Photodiodes

Stavros Iezekiel
Department of Electrical and Computer Engineering
University of Cyprus
OPTOELECTRONIC (O/E) CONVERSION
• In optical-to-electrical (O/E) conversion, our aim is to convert an incoming time-varying optical power into corresponding variations of electrical signal (current, perhaps followed by a transimpedance amplifier).

In addition to having sufficient bandwidth and adequate conversion efficiency, we require that the output is an exact copy of the input – i.e. noise is bad news.

• Definitions used here: a photodiode is a one-port electrical device with an optical input which is based on a semiconductor diode. A photodetector is a circuit containing a photodiode as the front end followed by electronic amplification.
Photocurrent

\[ \text{Slope is given by responsivity} \]

- In an ideal photodiode (no noise, no nonlinearity), there is a linear correspondence between input optical power and photocurrent.

- One consequence of this is that optical loss in dB is double the corresponding electrical loss in dB (1 dBo = 2 dBe).

- Note that the photodiode is actually classified as a square law device, since optical power varies directly with the square of the electric field magnitude.

\[
\text{Responsivity} = \frac{I_P}{P_O} \text{(A/W)}
\]

This is with reference to the static characteristic

\[
\text{Quantum efficiency} = \frac{\text{number of e- hpairs}}{\text{no. of incident photons}}
\]

\[
= \frac{I_p/q}{P_o/hf} = R \frac{hc}{q\lambda}
\]
Photodiode Requirements

- High sensitivity at operating wavelengths
- Minimum noise
- High e/o conversion efficiency
- Fast response times
- High linearity
- Small size
- Low bias voltages
- High reliability
- Efficient coupling of light (anti-reflection coating)
TAXONOMY
Classification according to electrical (microwave) properties

**Lumped**
- Vertical illumination
- Edge illumination
- Tapered waveguide

**Distributed**
- Travelling wave – fully distributed
- Travelling wave – periodically distributed

Electrode configuration:
- Vertical
- Interdigitated
- Lateral collection
Classification according to optical collection/propagation

**Vertical illumination**
- Single pass
- Double pass
- Resonant cavity

**Edge illumination**
- Edge absorbing
- Waveguide
- Travelling Wave
BASIC PRINCIPLES OF PHOTODETECTION – PIN STRUCTURES
Vertically-illuminated PIN photodiode

Device Layer Structure

Band diagram showing carrier movement in E-field

Light intensity as a function of distance below the surface

Bias voltage usually needed to fully deplete the intrinsic “i” region for high speed operation

Incident photons must have sufficient energy to meet the band gap requirement. Leads to concept of cut-off wavelength.

Carriers absorbed here must diffuse to the intrinsic layer before they recombine if they are to contribute to the photocurrent. Slow diffusion can lead to slow “tails” in the temporal response.
Typical current-voltage characteristics

$I_d$ - Dark current
Unwanted component generated under no light
Leads to noise

Operate under reverse bias
Increased incident power leads to increased photocurrent
Optical radiation is absorbed in the semiconductor material according to:

\[ P(x) = P_0 (1 - \rho) e^{-\alpha(\lambda)x} \]

- Incident optical power
- Front-facet reflectivity Reduced with anti-reflection coating
• The upper wavelength cut-off $\lambda_c$ is determined by the band-gap energy $E_g$ (eV):

$$\lambda_c (\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g \text{ (eV)}}$$

• Longer wavelengths do not have high enough photon energies to excite electrons from the valence to the conduction band.

• If the depletion width is $w$, the total power absorbed is:

$$P_A = P_O (1 - \rho)(1 - e^{-\alpha(\lambda)w})$$

• In some devices this can be increased through back reflection from the bottom metal contact:

$$P_A = P_O (1 - \rho)(1 + \rho_B e^{-\alpha(\lambda)w})(1 - e^{-\alpha(\lambda)w})$$
Basic figures of merit

• Internal quantum efficiency

\[ \eta_i = \frac{\text{number of } e^-\text{h pairs collected}}{\text{no. of photons entering device}} = 1 - e^{-\alpha(\lambda)w} \]

• External quantum efficiency

\[ \eta_e = \frac{\text{number of } e^-\text{h pairs collected}}{\text{no. of photons incident on device}} = (1 - \rho)(1 - e^{-\alpha(\lambda)w}) = \frac{I_p}{P_o/hf/q} \]

• Responsivity

\[ R = \frac{\text{photocurrent}}{\text{incident optical power}} = \frac{I_p}{P_o} \quad \text{Units of A/W} \]

\[ R = \frac{\eta q}{hc} \lambda \]
- Increases with wavelength until cut-off
- Maximum value of quantum efficiency is unity, which places an upper limit on responsivity
PIN bandwidth and quantum efficiency versus absorption layer thickness for different area diameters (10, 20, 40 & 100 μm).
Trade-off between bandwidth and quantum efficiency

Bandwidth is limited by both transit time and RC product, which are both dependent on thickness, as is quantum efficiency.

\[
f_{3dB} = \left( \frac{1}{f_T^2} + \frac{1}{f_{RC}^2} \right)^{-\frac{1}{2}} = \left( \frac{2\pi d}{3.5v_{eh}} \right)^2 + \frac{2\pi \varepsilon A(R_S + R_L)}{d} \right)^{-\frac{1}{2}}
\]
Vertically illuminated photodiode

- Photons enter through top layer of device
- Absorption throughout device
- Only depletion region absorption useful
- Long depletion region:
  - High absorption (efficient)
  - Transit time limited

\[\begin{array}{c}
\text{photons} \\
p \\
\text{absorption region} \\
i \\
n \\
\text{absorption region} \\
+\text{ve bias} \\
-\text{ve bias}
\end{array}\]
**Edge coupled photodiode**

- Light enters from edge
- Coupled into absorption region optical waveguide
- Can be long but narrow
  - Short transit times/good absorption
  - High device capacitance, 3dB bandwidth given by:

\[
f_{3dB} = \frac{f_{CR}}{\sqrt{1 + \left( \frac{f_{CR}}{f_t} \right)^2}}
\]
PHOTODIODE & PHOTODETECTOR
NOISE
Photodetector Noise

- Photodiodes must detect very weak optical signals. Must maintain an adequate signal to noise ratio:

\[ SNR = \frac{\text{signal power from photocurrent}}{\text{photodiode noise power} + \text{amp noise power}} \]

Photodiode noise is caused by statistical nature of photon-electron conversion process, while the amplifier noise is due to thermal noise.
• To achieve high SNR:

(1) The photodiode must have a high quantum efficiency to generate a large signal power

(2) Photodiode and amplifier noises must be minimised.

• Photodiode efficiencies are normally high, hence it is the noise currents that determine the minimum optical power level that can be detected.

• *Minimum detectable optical power* = optical power needed to produce a photocurrent of same magnitude as rms of the total noise current. This is equivalent to having an SNR of unity.
Sources of noise in a photoreceiver:

- AMPL
- Photodiode
- Bias voltage
- Thermal noise
- Quantum noise
- Dark current noise
- Multiplication noise (only for APDs)
- Amplifier noise

**Input (photon stream)**

**Output**

*APD = avalanche photodiode*
Impact on digital reception

A: ideal signal (no noise)
B: output of photoreceiver (noise due to amplifier and photodiode)
C: output of comparator; noise can generate bit errors
SNR performance of PIN photoreceiver

• Let detected signal (photocurrent) be $I_P$:

$$I_P = I_m + i_p$$

mean value (“DC”) signal component

• signal power is proportional to: $\overline{i_p^2}$ (normalise to $R_L$)

N.B. this is a mean square current, units $A^2$
• quantum noise: due to random arrival of photons hence

detected current = mean value + random fluctuations

Can be modelled as a current source with mean square given by:

\[ i_Q^2 = 2qBI_m \]

\( B = \) bandwidth
\( q = \) electron charge

N.B. Also known as shot noise.
• dark current noise: extra shot noise component due to dark current (i.e. current that is present in the absence of optical illumination)

\[ i_D^2 = 2qBI_D \]

\( I_D \) = mean value of dark current

• thermal noise: due to bias resistor \( R_L \)

\[ i_T^2 = \frac{4kTB}{R_L} \]

\( k \) = Boltzmann’s constant = \( 1.381 \times 10^{-23} \) J/K

\( T \) = absolute temperature in K
• amplifier noise: introduced by amplifier circuitry.

We can combine $i_T$ and $i_{AMP}$ as follows:

$$i_T^2 = 4kTBF_n / R_L$$

$F_n = \text{amplifier noise figure}$

• Hence:  \[ \text{SNR} = \frac{\text{average signal power}}{\text{average noise power}} \]

$$= \frac{i_p^2}{2qB(I_m + I_D) + 4kTBF_n / R_L}$$
• SNR is maximised by:
  – low receiver noise figure
  – low bandwidth
  – large load/bias resistance, although this tends to increase receiver time constant, reducing the bandwidth
Typical SNR plots for APDs and PINs

APD = avalanche photodiode
AVARLANCHE PHOTODETECTION

http://impact-ionisation.group.shef.ac.uk/tools/
APD structure and electric field variation

Optical input

- $n^+$
- $p$
- $i$ ($\pi$)
- $p^+$

Depletion region

Electric field

$W_M$

Avalanche region (provides current gain)

Minimum field required for impact ionization

Photons absorbed here to give primary photocurrent
Device is operated under reverse bias; relatively high voltages (20 V or more) needed to achieve the high electric field in the avalanche region.

Most photons are absorbed in the depletion region, where they generate electron-hole pairs in much the same way as in a pin photodiode. The resulting photocurrent is known as the primary photocurrent.

In the high field region, photo-generated carriers are accelerated and gain enough energy to ionise covalent electrons in the valance band if they collide, thus releasing more e-h pairs. This process of carrier multiplication is termed impact ionisation. Newly created carriers are also accelerated by the high electric field, gaining enough energy to cause further impact ionisation. This phenomenon leads to the avalanche effect. In most devices, impact ionisation is confined to electrons alone.

The multiplication factor $M$ for all carriers generated in the photodiode is:

$$M = \frac{I_M}{I_P}$$

- $I_M$ is the average value of the total multiplied current and $I_P$ is the primary (i.e. un-multiplied) current

- Responsivity of an APD is:

$$R = \frac{\eta q}{h\nu} M = R_0 M$$

where $R_0$ is the unity gain responsivity.
Application of sufficient reverse bias leads to avalanche multiplication, i.e. internal gain.

However, the dark current also increases.

In addition, the avalanche effect is random in nature, and this introduces a new source of noise:

Variable gain $m$: $m = M + m_n$

Random “arrival” of carriers

These are multiplied through avalanche process, which is noisy (random nature); i.e. there is multiplication noise

Photocurrent

Quantum and shot noise are increased by excess noise of APD (multiplication noise)
• It has been found experimentally that: \( m^2 = M^{2+x} \)

where \( 0 < x < 1 \), and this value depends on the material, e.g. for silicon, \( 0.1 < x < 0.5 \), for germanium, \( 0.85 < x < 1.0 \)

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**Excess Noise Factor**

**Definition:**

The ratio of the actual noise generated to the noise generated if all carrier pairs were multiplied by \( M \).

\[
F_e = \frac{\bar{m}^2}{M^2} = \frac{M^{2+x}}{M^2} = M^x
\]

**Note:**

\( M = \bar{m} \quad \bar{m}^2 > (\bar{m})^2 \)
APD Signal-to-Noise Ratio (SNR)

Both a PIN and APD will have contributions from shot noise, dark current noise and thermal noise, while an APD will also exhibit excess noise. However, for high values of multiplication $M$, an APD will achieve the shot noise limit (or quantum limit).

$$SNR_{APD} = \frac{M^2 \bar{i}_p^2}{2qB(I_m + I_D)M^{2+x} + \frac{4kTBF}{R_L}}$$

$$= \frac{\bar{i}_p^2}{2qB(I_m + I_D)M^x + \frac{4kTBF}{M^2R_L}}$$

$$SNR_{PIN} = \frac{\bar{i}_p^2}{2qB(I_m + I_D) + \frac{4kTBF}{R_L}}$$