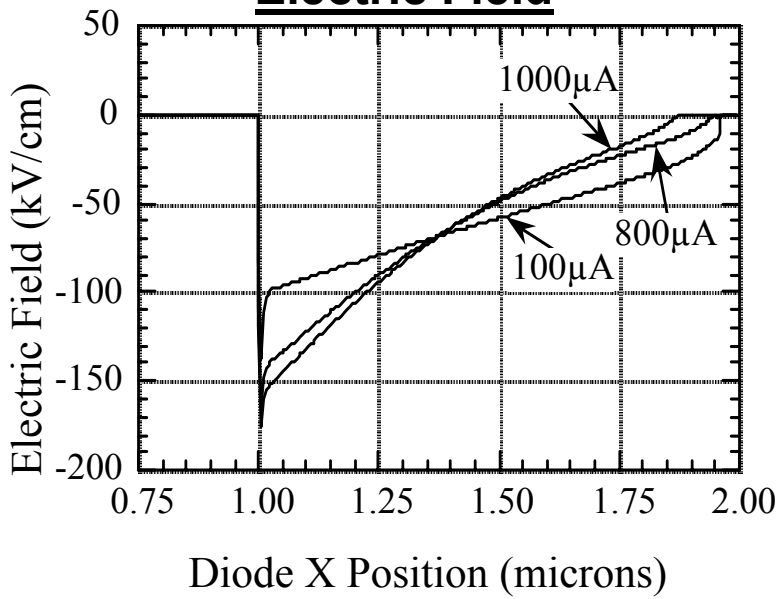
High Current Photodetector Design

Photodiode Compression

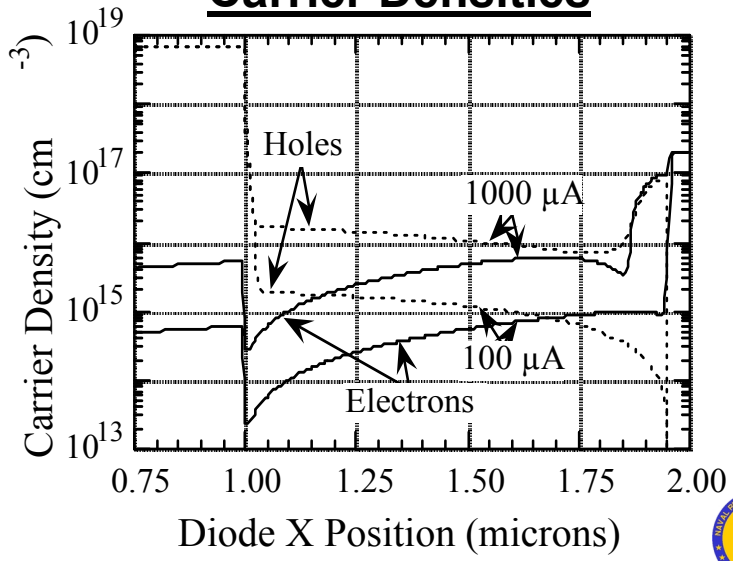
Large-Signal vs Small-Signal Modulation Conditions



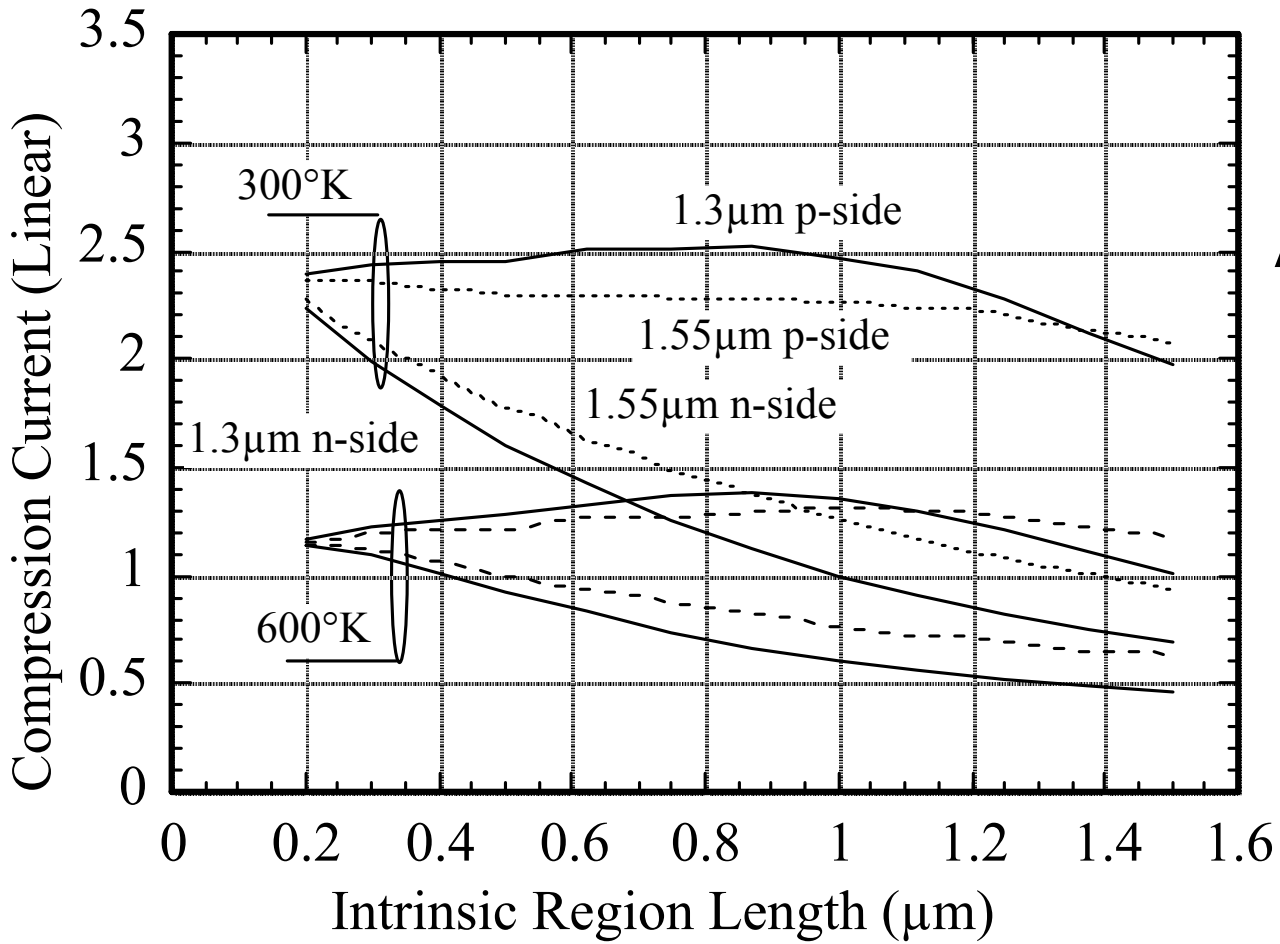
Electric Field



Carrier Densities



Space-Charge Effects - 20 GHz PDs

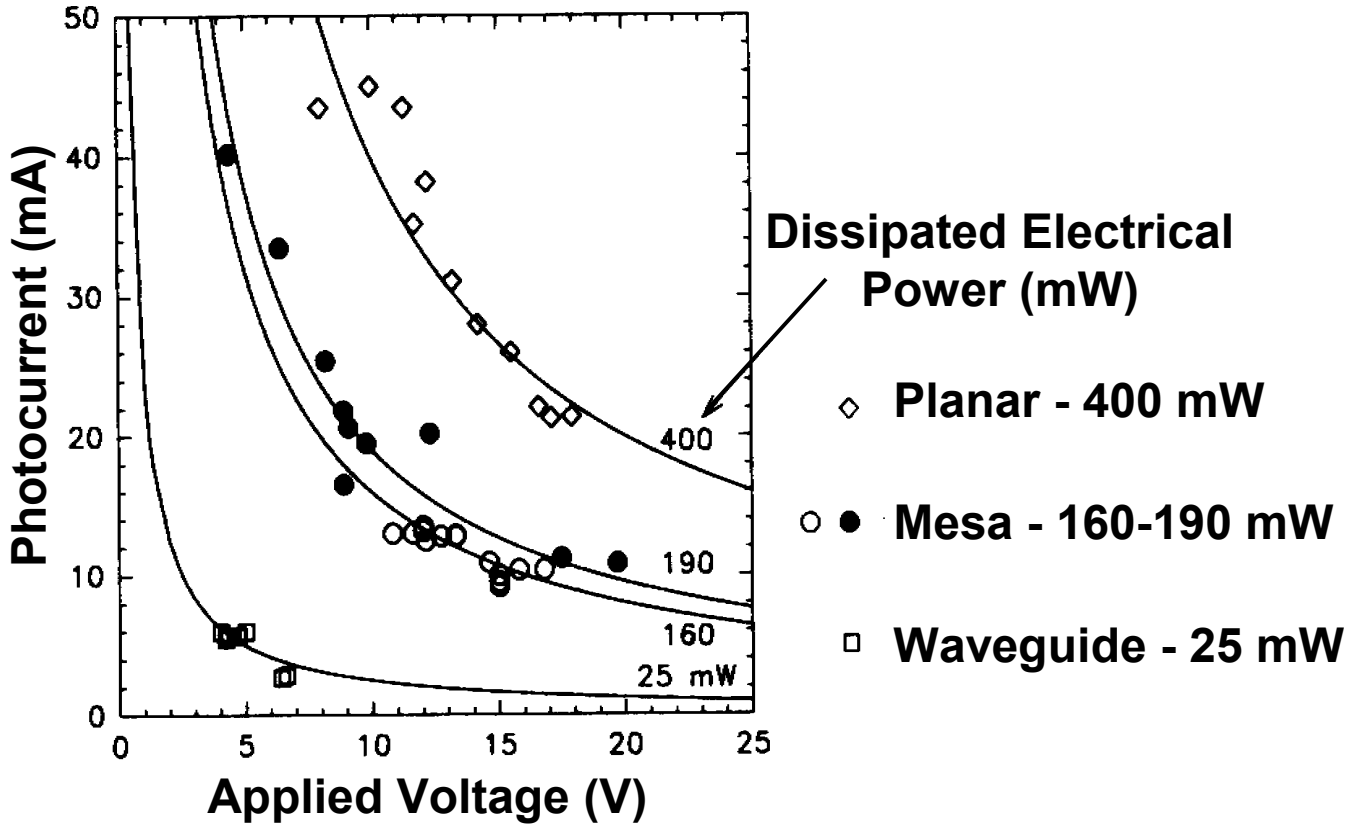


100% InGaAs Absorber

- Assumes Constant Electric Field Strength & Capacitively-Limited Bandwidth

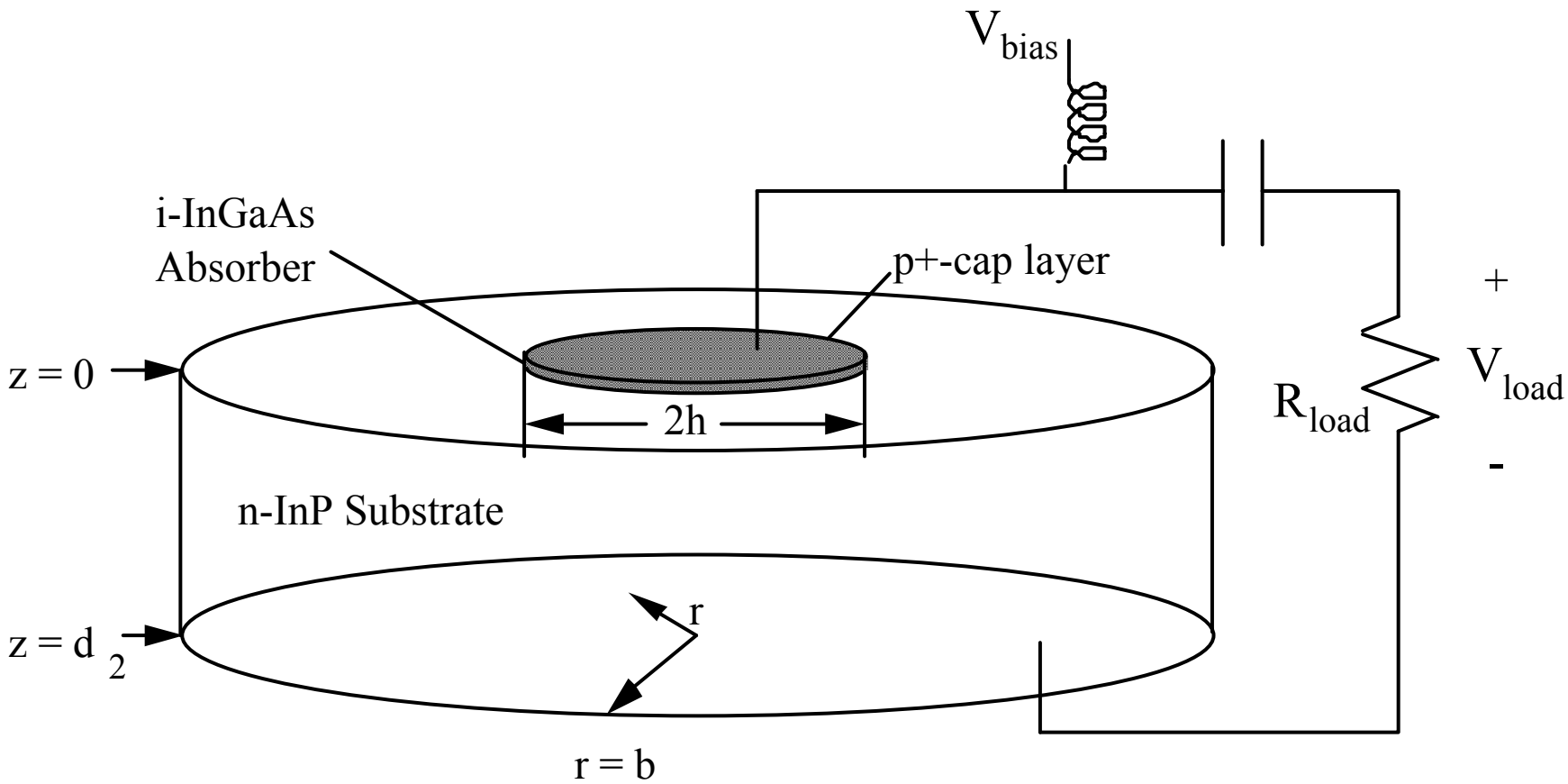
Electric Field ∝ Voltage/Length -> The 0.2 μm PD operates at 1/5 the Voltage (and Power) of the 1.0 μm PD

Thermal Failure



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

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:

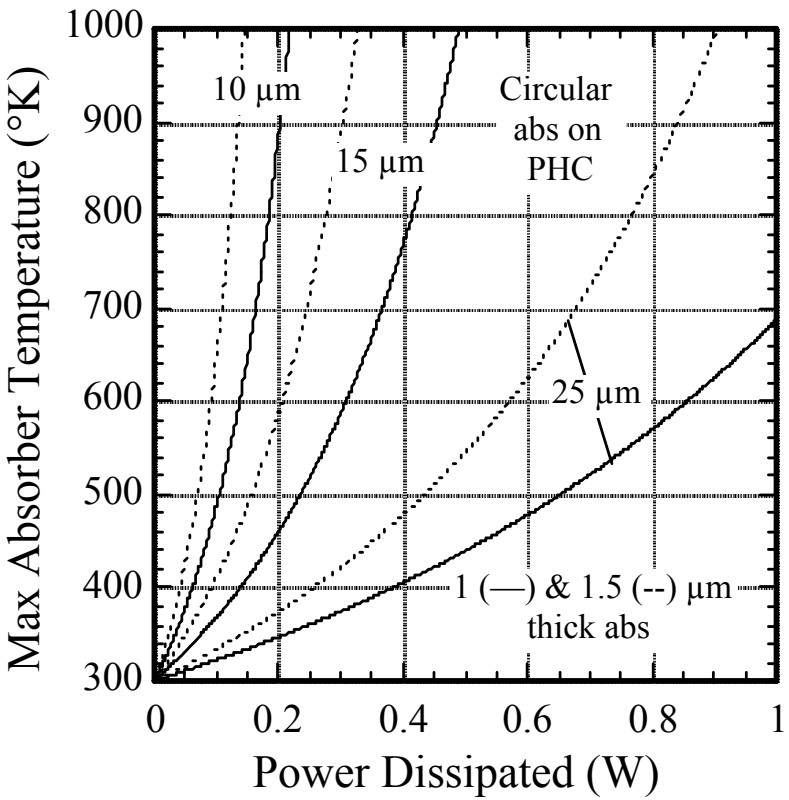
$$\theta_{sub}(r,z) = \frac{d_2}{k_2 \pi b^2} + \frac{2}{k_2 \pi h b^2} \sum_{l=1}^{\infty} \frac{\sinh(\varphi_1 (d_2 - z))}{\varphi_1^2 \cosh(\varphi_1 d_2)} \frac{J_1(\varphi_1 h) J_0(\varphi_1 r)}{J_0^2(\varphi_1 b)}$$

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
$J_1(\varphi_j b) = 0$

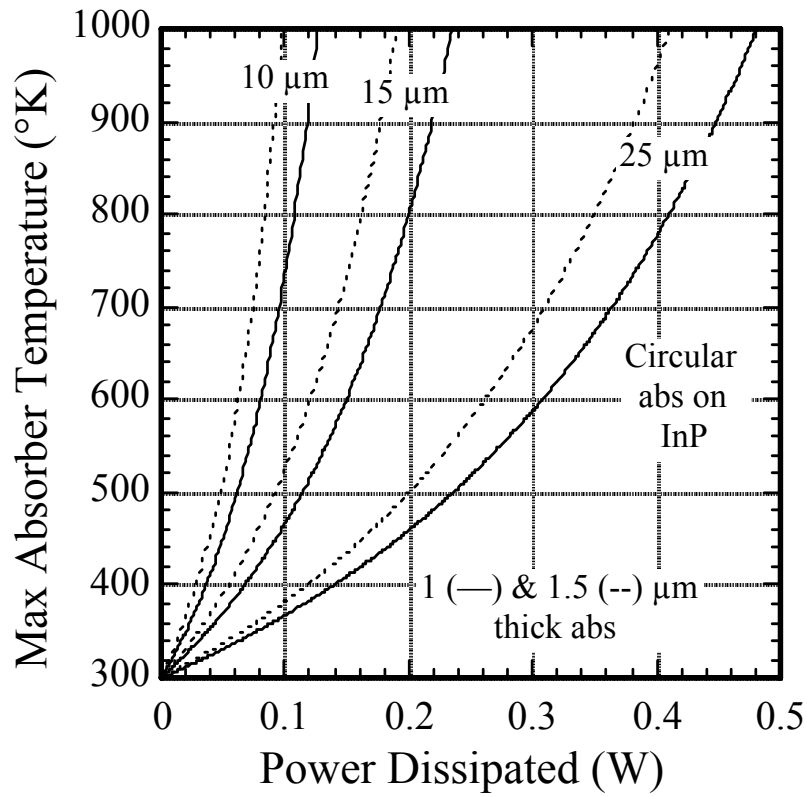
Maximum Possible Power Dissipation

InGaAs Absorber Only



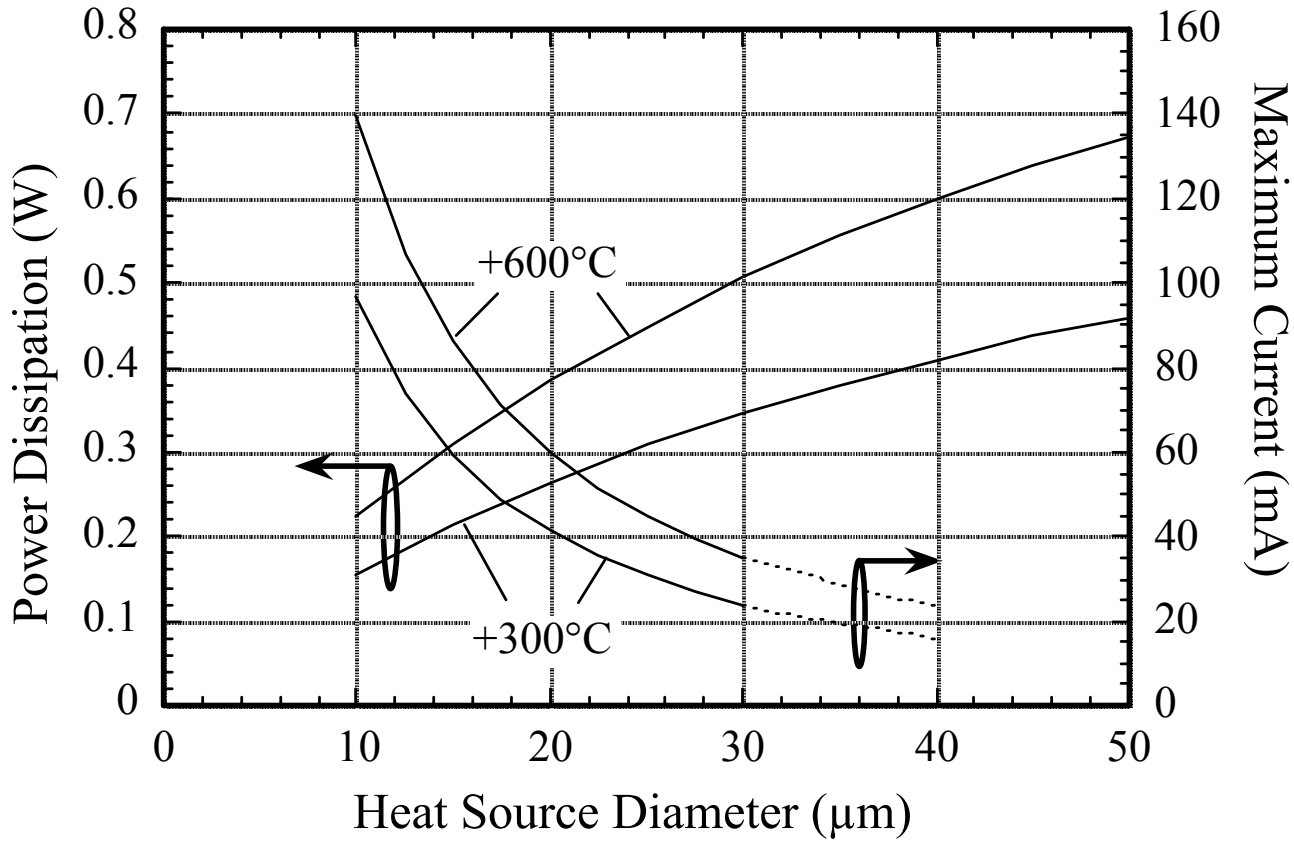
- Thermal Impedance ~ D/kA

InGaAs Absorber on InP



- Thermal Impedance ~ D/kA +1/kA

Geometry Optimization

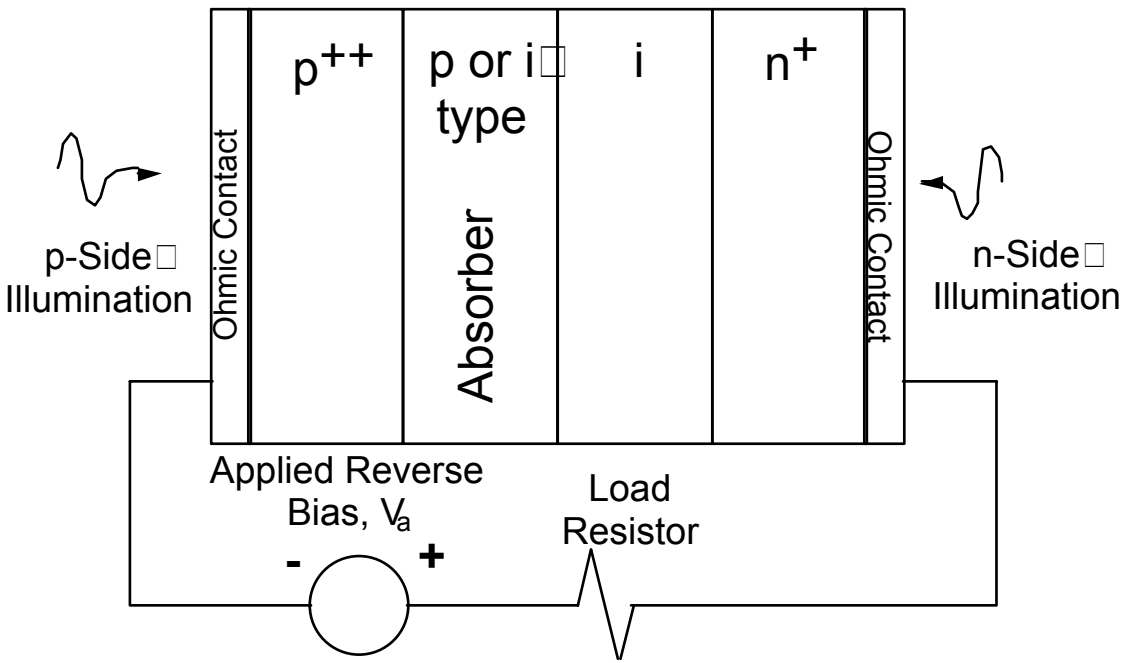


- Thinner, Thinner, Thinner
- Lower Quantum Efficiency
- Double- or Multi-Pass Absorbers

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

p-i-n Structures under Investigation



Conventional: p^{++} InGaAs or InP, i-InGaAs, n^{+} InP

Dual Depletion Region (DDR): i-InGaAs & i-InP

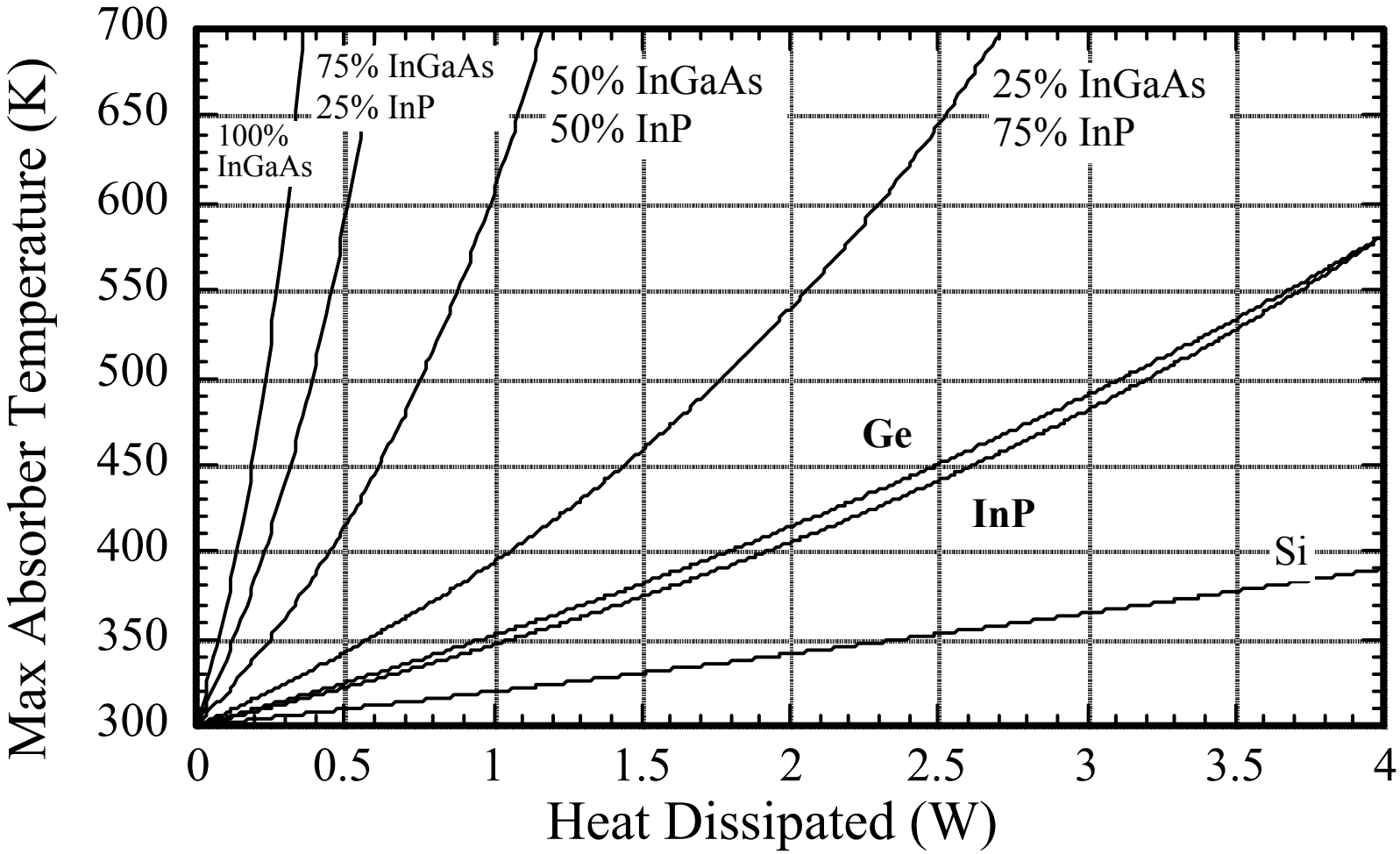
Uni-Traveling Carrier (UTC): p-InGaAs, i-InP or InAlAs

Germanium: Ge-pin

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)	10×10^6	6×10^6	15×10^6		
Hole Velocity @ E=20kV/cm (cm/s)	3×10^6	6×10^6			
Electron Velocity @ E=100 kV/cm (cm/s)	6×10^6	6×10^6	8×10^6		
Hole Velocity @ E=100 kV/cm (cm/s)	5×10^6	9×10^6			
Thermal Resistivity (¡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			

Other p-i-n Structures & Materials

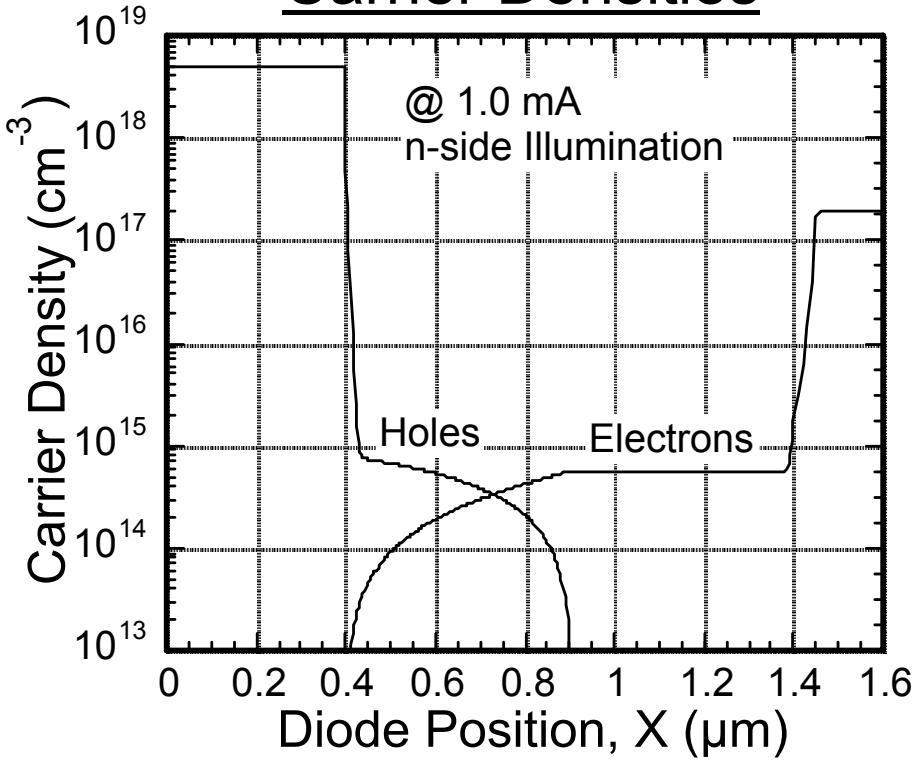


High Current Photodetector Design Optimization

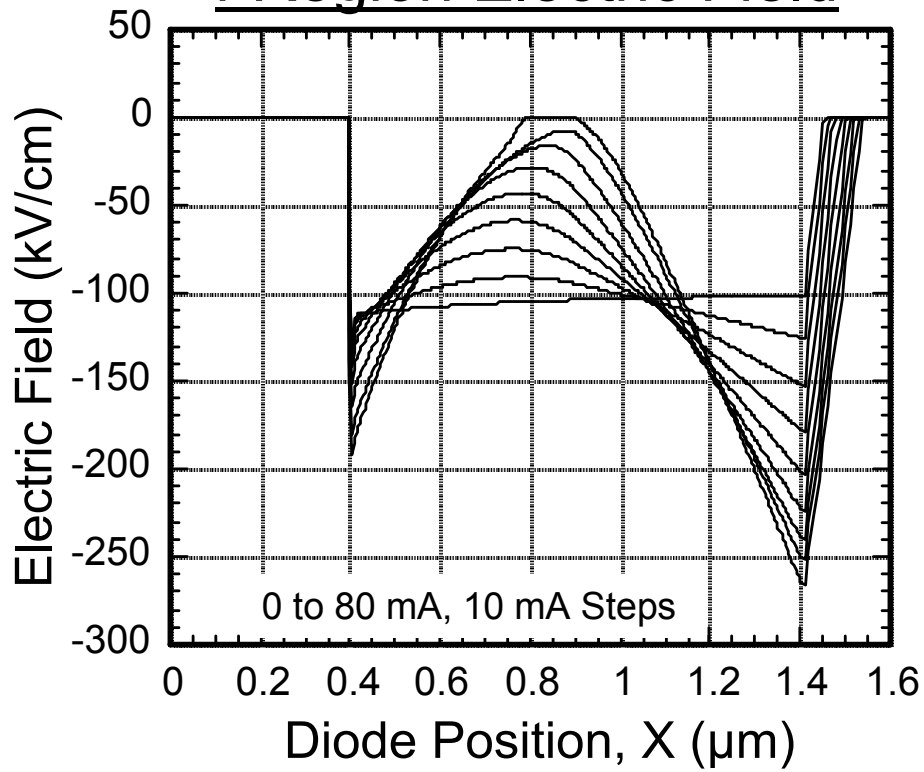
- Consider First a 20 GHz DDR PD
  - 25 µm Dia, 15 µm Spot Size, 1µm i-region length

Dual Depletion Region PD Simulations

Carrier Densities



i-Region Electric Field



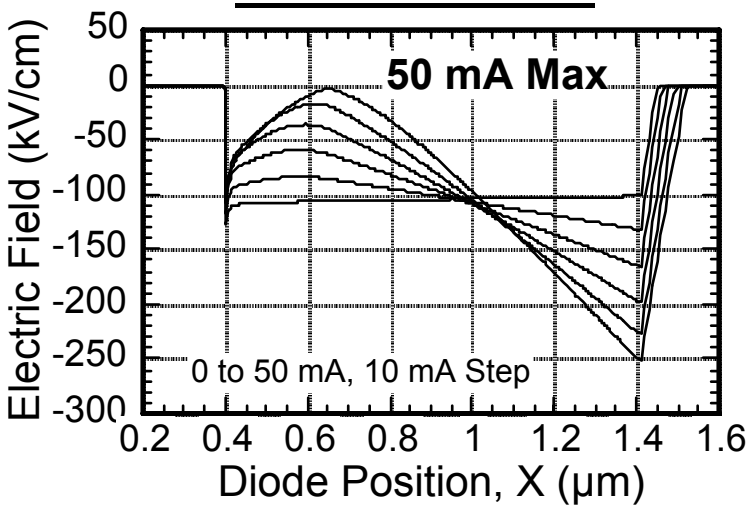
E-Field: $$\nabla \cdot E = \frac{q}{\varepsilon}\left(p - n + N_d - N_a\right)$$

- n-side Illuminated @ 1.3μm
- 50% InGaAs, 50% InP
- 25 μm Dia, 15 μm Spot Size
- 70 mA Maximum

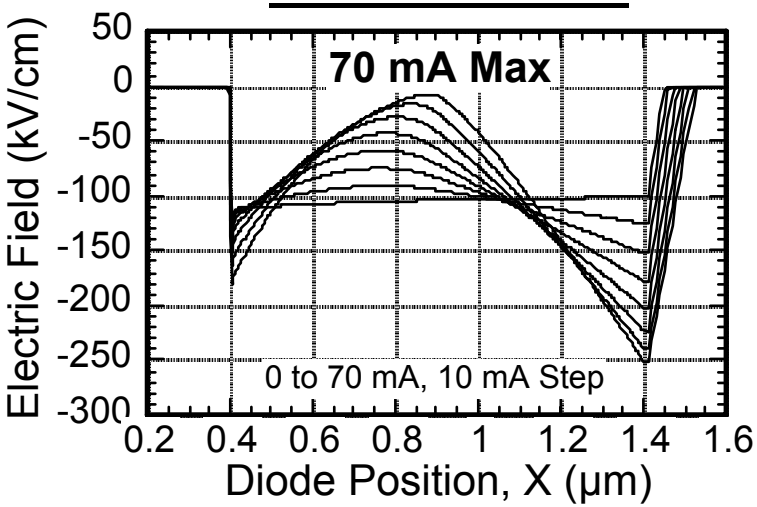
n-side Illuminated DDR PD Sims

NRL MICROWAVE PHOTONICS 5650

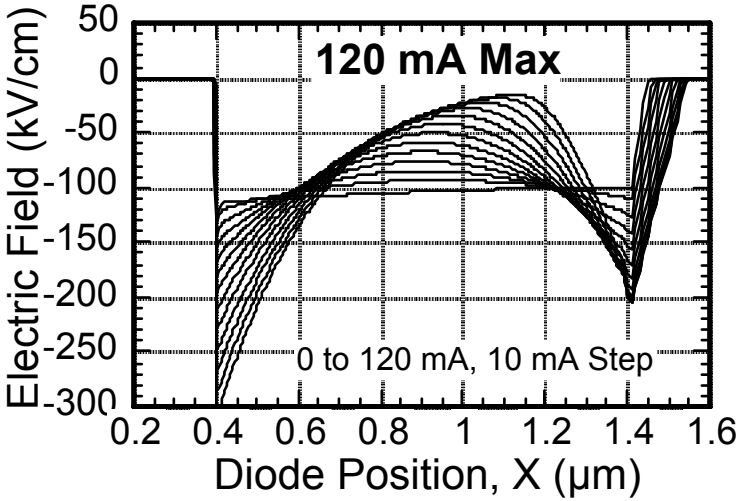
25% InGaAs



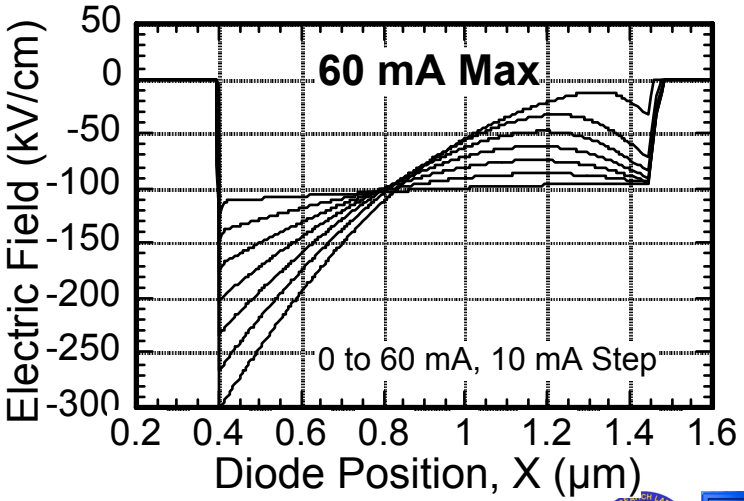
50% InGaAs



75% InGaAs

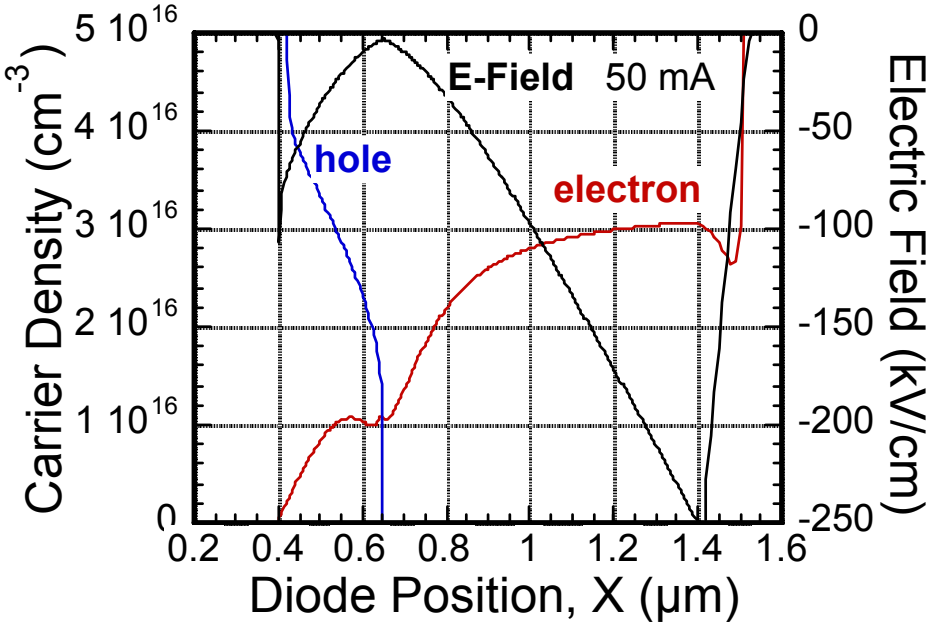


100% InGaAs

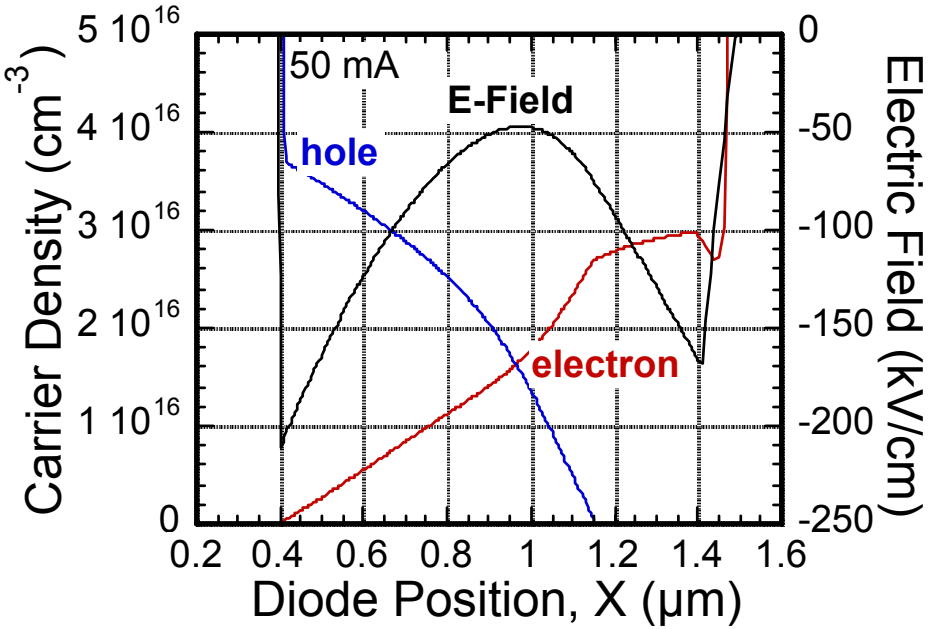


Designing for Maximum Current

25% InGaAs



75% InGaAs

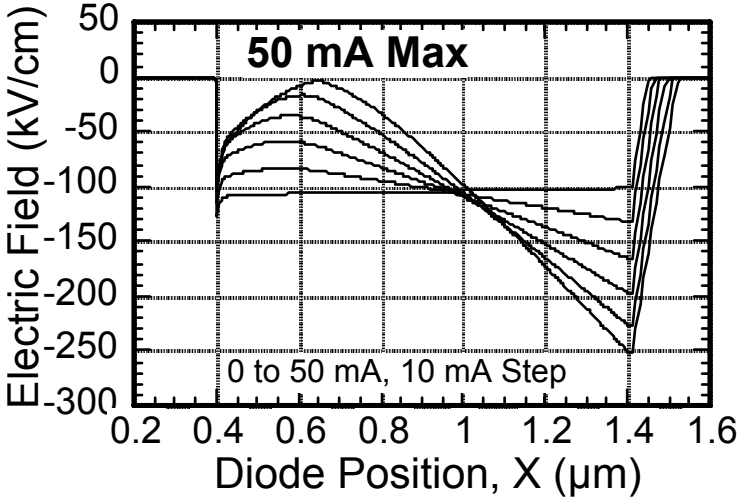


- Optimum design occurs when the shape of hole and electron densities distributions are equivalent (Equal numbers of holes and electrons in i-region)

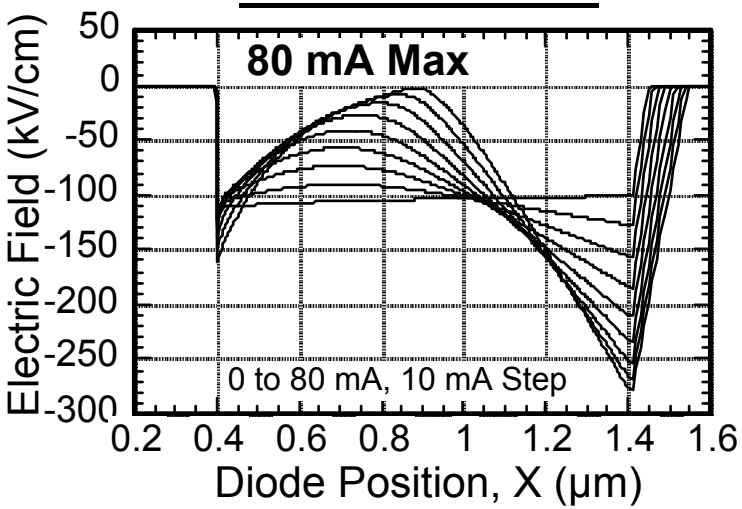
p-side Illuminated DDR PD Sims

NRL MICROWAVE PHOTONICS 5650

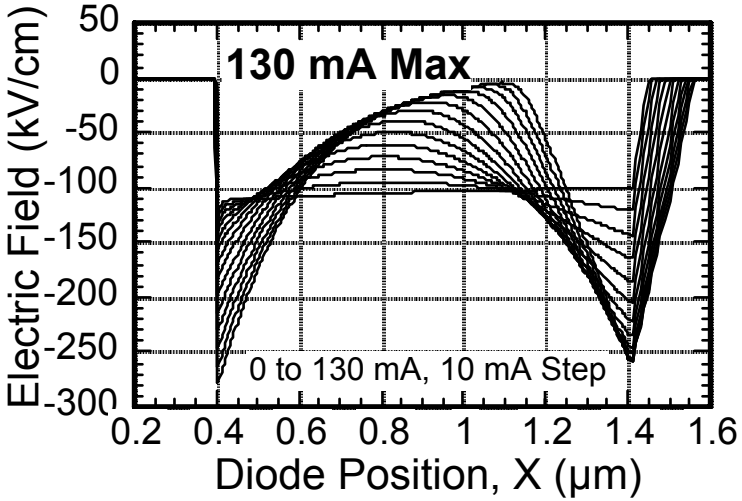
25% InGaAs



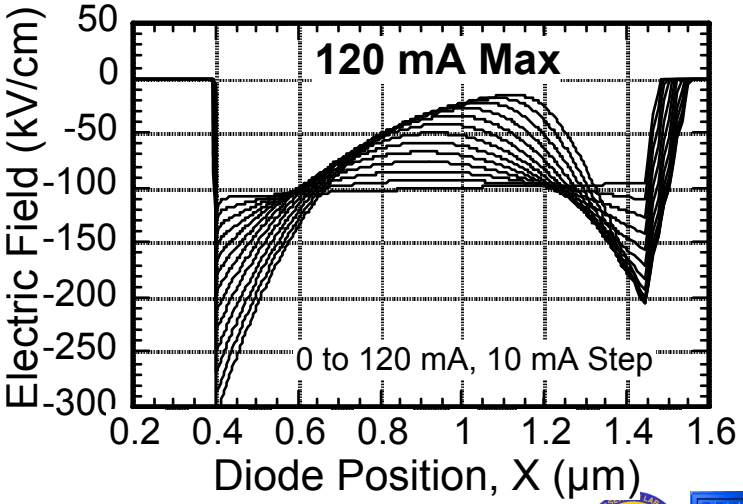
50% InGaAs



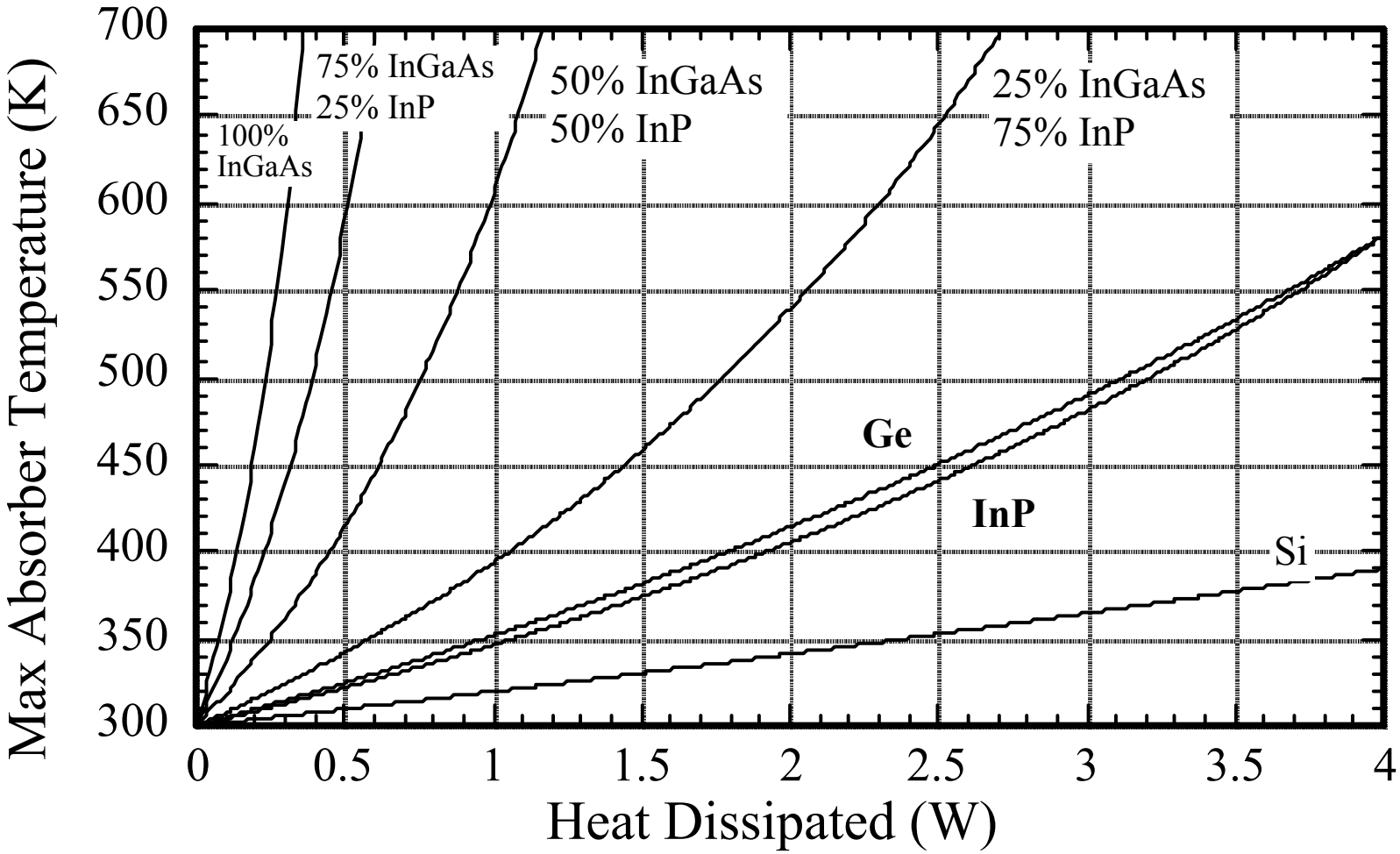
75% InGaAs



100% InGaAs



Other p-i-n Structures & Materials



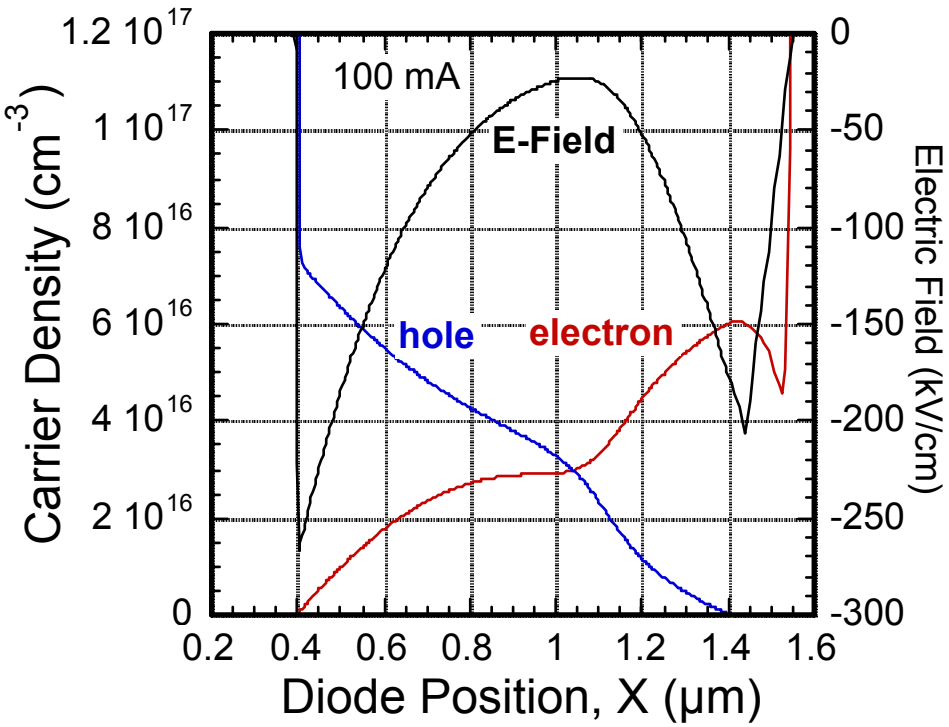
Preliminary Observations - InGaAs/InP

- Uni-Traveling Carrier (UTC) Design Less Desirable from Space-Charge Perspective
- Desire Charge Balance Within Intrinsic Region
- Need Some Intrinsic InP For High Electrical Power Handling (50-75% of i-region preferred for n-side illuminated) - Multipass or p-InGaAs to maintain QE
- n-side Illuminated DDR PDs may outperform p-side Illuminated Devices (more optimum for higher percentage of i-InP)
- Need Another Independent Variable for Optimization

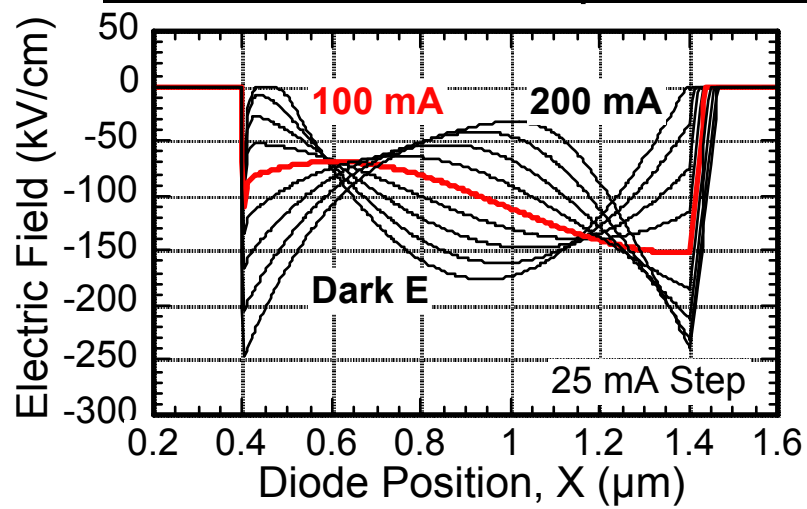
Charge Compensation - 100% InGaAs p-side

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

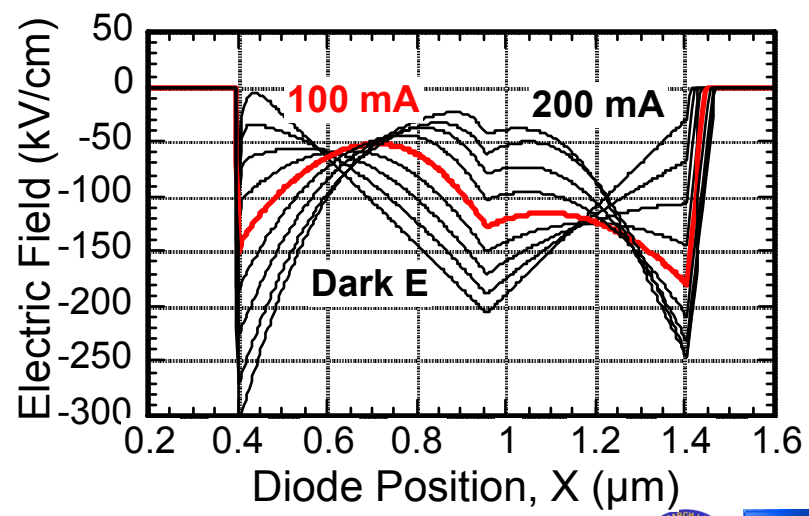
Uncompensated (Ndi = 10^{15})



100 mA Linear Compensation

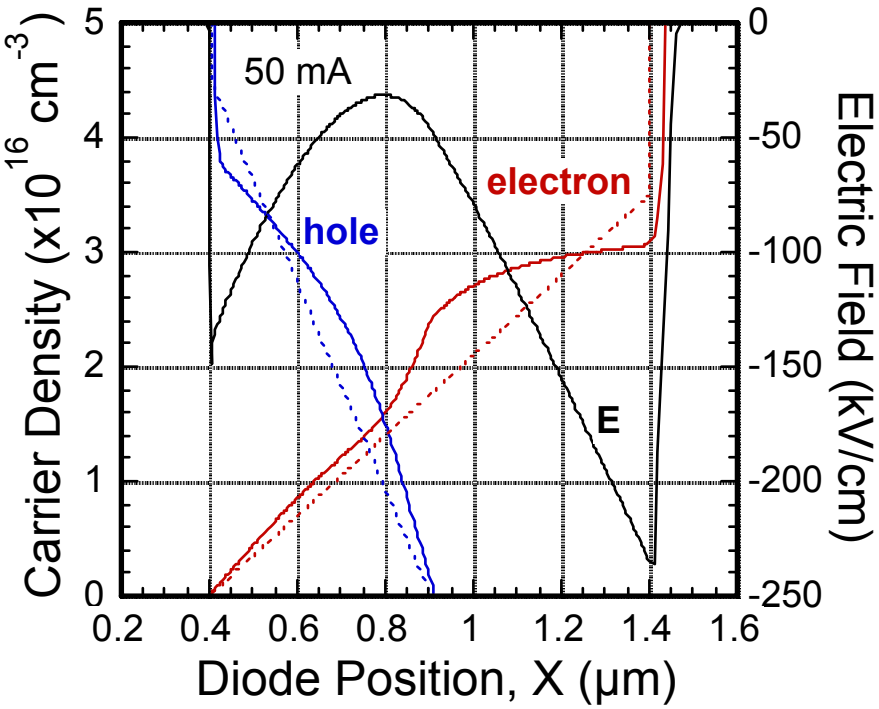


100 mA Constant Compensation

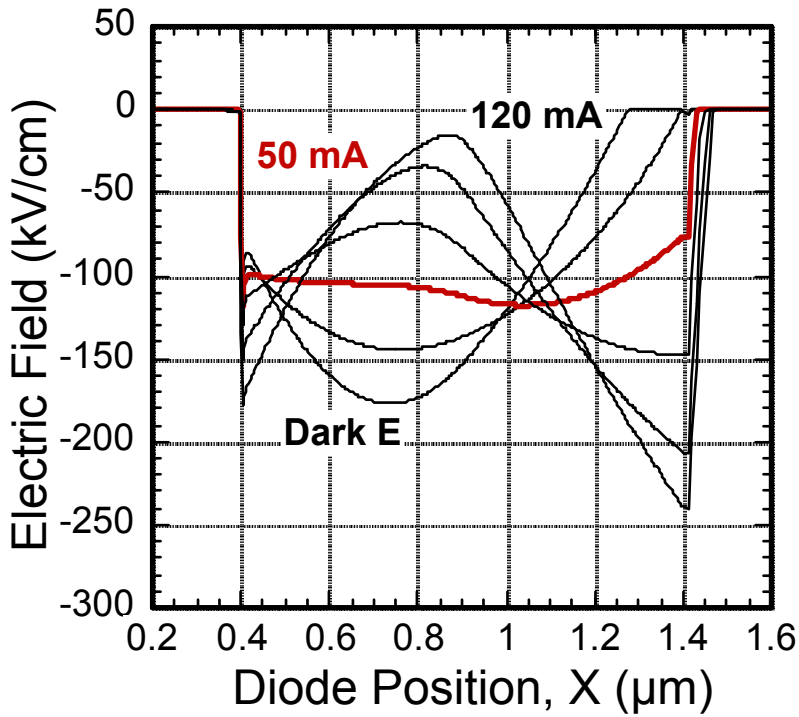


Charge Compensation - 50/50 InGaAs/InP

Uncompensated



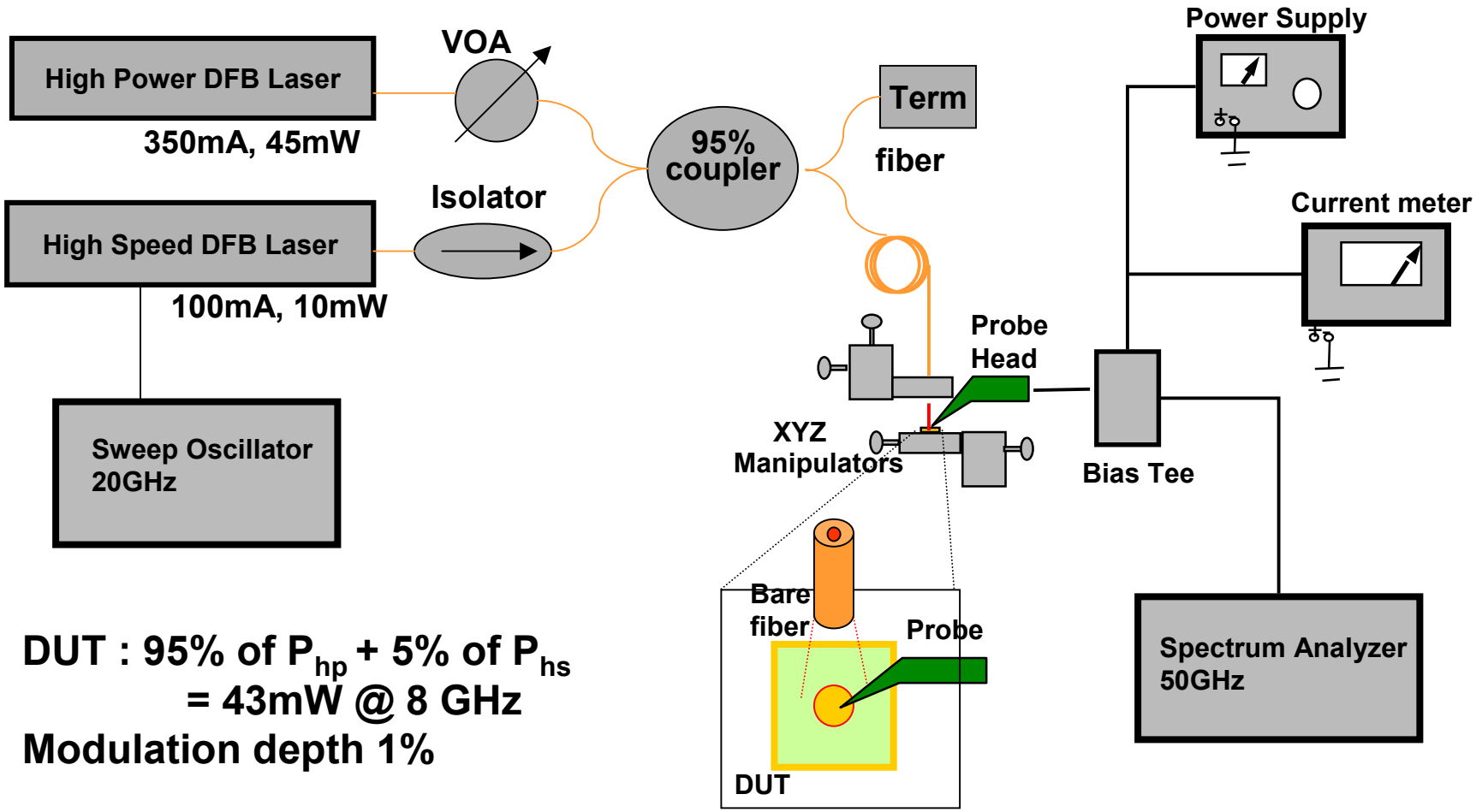
Linear Compensated



- Charge compensation can be used to approximately double photocurrent of uncompensated design
- Compensation can also be used to limit peak Electric Fields

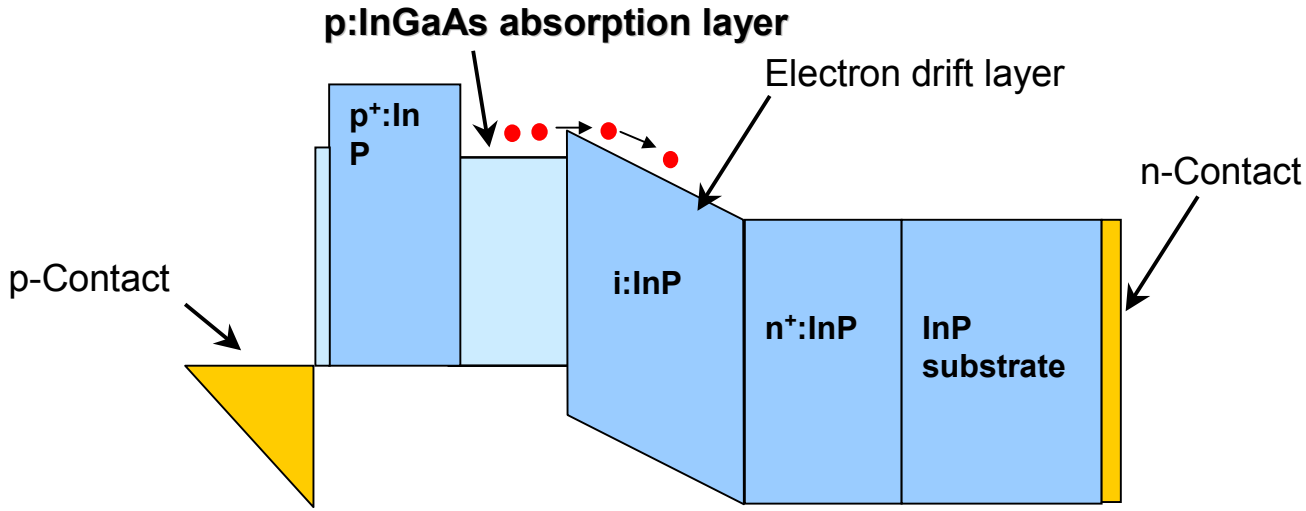
Fabrication of UTC Photodiodes

Saturation Current Measurement Setup



DUT : 95% of P_{hp} + 5% of P_{hs}
= 43mW @ 8 GHz
Modulation depth 1%

InP-Based UTC Photodiodes



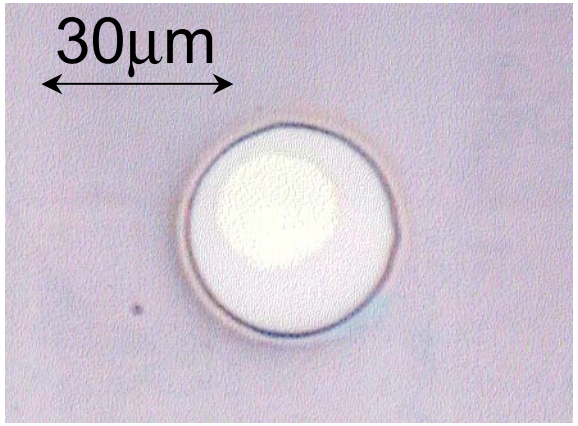
Single-carrier (electron) transport

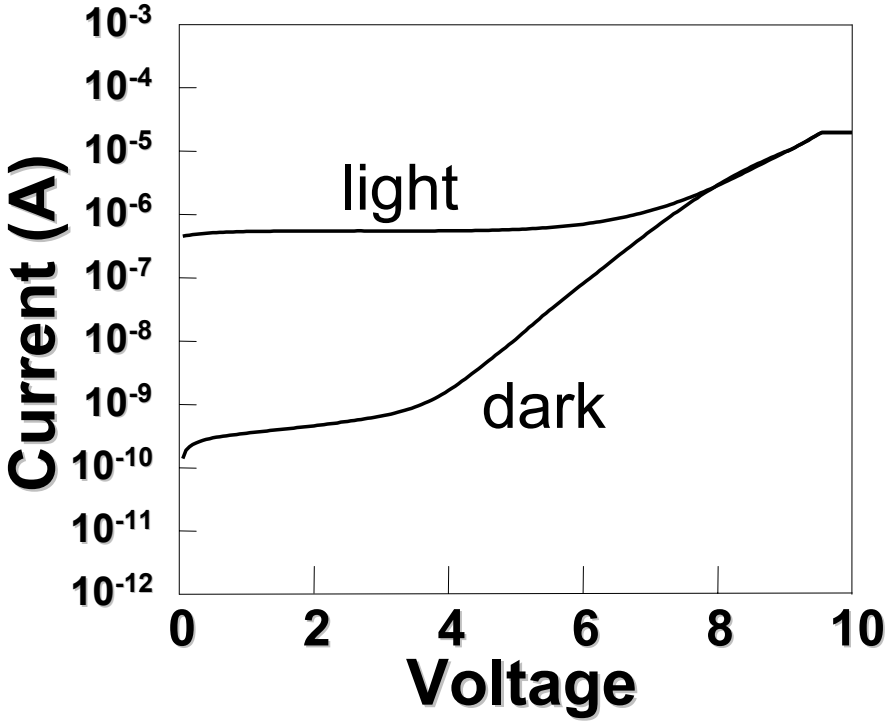
High Speed

High Electrical Power Dissipation Levels

InP-Based UTC Photodiodes

30nm InGaAs p^+:1×10^{19}
500nm InP p^+:1×10^{19}
200nm InGaAs p:2×10^{18}
200nm InP "i"< 5×10^{15}
700nm InP n^+:1×10^{19}
n+:InP substrate



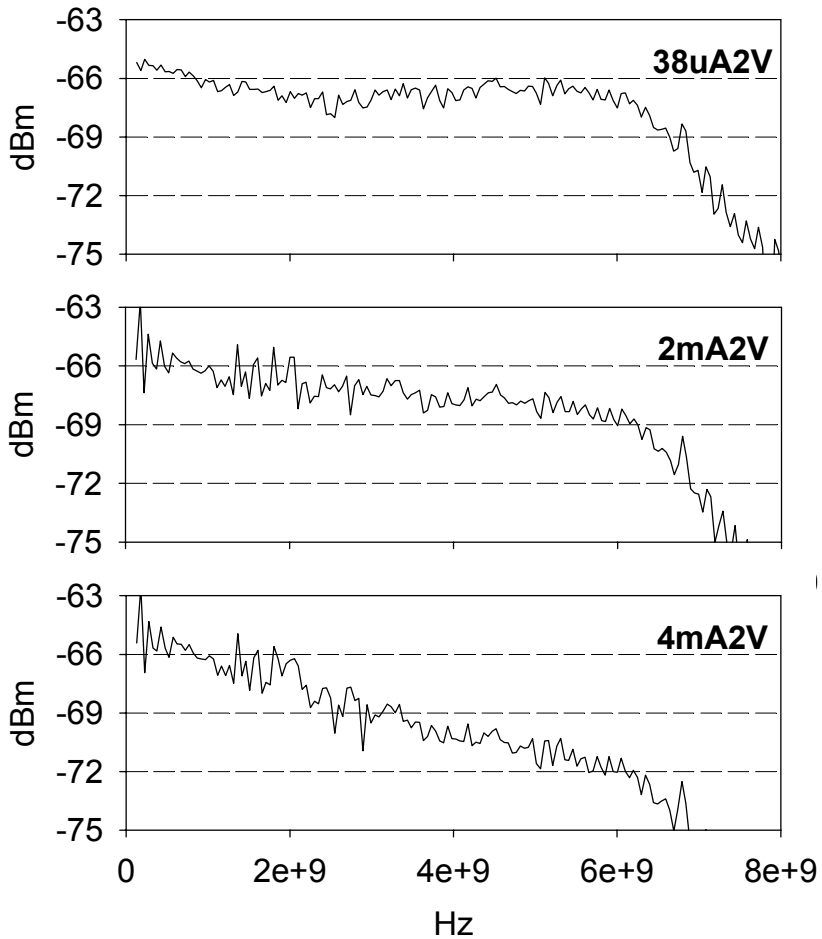


Saturation characteristics of InP UTC PIN

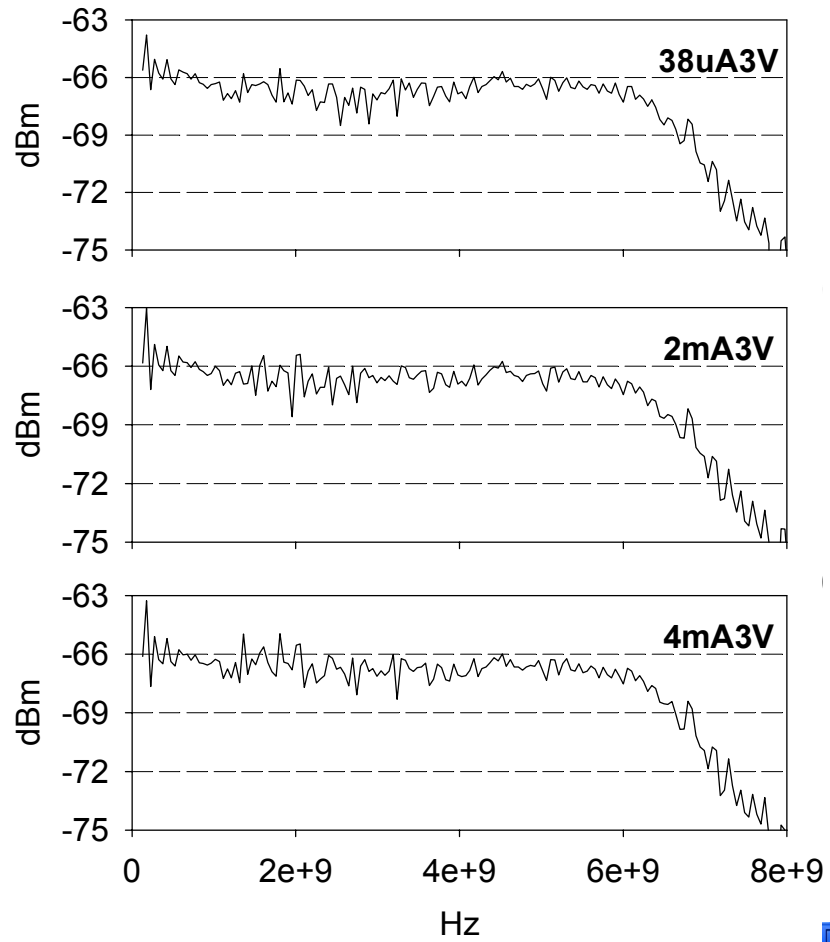
NRL MICROWAVE PHOTONICS 5650

Diameter = 30 μm
"i" layer thickness = 0.2 μm

Saturation begins at 2mA @ 2V

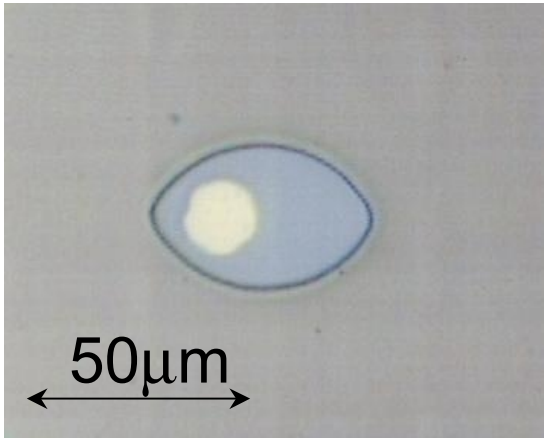


Saturation begins at 4mA @ 3V

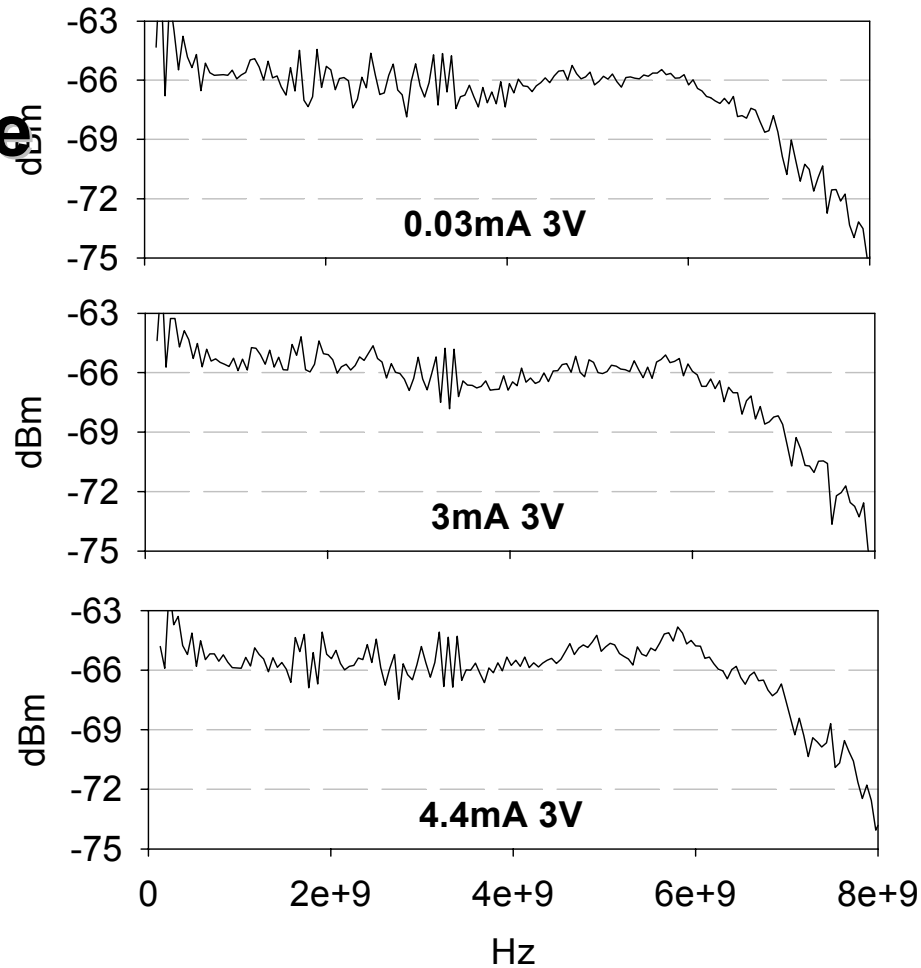


Saturation characteristics of InP UTC PIN

Eye-shaped structure



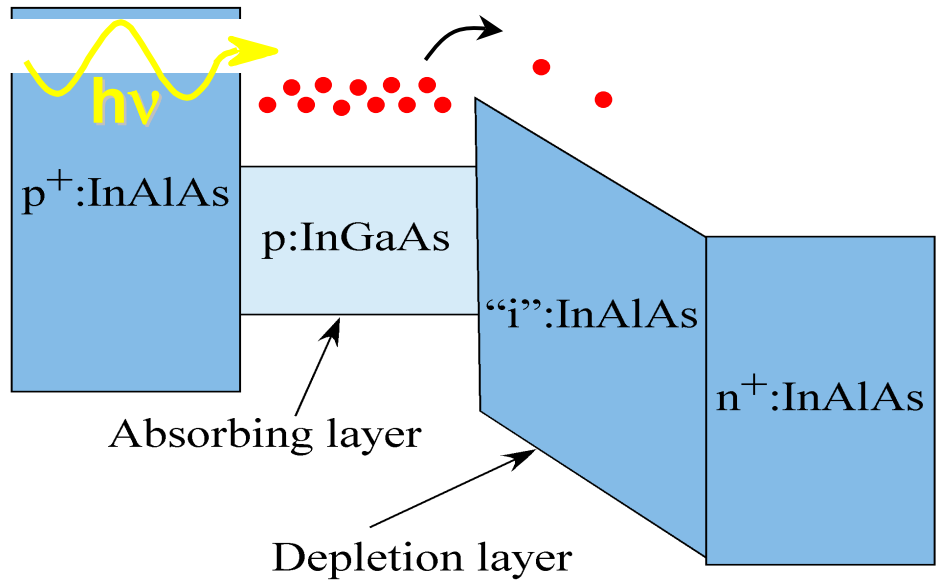
4.4mA at 7GHz without saturation

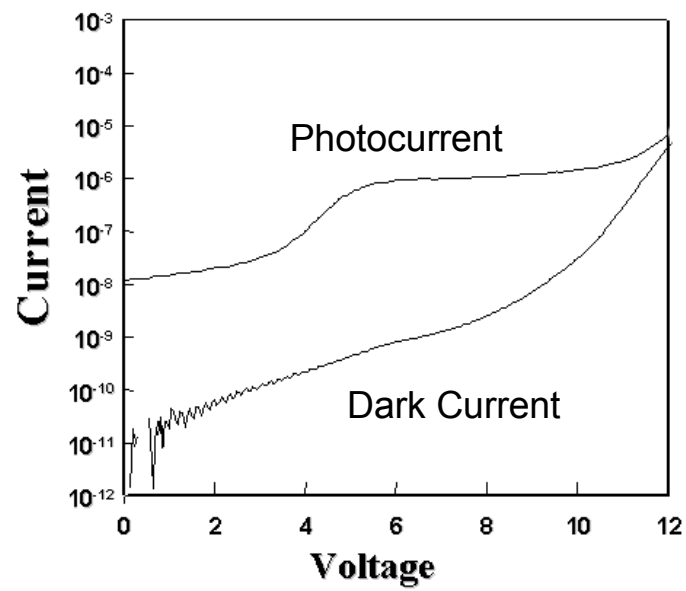


$In_{0.48}Al_{0.52}As$-based UTC PIN

NRL MICROWAVE PHOTONICS 5650

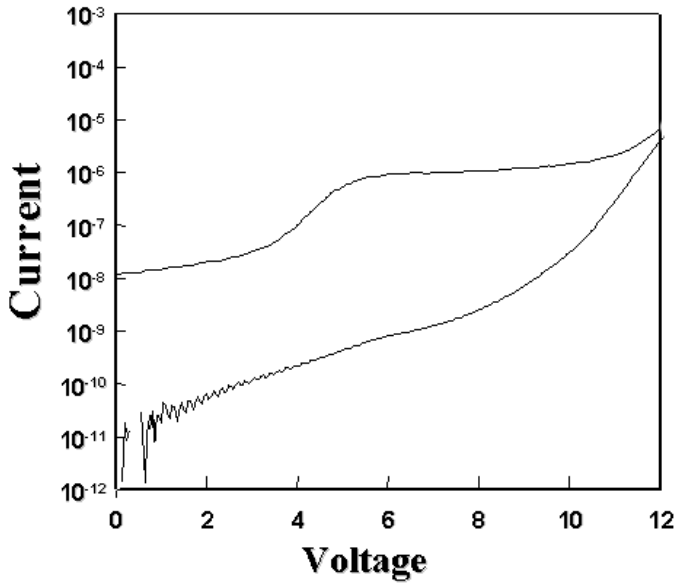
30nm $In_{0.53}Ga_{0.47}As$ p^+:1×10^{19}
500nm $In_{0.52}Al_{0.48}As$ p^+:1×10^{19}
500nm $In_{0.53}Ga_{0.47}As$ p:2×10^{18}
200nm $In_{0.52}Al_{0.48}As$ "i"< 5×10^{15}
700nm $In_{0.52}Al_{0.48}As$ n^+:1×10^{19}
n^+:InP substrate

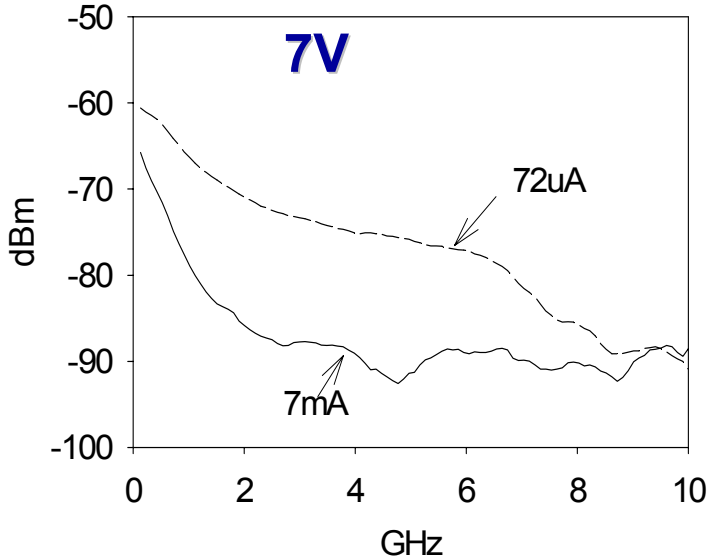


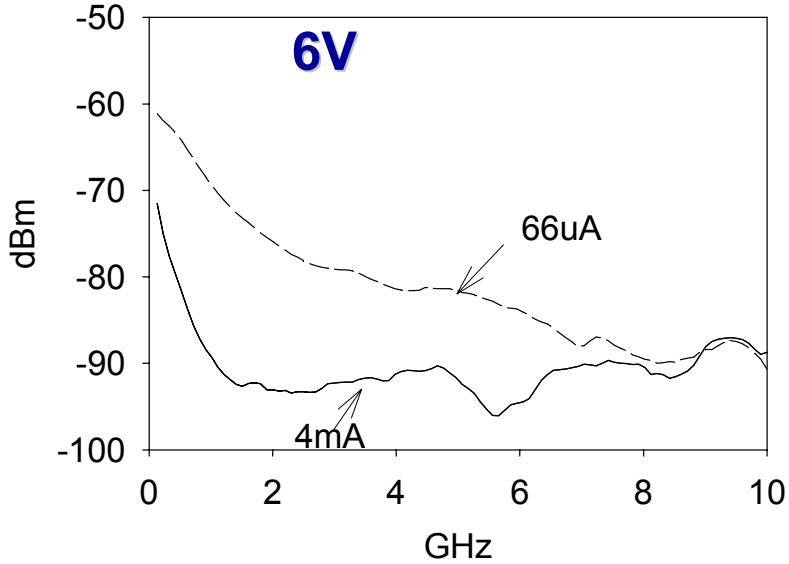


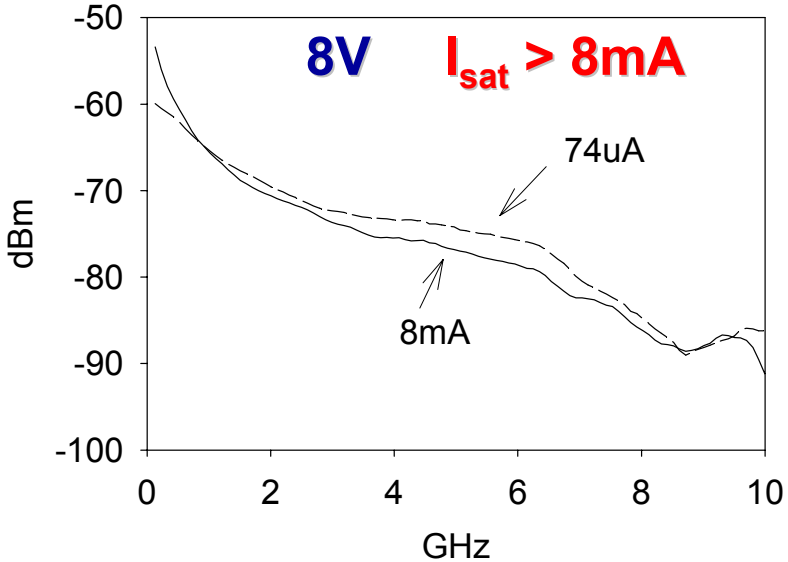
$In_{0.48}Al_{0.52}As$-based UTC PIN

NRL MICROWAVE PHOTONICS 5650

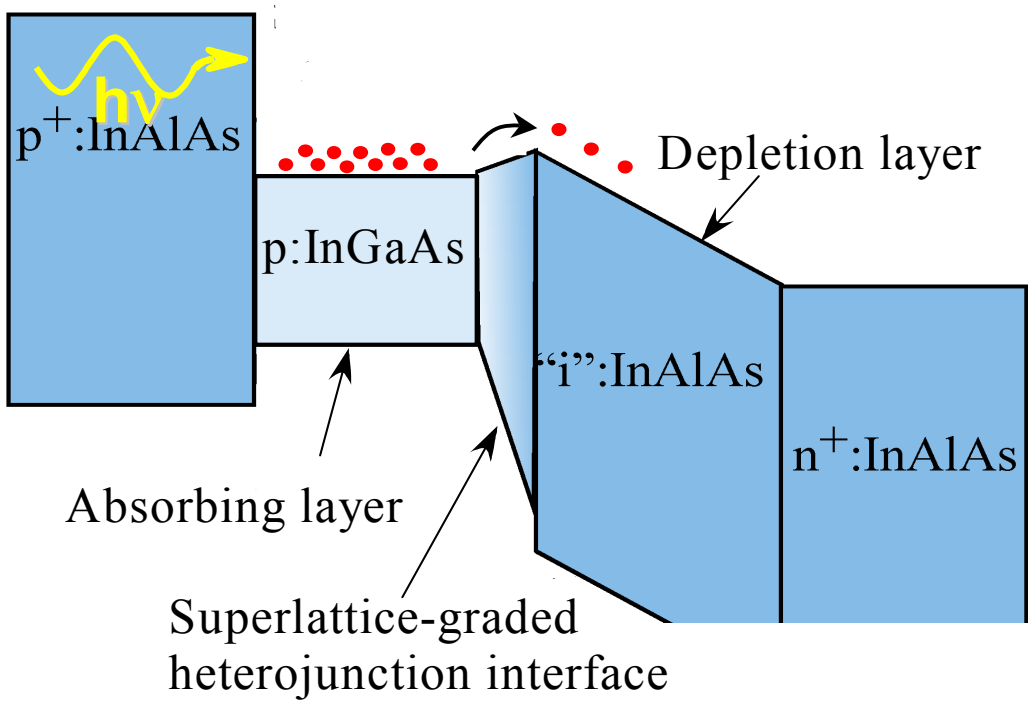


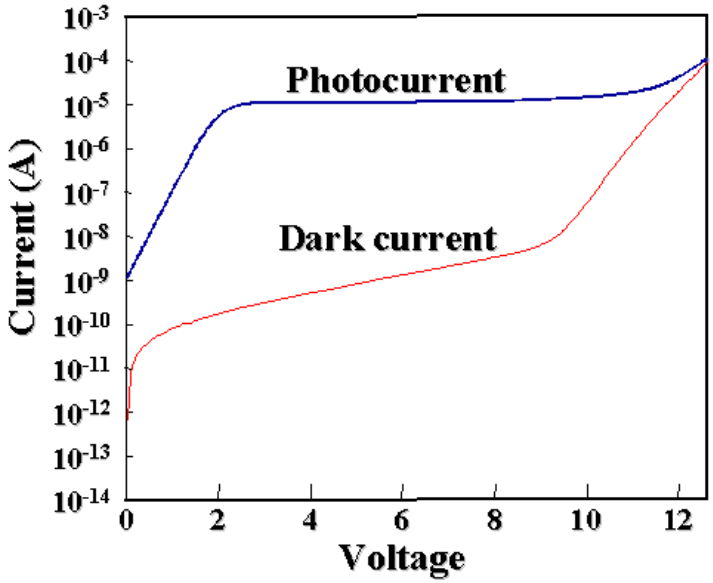




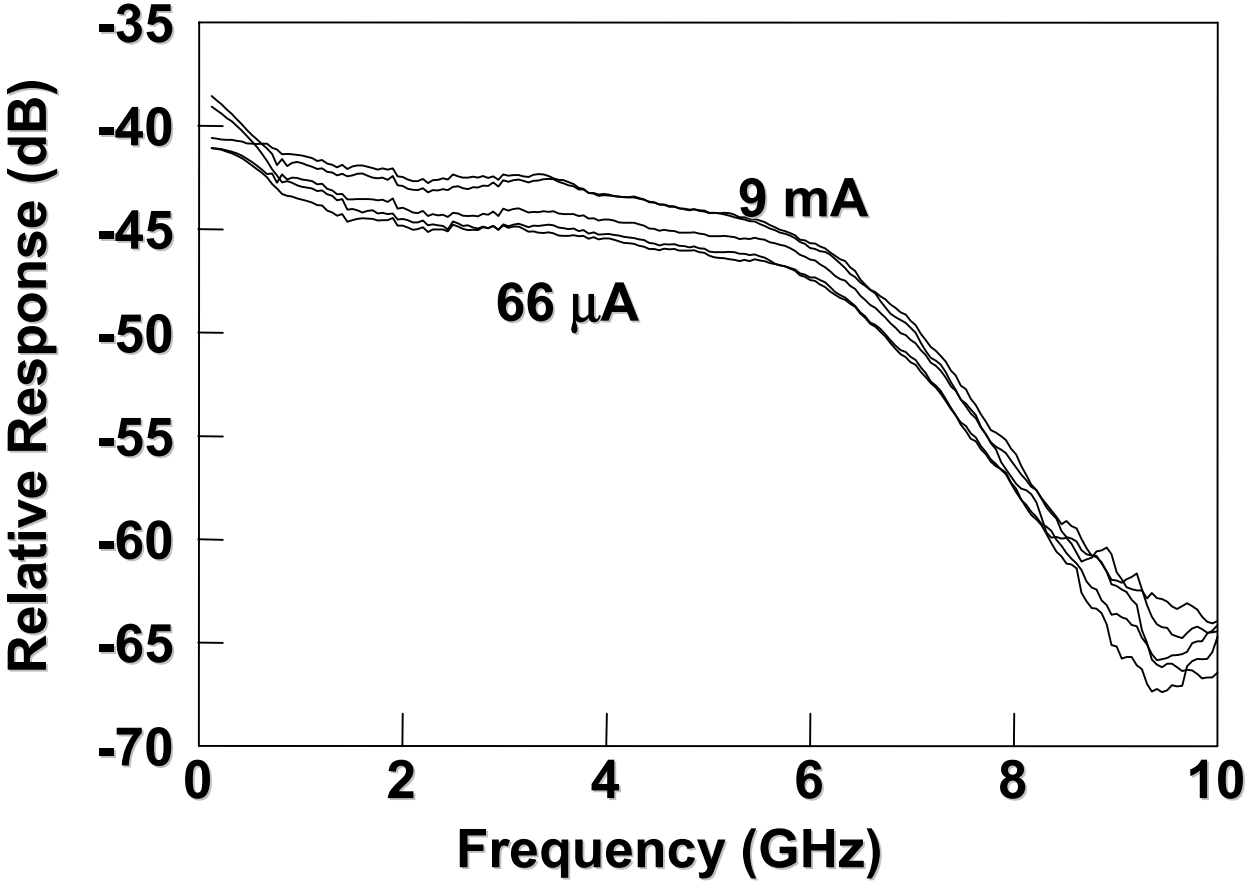


InAlAs UTC PIN with Graded Heterojunction Interface



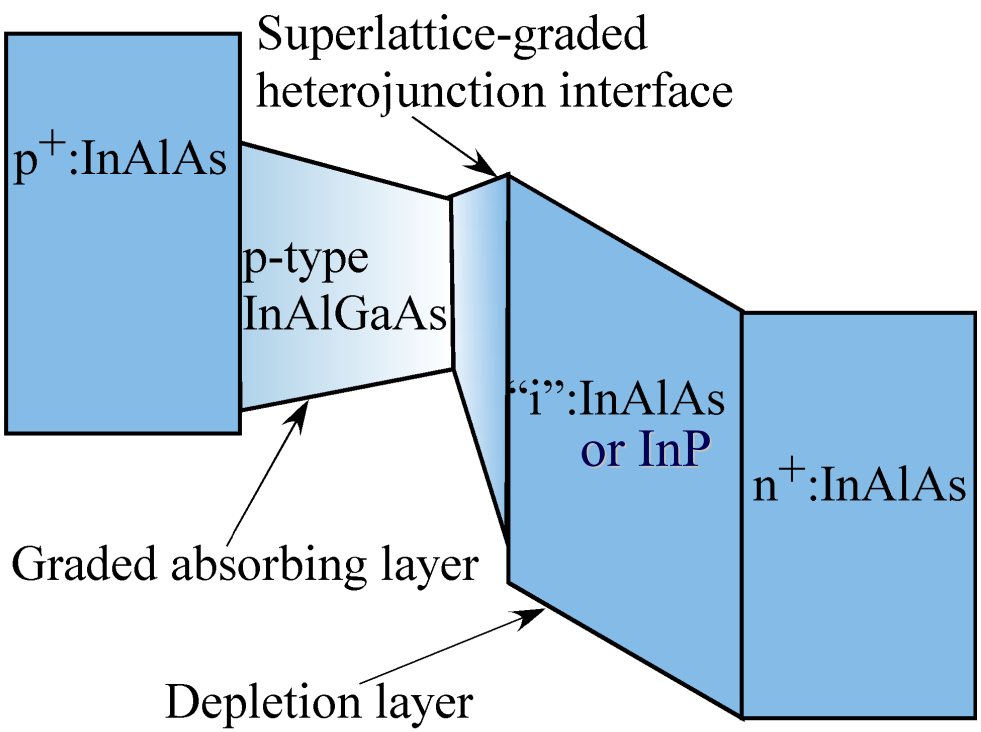


InAlAs UTC PIN with Graded Heterojunction Interface



Saturation current > 9 mA at 7 GHz

InAlAs UTC PIN with Graded Interface and Absorption Layer



Graded absorption layer

↓

Increase the electron velocity

↓

Higher bandwidths

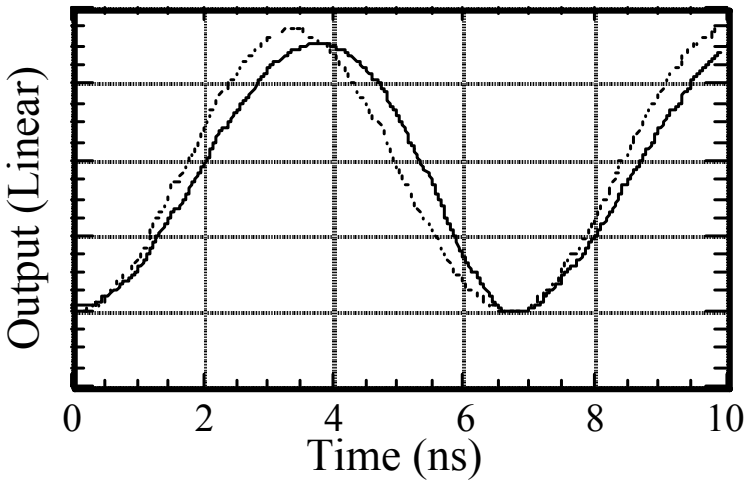
Linear Photodetection

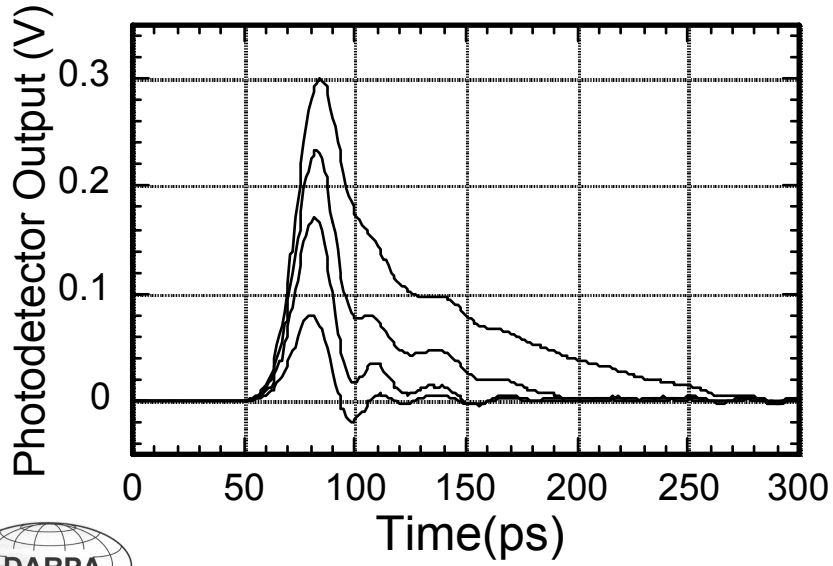
Nonlinear Mechanisms

Mechanism	Included in Present 1-D Model
Space-Charge Electric Fields	Yes
Scattering - Lower Carrier Mobilities	Yes
Loading in the External Circuit	Yes
Generation in Undepleted Regions	Yes
Diffusion	Yes
Trapping	Partial
Heterojunctions	Partial
Finite Carrier Acceleration Time	No
Transient Temperature Rise	No
Carrier Bleaching	No
Free Carrier Absorption	No

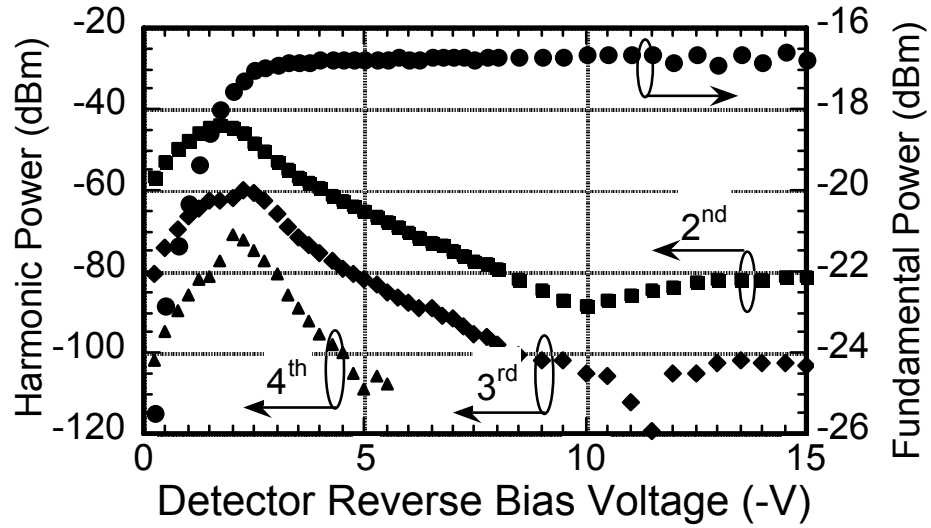
Photodetector Nonlinearities

Space-Charge-Induced Time Delay

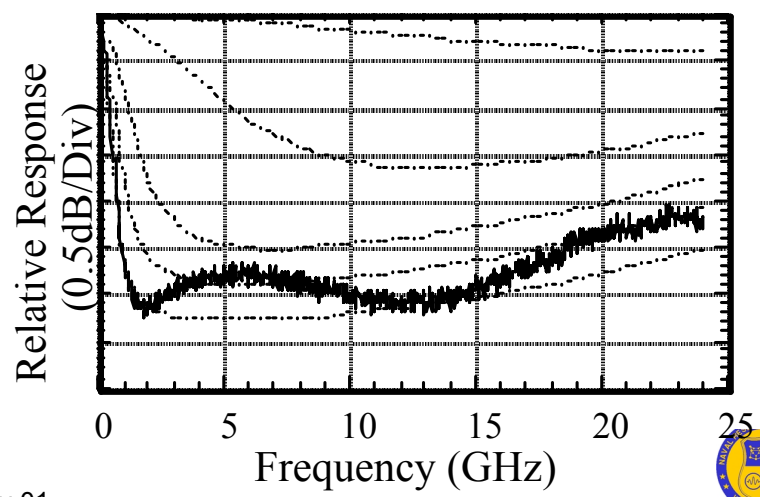




Harmonic Distortion



Power-Dependent Responsivity



Transport Equations

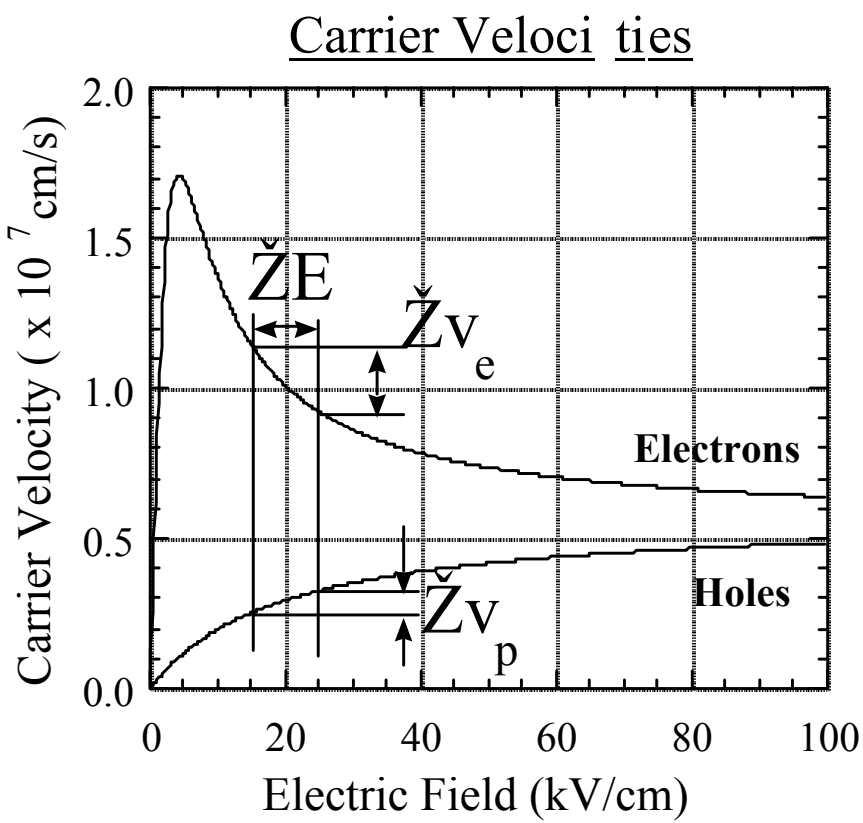
$$\frac{\partial p}{\partial t} = G - R - \frac{1}{q}\nabla \cdot \left(J_{pdrift} + J_{pdiff}\right)$$

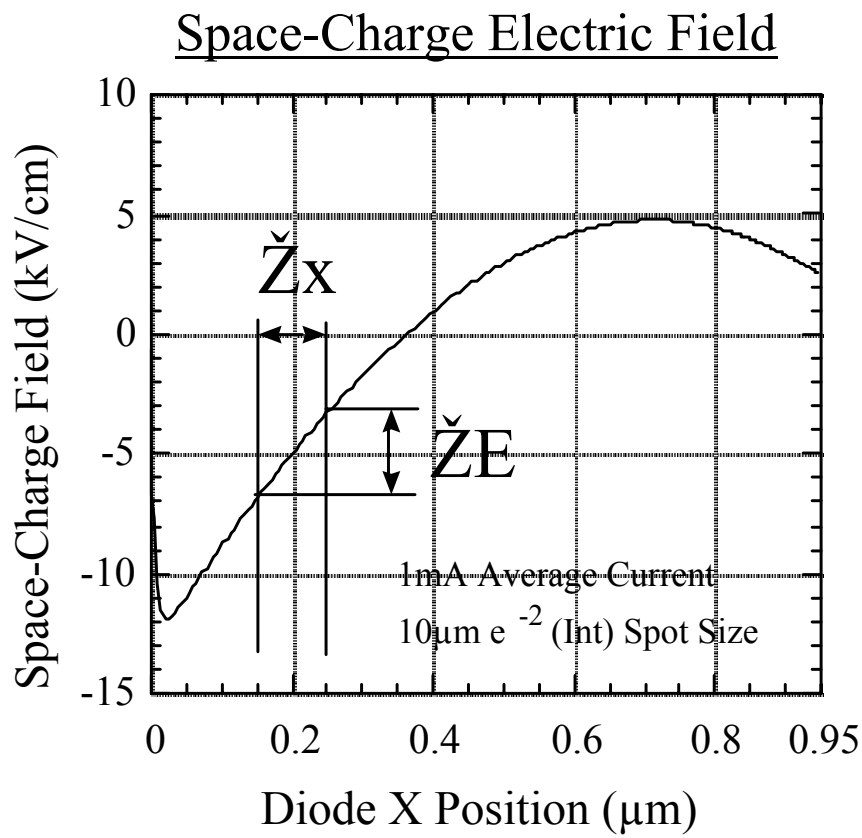
$$\frac{\partial n}{\partial t} = G - R - \frac{1}{q}\left[v_n \frac{\partial n}{\partial x} + n\frac{\partial v_n}{\partial x} + q\frac{\partial D_n}{\partial x}\frac{\partial n}{\partial x} + qD_n \frac{\partial^2 n}{\partial x^2}\right]$$

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

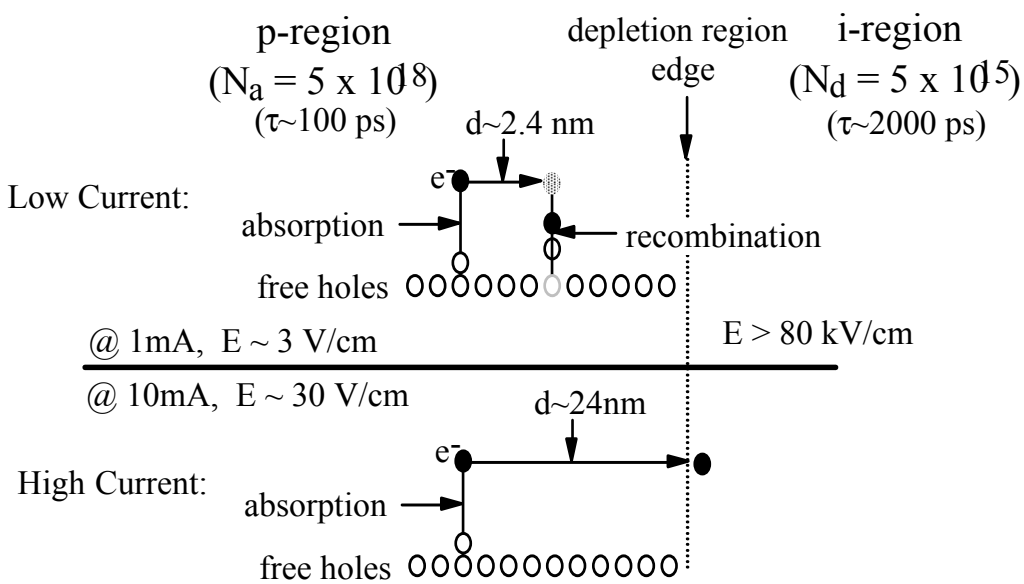
Carrier Velocity Nonlinearities

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

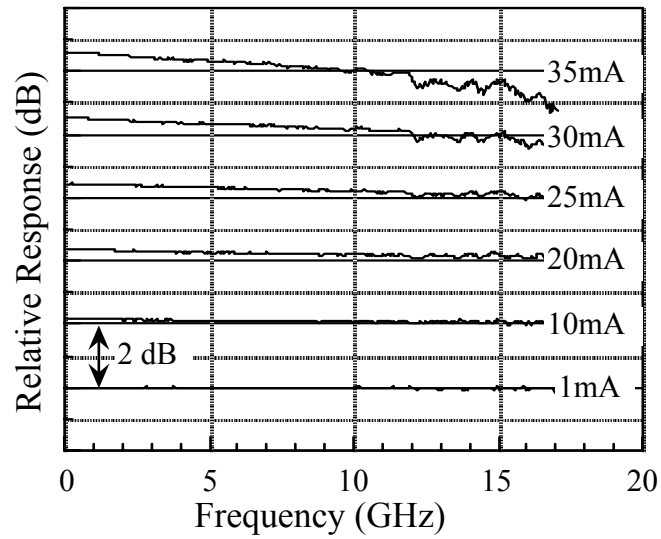


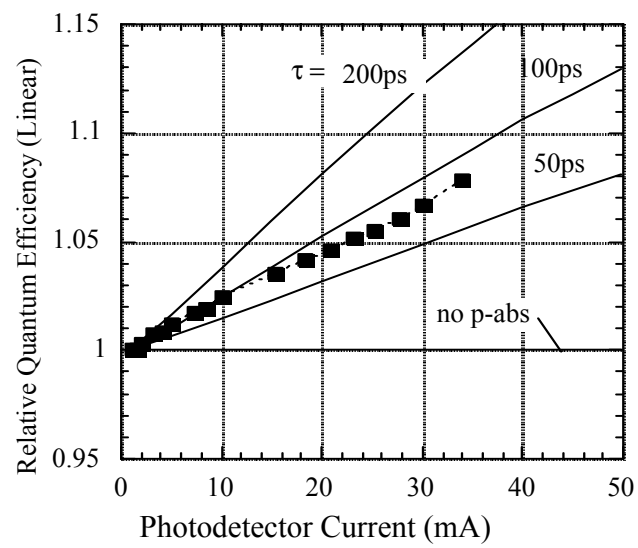


Nonlinear Recombination



Responsivity (Current)





-> Higher Photocurrent Leads to Less Recombination

Nonlinearities from NL Recombination

DC & RF QE (Power)

$$QE = I/P = c_1 + c_2P$$

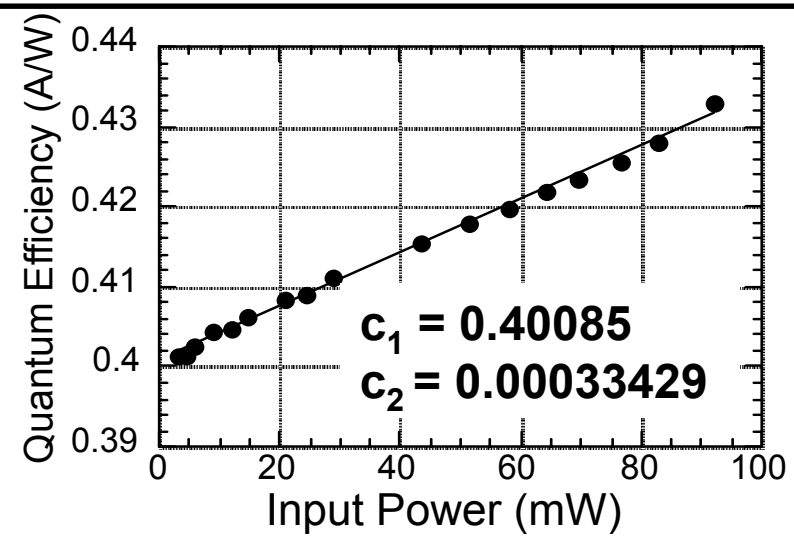
$$I = c_1P + c_2P^2$$

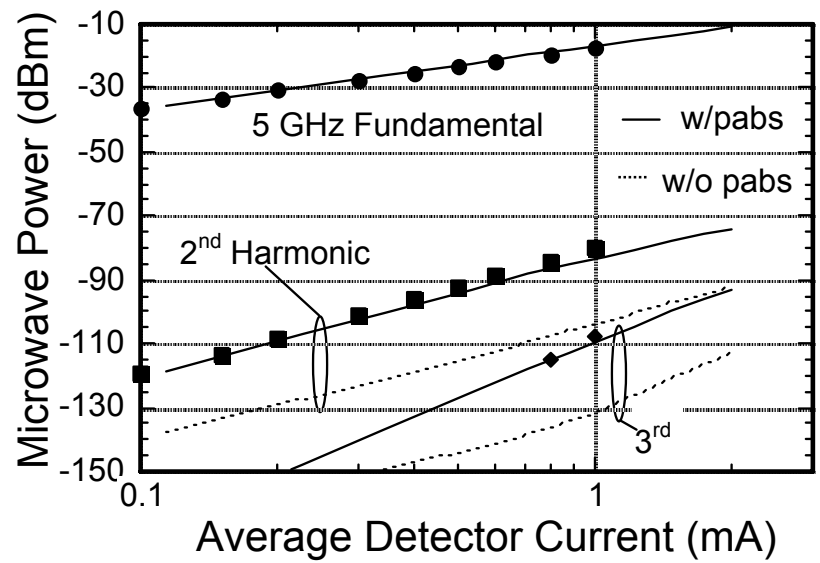
$$P = c_3(1+\sin\omega t)$$

$$\frac{I(2\omega)}{I(\omega)} = \frac{c_2c_3^2}{2c_1c_3 + 4c_2c_3^2}$$

= -59.6 dBc

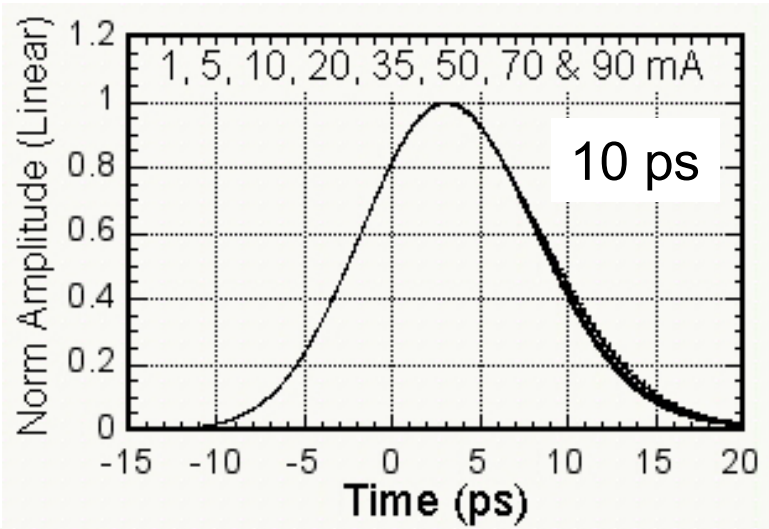
For c_3 = 2.5 mW (1mA)

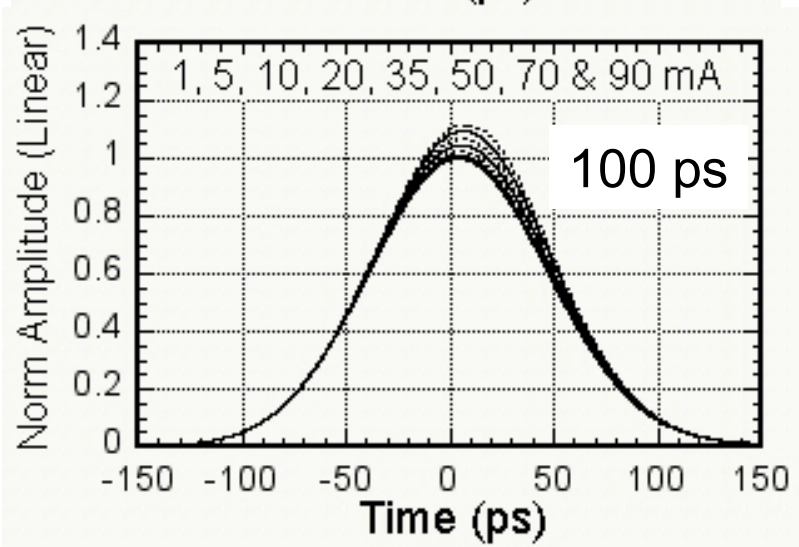




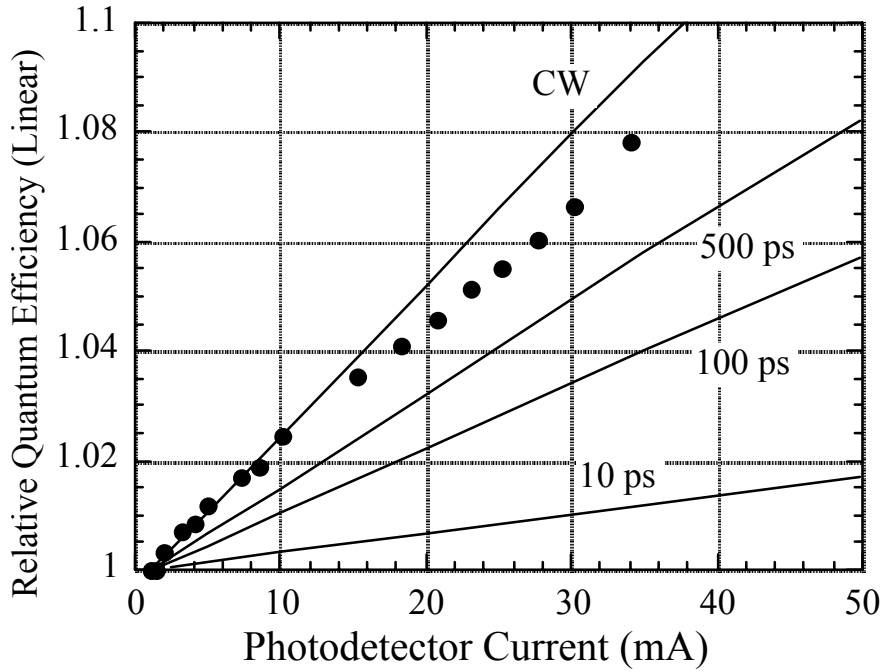
Linear PDs for PADCs

Pulsed Simulations





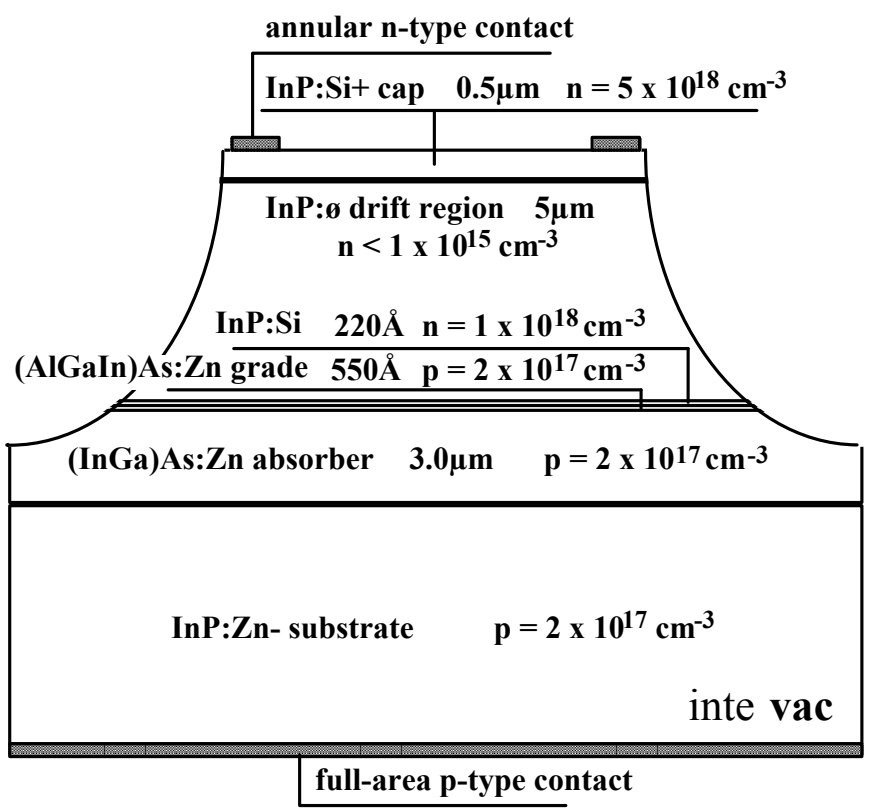
Integrated QE Nonlinearities

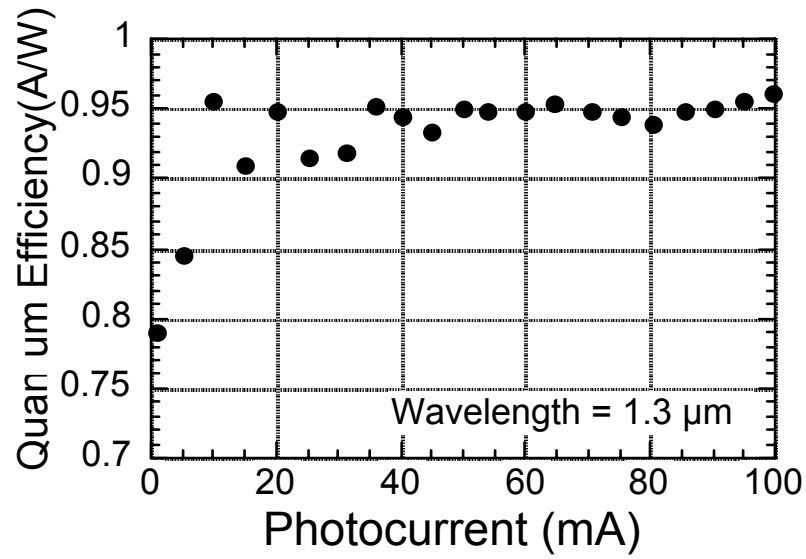


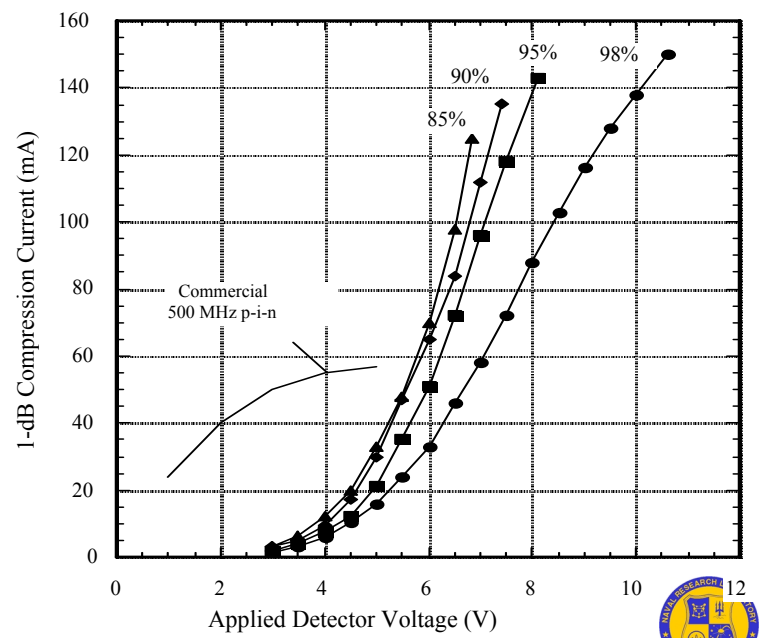
-> QE Nonlinearities may be more Important than Space-Charge-Induced Nonlinearites for PADC

UTC Photodetector - Intevac*

Layer Structure





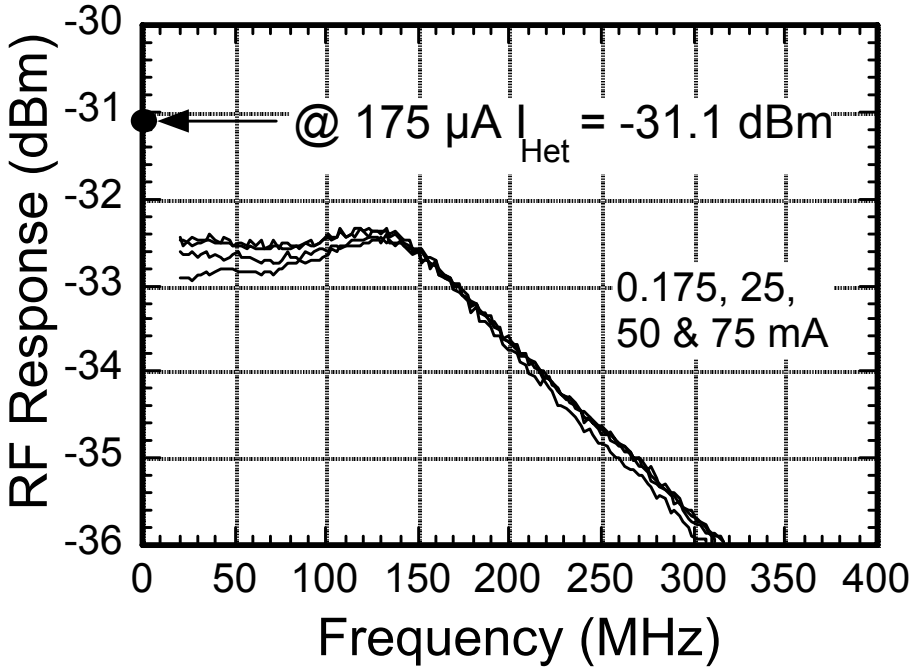


* Sponsored by ONR/NRL

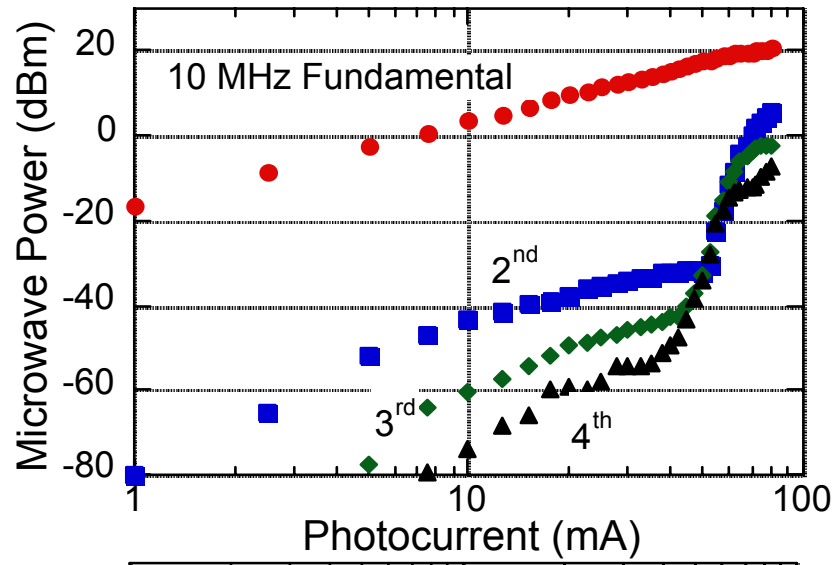
UTC Photodetector - Nonlinearities

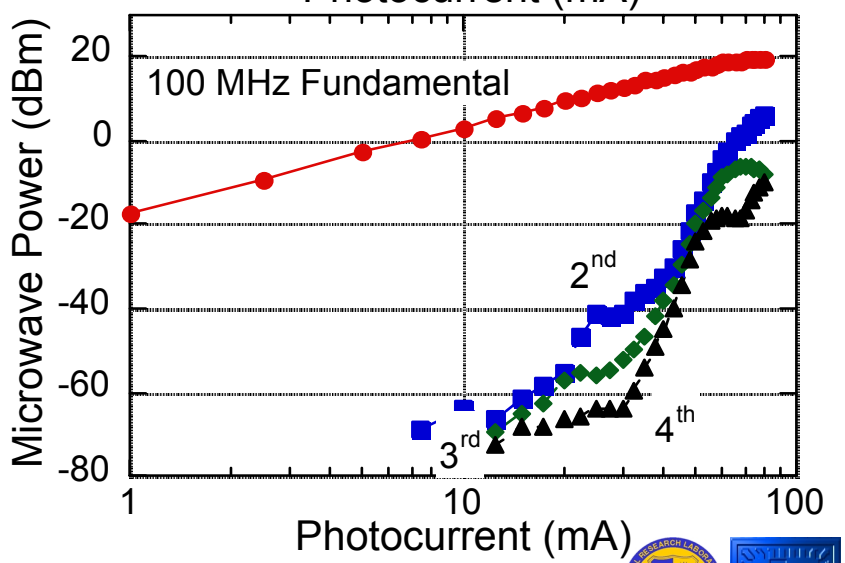
NRL MICROWAVE PHOTONICS 5650

Frequency Response (Current)



RF Nonlinearities

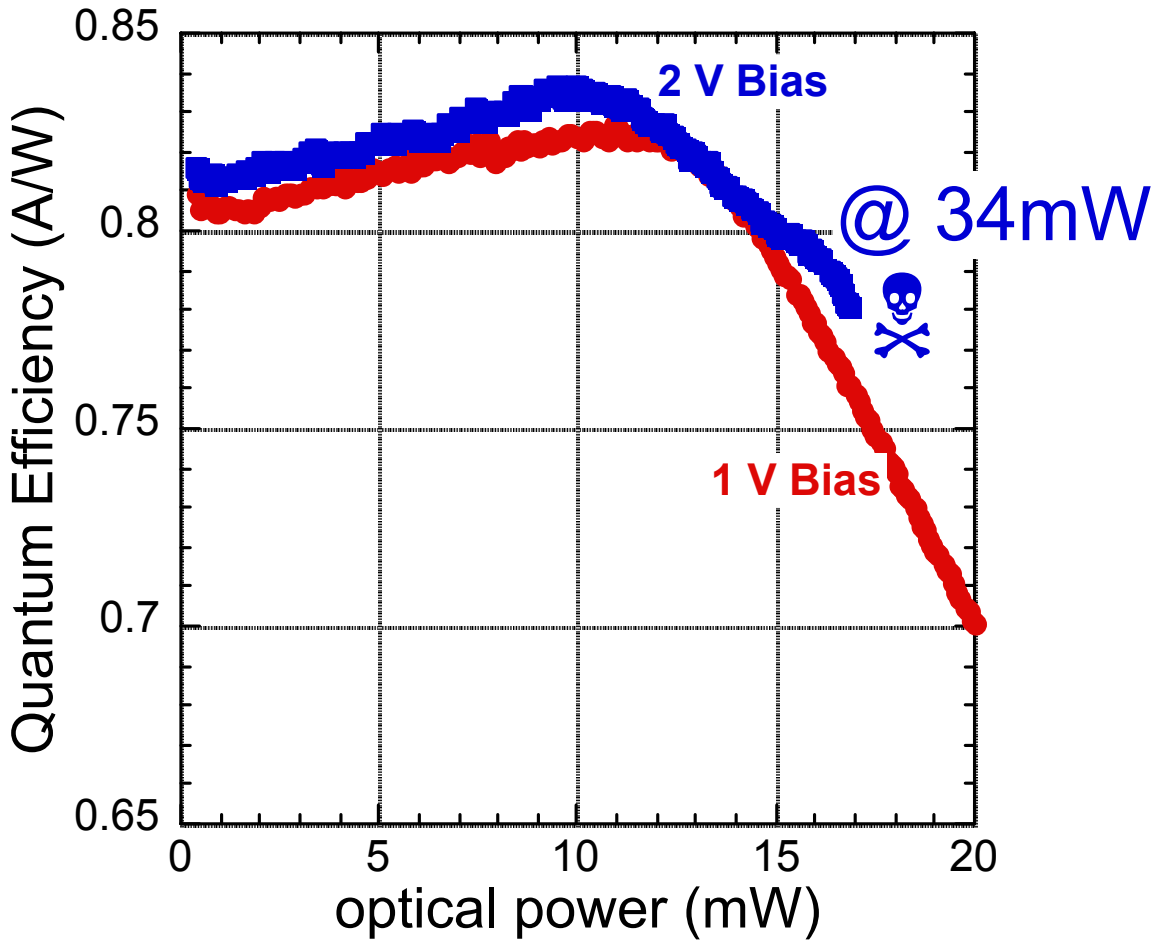




-> QE NL has Bandwidth Limitation

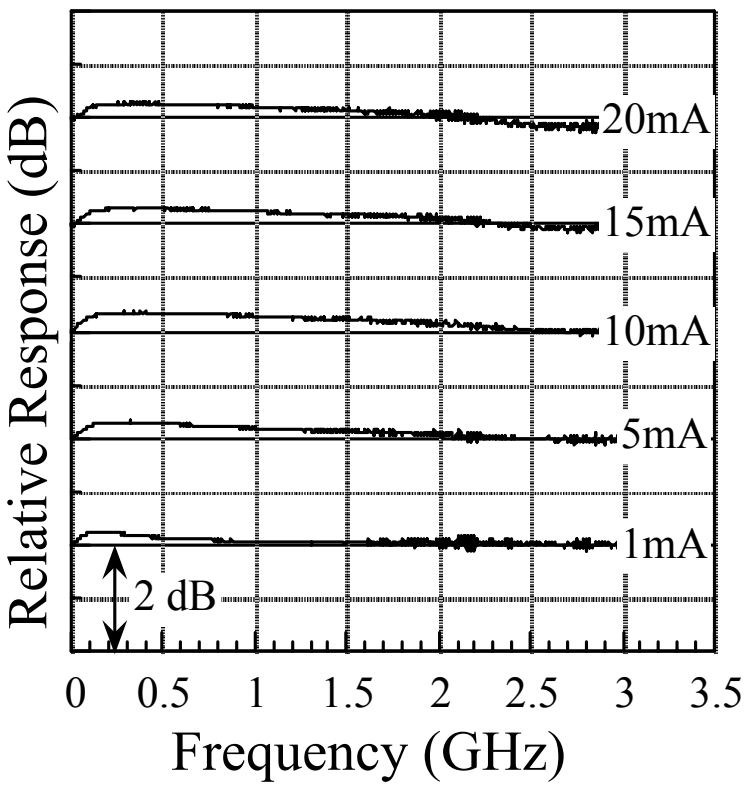
NEL UTC Photodiode - 50 GHz BW

DC QE Nonlinearity

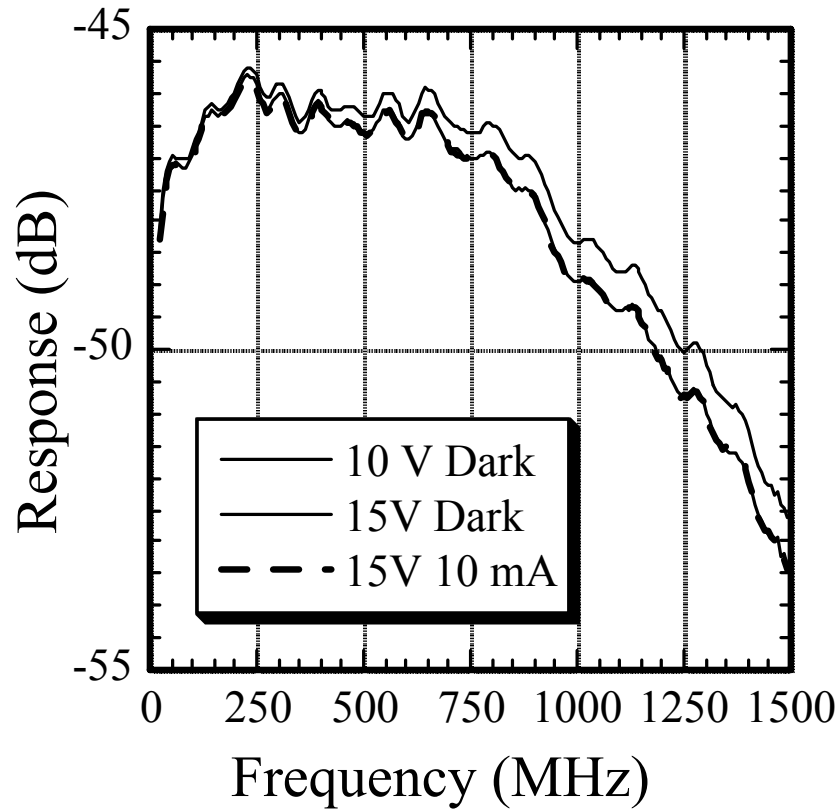


Nonlinear Capacitance

Decreasing Capacitance w/Increasing Current

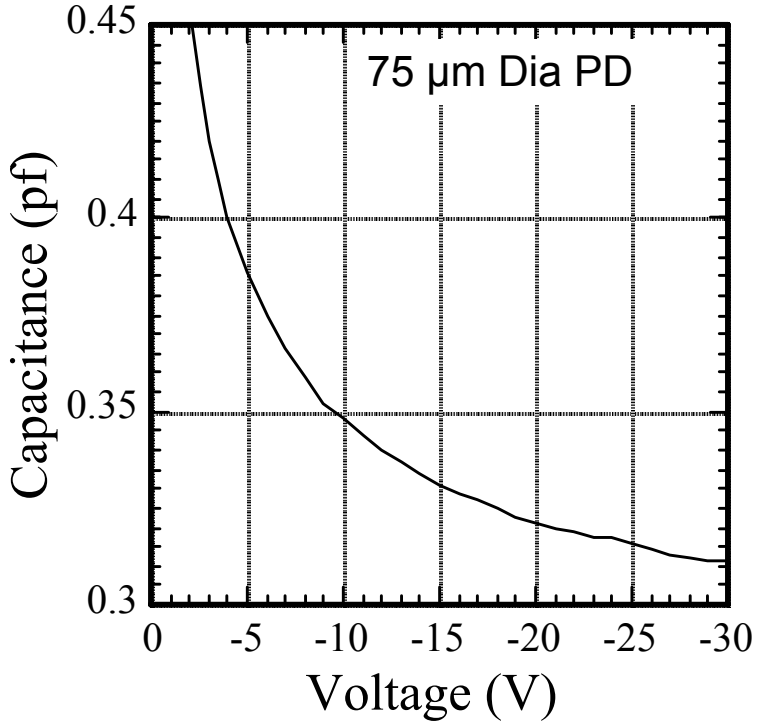


Increasing Capacitance w/Increasing Current

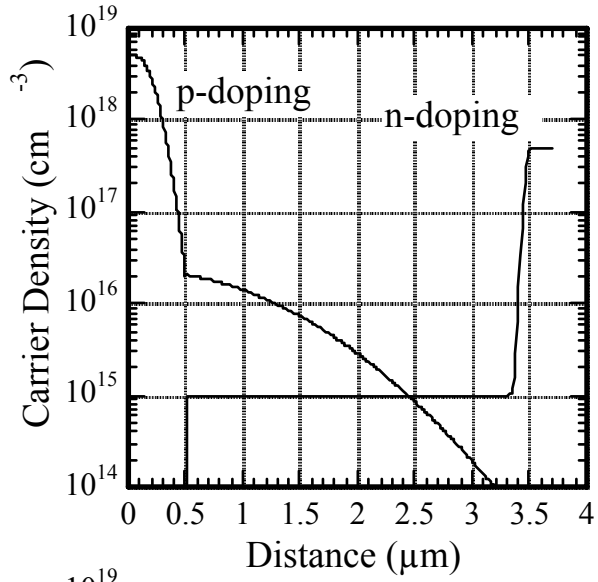


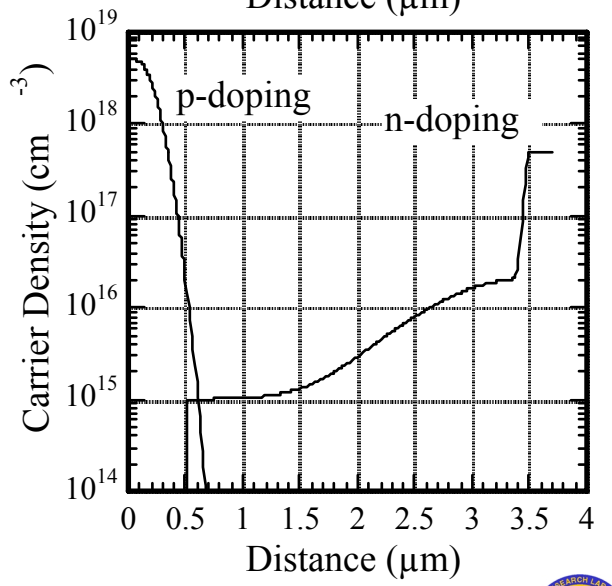
Static Capacitance

C-V Measurements Under Dark Conditions



Possible Doping Profiles

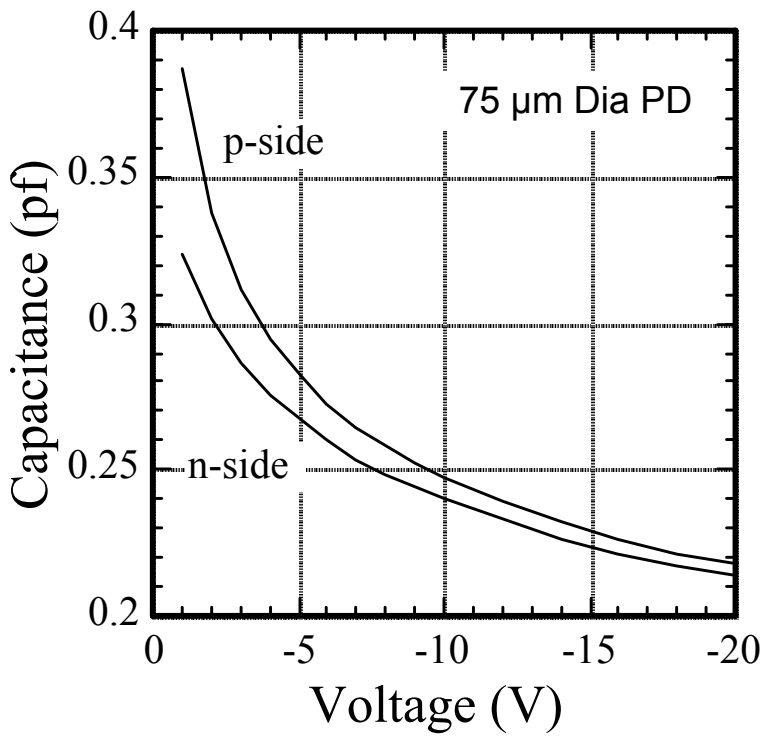




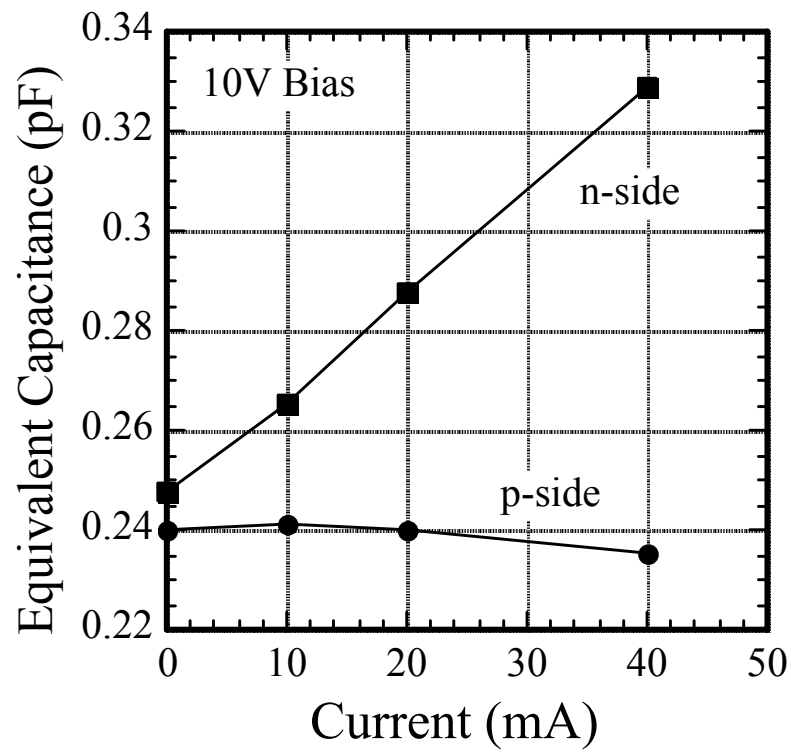
Nonlinear Capacitance - Simulations

$$\text{Capacitance} = \frac{dQ}{dV}$$

Dark Conditions

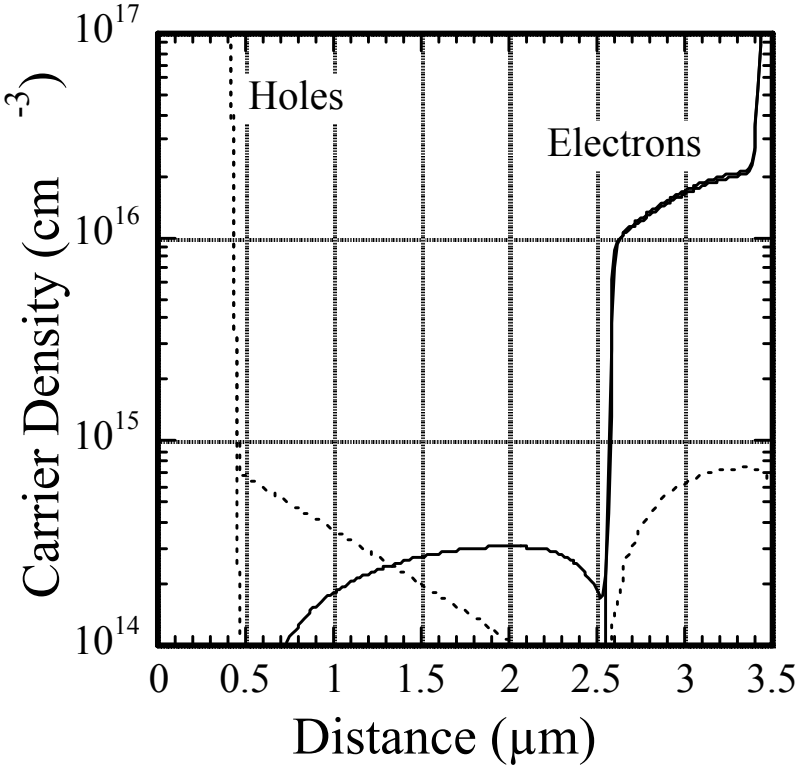


Under Illumination

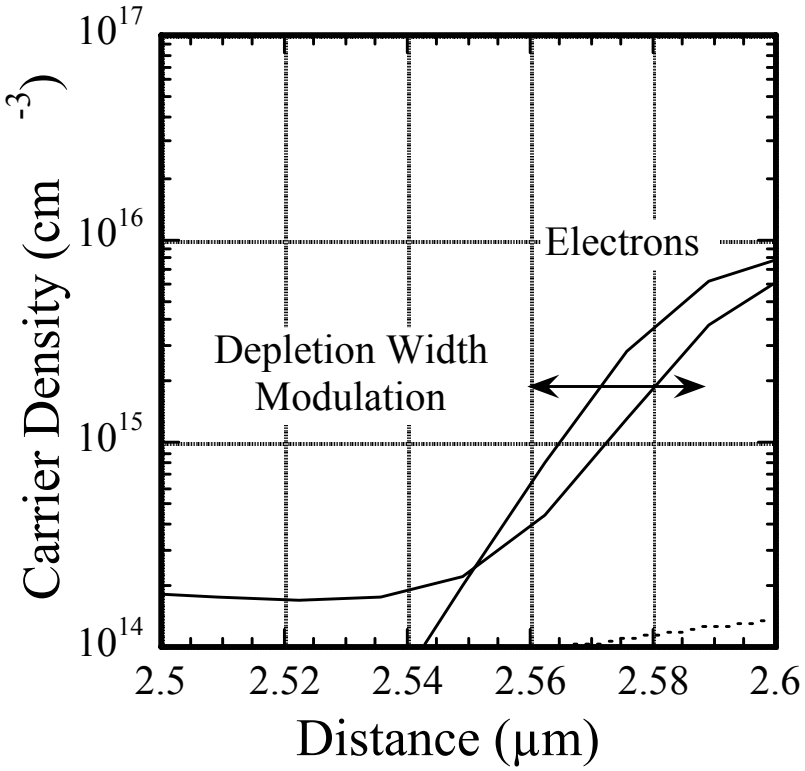


Carrier Density Calculations

Carrier Densities under Dark Conditions And for 20 mA Photocurrent

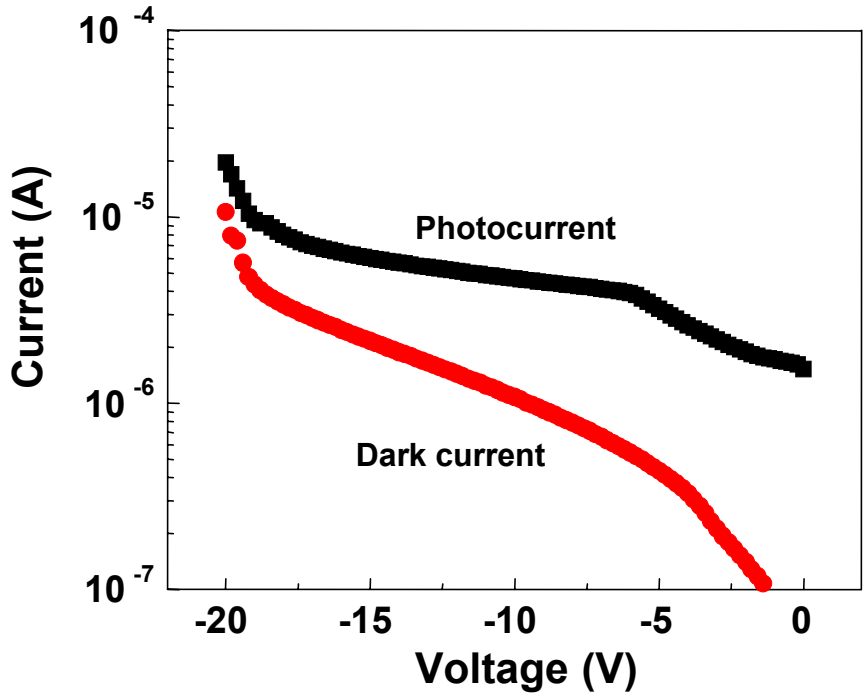


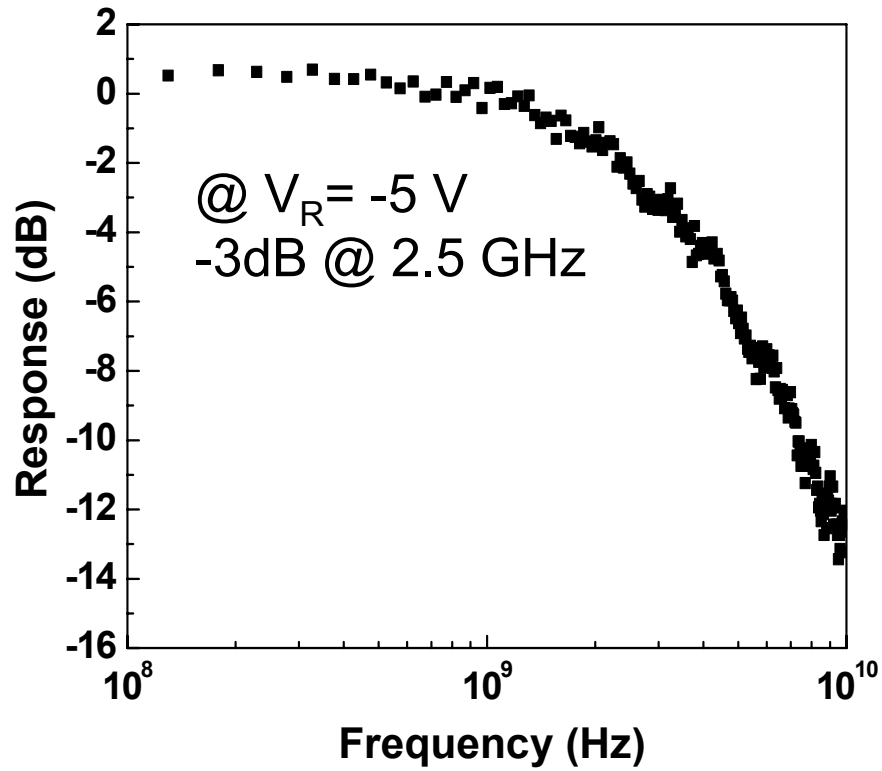
Zoom on n-side



Germanium Photodetectors

Germanium PINs: Fabrication & Testing at UT

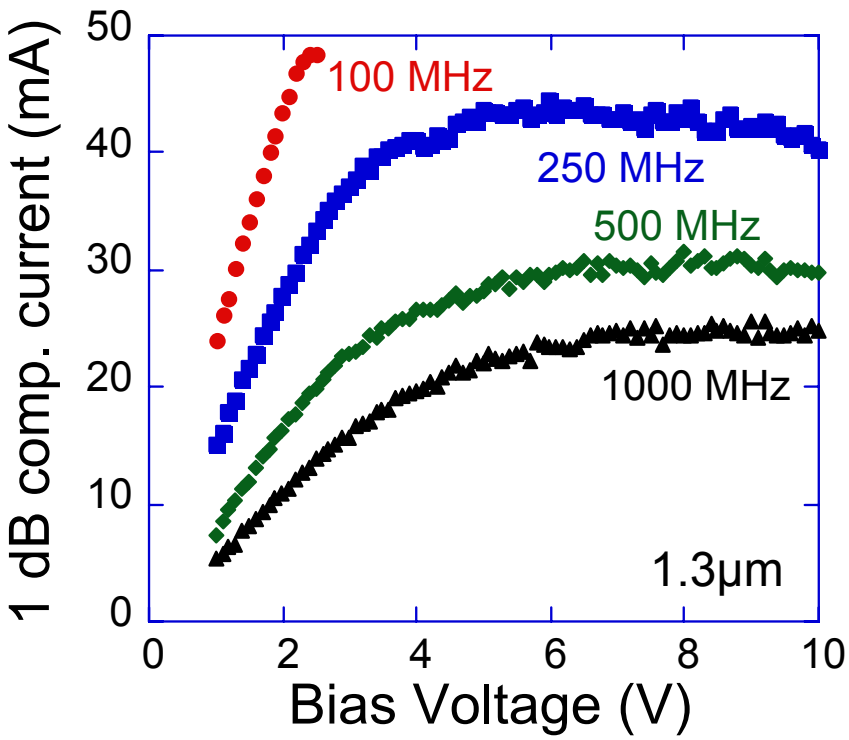




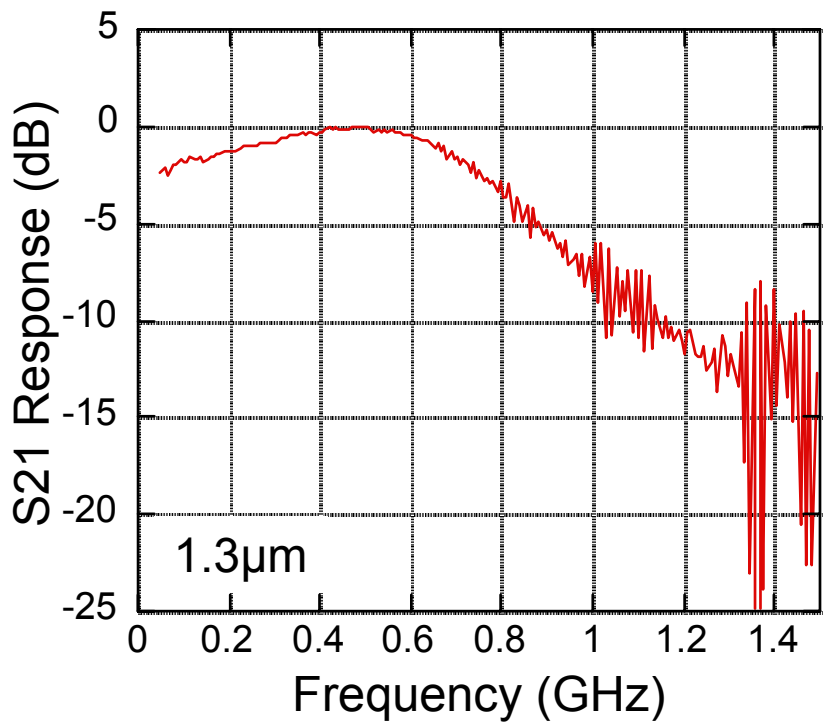
- Interdigitated p-i-n (finger width = 2 μm, finger spacing = 5 μm)

Commercial Germanium Photodetectors

Compression Current



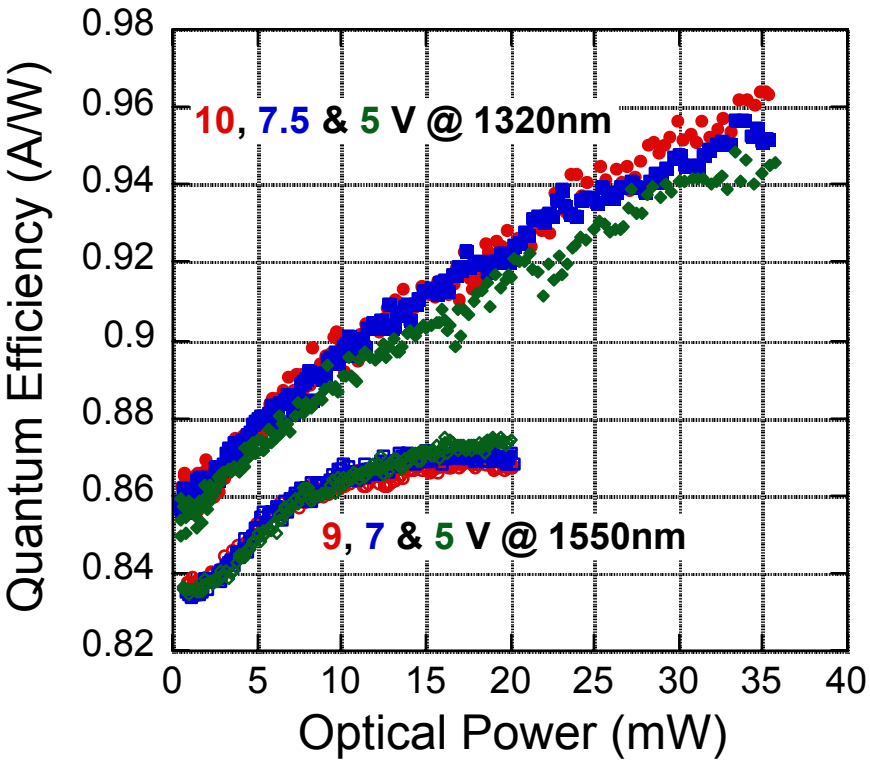
Frequency Response



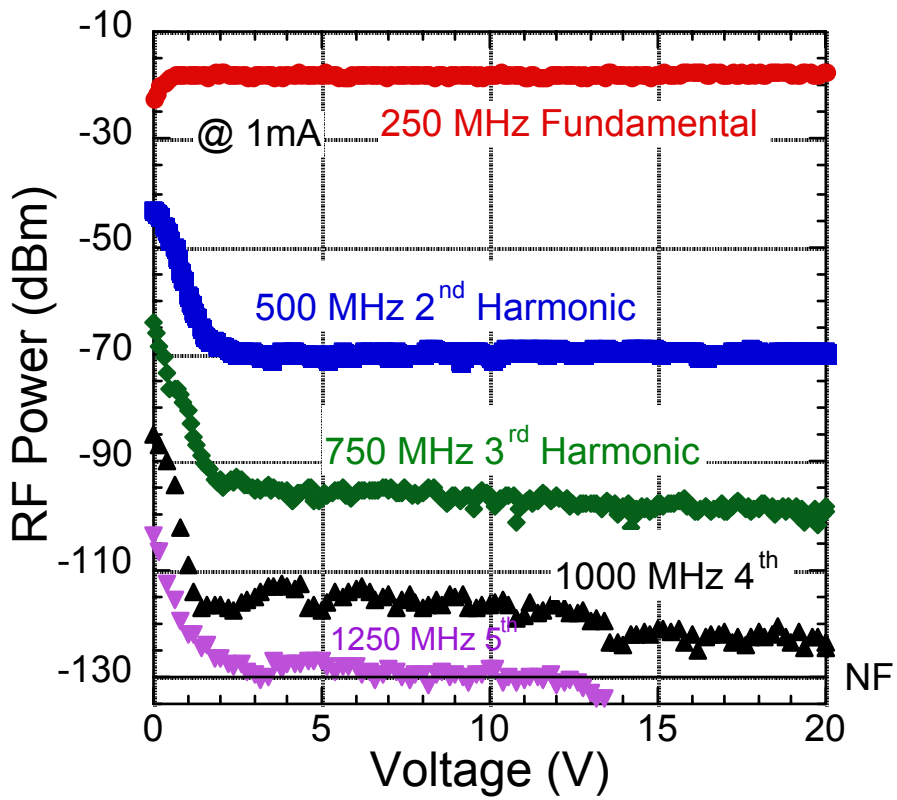
250 μm Diameter, n-side illuminated, 3-4 μm i-region length

Commercial Germanium PD Nonlinearities

Responsivity



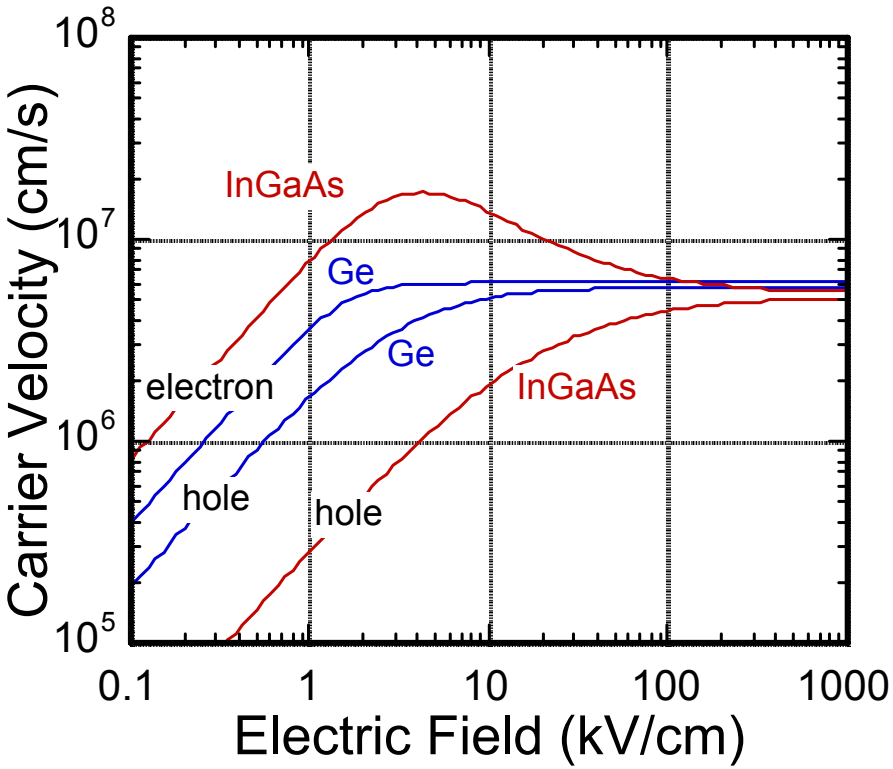
Harmonic Distortion



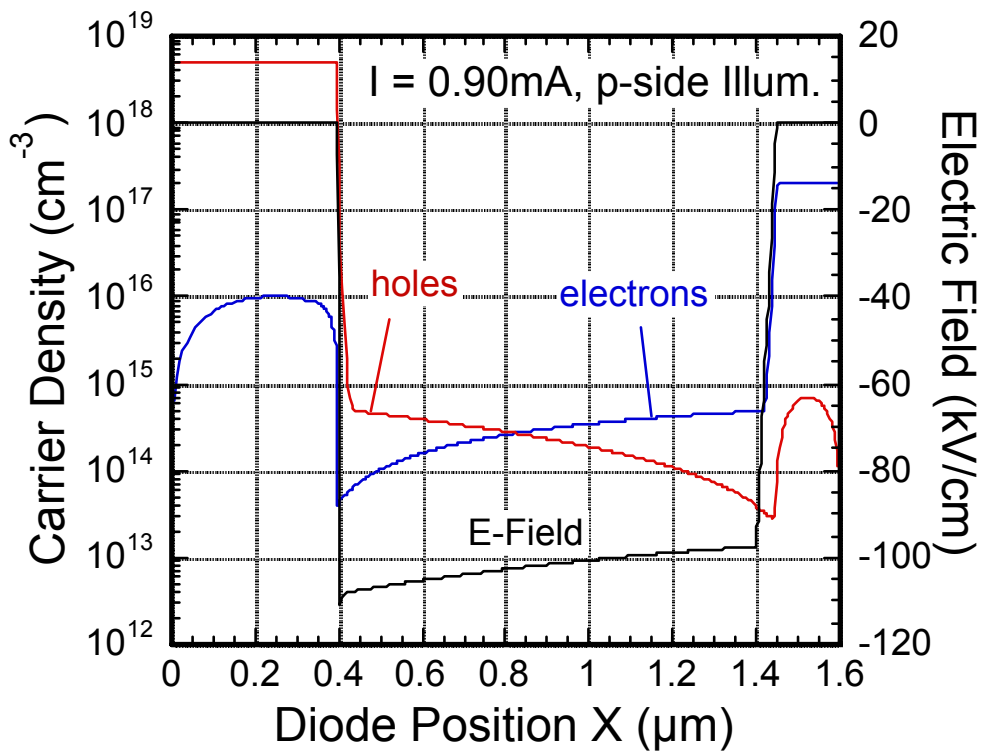
- Also Observed a 1.5 dB increase in RF QE (250 MHz) @ 35 mW

Germanium Simulations

Carrier Velocities

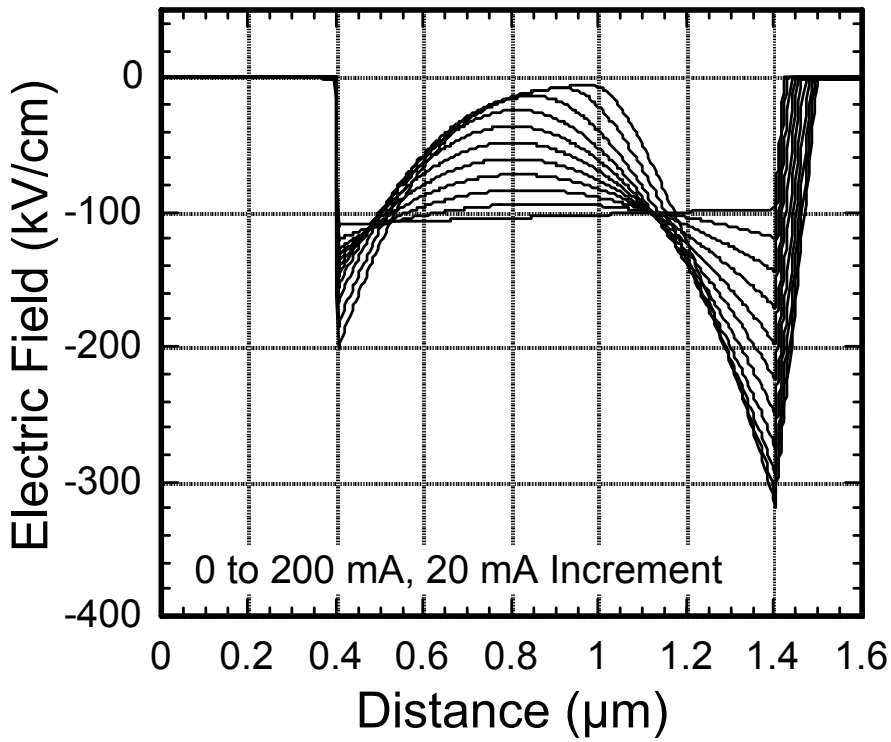


Calculated n, p & E-Field

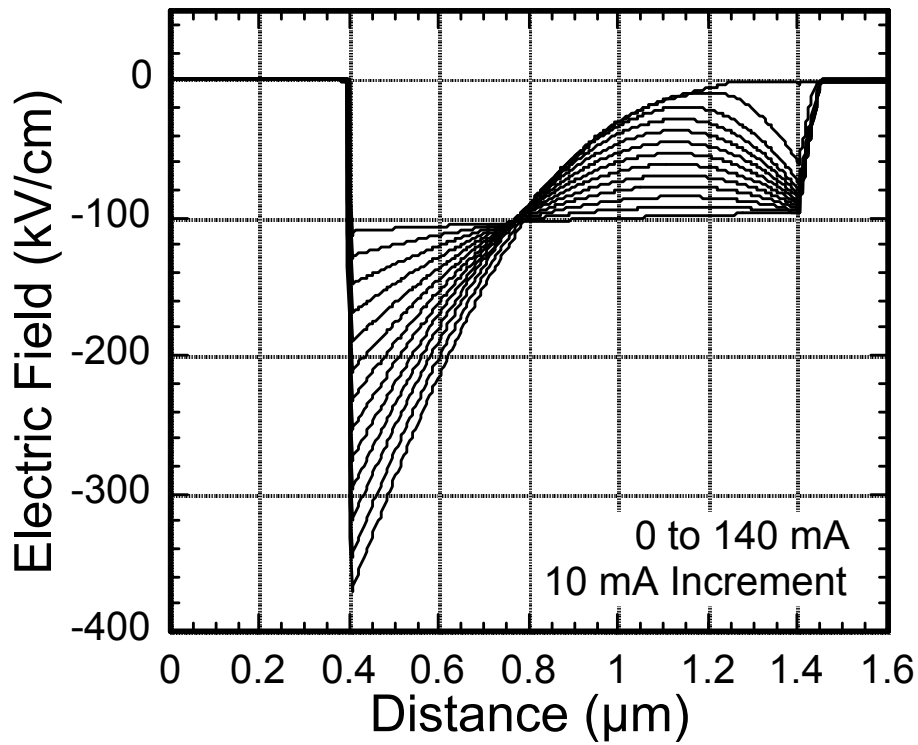


Germanium E-Field Simulations - 20 GHz PD

p-side Illumination



n-side Illumination



- Charge Compensation should be used to minimize peak Electric Fields

  - 25 μm dia, 15 μm Spot Size, 1-μm i-length

Accomplishments

- Incorporation of InP and Ge Transport Properties into Numerical Model

- Comprehensive Modeling to Design p-i-n Structures Optimized for High Power

- Fabrication of UTC and Ge PDs

Most Significant

Program Roadmap

- Identification of Limiting Nonlinear Mechanisms - Dec 2001
- Fabrication of 100 mA PD - June 2002
- Fabrication of 60 dB Dynamic Range Photodetector - June 2003
- Fabrication of 500 mA PD - Sept 2003