Lecture 3: Photodetectors
Photodetectors (Continued)

- Last lecture we covered
  - photoconductors and the dominant photon absorption mechanism: Intrinsic (Band-to-Band)
  - the power absorbed as a function of wavelength for different materials and derived the efficiency $\eta(\lambda, x)$
  - the concept of carrier lifetime and transit time and the resulting photoconductive gain (G) that results from a mismatch in electron and hole mobilities
  - Frequency response of photoconductive photodetectors
Biased p-n Junction Photodiodes

Reverse biased

Forward biased

P-type: Semiconductor doped with acceptor atoms
N-type: Semiconductor doped with donor atoms

ECE228B, Prof. D. J. Blumenthal
Lecture 3, Slide 3
p-n Junction Photodiode Equation

\[
I = (I_s)[\exp\left(\frac{qV_{\text{bias}}}{K_B T}\right) - 1] - I_{\text{photo}}
\]

\[
= I_{\text{dark}} - I_{\text{photo}}
\]

- \(I_{\text{dark}}\) = is the current that occurs with zero optical input
- \(I_s = I_{\text{th}}\) = is the thermal or saturation current that occurs in normal (non-illuminated) diode operating mode
- \(I_{\text{photo}}\) = photo-generated current = \(\eta g P_{\text{rcvd}}\)
- \(q \) = is the electron charge
- \(V_{\text{bias}}\) = is applied bias voltage (positive = forward, negative=reverse)
- \(K_B\) = is Boltzman’s constant
- \(T\) = is temperature (usually in Kelvin, depending on units of \(K_B\))
p-n Junction Photodiode Regions of Operation

Zero light, electrical only

Increasing optical power

Photoconductive Operation

Reverse bias $V_{RB}$

Forward bias $V_{FB}$

Increasing optical power

Photovoltaic Operation

$I_0 \approx R P_0$

$I_1 \approx R P_1$
pn-Junction Carrier Dynamics (1)

- Carrier diffusion time (~ns/µm) is typically much longer than carrier transit time (~10ps/µm)
- Electron and hole velocities saturated in depletion region due to high field strength
- Once away from depletion region carrier velocities fall below saturation
- Space charge barrier prevents carriers from entering the depletion region, therefore the multiple carrier effect seen in photoconductors does not occur when carrier velocities are mismatched

![Diagrams showing carrier dynamics in a pn-junction](image-url)
pn-Junction Carrier Dynamics (2)

- Photons absorbed within one diffusion length outside the depletion region will be absorbed and the current contributing carriers will suffer both diffusion time and transit time delays
- Effect is geometry and material dependent

\[ i_{\text{photo}}(\omega) = \eta_{\text{DC}} - \eta_{\text{AC}} \cdot \frac{P_{\text{rcvd}}(\omega)}{h\nu} \cdot \sqrt{1 + \left(\frac{\omega}{\omega_D}\right)^2} + q\eta_{\text{AC}} \cdot P_{\text{rcvd}}(\omega) \]
pn-Junction Carrier Dynamics (3)

- The separation of charge in the depletion region (due to uncompensated Donors and Acceptors) leads to a capacitive effect that also impacts the detector bandwidth.

\[ C_j = \frac{\varepsilon_0 \varepsilon_r A}{l_d} \]

- The frequency at which the detector bandwidth rolls off by 3-dB due to the junction capacitance is

\[ \omega_{RC} = \frac{1}{R_s C_j} \]

\( \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m} = \text{vacuum permittivity} \)

\( \varepsilon_r = \text{semiconductor relative permittivity} \)

\( A = \text{area of depletion region} \)

\( l_d = \text{depletion region length} \)
p-i-n Photodiodes

- To increase the photon absorption region, a layer of intrinsic semiconductor material can be added between the p and n material.
- The pin photodetector gain-bandwidth product improves over that of a simple pn junction since the depletion region is almost entirely contained in the intrinsic region and the intrinsic region can be made long.
- Carrier diffusion effects minimized since all light absorbed in intrinsic region.
- The junction capacitance is reduced compared to a pn-junction because the distance between the effective plates is increased.
- Carriers reach saturation velocity while traveling in intrinsic region, so even though pin depletion length $l_p + l_d$ is longer than pn-junction depletion length, lower transit time than pn-junction where carrier velocity drops below saturation not far from metallurgical junction.
p-i-n Photodiodes

As with the pn-junction, the quantum efficiency is defined by the following equation, however the distance can now be integrated over the larger intrinsic region

\[ P_{abs}(x) = P_i (1 - R)(1 - e^{-\alpha(\lambda)x}) = \eta(\lambda, x)P_i \]

As the depletion region length is increased, \( \eta \) increases, the junction capacitance \( C_j \) decreases, and the transit time \( \tau_{trans} \) increases. The detector design must be optimized to maximize both efficiency and bandwidth. An estimate of the bandwidth is given by

\[ B_{pin} = \frac{1}{\sqrt{\left( \frac{1}{f_{RC}} \right)^2 + \left( \frac{1}{f_{trans}} \right)^2}} = \frac{1}{\sqrt{\left( 2\pi R_s\varepsilon_0\varepsilon_r \frac{A}{l_d} \right)^2 + \left( 0.44v_s \right)^2}} \]
Bandwidth-Efficiency Tradeoffs in p-i-n Photodiodes

- The quantum efficiency, $\eta$, can be approximated assuming $R=0$ (high quality anti-reflection coating) and intrinsic region length $l_d$. $\eta = 1 - e^{-\alpha l_d}$
- For small $l$, bandwidth is transit time limited
- For large $l$, bandwidth is RC limited
- Optimal bandwidth length where two effects are equal
- QE keeps increasing with increased length

If the detector area $A$ and length $l_d$ are both optimized, then bandwidth and quantum efficiency can both be maximized

$$A = \frac{l_d}{2\pi R_i \varepsilon_0 \varepsilon_r} \sqrt{\frac{1}{B^2} - \left( \frac{l_d}{0.44 \nu_s} \right)^2}$$

$$l_d = -\frac{1}{\alpha} \ln(1 - \eta)$$
Vertically Illuminated p-i-n Photodiodes

For a double pass vertically illuminated pin detector (see left figure), the quantum efficiency is

$$\eta = \left(1 + r e^{-\alpha l}\right) \left(1 - e^{-\alpha l}\right)$$

When the carrier transit distance is approximately equal to \(l\), and \(\alpha l \ll 1\), the bandwidth-efficiency for a double-pass vertically illuminated pin photodiode is approximately
Increasing Bandwidth-Efficiency in Photodetectors

As with the pn-junction, the quantum efficiency is defined by the following equation, however the distance can now be integrated over the larger intrinsic region
Bandwidth Efficiency Tradeoffs
Waveguide Photodiodes
Distributed Photodetectors
Resonant Cavity Photodetectors
Uni-Traveling Carrier Photodiodes
APDs
Staircase and Supperlattice APDs