High-Speed Photodetection Exploiting Quasi-Unipolar Charge Transport

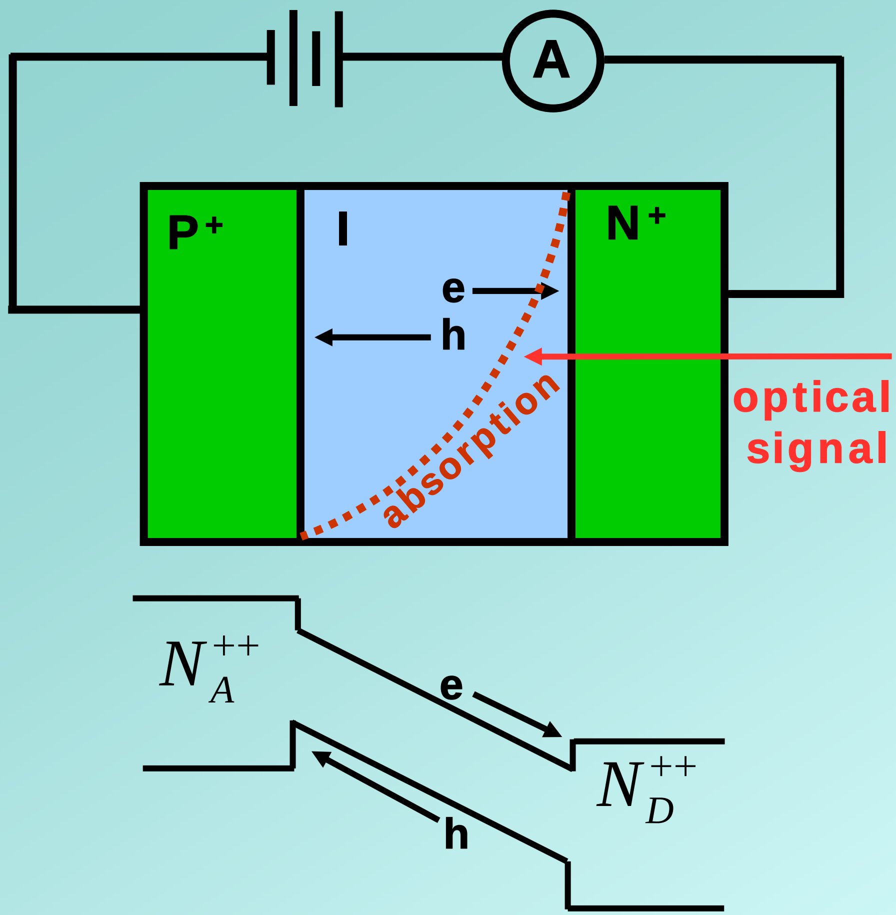
P. D. Yoder

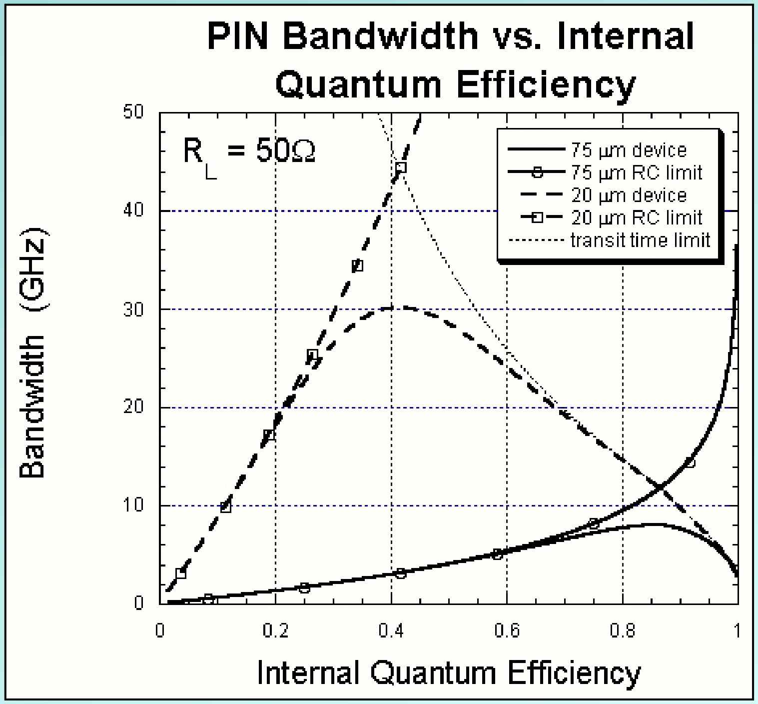
School of Electrical and Computer Engineering
Computational Electronics Group
Georgia Institute of Technology

Outline

- *Background*
  - *Limitations of the heterojunction p-i-n design*
  - *Alternative design strategies*
- *Theory of the quasi-unipolar photodiode operation*
- *Device measurement*
- *Monte Carlo simulation*
- *Summary*

The Heterojunction p-i-n Photodiode

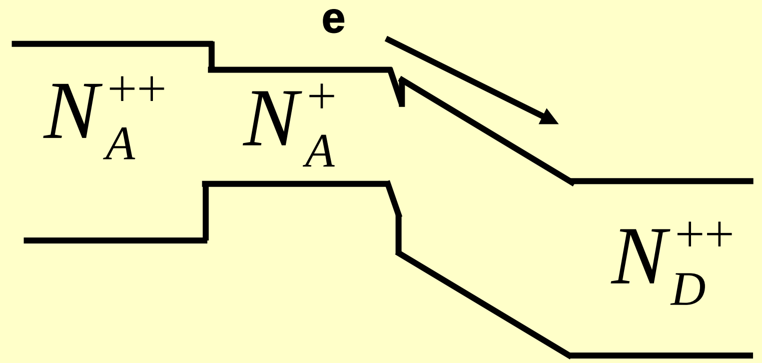




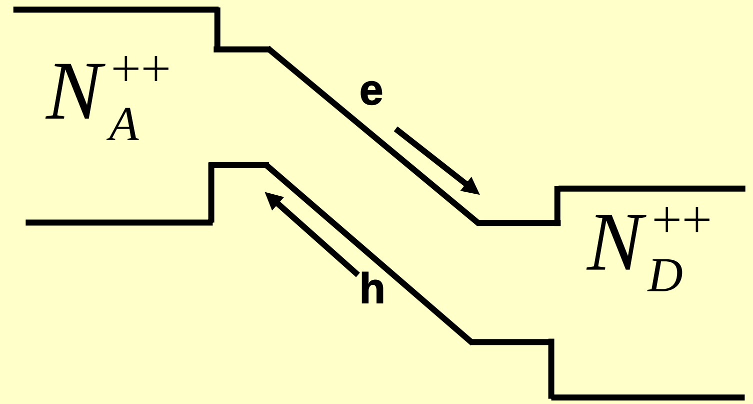
High QE achieved at the cost of bandwidth

Alternative Design Strategies

- *Uni-traveling Carrier (UTC)*
  - *T. Ishibashi et al., Jap. J. Appl. Phys.* ***36****, 1997.*

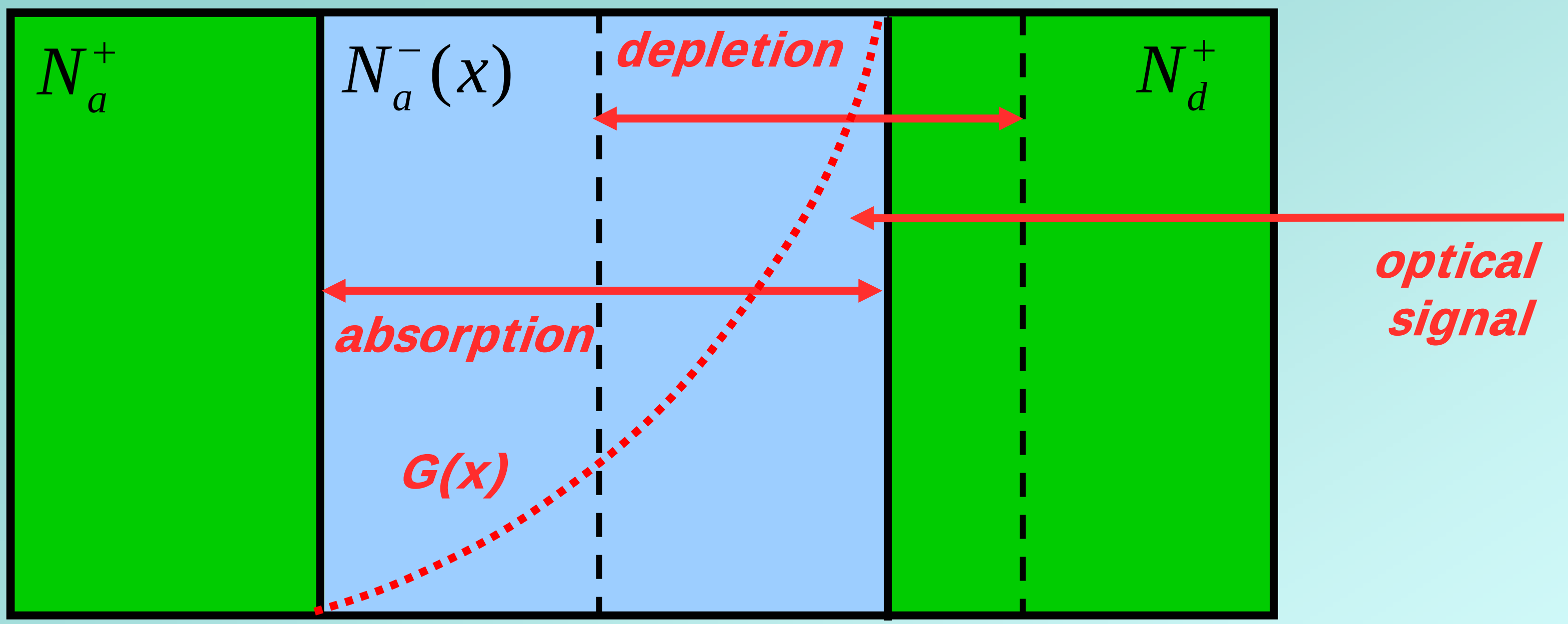


- *Partially Depleted Absorber (PDA)*
  - *D.A. Tulchinsky et al., IEEE J. Selected Topics on Q. Mech.* ***10****, 2004.*



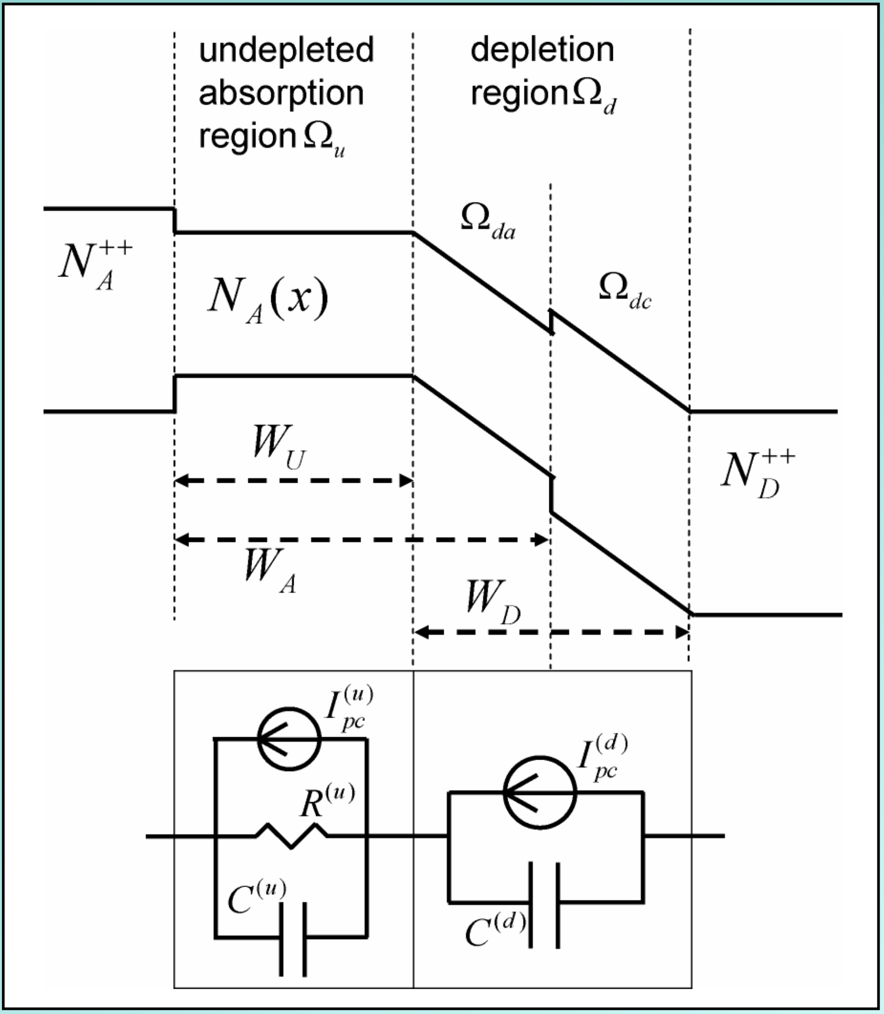
- *Quasi-Unipolar (QU)* *Yoder and Flynn, J. Lightwave Tech.* ***24****, 2006.*

The Quasi-Unipolar Photodiode



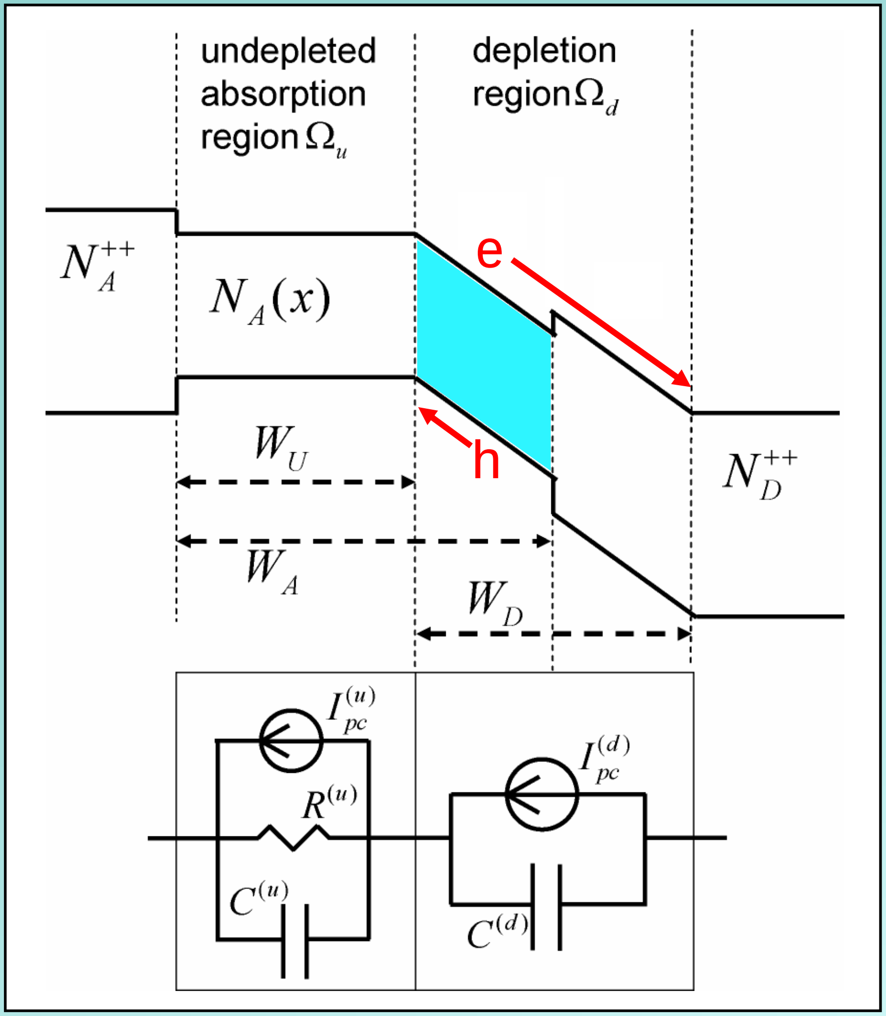
- Absorption and depletion regions are overlapping
- Depletion region offset is controlled by doping and bias
  - InP buffer doping
  - Zn diffusion profile through absorber

QU Photodiode Design



- 3 independent design parameters
  - Absorber thickness (W_A)
  - Undepleted absorber width (W_U)
  - Depletion region thickness (W_D)
- Controlled by doping and bias

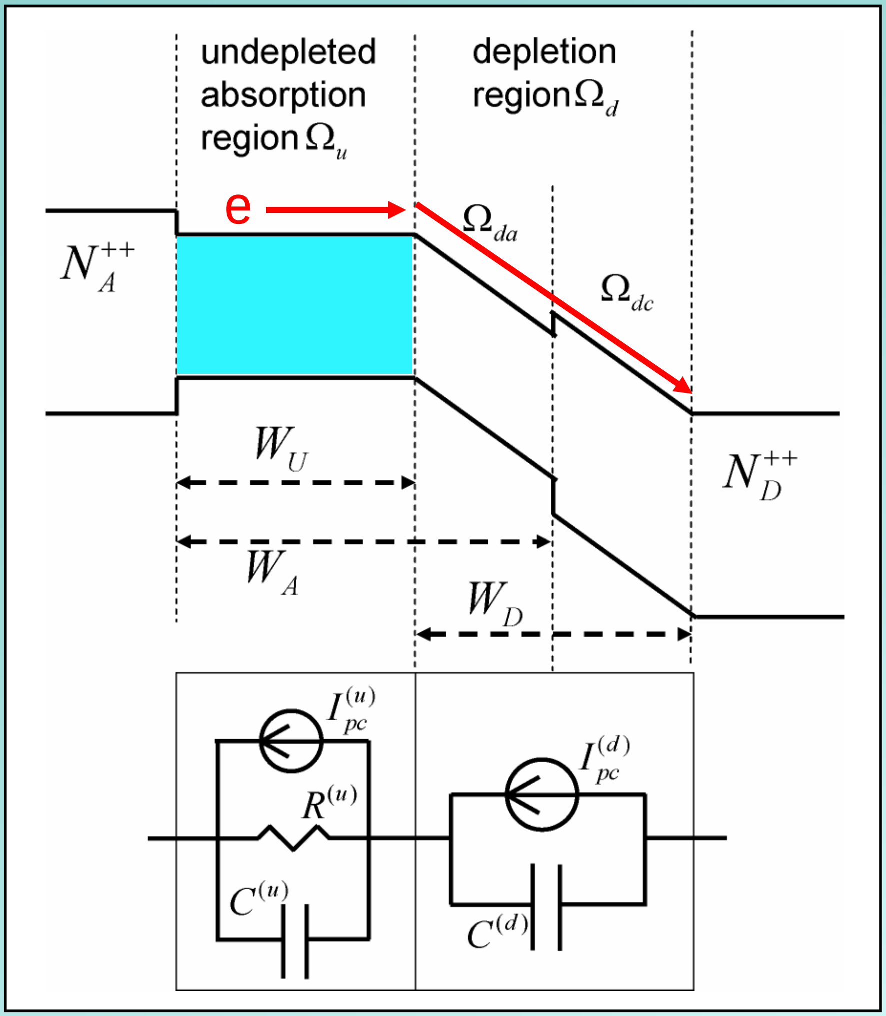
Photogeneration in Depleted Absorber



- *E-h pairs generated within depleted absorber region drift to their respective depletion region edges*
- *Maximum hole transit distance limited to W_A-W_U .*

Controlled by design!

Photogeneration in Undepleted Absorber



- *Electrons photogenerated within Ω_u escape into Ω_d by:*
  - *Drift in static field*

$$E_{static} \approx \frac{k_B T}{q} \frac{\nabla N_A}{N_A}$$

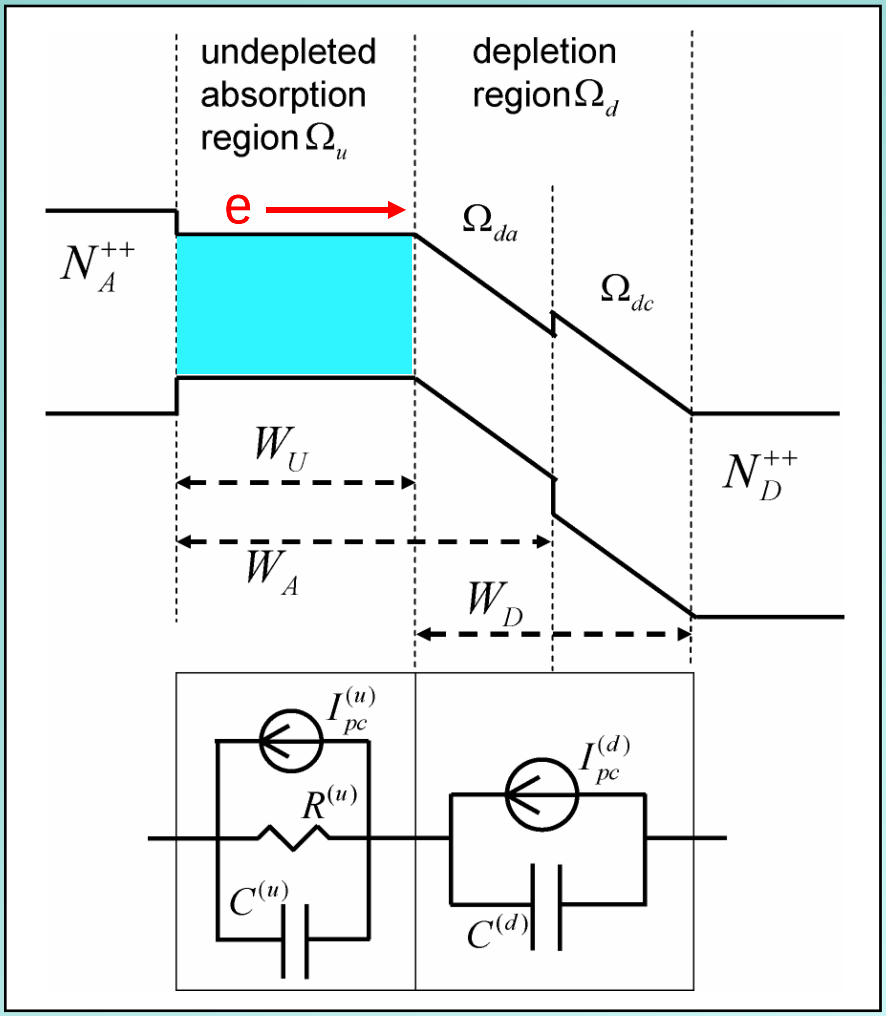
  - *Drift in dynamic field*

$$E_{dynamic} \approx J_{pc}^{(d)} \Big/ \left(q N_A \mu_p \right)$$

  - *Diffusion*

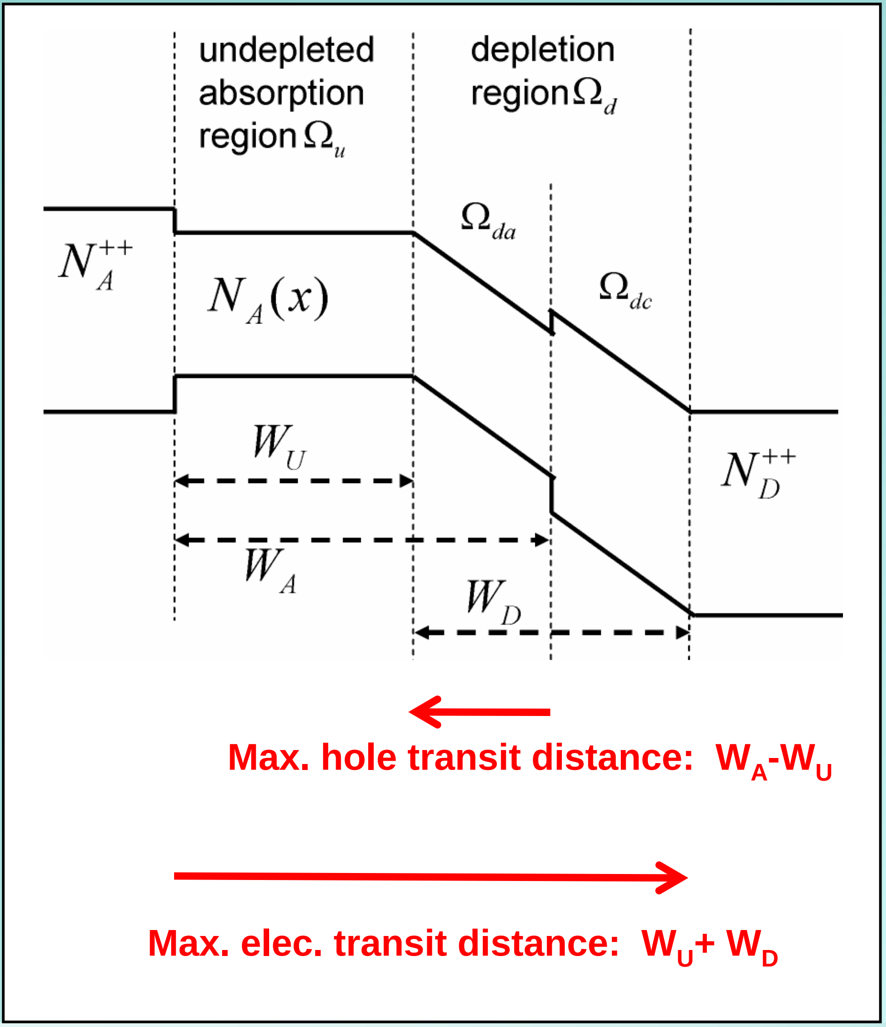
$$\tau \approx W_U^2 \Big/ 2D_e$$

QU Photodiode Operation



- *Electron motion in Ω_u is decoupled from external circuit*
- *Holes generated within Ω_u do not contribute to photocurrent*
- *Fraction of photocurrent carried by holes depends on W_U and W_D*
- *Maximum electron transit distance limited to W_U+W_D*
  Controlled by design!
- *Electron transit distance always shorter than for UTC device*

QU Photodiode Operation



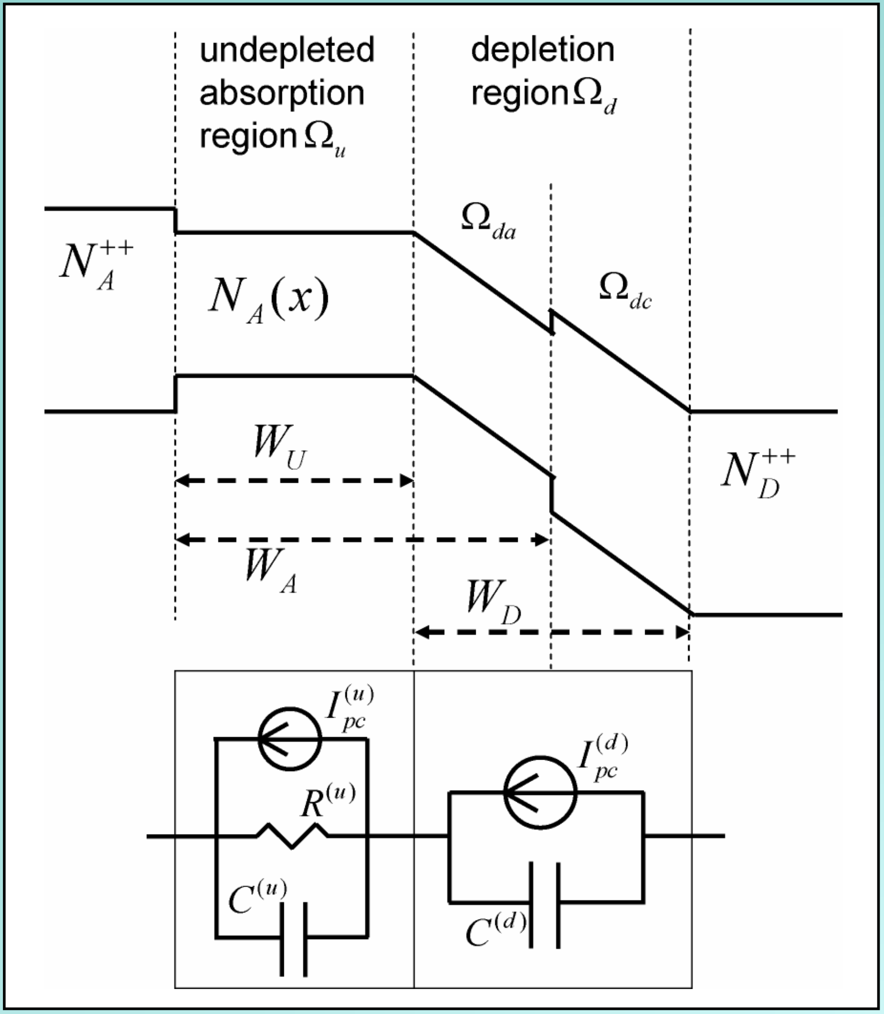
For arbitrary W_A and W_D :

Increasing W_U from 0 to W_A

- *Reduces the number of holes participating in photocurrent*
- *Trades electron against hole transit time*

3dB bandwidth is approximately maximized when temporal extent of electron and hole photocurrent response to an optical impulse are "balanced".

QU Photodiode Operation



Limiting cases of QU design:

- *UTC device:* $W_U \to W_A$
- *p-i-n:* $W_U \to 0,\ W_D \to W_A$
- *PDA:* $W_U + W_D < W_A$

Analytic Model: Linearized Moments of BTE

Within Ω_u (undepleted absorber material):

$$\left(\frac{\partial}{\partial t}\left(1+\tau_p^{(u)}\frac{\partial}{\partial t}\right)+\frac{e\mu_p p_0}{\varepsilon}\right)\delta p - D_p\nabla^2\delta p + \mu_p\vec{E}_0\bullet\nabla\delta p = \frac{e\mu_p p_0}{\varepsilon}\delta n + \left(1+\tau_p^{(u)}\frac{\partial}{\partial t}\right)G(x,t)$$

$$\frac{\partial}{\partial t}(1+\tau_n\frac{\partial}{\partial t})\delta n - D_n\nabla^2\delta n + v_n\nabla\delta n = (1+\tau_n\frac{\partial}{\partial t})G(x,t)$$

Within Ω_{du} (depleted absorber material):

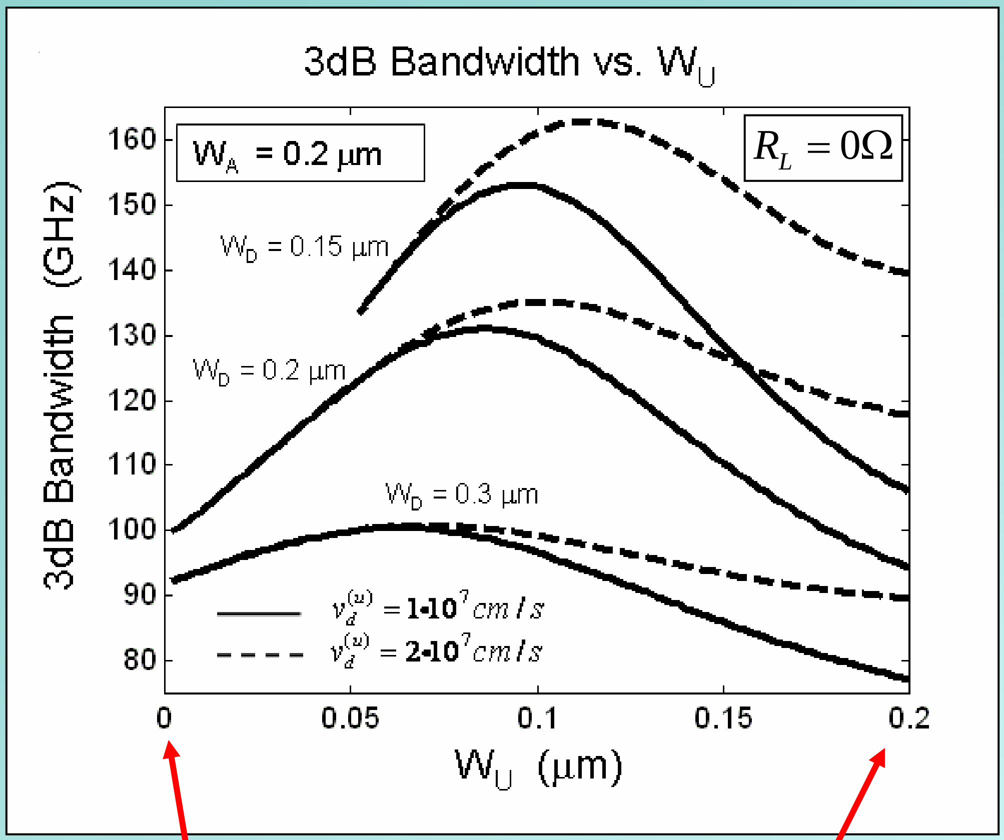
$$\frac{\partial}{\partial t}(1+\tau_p\frac{\partial}{\partial t})\delta p - D_p\nabla^2\delta p + v_p\nabla\delta p = (1+\tau_p\frac{\partial}{\partial t})G(x,t)$$

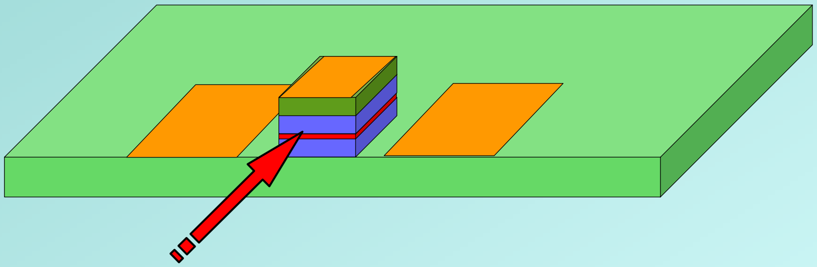
$$\frac{\partial}{\partial t}(1+\tau_n\frac{\partial}{\partial t})\delta n - D_n\nabla^2\delta n + v_n\nabla\delta n = (1+\tau_n\frac{\partial}{\partial t})G(x,t)$$

Within Ω_{dc} (depleted collector material):

$$\frac{\partial}{\partial t}(1+\tau_n\frac{\partial}{\partial t})\delta n - D_n\nabla^2\delta n + v_n\nabla\delta n = (1+\tau_n\frac{\partial}{\partial t})G(x,t)$$

Application to QU Waveguide Geometry Designs



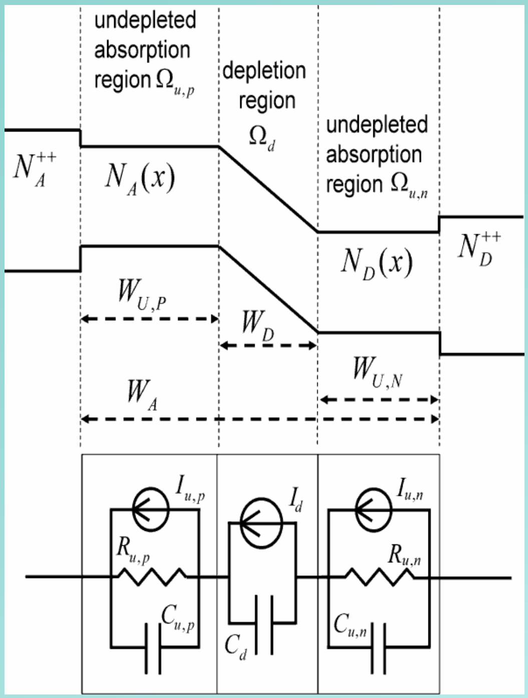


p-i-n limit (fully bipolar)

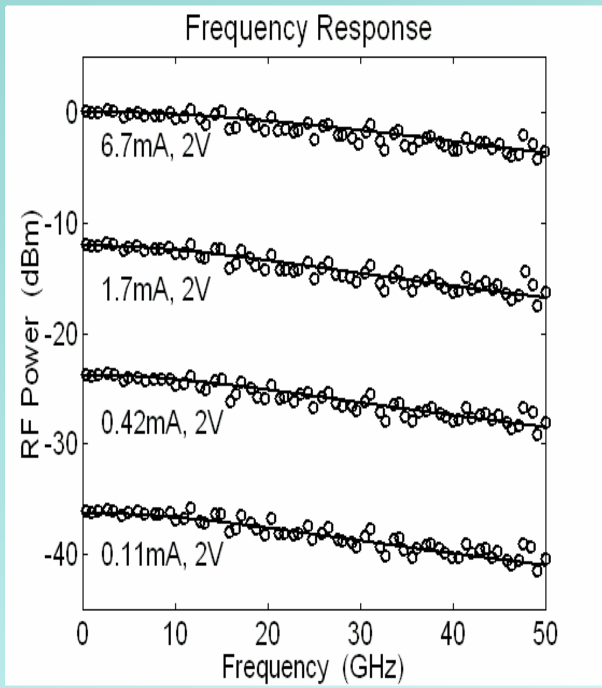
UTC limit (fully unipolar)

For fixed QE and C_j, optimal 3dB bandwidth is achieved by QU rather than purely unipolar or purely bipolar operation

Aside: Application to PDA Designs

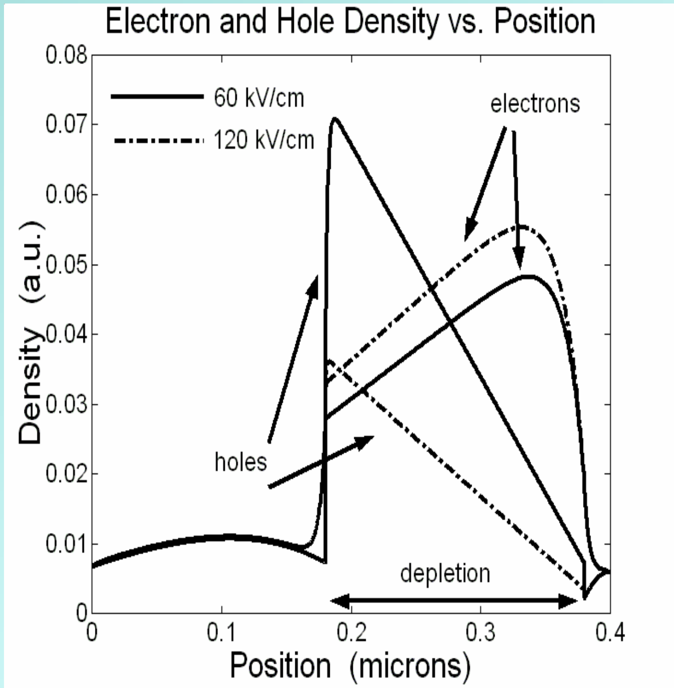


Band diagram and equivalent circuit model



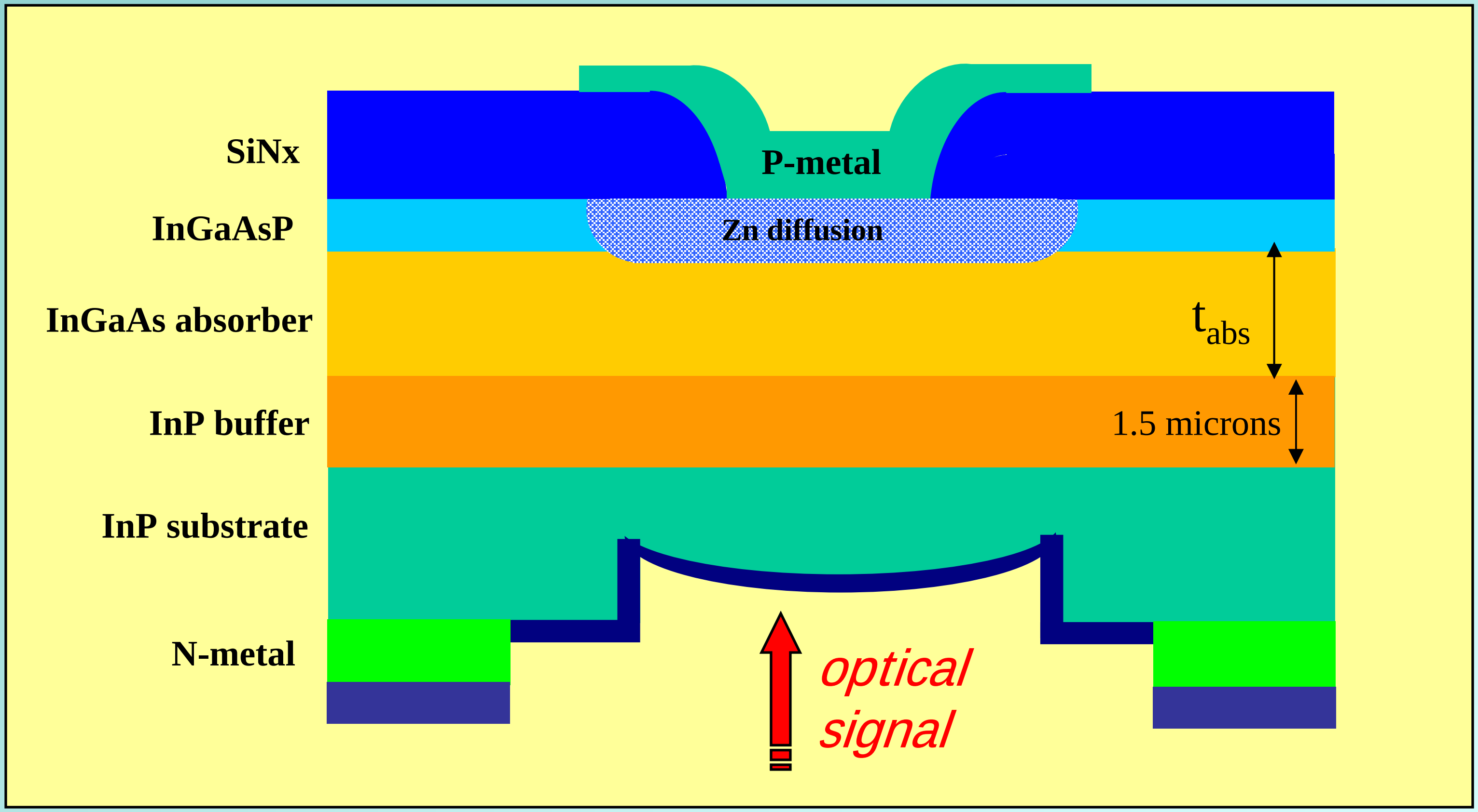
Comparison with experiment

Measurement : X. Li *et al.*, *IEEE Photonics Technology Letters*, 2004.



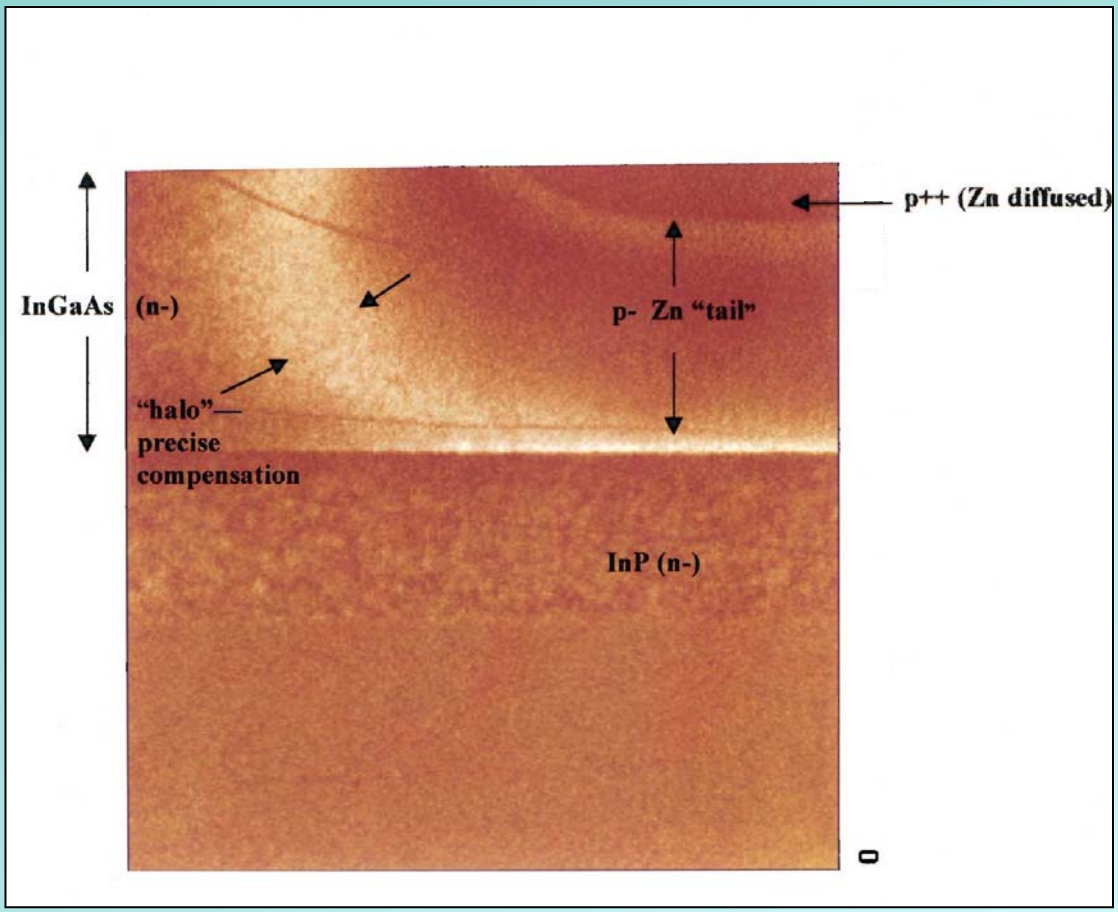
Investigation of "charge balancing"

Vertical Illumination QU Photodetector



- MOCVD growth
- Post-growth Zn diffusion + thermal anneal

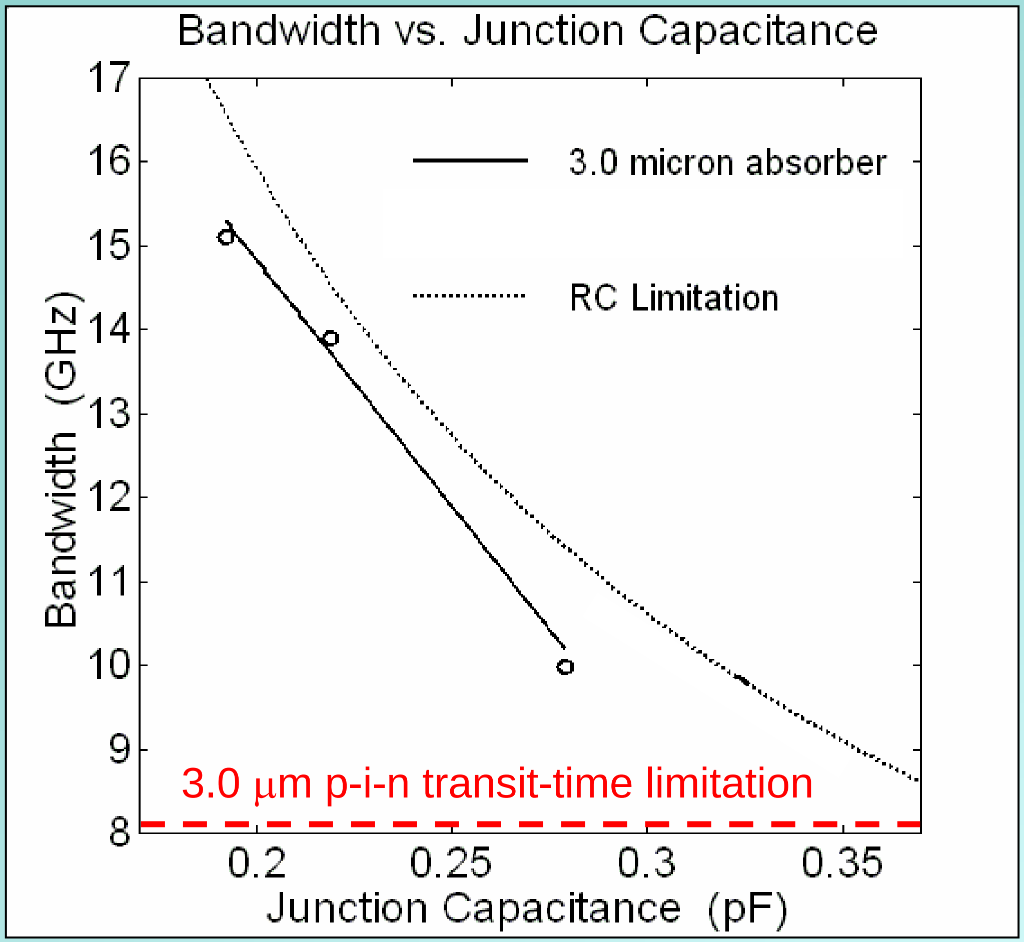
Scanning Capacitance Measurement



Courtesy of D. V. Lang

- *Intensity proportional to free carrier density*
- *Peripheral "halo" indicates p-n junction at InGaAs/InP interface*
- *Depletion region straddles InP buffer and InGaAs absorber*

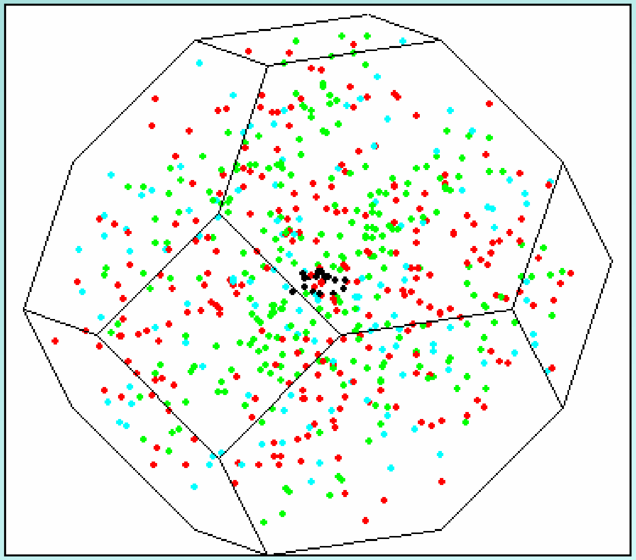
S12 Measurement at 0 dBm Optical Power



- *3dB bandwidth far exceeds p-i-n limitations*
- *QU device is RC-limited*
- *Further BW improvement is possible*

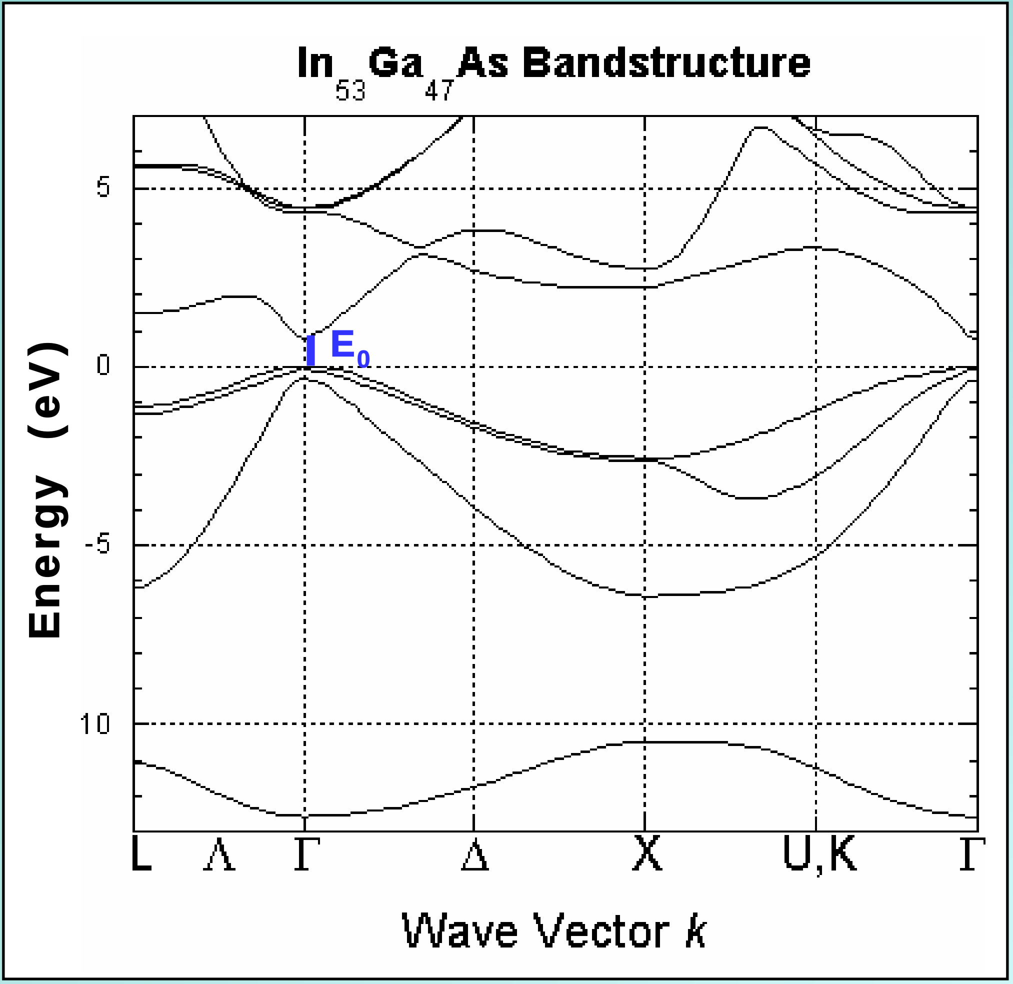
Monte Carlo Charge Transport Model

- Full band structure of InGaAs and InP
- Electron and hole ensemble
- Scattering mechanisms:
  - Polar optical electron-phonon scattering
  - Optical deformation potential scattering
  - Inelastic acoustic deformation potential scattering
  - Ionized impurity scattering
- Exact integration of the linearized BTE to precision of the phase space grids
- Mixed-mode simulation, fully coupled to external circuit



Bandstructure Calculations

(Nonlocal Empirical Pseudopotential Method w/S-O)



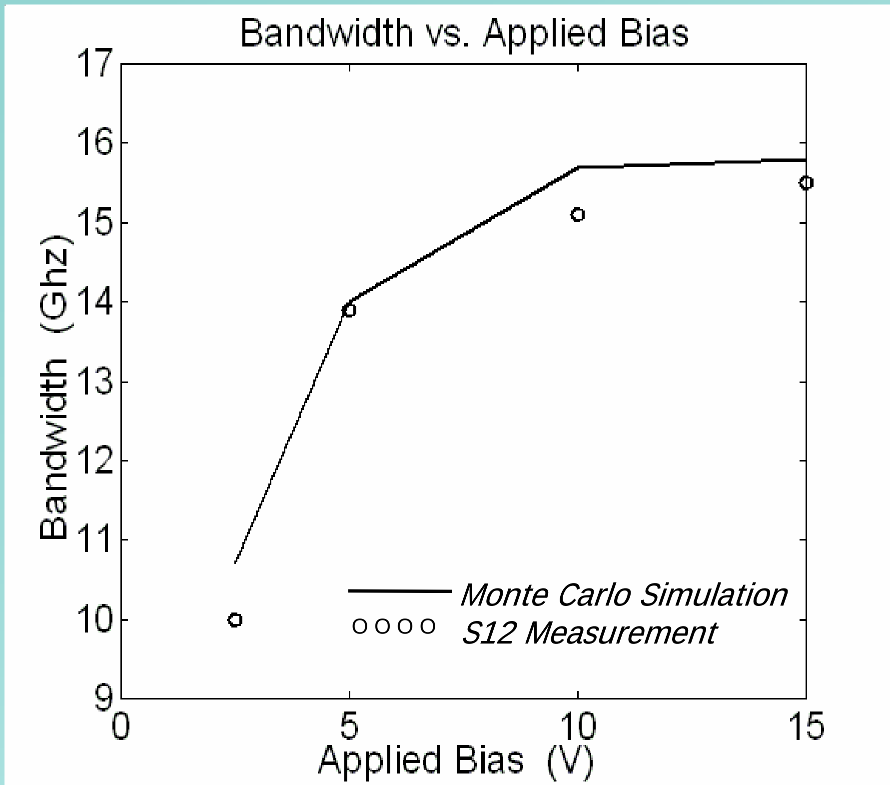
Developed an algorithm to generate pseudopotential parameters optimized to reproduce measured values of:

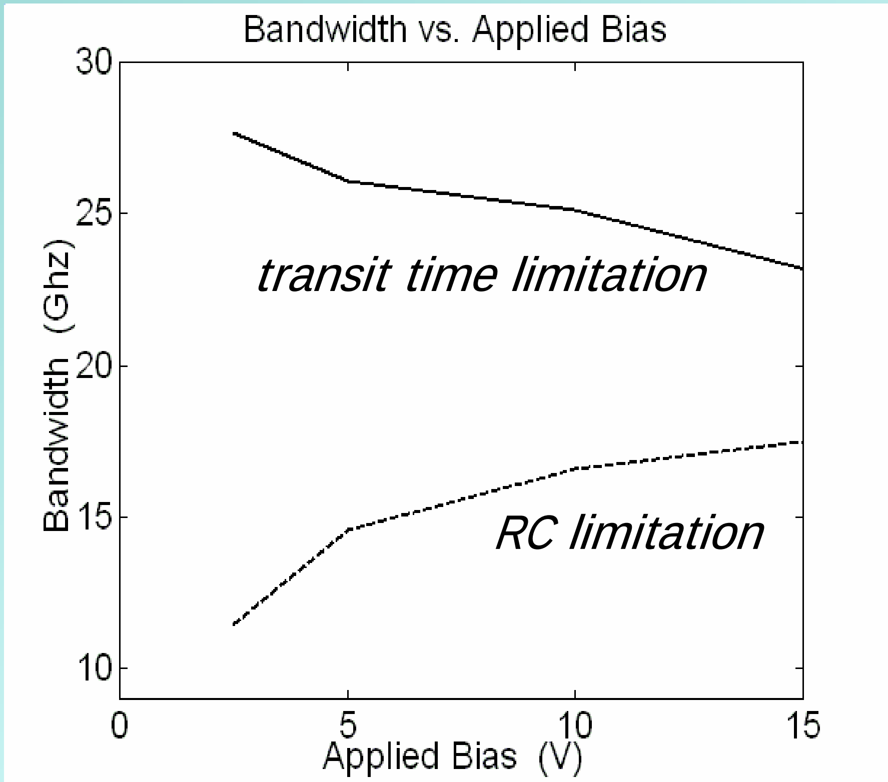
1) *Optical transition energies E_0, $E_0+\Delta_0$, E_1, $E_1+\Delta_1$, E_0', and $E_0'+\Delta_0'$ determined by spectroscopic ellipsometry, reflectrometry*

2) *Effective masses of band-edge electrons and holes, determined by cyclotron resonance*

New bandstructures generated for $In_{53}Ga_{47}As$ and InP

BW vs. Bias with 3.0 μm Absorber





Simulation confirms understanding of device operation

BW may be improved by increasing W_D and decreasing W_U

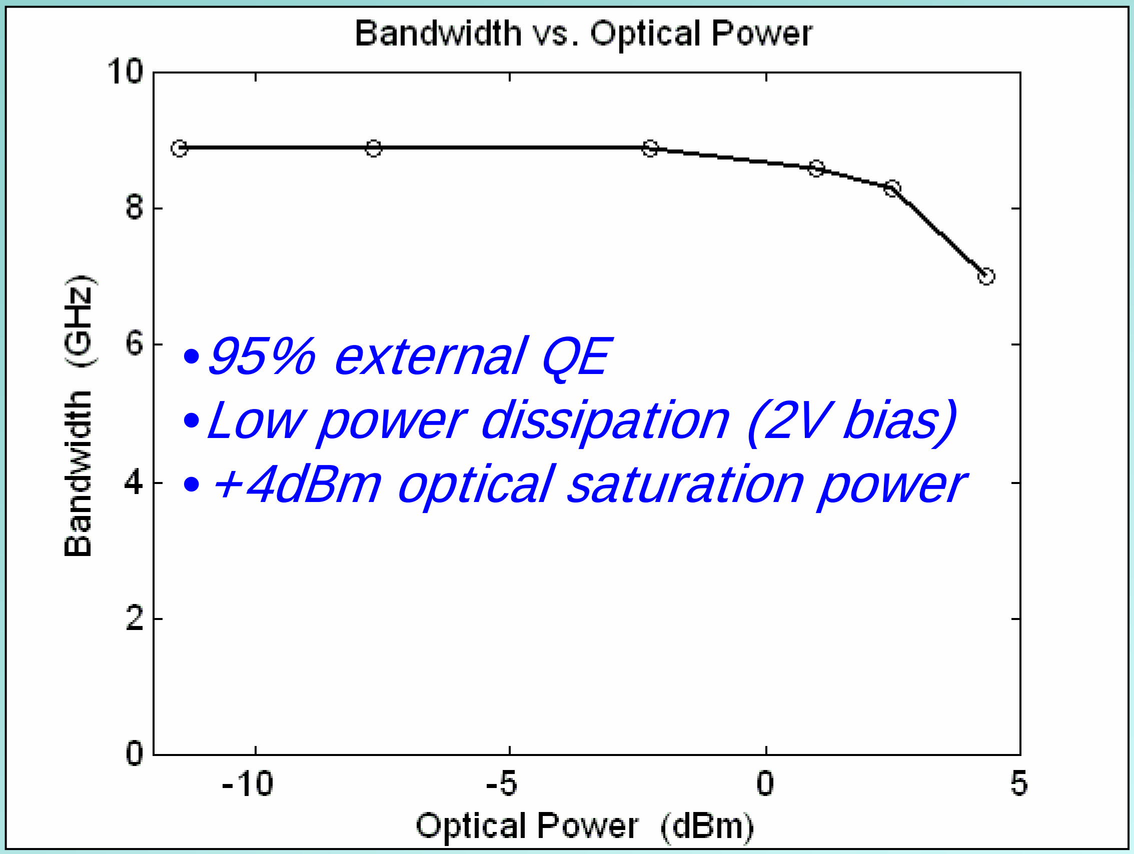
Summary

- *QU design strategy proposed as alternative to UTC and p-i-n approaches*
    - *UTC and p-i-n detectors are limiting cases of the QU design strategy*
    - *BW may be maximized by "balancing" electron and hole photocurrent responses.*

- *New equivalent circuit and analytic model proposed for QU and UTC photodiode operation*

- *Device measurements reveal significant improvements in 3dB bandwidth w.r.t. p-i-n design.*

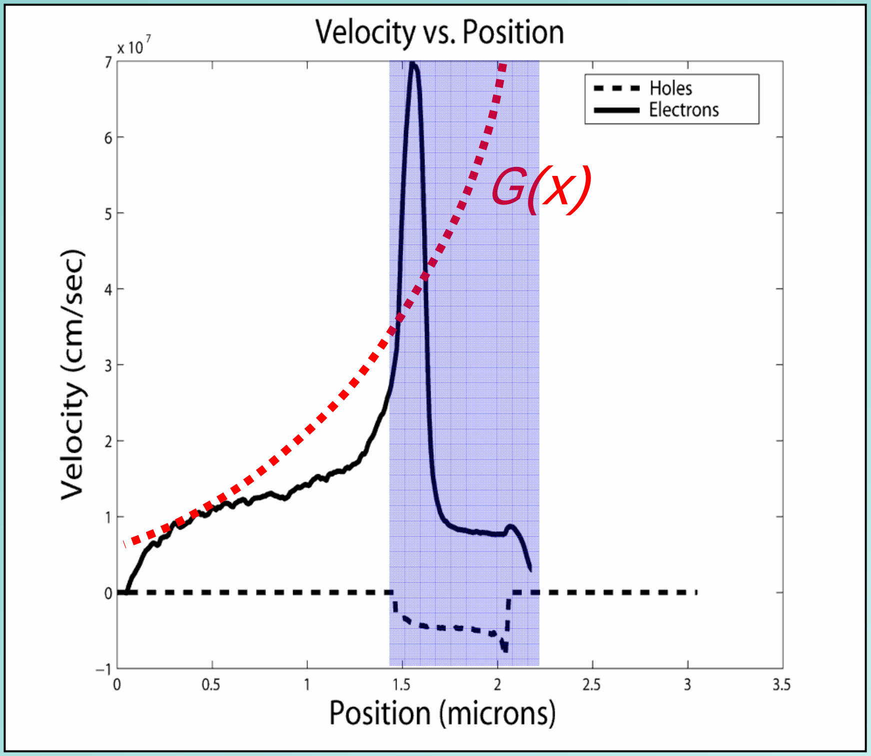
Optical Saturation Power
(2.5μm absorber, 2V bias)

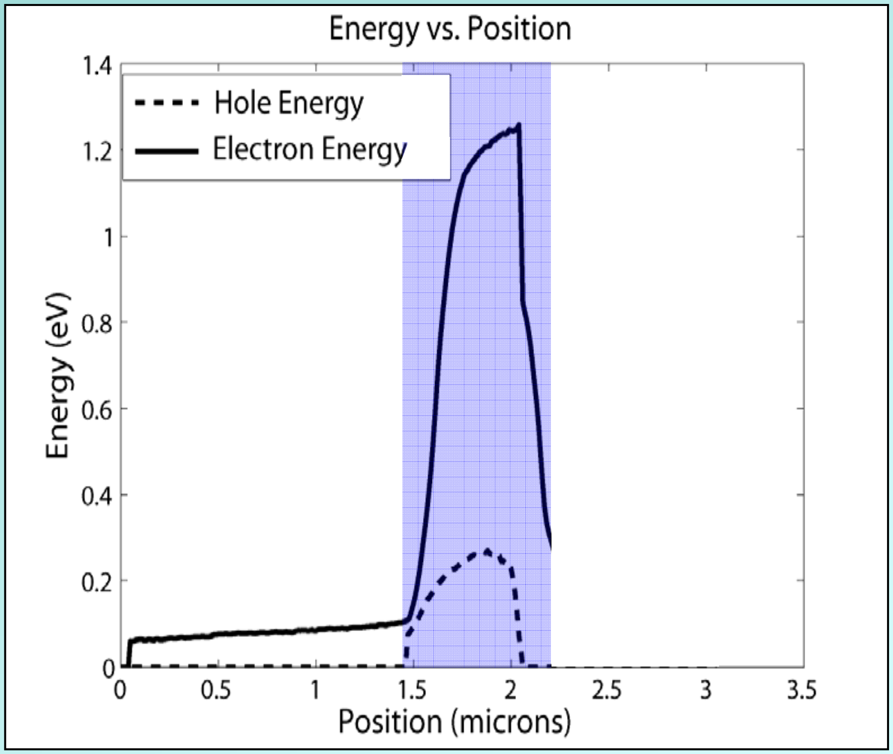


Bandwidth may be traded for optical saturation power via reduction of W_D without penalty to quantum efficiency.

Highest reported 10 Gbps optical saturation power with 95% QE

Monte Carlo Simulation Results
(2μm absorber, 5V bias)

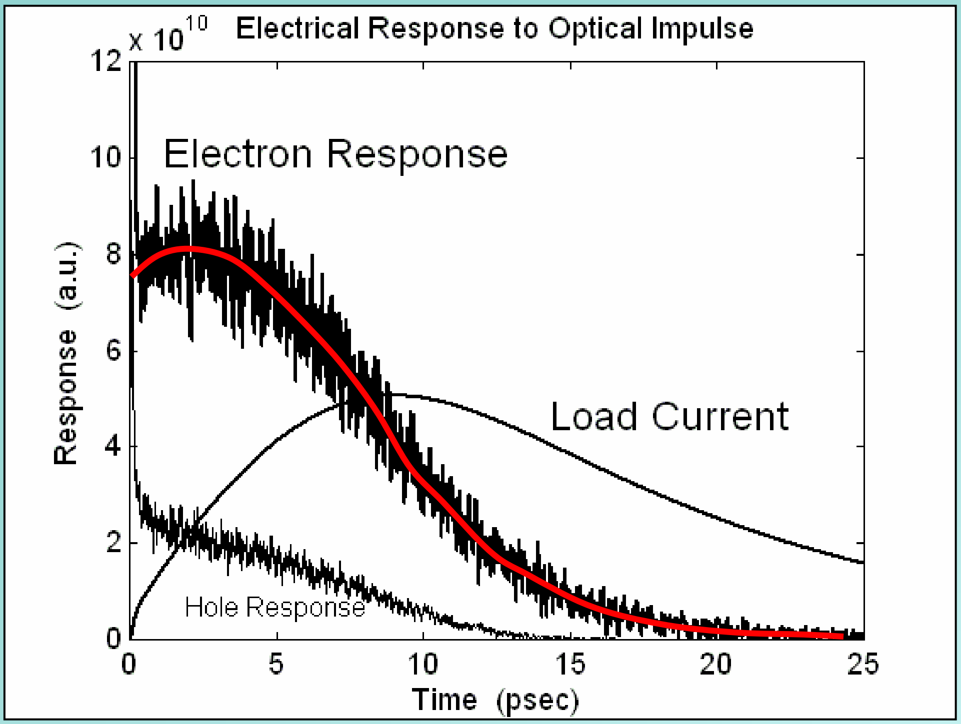


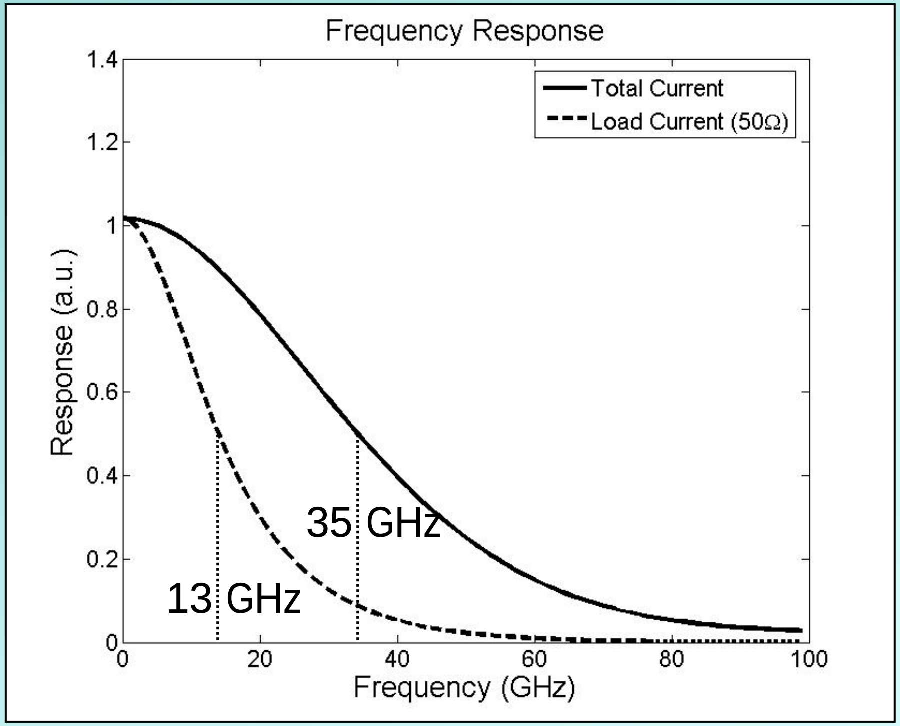


Dopant gradient-induced fields lead to high electron velocity in Ω_U.

Electron transport is non-local throughout active region

Simulated Impulse/Frequency Response
(2μm absorber, 5V bias)





"Balancing" electron and hole response through design of W_U and W_D optimizes modulation bandwidth for arbitrary W_A.