Photodetectors for Fiber Optic Communication

Randhir Bhatnagar
Chief Scientist, CSIR-CSIO, Chandigarh
Photodetectors find applications in the area of medical, automobile, safety and analytical equipments, cameras, astronomy, industry and communications.

Types of Photodetectors

- Photodiode, P-i-N photodiode
- Avalanche Photodiode
- Photomultiplier Tube (PMT), Microchannel Plate (MCP), Image Intensifier
- Charge Coupled Device (CCD)
Photodetector Requirements for Performance

- High sensitivity at the operating wavelength of the source
- Short response time to obtain a desirable bandwidth
- Minimum noise contribution
- Compatible size for efficient coupling and packaging
- Linear response over a wide range of light intensity
- Stability of performance characteristics
- Low bias voltage
- Low cost
Photodetection Mechanisms

Photodetector converts light (power) into electrical signal (photocurrent)

There are two distinct photodetection mechanisms

1. External photoelectric effect:
   - Photomultiplier Tubes (PMT)

2. Internal photoelectric effect:
   - PN junction photodiodes
   - PIN photodiodes
   - Avalanche photodiodes
Photoelectric Effect (External)

- An incident stream of photons strikes the surface of a material having low work function. If the energy of photon is higher than the binding energy of electron then this electron will be freed from the material surface by absorption of the incident photon energy.

- A minimum amount of energy is required to liberate a single electron from the material is called work function and denoted by $\varphi$. The ejected electrons are known as photoelectrons.

- This photodetection mechanism is used in PMT

$$E_{ke} = h\nu - BE$$
Photocathode of Ag-O-Cs, Sb-Cs, Ag-Bi-O-Cs having low work function.

The electrons hitting the dynode have high kinetic energy due to established high electric field.

The electron give up this kinetic energy, causing the release of electrons from the dynode. This process is called the secondary emission.

The incident electron at dynode can liberate more than one secondary electron. Thus amplifying the detected current.
Current to Voltage Conversion for PMT

Photomultiplier tube and output circuit
PMT Characteristics

- Photocathode of Ag-O-Cs, Sb-Cs, Ag-Bi-O-Cs
- Dynaodes made of either Nickel or stainless steel or Cu-Be alloy, coated with BeO, MgO, GaAsP
- Electron multiplication ~ 10 to 108 times
- For n dynodes, if electron multiplication is 10, gain will be $10^n$
- Quantum efficiency (ratio of photoelectron emitted from cathode to no. of incident photons), Electron transit time, electron collection efficiency, Spectral response characteristics, Gain, linearity, drift, Hysterisis, Dark current
- Output Variations due to HV supply ripple, temperature stability, and load regulation, Magnetic interference
For NIR PMT H10330B-75  M/s. Hamamatsu
Photocathode material  - InP / InGaAs
Principle of Photodetection (In Semiconductor)

- In semiconductors, conduction band and valence band are separated by a forbidden band gap.

- Electrons at the valance band are bound. The electrons in the conduction band are free and when small voltage is applied they move and causes current flow.

- Populating the conduction band with electrons causes the semiconductor to conduct current.

- The value of band gap $E_g$ determines the conductive properties of semiconductor.
A PN junction can be formed by diffusing either a P-type impurity such as Boron, into a N-type bulk silicon wafer, or a N-type impurity, such as Phosphorous, into a P-type bulk silicon wafer.
Photodetection

(a) Photogeneration of e-h pair
(b) Reverse biased p-n junction with carrier drift in depletion region
(c) Energy band diagram showing photogeneration and separation of e-h pair
All semiconductor photodetectors use photon absorption in depletion region to convert photons into electron hole pairs, and then sense them.

When a semiconductor is illuminated by light having an energy $E = h\gamma$ greater than its band gap energy $E_g$ the light is absorbed in the semiconductor and electron hole pairs are generated. $\gamma$ is the frequency of light.

Incident photon after passing through p-region will be absorbed in the depletion layer. The absorbed energy creates $EHP$, Electron raises to conduction band and hole fall to valance band. The free electron travel down the barrier and the free hole will travel up the barrier to constitute current flow.

The photon absorbed in the neutral p or n regions, outside the depletion region create $EHP$, but these free charges will not move quickly due to lack of strong electric field. Most of the free charges will diffuse slowly through the diode and may recombine before reaching the junction. These charges produce negligible current, thus reducing the detector’s responsivity.
EHP created close to the depletion layer can diffuse and subsequently be swept across the junction by the large electric field due to applied reverse biased voltage. An external current is produced but it is delayed with respect to variations in the incident optical power.

It is desirable that photon be absorbed in the depletion layer so that it can contribute maximum in generation of photocurrent.

Typical pn photodiodes have a rise time of the order of microseconds making them unsuitable for high speed optical systems.

The existence of electric field across the junction facilitate the rise of photocurrent.

The primary operating wavelength regions for FO communication systems are 850nm, 1310nm and 1550 nm. The photodetectors which are used in these systems are:

- PN junction photodiodes
- PIN photodiodes
- Avalanche photodiode
Photodetector $I$-$V$ curve under Illumination

The $I$-$V$ characteristic of a photodiode with no incident light is similar to a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as

$$I_D = I_{SAT} \left( e^{\frac{qV_A}{k_BT}} - 1 \right)$$

where $I_D$ is the photodiode dark current, $I_{SAT}$ is the reverse saturation current representing thermally generated free carriers which flow through the junction, $q$ is the electron charge, $V_A$ is the applied bias voltage, $k_B=1.38\times10^{-23}$ J/K, is the Boltzmann Constant and $T$ is the absolute temperature ($273$ K = $0^\circ$C)

Illuminating the photodiode with optical radiation, shifts the $I$-$V$ curve by the amount of photocurrent ($I_P$)
A silicon photodiode can be represented by a current source in parallel with an ideal diode. The diode represents the p-n junction, $C_j$ junction capacitance, $R_{SH}$ shunt resistance, $R_S$ Series resistance, $R_L$ load resistance.
**Shunt resistance:** An ideal photodiode should have an infinite $R_{SH}$, but actual values range from 10’s to 1000’s of Mega ohms. $R_{SH}$ is used to determine the noise current in the photodiode

**Series resistance:** $R_S$ of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon and its value ranges from 10 to 1000 Ω’s. This is used to define the linearity of photodiode.

**Junction capacitance:** The boundaries of the depletion region acts as the plates of a parallel plate capacitor. The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region. Junction capacitance is used to determine the speed of the response of the photodiode

**Response Time:** There are three factors defining the response time of a photodiode:

1. $t_{DRIFT}$, the charge collection time of the carriers in the depleted region of the photodiode.
2. $t_{DIFFUSED}$, the charge collection time of the carriers in the undepleted region of the photodiode.
3. $t_{RC}$, the $RC$ time constant of the diode-circuit combination.
\[ t_{RC} = 2.2RC \], where \( R \), is the sum of the diode series resistance and the load resistance \((R_S + R_L)\), and \( C \), is the sum of the photodiode junction and the stray capacitances \((C_j + C_S)\). Since the junction capacitance \((C_j)\) is dependent on the diffused area of the photodiode and the applied reverse bias, faster rise times are obtained with smaller diffused area photodiodes, and larger applied reverse biases.

The total rise time is determined by

\[ t_R = \sqrt{t_{DRIFT}^2 + t_{DIFFUSED}^2 + t_{RC}^2} \]

**Capacitance of Photoconductive Devices versus Reverse Bias Voltage**
Photodiode Characteristics (Optical)

Responsivity: The responsivity of a silicon photodiode is a measure of the sensitivity to light, and is defined as the ratio of the photocurrent $I_P$ to the incident light power $P$ at a given wavelength.

$$R_\lambda = \frac{I_P}{P}$$

$R_\lambda$ varies with the wavelength of the incident light as well as applied reverse bias and temperature. It is a measure of the effectiveness of the conversion of the light power into electrical current.

The **responsivity variations due to change in temperature** is due to decrease or increase of the band gap, because of increase or decrease in the temperature respectively.
Quantum Efficiency (Q.E.)

Quantum efficiency is defined as the fraction of the incident photons that contribute to photocurrent.

\[
\eta = \frac{\text{number of emitted electrons}}{\text{number of incident photons}}
\]

One of the major factors which determine the quantum efficiency is the absorption coefficient of the semiconductor material used within the photodetector. \( \eta < 1 \) quoted as a percentage say 85% i.e. 85 electrons collected per 100 incident photons.

It is related to responsivity by

\[
Q.E. = R_\lambda \frac{hc}{\lambda q}
\]

\( R_\lambda \) is the responsivity in A/W.
Quantum Efficiency is not constant at all wavelengths—varies according to photon energy.

For a given material, as the wavelength of the incident photon becomes larger, the photon energy becomes less than that required to excite an electron from the valence band to the conduction band.

Responsivity falls off rapidly beyond cutoff wavelength.
The reflectivity of a polished silicon wafer is determined from the complex refractive index.

The light is absorbed exponentially with distance and is proportional to the absorption coefficient.

The absorption depth is given by the inverse of the absorption coefficient, or $\alpha^{-1}$.

Absorption coefficient of semiconductor materials is strongly dependent on wavelength.
Biasing Photodiode

Photovoltaic Mode

The photovoltaic mode of operation (unbiased) is preferred when a photodiode is used in low frequency applications as well as ultra low light level applications. The photocurrents in this mode have less variations in responsivity with temperature.

For stability, select $C_F$ such that

$$\sqrt{\frac{GBP}{2\pi R_F (C_A + C_F + C_J)}} > \frac{1}{2\pi R_F C_F}$$

Operating bandwidth after gain peaking compensation is

$$f_{OP} (Hz) = \frac{1}{2\pi R_F C_F}$$
Photoconductive Mode

Application of a reverse bias improves the speed of response.

Effect of reverse bias

- Increase in the depletion region width
- Decrease in junction capacitance.
- Increase in the dark and noise currents.
- Decrease in rise time ($t_r$).

$$f_{3dBMax} [Hz] = \sqrt{\frac{GBP}{2 \pi R_F (C_J + C_F + C_A)}}$$

Where GBP is the Gain Bandwidth Product of amplifier (A1) and $C_A$ is the amplifier input capacitance.

A feedback capacitor ($C_F$) will limit the frequency response and avoids gain peaking.
Noise Sources in Photodiode:

**Shot noise** is related to the statistical fluctuation in both the photocurrent and the dark current.

\[ I_{sn} = \sqrt{2q(I_P + I_D)\Delta f} \]

Where \( q = 1.6 \times 10^{-19} \text{C} \), is the electron charge, \( I_P \) is the photogenerated current, \( I_D \) is the photodetector dark current and \( \Delta f \) is the noise measurement bandwidth. Shot noise is the dominating source when operating in photoconductive (biased) mode.

**Thermal or Johnson Noise** The shunt resistance in a photodetector has a Johnson noise associated with it. This is due to the thermal generation of carriers.

\[ I_{jn} = \sqrt{\frac{4k_B T \Delta f}{R_{SH}}} \]

Where \( k = 1.38 \times 10^{-23} \text{J/ºK} \), is the Boltzmann Constant, \( T \), is the absolute temperature in degrees Kelvin, \( \Delta f \) is the noise measurement bandwidth and \( R_{SH} \), is the shunt resistance of the photodiode. This type of noise is the dominant current noise in photovoltaic (unbiased) operation mode.

All resistors have a Johnson noise associated with them, including the load resistor.
Various figure of merit parameters have been used to assess the noise performance of optical detectors. Most commonly used are Noise equivalent power (NEP), Detectivity (D) and Specific detectivity (D*).

Noise Equivalent Power (NEP): The minimum input optical power required to generate photocurrent, equal to the rms noise current in a 1Hz bandwidth. NEP is essentially the minimum detectable power.

Detectivity (D): The characteristic detectivity (D) is the inverse of NEP, 1/NEP.

Specific Detectivity (D*): It is detectivity multiplied by the square root of the area (A) of the photodetector, (D* = D√A) for a 1Hz bandwidth.

D* allows different photodetectors to be compared independent of sensor area and system bandwidth; a higher detectivity value indicates a low-noise device.
The P-Intrinsic-N structure increases the distance between the P and N conductive layers, **decreasing capacitance, increasing speed**. The volume of the photo sensitive region also increases, enhancing **photoconversion efficiency**. The bandwidth can extend to 10's of GHz. PIN photodiodes are the preferred for **high sensitivity, and high speed at moderate cost**.
P-i-N PHOTODIODE

- A typical P-i-N photodiode consists of a highly-doped transparent $p$-type contact layer on top of an undoped absorbing layer (i) and an $n$-type highly doped contact layer on the bottom.

- This diode is evolved mainly from one basic requirement: light should be absorbed in the depletion region of the diode to ensure that the electrons and holes are separated in the electric field and contribute to the photocurrent, while the transit time must be minimal.

- This implies that a depletion region larger than the absorption length must exist in the detector. This is easily assured by making the absorbing layer undoped. Only a very small voltage is required to deplete the undoped region.

- An added advantage is that the recombination/generation time constant is longest for undoped material, which provides a minimal thermal generation current.
### Avalanche Photodiodes (APD) – Photodetector with Internal gain

- **Photodiode with Internal gain**: Internally multiply the primary signal photocurrent before it enters the input circuitry of the amplifier.
- **Increases receiver sensitivity**: the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit.
- **For carrier multiplication**, the photogenerated carriers must traverse a region where a very high electric field is present.

![Avalanche photodiode showing high electric field region](image-url)
- In the **high field region**, a photogenerated electron or hole can gain enough energy so that it ionizes bonds in the valence band upon colliding with them. This is known as **Impact Ionization**

- The newly created carriers are also accelerated by the high electric field, gaining enough energy to cause further impact ionization. This phenomenon is the **Avalanche Effect**

- Create an extremely high electric field region (approximately $3 \times 10^5$ V/cm)

- Requires high reverse bias voltages (100 to 400 V) in order that the new carriers created by impact ionization

- Carrier multiplication factors as great as $10^4$ may be obtained
- When carriers are generated in undepleted material, they are collected somewhat slowly by the diffusion process. This has the effect of producing a long 'diffusion tail' on a short optical pulse.
- When the APD is fully depleted by employing high electric fields, all the carriers drift at saturation-limited velocities.
- The response time for the device is limited by three factors:
  - the transit time of the carriers across the absorption region (i.e. the depletion width)
  - the time taken by the carriers to perform the avalanche multiplication process
  - the RC time constant incurred by the junction capacitance of the diode and its load
- At low gain the transit time and RC effects dominate giving a definitive response time and hence constant bandwidth for the device
- At high gain the avalanche build-up time dominates and therefore the device bandwidth decreases proportionately with increasing gain
• The rise time between 150-200ps and fall time of 1ns or more are quite common and this *limits the overall response of the device*

• Multiplication factor $M$ is a measure of the internal gain provided by the APD and is defined as

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

where $I_M$ is the average value of the total multiplied output current and $I_P$ is the primary photocurrent.

• The avalanche mechanism is a statistical process, and not every carrier pair generated in the APD experiences the same multiplication. Thus, the measured value of $M$ is expressed as an average quantity which is as great as $10^4$. 
Silicon Reach-through APD

To ensure carrier multiplication without excess noise for a specific thickness of multiplication region within APD; necessary to reduce the ratio of ionization coefficients for electron and holes (k).

- k is strong function of electric field in Silicon; 0.1 at $3 \times 10^5 \text{ Vm}^{-1}$ to 0.5 at $6 \times 10^5 \text{ Vm}^{-1}$.

- For minimum noise, the electric field at avalanche breakdown must be as low as possible (*smaller k value*) and the impact ionization should be initiated by electrons.

- This Limits the transit time and ensures a fast response
Silicon Reach-through APD

The silicon 'reach through' APD (RAPD) consists of $p^+\text{-'pie'-}p\text{-}n^+$ layers

Structure of a silicon RAPD
Field distribution in a Silicon RAPD showing gain region across p-n\textsuperscript{+} junction

- High field region, where avalanche multiplication takes place is relatively narrow and centered on the p-n\textsuperscript{+} junction.
- Under low reverse bias most of the voltage dropped across the p-n\textsuperscript{+} junction
- When the reverse bias voltage is increased; the depletion layer widens across the p-region until it ‘reaches through’ to the nearly intrinsic (lightly doped) \pi-region.
- Since \pi-region is much wider than the p-region, the field in the \pi-region is much lower than that at the p-n\textsuperscript{+} junction.
This has the effect of removing some of the excess applied voltage from the multiplication region to the $\pi$-region giving a relatively slow increase in multiplication factor with applied voltage.

Although the field in $\pi$-region is lower than the multiplication region, it is high enough ($2 \times 10^4 \text{ V/cm}$), when the photodiode is operating to sweep the carriers through to the multiplication region at their scattering limited velocity ($10^7 \text{ cm/s}$).

- Limits the transit time and ensures a fast response $\approx 0.5 \text{ ns}$. 
Advantages & Drawbacks of APDs

Advantages

- Provides an increase in sensitivity of between 5 dB to 15dB over p-i-n photodiodes i.e. detection of very low level light signals.

- Wider dynamic range as a result of their gain variation with response time and reverse bias

Drawbacks

- Fabrication difficulties due to their more complex structure and hence increased cost.

- The random nature of the gain mechanism which gives an additional noise contribution.

- Often high bias voltages required (50 to 400 V)

- The variation of the gain (multiplication factor) with temperature i.e. temperature compensation is necessary to stabilize the operation of the device.
## Photodetectors

- **APD vs p-i-n diode**

### Typical Performance Characteristics of Photodetectors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Silicon</th>
<th>Germanium</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PIN</td>
<td>APD</td>
<td>PIN</td>
</tr>
<tr>
<td>Wavelength range (nm)</td>
<td>400–1100</td>
<td>800–1800</td>
<td>900–700</td>
</tr>
<tr>
<td>Peak (nm)</td>
<td>900</td>
<td>830</td>
<td>1550</td>
</tr>
<tr>
<td>Responsivity R (A/W)</td>
<td>0.6</td>
<td>0.65–0.7</td>
<td>0.65–0.7</td>
</tr>
<tr>
<td>Quantum efficiency (%)</td>
<td>65–90</td>
<td>77</td>
<td>50–55</td>
</tr>
<tr>
<td>Gain</td>
<td>1</td>
<td>150–250</td>
<td>1</td>
</tr>
<tr>
<td>Excess noise factor</td>
<td>—</td>
<td>0.3–0.5</td>
<td>—</td>
</tr>
<tr>
<td>Bias voltage (V)</td>
<td>45–100</td>
<td>220</td>
<td>6–10</td>
</tr>
<tr>
<td>Dark current (nA)</td>
<td>1–10</td>
<td>0.1–1.0</td>
<td>50–500</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>1.2–3</td>
<td>1.3–2</td>
<td>2–5</td>
</tr>
<tr>
<td>Rise time (ns)</td>
<td>0.5–1</td>
<td>0.1–2</td>
<td>0.1–0.5</td>
</tr>
</tbody>
</table>
The MPPC (Multi-Pixel Photon Counter) is a new type of photon-counting device made up of multiple APD (avalanche photodiode) pixel. The sum of the output from each APD pixel forms the MPPC output. This allows the counting of single photons or the detection of pulses of multiple photons.

The MPPC is used in diverse applications including fluorescence analysis, fluorescence lifetime measurement, flow cytometry, single molecule detection, neutrino detection, and PET (positron emission tomography).
RGB color mixing or sensing

Typical CCD device used for present digital camera, 10 megapixel

Bayer’s filter, mosaic array for color imaging mask of CCD device. There are twice as many green as red/blue pixels to mimic the eye’s sensitivity to green light.
Digitization of each column, row pixel from charge transfer plane sequentially by clock pulses.
Working Principle

1. Generate Charge from light - Photoelectric Effect
2. Collect Charge - Pixels (gates)
4. Detect Charge - Individual charge packets are converted to an output voltage in digitized form.
5. Transfer digitized signal serially for storing/processing

Advantages of CCD

- Quantum efficiency (QE) \( \sim 80\% \)
- Low noise
- High dynamic range (~50K).
- High photometric precision
- Very linear behavior
- Immediate digital conversion of data
- Low voltages required (5V-15V)
- Geometrically stable (Good for astronomy).
- Rapid clocking
Optical Signal Detection Techniques

Signal
- Amplitude, Frequency, Phase

Noise
- Johnson Noise
- Shot Noise
- 1/f or pink noise
- Stray Light
- Light Source Fluctuation
- Drift, Capacitative Coupling Noise

Detection
- Time Averaging (Smoothing)
- Lock-in- amplifier
- Ratiometric
The purpose of the receiver is:
- To convert the optical signal to electrical domain
- Recover data

Direct-Detection Receiver:
Coherent-Detection Receiver

- For detecting weak signal, coherent detection scheme is applied where the signal is mixed with a single-frequency strong local oscillator signal.
- The mixing process converts the weak signal to an intermediate frequency (IF) for improved detection and processing.
Let the electric field of the received signal be

\[ E_{\text{sig}} \cos(\omega_{\text{sig}} t + \varphi) \]

and that of the local oscillator be

\[ E_{\text{LO}} \cos(\omega_{\text{LO}} t) \].

the output \( I \) of the detector is proportional to the square of the amplitude:

\[
I \propto (E_{\text{sig}} \cos(\omega_{\text{sig}} t + \varphi) + E_{\text{LO}} \cos(\omega_{\text{LO}} t))^2
\]

\[
= \frac{E_{\text{sig}}^2}{2} (1 + \cos(2\omega_{\text{sig}} t + 2\varphi))
+ \frac{E_{\text{LO}}^2}{2} (1 + \cos(2\omega_{\text{LO}} t))
+ E_{\text{sig}} E_{\text{LO}} [\cos((\omega_{\text{sig}} + \omega_{\text{LO}}) t + \varphi) + \cos((\omega_{\text{sig}} - \omega_{\text{LO}}) t + \varphi)]
\]

\[
= \left( \frac{E_{\text{sig}}^2 + E_{\text{LO}}^2}{2} \right) + \frac{E_{\text{sig}}^2}{2} \cos(2\omega_{\text{sig}} t + 2\varphi) + \frac{E_{\text{LO}}^2}{2} \cos(2\omega_{\text{LO}} t) + E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} + \omega_{\text{LO}}) t + \varphi)
\]

\[ \text{constant component} \]

\[ + E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} - \omega_{\text{LO}}) t + \varphi). \]

\[ \text{high frequency component} \]
Thank You