Optoelectronics
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John D. Williams, Ph.D.
Department of Electrical and Computer Engineering
406 Optics Building - UAHuntsville, Huntsville, AL 35899
Ph. (256) 824-2898  email: williams@eng.uah.edu
Office Hours: Tues/Thurs 2-3PM
PHOTODETECTORS

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- 5.2 Ramo's Theorem and External Photocurrent
- 5.3 Absorption Coefficient and Photodiode Materials
- 5.4 Quantum Efficiency and Responsivity
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  - A. The \( pn \) Junction and the \( pin \) Photodiodes
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**pn Junction Diode**

- **Photoconductors** convert light signal into an electrical signal such as voltage or current.
- Typical **pn photodiode** has a $p^+n$ type junction:
  - The Acceptor concentration ($N_a$) in the $p$ side is much greater than the donor concentration ($N_d$) on the $d$ side.
- The illuminated side has an annular (ring shaped) electrode open in the center for light absorption.
- A $\text{Si}_3\text{N}_4$ antireflective coating is present on Silicon photodiodes to increase transmission of light into the diode. (similar antireflective coatings are also grown on SiGe and InGaAs diodes)
- The $p$ side is very thin ($< 1 \mu m$) and is usually formed by a diffusion or ion implantation process performed on the $n$ type crystal layer:
  - Note this means that the $p$ type structure has many defects and is not a perfect crystalline structure.
pn Junction Diode

- pn photodiodes are reversed biased
- A strong negative bias is generated over a very small lateral dimension in the p+ side
- The depletion region extends deep into the thickness of the n side of the device
- The total bias in the device $V = V_o + V_r$, where $V_o$ is the built in voltage inherent in the junction
- When a photon of energy greater than the bandgap is incident, it becomes absorbed and is said to photogenerate a free electron hole pair (EHP)
- Usually the energy of the photon is such that the photogeneration takes place in the depletion layer
- The electric field present in the depletion layer pulls the EHP apart until they reach the neutral regions of the device
- Motion of the electrons photogenerated in the device by the electric field produces a photocurrent, $I_{ph}$ in the device
  - Are we sure that current is not due to electrons AND holes?
  - YES, b/c if one integrates the current to determine how much charge flowed, then we get a total number of photogenerated electrons $N_e$, and not $2N_e$ from the entire EHP system.

(a) A schematic diagram of a reverse biased pn junction photodiode. (b) Net space charge across the diode in the depletion region. $N_d$ and $N_a$ are the donor and acceptor concentrations in the $p$ and $n$ sides. (c). The field in the depletion region.

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Ramo’s Theorem and External Photocurrent

- Consider a material with negligible dark photoconductivity
- Such electrodes do not auto-inject carriers due to their self bias, but allow excess carriers in the sample to leave and become collected by the battery
- Under such conditions, the electric field throughout the sample is uniform and can be defined as $E = V/L$
- Suppose that a single photon is absorbed to create an EHP at $x = l$
- The respective drift velocities are $v_e = \mu_e E$ and $v_h = \mu_h E$
- The transit times associated with the carriers and holes are $t_e = \frac{L - l}{v_e}$ and $t_h = \frac{l}{v_h}$

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Ramo’s Theorem (Cont.)

- Consider first, only the drifting electron
- The work done by the battery is

$$W = eE dx = Vi_e(t) dt$$

where

$$E = \frac{V}{L}$$

$$v_e = \frac{dx}{dt}$$

yielding

$$i_e(t) = \frac{ev_e}{L}; t < t_e$$

$$i_h(t) = \frac{ev_h}{L}; t < t_h$$

Thus,

$$Q_{collected} = \int_0^{t_e} i_e(t) dt + \int_0^{t_h} i_h(t) dt = e$$

- The total charge generated by the photocurrent is a single electron. Thus the total current due to optical activity within the device can be defined as

$$i(t) = \frac{Ne v_d(t)}{L}; t < t_{transit}$$
Absorption Coefficient and Photodiode Materials

- Upper cut-off wavelength (or threshold wavelength) of the device is
  \[ \lambda_g = \frac{hc}{E_g} = \frac{1.24(eV \cdot \mu m)}{E_g (eV)} \]
  - Silicon, \( E_g = 1.12 \text{ eV} \) and \( \lambda_g = 1.11 \mu m \)
  - Ge, \( E_g = 0.66 \text{ eV} \) and \( \lambda_g = 1.87 \mu m \)
- Can Silicon be used for the optical communication band (1.3-1.5 \( \mu m \))? 
- Photons at wavelengths above the cut-off transmit through the material
- Photons at wavelengths shorter than the cut-off are absorbed exponentially in space as they travel through the device
- The intensity of light at a distance \( x \) into the photodiode is
  \[ I(x) = I_o e^{(-\alpha/x)} \]
  where \( I_o \) is the incidence intensity, and \( \alpha \) is the absorption coefficient

**Figure 5.3**
Absorption coefficient (\( \alpha \)) vs. wavelength (\( \lambda \)) for various semiconductors (Data selectively collected and combined from various sources.)
Direct vs. Indirect Bandgap

- Indirect bandgap materials (Si, Ge) require $h\nu = E_g + h\nu$ where $\nu$ is the frequency of the phonons generated in the lattice.
- Thus indirect bandgap semiconductor photodiodes actually have a cut-off energy just a bit above $E_g$ (approximately $E_g + 0.1eV$) to compensate for the momentum loss due to lattice vibrations.

(a) GaAs (Direct bandgap)

(b) Si (Indirect bandgap)

(a) Photon absorption in a direct bandgap semiconductor. (b) Photon absorption in an indirect bandgap semiconductor (VB, valence band; CB, conduction band)

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Quantum Efficiency and Responsivity

- Quantum efficiency is the efficiency of the conversion process between received photons and EHP generation

\[ \eta = \frac{\text{Number of free EHP generated and collected}}{\text{Number of incident photons}} \]

\[ \eta = \frac{I_{ph}/e}{P_o/hv} \]

\( P_o \Rightarrow \text{optical power} \)

- Responsivity characterizes the performance of a photodiode in terms of photocurrent generated per unit of optical power

\[ R = \frac{\text{Photocurrent}}{\text{Incident Optical Power}} = \frac{I_{ph}}{P_o} \]

\[ R = \eta \frac{e}{hv} = \eta \frac{e\lambda}{hc} \]

- Note: the \( \eta \) value depends on wavelength. Thus \( R \) is often termed spectral responsivity or radiate sensitivity when plotted over a range of wavelengths.

- Ideally (and not realistic) the quantum efficiency of a device is 100%, then the device is not wavelength dependent and \( \eta = 1 \).

Responsivity (R) vs. wavelength (\( \lambda \)) for an ideal photodiode with QE = 100% (\( \eta = 1 \)) and for a typical commercial Si photodiode.

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The pin photodiode

- pin (p⁺-intrinsic-n⁺) photodiode
- Photon absorption occurs within the intrinsic silicon (i-Si) layer
- Assume the i-Si region to be truly intrinsic with a significantly smaller dopant concentration than the p or n side
- The uniformity of the built in E field generates a zero potential within the intrinsic region and prevents carrier diffusion in the i-Si region
- Charging both ends generates a depletion layer capacitance in the pin diode which does not depend on the applied voltage as it would in a pn junction

\[ C_{dep} = \frac{\varepsilon_0 \varepsilon_r A}{W} \propto pf \]

\[ R = 50\Omega \]

\[ RC_{dep} \approx 50\, ps \]

- Any reverse bias applied across the junction drops almost entirely across the width of the i-Si region

\[ E = E_o + \frac{V_r}{W} \approx \frac{V_r}{W}; V_r >> V_o \]

The schematic structure of an idealized pin photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The pin photodiode in photodetection is reverse biased.

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Drift Diffusion in a pin Photodiode

- Response time is determined by the transit times of carriers across the width of the i-Si layer
  \[ t_{\text{drift}} = \frac{W}{v_d} \]
- \( v_d \) tends to saturate at \( 10^5 \text{m/s} \) at fields greater than \( E=10^6 \text{ V/m} \)
- For i-Si of width \( 10 \ \mu\text{m} \), \( t_{\text{drift}} = 0.1 \ \text{ns} \) which is longer than typical \( RC_{\text{dep}} \) time constants
- Thus the response times in pin photodiodes are limited by the transit time of photogenerated carriers

- But wait…. How does a truly i-Si depletion region with NO voltage bias generate a directional drift velocity for photoabsorbed electrons?
  - In actuality: pin photodiodes are actually slightly n-doped.
  - In essence, the intrinsic Si layer becomes the depletion region with a small concentration of positive donors so that the field is not entirely uniform across the photodiode

Drift velocity vs. electric field for holes and electrons in Si.

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Si pin photodiode

An infinitesimally short light pulse is absorbed throughout the depletion layer and creates an EHP concentration that decays exponentially.

The responsivity of two commercial Si pin photodiodes

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Example: Si pin photodiode

- A Si pin photodiode has an i-Si layer width of 20 µm. The p+ layer on the illumination side is very thin (0.1 µm). The pin is reverse biased by a voltage of 100 V and then illuminated with a very short optical pulse of wavelength 900 nm. What is the duration of the photocurrent if absorption occurs over the entire i-Si layer?

From the table on absorption coefficients, we find that Si at 900 nm has $\alpha = 30000/m$. Thus the absorption depths is approximately 33 µm. Assume that absorption occurs over the entire width of the i-Si layer.

$$E \approx \frac{V_r}{W} = \frac{100V}{20 \cdot 10^{-6} m} = 5 \cdot 10^6 V/m$$

$$v_e \approx v_{drift} \approx 10^5 m/s$$

$$v_h \approx 7 \cdot 10^4 m/s$$

$$t_h = \frac{W}{v_h} = \frac{20 \cdot 10^{-6} m}{7 \cdot 10^4 m/s} = 2.86 \cdot 10^{-10} s$$

This is the response of time of the pin as determined by the transit time of the slowest carriers, holes, across the i-Si layer. To improve the response time, the width of the i-Si layer has to be narrowed but this decreases the quantity of absorbed photons and hence the responsivity of the system.
Example: Photocarrier Diffusion in a pin Photodiode

- A reversed bias pin photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. In this case, the photogenerated electron has to diffuse to the depletion region where it is swept into the i-Si layer and drifted across. What is the speed of the photodiode if the i-Si layer is 20 μm and the p+ layer is 1 μm and the applied voltage is 100 V? Assume the diffusion coefficient of electrons in heavily doped p+ Si is $3 \times 10^{-4} \text{ m}^2/\text{s}$.

In this case, there is no electric field outside the depletion region. Thus the electron must drift diffusion across the p+ region.

$$l = \sqrt{2D_e t}$$

$$t_{\text{diff}} = \frac{l^2}{2D_e} = \frac{(1 \times 10^{-6} \text{ m})^2}{2(3 \times 10^{-4} \text{ m}^2/\text{s})} = 1.67 \times 10^{-9} \text{ s}$$

Once the electron regions the depletion region, it is drifted across by its saturation velocity.

$$E \approx \frac{V_r}{W} = \frac{100 \text{ V}}{20 \times 10^{-6} \text{ m}} = 5 \times 10^6 \text{ V/m}$$

$$v_e \approx v_{\text{drift}} \approx 10^5 \text{ m/s}$$

$$t_{\text{drift}} = \frac{W}{v_e} = \frac{20 \times 10^{-6} \text{ m}}{1 \times 10^5 \text{ m/s}} = 20 \times 10^{-10} \text{ s}$$

The total response time is $t_{\text{diff}} + t_{\text{drift}} = 1.67 \text{ ns} + 0.2 \text{ ns} = 1.87 \text{ ns}$.
Responsivity in a pin Photodiode

• A Si pin photodiode has an active light receiving area of diameter 0.4 mm. When radiation of wavelength 700 nm and intensity 0.1 mW/cm² is incident it generates a photocurrent of 56.6 nA. What is the responsivity and quantum efficiency of the photodiode at 700 nm.

Incident power on the pin photodiode is

\[ P_o = AI = \pi (0.02 \text{cm})^2 \left( 0.001 \text{W/cm}^2 \right) = 0.126 \mu \text{W} \]

The responsivity is

\[ R = \frac{I_{ph}}{P_o} = \left( 56.6 \cdot 10^{-9} \text{A} \right) \left( 1.26 \cdot 10^{-7} \text{W} \right) = 0.45 \text{A/W} \]

The quantum efficiency is

\[ \eta = R \frac{hc}{e \lambda} = \left( 0.45 \text{A/W} \right) \frac{1240 \text{eV} \cdot \text{nm}}{e \cdot 700 \text{nm}} = 0.80 = 80\% \]

The responsivity of two commercial Si pin photodiodes

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Other pin Diode Responsiveties

The responsivity of an InGaAs *pin* photodiode

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The responsivity of a commercial Ge *pn* junction photodiode

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Avalanche Photodiodes

- Avalanche photodiodes (APDs) are used widely in optical communications due to their high speed and internal gain.
- The n+ side is very thin and illuminated directly by light incident upon it.
- Three p type layers are buried within the thickness of the substrate.
  - A thin p- layer is diffused or implanted under the n+ region.
  - The middle layer is nearly intrinsic yielding only a slight potential across the thickness of the device.
  - p+ region is located at the counter electrode.
- The diode is reversed biased to increase fields within the depletion region where absorption occurs.

(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

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Avalanche Photodiodes

• When drifting electrons generated within the near intrinsic region drift diffuse into the p-region then they experience large E fields that provide sufficient kinetic energy (greater than $E_g$) to impact-ionize some of the Si covalent bonds and release more EHPs.

• The secondary EHPs are also accelerated by the same high fields, ionize and generate even more EHPs.

• This effect leads to an avalanche of impact ionization processes and the photodiode can be said to possess and internal gain mechanism that amplifies the effect of a single EHP absorption in the intrinsic region.

• The photocurrent generated in the APD in the presence of avalanche multiplication thus corresponds to a quantum efficiency greater than 1.

(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

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• The avalanche multiplication factor applied to efficiency and responsivity calculations is

$$M = \frac{\text{Multiplied \_ \ photocurrent}}{\text{Primary\_\ unmultiplied\_\ photocurrent}} = \frac{I_{ph}}{I_{pho}}$$

$$M = \frac{1}{1 - \left(\frac{V_r}{V_{br}}\right)^2}$$

• $V_{br}$ is the avalanche breakdown voltage, $V_r$ is the reverse bias, and $n$ is a characteristic index that is used to best fit the experimental data.
APD Design

- Speed of the APD diode depends on three factors: electron diffusion time in the intrinsic region, the time required to build up the avalanche process, and the time it takes for the last hole generated by the avalanche process to transit through to the intrinsic region.
- One practical drawback to APD design is that the periphery of the device reaches avalanche breakdown before the illuminated region.
- This is corrected by the establishment of an n type guard ring around the central illuminated region that prevents peripheral breakdown.

(a) A Si APD structure without a guard ring. (b) A schematic illustration of the structure of a more practical Si APD.

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Example: InGaAs APD Responsivity

- An InGaAs APD has a quantum efficiency of 60% at 1.55 μm in the absence of multiple amplification. It is biased to operate with a multiplication of 12. Calculate the photocurrent if the incident optical power is 20 nW. What is the responsivity when the multiplication factor is 12.

For $M = 1$, the quantum the responsivity is

$$R = \eta \frac{e\lambda}{hc} = (0.6) \frac{e \cdot 1500\text{nm}}{1240\text{eV} \cdot \text{nm}} = 0.75 \text{A/W}$$

If $I_{\text{pho}}$ is the primary photocurrent and $P_0$ is the incident optical power, then by definition,

$$R = \frac{I_{\text{pho}}}{P_0}.$$  

$$I_{\text{pho}} = RP_0 = (0.75 \text{A/W}) (20 \cdot 10^{-9} \text{W}) = 1.5 \cdot 10^{-8} \text{A}$$

The photodiode current $I_{\text{ph}}$ in the APD is

$$I_{\text{ph}} = MI_{\text{pho}} = (12)(1.5 \cdot 10^{-8} \text{A}) = 1.8 \cdot 10^{-7} \text{A}$$

The responsivity at $M = 12$ is

$$R = M \eta \frac{e\lambda}{hc} = (12)(0.75 \text{A/W}) = 9 \text{A/W}$$
Example: Silicon APD

- A silicon APD has a QE of 70% at 830 nm in the absence of multiplication. The APD is biased to operate with a multiplication of 100. If the incident optical power is 10 nW, then what is the photocurrent?

The unmultiplied responsivity is

\[ R = \eta \frac{e \lambda}{hc} = (0.7) \frac{e \cdot 830\text{nm}}{1240\text{eV} \cdot \text{nm}} = 0.47 \text{A/W} \]

The unmultiplied primary photocurrent from the definition of R is

\[ I_{\text{pho}} = RP_o = (0.47 \text{A/W}) \left( 10 \cdot 10^{-9} \text{W} \right) = 4.7 \text{nA} \]

The multiplied photocurrent is

\[ I_{\text{ph}} = MI_{\text{pho}} = (100)(4.7 \text{nA}) = 0.47 \mu\text{A} \]
Heterojunction Photodiodes

- Separate Absorption and Multiplication (SAM) APD
- Heterojunction of two different materials within the same photodiode
- p type surface with three n type layers of yielding different electric fields throughout the device
- Absorption occurs in the lightly doped n type region and the multiplication region is set by the doped N type region
- Bandgap differences between InGaAs and InP trap drive the different regimes and help to move electrons across the device
- Holes in the device tend to be trapped by the changes in valance band energy. This leads to slower response times. Even if the multiplier for such devices is many times higher than homojunction diodes.

Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. P and N refer to p and n -type wider-bandgap semiconductor.

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Separation Absorption Grading and Multiplication (SAGM) APDs

- The sharp interface from between $n$ layers in the SAM diode tends to trap holes and degrade drift diffusion efficiency
- The addition of grading layers and multiple short acceleration regions
  - to improve avalanche efficiency at the $p$ side of the device
  - Reduces hole trapping by lowering the energy difference between $n$ type barriers

(a) Energy band diagram for a SAM heterojunction APD where there is a valence band step $\Delta E_v$ from InGaAs to InP that slows hole entry into the InP layer.

(b) An interposing grading layer (InGaAsP) with an intermediate bandgap breaks $\Delta E_v$ and makes it easier for the hole to pass to the In layer.

Simplified schematic diagram of a more practical mesa-etched SAGM layered APD.
Superlattice APDs

- Institution of single carrier multiplication by the incorporation of quantum wells through MBE deposited multilayer devices
- The multi-quantum well effect is used to create a staircase superlattice APD in which the bandgap is graded in each layer from $E_{g1}$ to $E_{g2}$.
- Electrons drift in the conduction band and holes drift in the valance band of each quantum well as it is lined up by the applied electric field.
- Multiplication of electrons by impact ionization generates the effect commonly known by the device name a **Solid state photomultiplier**

Energy band diagram of a staircase superlattice APD (a) No bias. (b) With an applied bias.

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Phototransistors

- A bipolar junction transistor (BJT) that operates as a photodetector with photocurrent gain.
- In an ideal phototransistor, only the depletion regions (space charge layer or SCL) contain an electric field.
- E fields present in the SCL region separate EHP generated by absorbed photons.
- When the drifting electron reaches the collector, it is neutralized by the battery.
- However, when holes enter the neutral region (base), they can only be neutralized by injecting a large number of electrons from the emitter.
  - The long EHP recombination time in the neutral base region requires a significant number of electrons to be injected from the emitter for every hole drifted into the region.
  - The excess electrons diffuse across the base and reach the collector, and thus amplify the effect of the optical photocurrent generation process.

The principle of operation of the photodiode. SCL is the space charge layer or the depletion region. The primary photocurrent acts as a base current and gives rise to a large photocurrent in the emitter-collector circuit.

\[ I_{ph} = \beta I_{pho} \]

\[ I_E \propto e^{(eV_{BE} / k_B T)} \]

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Photoconductive Detectors and Gain

- Two electrodes are attached to a semiconductor with a desired absorption coefficient and quantum efficiency over the wavelength of interest.
- Response of the detector depends on whether the contacts are ohmic or blocking due to carrier recombination at the contact.
- In this class, we consider ohmic contacts such as a metallic contact pad.
- Photoconductive gain is achieved through the conservation of electric field.
  - We know that electrons drift much faster than holes.
  - So as an electron reaches the ohmic contact on the positive side, the hole has not yet reached the negative contact.
  - Thus an electron is ejected from the negative side contact to balance the charge.
  - This creates a gain multiplier based on the number of electrons that drift across the length of the photoconductor in the time it takes for a single hole to drift to the negative side of the device or recombine with an injected electron (whichever comes first).
Mathematical Assesment

• Suppose a photoconductor is suddenly illuminated by a step light. If $\Gamma_{ph}$ is the number of photons arriving per unit area per unit second, then $\Gamma_{ph} = \frac{I}{hv}$ (intensity/energy of photon)

• The number of EHP generated per unit volume per second is

$$g_{ph} = \eta \frac{A \Gamma_{ph}}{Ad} = \eta \frac{I}{hv} = \frac{\eta I \lambda}{hcd}$$

where $A$ is the area

• At any given second, the excess electron concentration (difference between photogenerated electrons and dark elections) is

$$\Delta n = n - n_o = \Delta p$$

• And the rate increase of excess electron concentration is the rate of photogeneration minus the rate of recombination of excess elections

• If $\tau$ is the mean recombination time of excess electrons, then one can determine the rate of change of $\Delta n$

$$\frac{d\Delta n}{dt} = g_{ph} - \frac{\Delta n}{\tau} = \frac{\eta I \lambda}{hcd} - \frac{\Delta n}{\tau}$$

• In the steady state condition (the point at which time dependence goes to zero)

$$\Delta n = \tau g_{ph} = \tau \frac{\eta I \lambda}{hcd}$$
Mathematical Assessment

• From our basic understanding of semiconductors, the conductivity in the device is given by
  \[ \sigma = e\mu_e n + e\mu_h p \]

• And the change in the conductivity due to photogenerated carrier activity is
  \[ \Delta\sigma = e\mu_e \Delta n + e\mu_h \Delta p = e\Delta n (\mu_e + \mu_h) \]
  \[ \Delta\sigma = \frac{e\eta I \lambda \tau (\mu_e + \mu_h)}{hcd} \]

• From this, one can write the current density as
  \[ J_{ph} = \Delta\sigma \frac{V}{l} = \Delta\sigma E \]

• And the number of electrons flowing in the circuit as
  \[ I_{ph} = \frac{w d J_{ph}}{e} = \frac{w e \eta I \lambda \tau (\mu_e + \mu_h) E}{hc} \]

• However, the rate of EHP photogeneration is only
  \[ (volume)g_{ph} = w l \frac{\eta I \lambda}{hc} \]

• Thus the photoconductive gain, G, in the system must equal
  \[ G = \frac{\tau (\mu_e + \mu_h) E}{l} \]
Mathematical Assessment

• Also recall that one can solve for the transit (drift) time of electrons or holes in a semiconductor as

\[
t_e = \frac{l}{\mu_e E} \quad \text{and} \quad t_h = \frac{l}{\mu_h E}
\]

• Substitution of transit times for carrier mobility gives the Gain as a function of drift time

\[
G = \frac{\tau}{t_e} + \frac{\tau}{t_h} = \frac{\tau}{t_e} \left(1 + \frac{\mu_h}{\mu_e}\right)
\]

• Thus the photoconductive gain can be quite high if \(\tau/t_e\) is kept large which requires a long recombination time and a short transit time.

• As one might imagine, the transit time can be made shorter by applying a greater field, but this will also increase the dark current which thereby increases the noise in the system.
Noise in a Photodetector

- The lowest signal that a photodetector can detect is determined by the extent of random fluctuations in dark current within the device from statistical processes in the device.
- The fluctuations, or shot noise, in the device is due to the fact that EHP excitations and recombinations are actually discrete instances that sum to produce randomly generated electrical current within the device.
- The root mean square (rms) value of shot noise due to dark current can be derived from the frequency bandwidth, $B$, of the detector and the dark current, $I_d$ present.

$$i_{n-dark} = \sqrt{2eI_dB}$$

In $pn$ junction and $pin$ devices the main source of noise is shot noise due to the dark current and photocurrent.
Noise in a Photodetector (Cont.)

• Because shot noise is actually based on single electron events we can also assign a quantum noise component to the system

\[ i_{n-quantum} = \sqrt{2eI_{ph}B} \]

• Such that the total rms noise in the system is

\[ i_n^2 = i_{n-dark}^2 + i_{n-quantum}^2 = \sqrt{2e(I_d + I_{ph})B} \]

• And the total current in the system is

\[ I = I_d + I_{ph} + i_n \]

• The Signal to noise ratio, SNR = signal noise /noise power. For a simple photodetector, the SNR is simply the ratio of \( I_{ph}^2 / i_n^2 \).

• And for a receiver must include the noise power generated by the thermal noise (impedance) in the input elements

• The noise equivalent power (NEP) is frequently quoted for photodetectors. NEP is the optical signal power required to generate a photocurrent signal \( I_{ph} \) that is equal to the total noise current \( i_n \) at a given wavelength and within a bandwidth of 1 Hz.

  — ie. NEP is the value \( SNR = 1 \) at a given \( \lambda \) and \( B = 1Hz \)
• If R is the responsivity and Po is the monochromatic incident power, then the generated photocurrent is

\[ I_{ph} = R P_o \]

• The NEP requires that \( I_{ph} = i_n \) so, one can then write

\[ R P \Rightarrow R P_1 = \sqrt{2e(I_d + I_{ph})B} \]

• From this we can find the optical power per square root of bandwidth (noise equivalent power) as

\[ \frac{P_1}{\sqrt{B}} = \frac{1}{R} \sqrt{2e(I_d + I_{ph})} \]

• Taking \( B = 1 \) Hz, then \( P_1 = \text{NEP} \) in the units of W/Hz\(^{1/2}\)

• The detectivity, D, of any photoconductor = \( 1/\text{NEP} \) represents then limit of detection available by the device.
APD Noise

- In SPD devices, both photogenerated and thermally generated carriers enter the avalanche zone. As such the shot noise of both of these carriers is multiplied

- Yielding an APD noise value of

\[ i_n^2 = i_{n-dark}^2 + i_{n-quantum}^2 = \sqrt{2eM^2 F(I_{do} + I_{pho})B} \]

where F is called the excess noise factor and is a function of M and the impact ionization probabilities (coefficients).

\[ F \approx M^x \]

The value x is experimentally determined for the semiconductor.

- For Silicon APDs, x varies between 0.3 and 0.5
- For Ge and III-V compounds such as InGaAs, x varies between 0.7 and 1