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)


\[ N_{A}^{++} \rightarrow N_{A}^{+} \rightarrow N_{D}^{++} \]

• Partially Depleted Absorber (PDA)


\[ N_{A}^{++} \rightarrow N_{A}^{+} \rightarrow N_{D}^{++} \]

• Quasi-Unipolar (QU)

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 $\Omega_u$ escape into $\Omega_d$ by:
  - **Drift in static field**
    \[ E_{\text{static}} \approx \frac{k_B T}{q} \frac{\nabla N_A}{N_A} \]
  - **Drift in dynamic field**
    \[ E_{\text{dynamic}} \approx J_{pc}^{(d)} / \left( qN_A \mu_p \right) \]
  - **Diffusion**
    \[ \tau \approx W_U^2 / 2 D_e \]
QU Photodiode Operation

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

Controlled by design!
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”.

Max. hole transit distance: $W_A - W_U$

Max. elec. transit distance: $W_U + W_D$
QU Photodiode Operation

Limiting cases of QU design:

- **UTC device:** \( W_U \rightarrow W_A \)
- **p-i-n:** \( W_U \rightarrow 0, \ W_D \rightarrow W_A \)
- **PDA:** \( W_U + W_D < W_A \)
Analytic Model: Linearized Moments of BTE

Within $\Omega_u$ (undepleted absorber material):

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

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

Within $\Omega_{du}$ (depleted absorber material):

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

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

Within $\Omega_{dc}$ (depleted collector material):

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

Investigation of “charge balancing”
Vertical Illumination QU Photodetector

- SiNx
- InGaAsP
- InGaAs absorber
- InP buffer
- InP substrate
- N-metal
- P-metal
- Zn diffusion
- Optical signal

- MOCVD growth
- Post-growth Zn diffusion + thermal anneal
**Scanning Capacitance Measurement**

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

Courtesy of D. V. Lang
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

**Bandwidth vs. Junction Capacitance**

- 3.0 micron absorber
- RC Limitation

3.0 μm p-i-n transit-time limitation
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, reflectometry

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

New bandstructures generated for $\text{In}_{53}\text{Ga}_{47}\text{As}$ and $\text{InP}$
**BW vs. Bias with 3.0 μm Absorber**

Simulation confirms understanding of device operation

- **BW** may be improved by increasing $W_D$ and decreasing $W_U$

- **Monte Carlo Simulation**
- **S12 Measurement**

**Transit time limitation**

**RC limitation**
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.

- 95% external QE
- Low power dissipation (2V bias)
- +4dBm optical saturation power

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 $\Omega_U$.

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 $W_A$. 