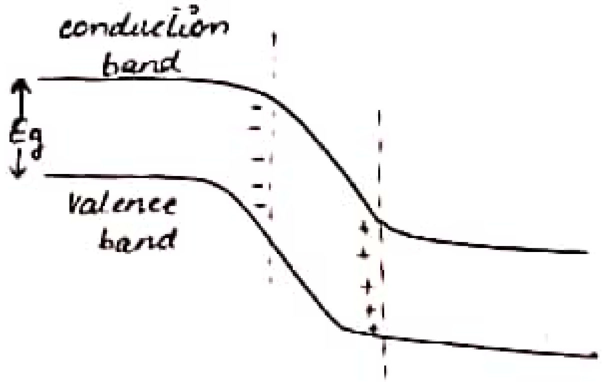
Opto-Electronics

• **Photodetector** - Photodetectors are also called Photosensors, are sensors of light or other electromagnetic radiation.

A photodetector has a pn-junction that converts light photons into current. The absorbed photons make electron hole pairs in the depletion region. Photodiodes and Phototransistors are a few examples of Photodetectors.



Electron-hole pairs are generated by the absorption of a photon with energy $h\nu$,

i.e. $h\nu \geq E_g$

The absorption of a light of a photon is shown as -

$$[P_x = P_0 \cdot (1 - e^{-\alpha x})]$$

Depletion region is devoid of any charges.

• **Properties** - There are a number of performance metrics, also called figures of merit, by which photodetectors are characterized and compared.

→ **Spectral response** - The response of a photodetector as a function of photon frequency.

→ **Quantum efficiency** - The number of carriers generated per photon. (carriers ≡ electrons & holes)

→ **Responsivity** - The output current divided by total light power falling upon the photodetector.

→ Noise Equivalent Power - The amount of light power needed to generate a signal, comparable in size to the noise of the device.

→ Detectivity - The square root of the detector area divided by the Noise equivalent Power.

→ Gain - The output current of a photodetector divided by the current directly produced by the photons incident on the detector i.e. the built in current gain.

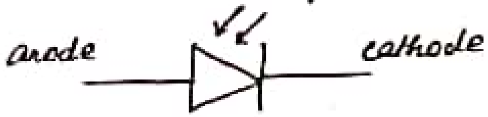
→ Dark Current - The current flowing through a photodetector even in the absence of light.

→ Response Time - The time needed for a photodetector to go from 10% to 90% of the final output.

→ Noise Spectrum - The intrinsic noise voltage or current as a function of frequency. This can be represented in the form of Noise Spectral density.

→ Non-linearity - The RF-output is limited by the non linearity of the photodetector.

• Photodiode - A photodiode is a pn-junction diode, that consumes light energy to produce electric current. Sometimes, it is also called as a photodetector, a light detector and a photosensor. These diodes are particularly designed to work in reverse bias condition, it means that the P-side of the photodiode is associated with the negative terminal of the battery. and N-side is connected to the positive terminal of the battery. The diode is very complex to light, so when the light falls on a diode, it easily changes into an electric current.



Photodiode symbol.

The types of photodiodes can be classified based on its construction and function as follows-

- PN Photodiode
- Schottky Photodiode
- PIN Photodiode
- Avalanche Photodiode

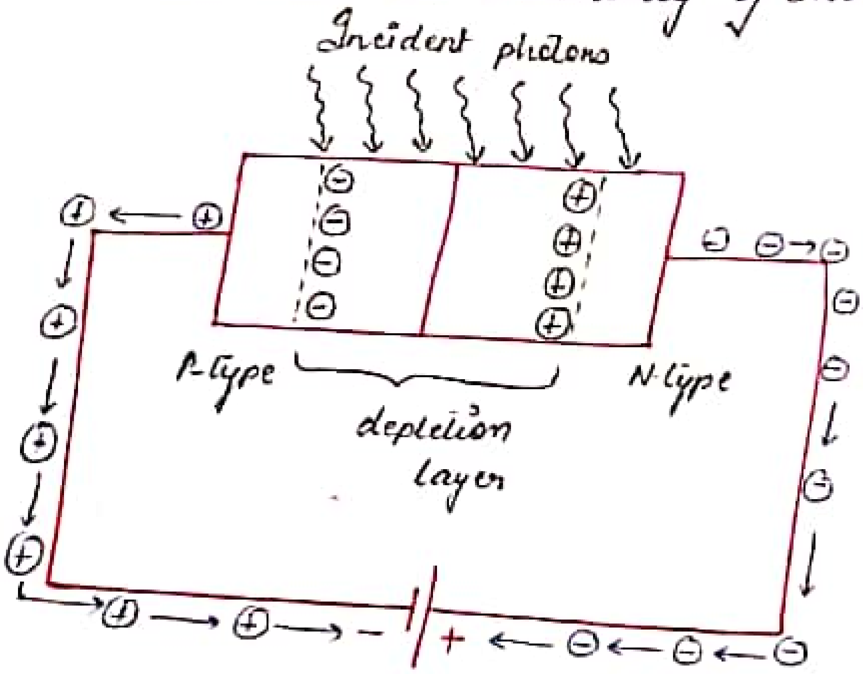
The main features of these diodes include the following -

- The linearity of the diode is good with respect to incident light.
- Noise is low
- The response is wide spectral
- Rugged mechanically
- Light weight and compact.
- long life.

* Si based photodiodes ($\lambda \equiv 190 - 1100\,nm$) produce lower noise than Ge based photodiodes ($\lambda \equiv 400 - 1700\,nm$), because of their better Bandgaps.

• Working Principle of a Photodiode -

The working principle of a photodiode is, when a photon of ample energy strikes the diode, it makes a couple of an electron-hole. This mechanism is also called as the inner photoelectric effect. If the absorption arises in the depletion region junction, then the carriers are removed from the junction by the inbuilt electric field of the depletion region. Therefore, holes in the region move towards the anode and electrons move towards the cathode, and a photocurrent will be generated. The entire current through the diode is the sum of the absence of light and the photocurrent. So the absent current must be reduced to maximize the sensitivity of the device.



Here;

P → optical power incident

i_d → detector current

η → Quantum efficiency

Quantum efficiency, $\eta = \frac{\text{No. of charge produced}}{\text{Total no. of incident photons}}$

$$\text{No. of photons} = \frac{P}{h\nu}$$

$$\text{Total charge } (e^- - h^+) \text{ produced} = \frac{\eta P}{h\nu} \cdot e$$

where,
e is the electric charge
P is the incident power.

Also, the drift current, $i_d = \frac{\eta P e}{h\nu} \cdot \lambda$

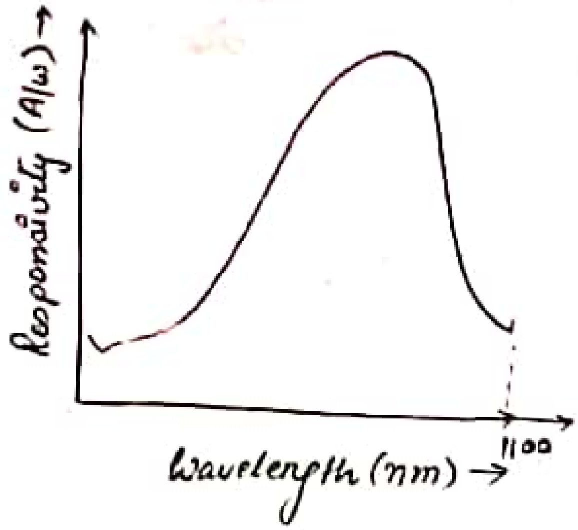
* Responsivity - The output current divided by total light power falling upon the photodetector.

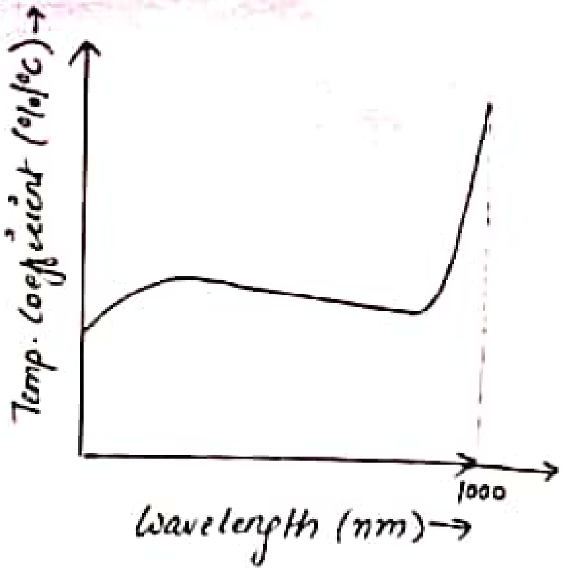
The responsivity of a photodetector is represented by 'R'.

i.e.

$R = \frac{i_d}{P}$ and is directly proportional to wavelength.

It is a measure of the sensor sensitivity to light, and is constant for a particular detector. It varies with the wavelength of the incident light, as well as the applied reverse bias and temperature. Its unit is Amp/watt.





* **Quantum Efficiency** - It can be defined as the number of carriers generated per photon.

i.e.

$$\eta = \frac{\text{No. of charge produced}}{\text{Total no. of incident photons}} = 0.6 \text{ or } 60\%$$

* **Cutoff Wavelength** - The cutoff wavelength for any mode is defined as the maximum wavelength at which that mode will propagate. It is denoted as λ_c

$$h\nu \geq E_g$$

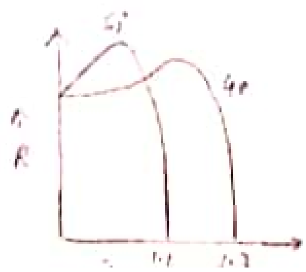
$$\Rightarrow \frac{hc}{\lambda_{cutoff}} \geq E_g$$

$$\Rightarrow \lambda_{cutoff} = \frac{hc}{E_g} = \frac{1.24}{E_g}$$

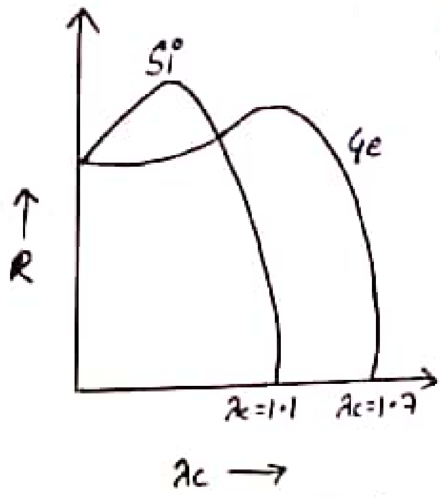
Mostly wavelength used in communication is 1300 nm - 1500 nm.

For Si, $\lambda_c = 1.1\,\mu m = 1100\text{ nm}$

For Ge, $\lambda_c = \frac{1.24}{1.67} = 1.7\,\mu m$

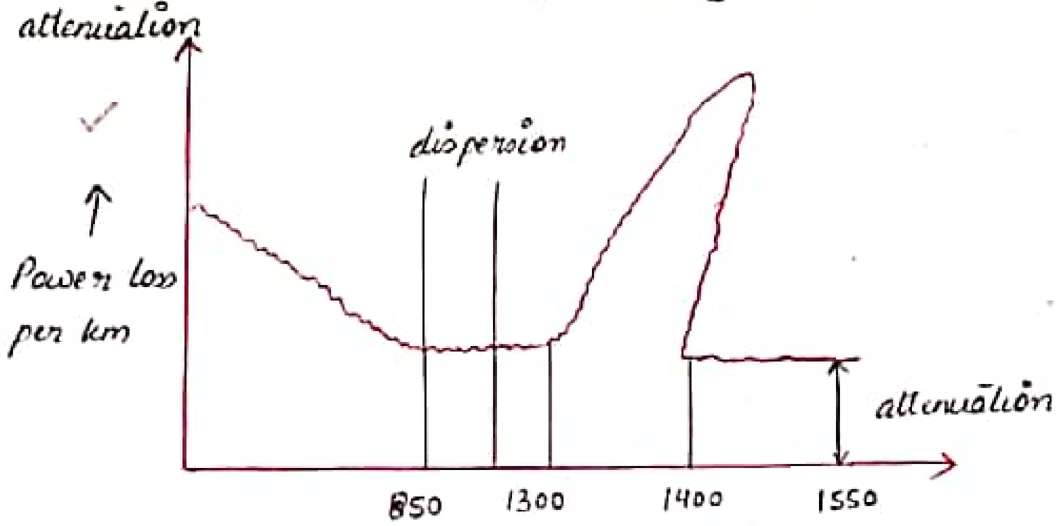


* Two processes occurs when light passes through fibres
  - ↳ Dispersion
  - ↳ Attenuation



Attenuation is the reduction in power of the light signal as it is transmitted. It is caused by passive media components.

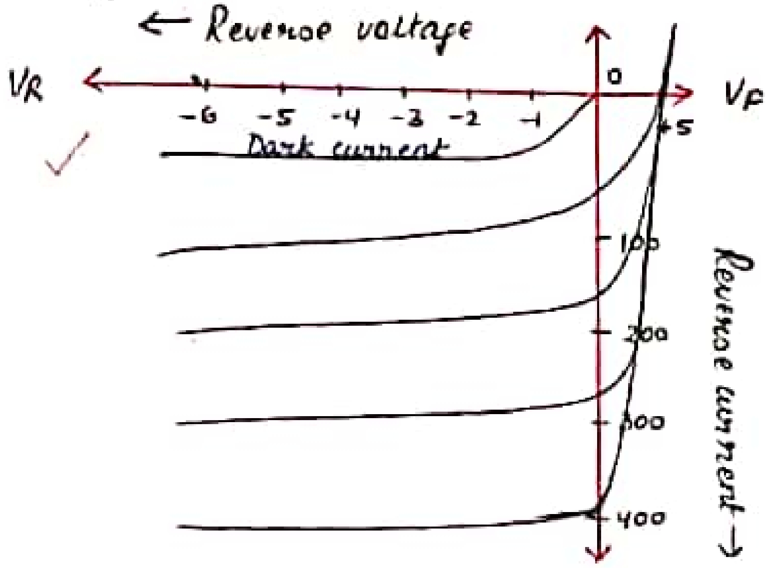
Dispersion is the spreading of the signal in time.



It is known as Multiplexing → Attenuation → 0·2 dB/km
↳ Dispersion → bit rate

• V-I Characteristics Of Photodiode -

A photodiode continually operates in a reverse bias mode. The photocurrent is nearly independent of reverse bias voltage which is applied. For zero luminance, the photocurrent is almost zero excluding for small dark current. It is of the order of nanoamperes. As optical power rises, the photocurrent also rises linearly.



* <u>Junction Capacitance</u> - The boundaries of a 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 layer. In addition, higher resistivity substrates have lower junction capacitance. It is used to determine the speed of the response of the photodiode.

$$C_J = \frac{(Si)_0 A}{\sqrt{2 (si)_0 (V_A + V_{bi})}}$$

where,

$_0 = 8.854 \times 10^{-14}$ F/cm , permittivity of free space

(Si) = ~~perm~~ 11.9 Si, dielectric constant

$\mu = 1400 \, cm^2/Vs$ at $300^\circ K$

$V_{bi} \rightarrow$ built in voltage

$V_A \rightarrow$ applied bias.

* Rise / Fall Time and Frequency response -

The rise time and the fall time of a photodiode is defined as the time for the signal to rise or fall from 10% to 90% or 90% to 10% of the final value respectively. This parameter can also be expressed as frequency response, which is the frequency at which the photodiode output decreases by 3dB. It is roughly approximated by,

$$t_r = \frac{0.35}{f_{3dB}}$$

There are three factors defining the response time of a photodiode - t_{DRIFT}, $t_{DIFFUSED}$, t_{RC}.

It can also be written as - $t_R = \sqrt{t_{DRIFT}^2 + t_{DIFFUSED}^2 + t_{RC}^2}$

where;

t_{DRIFT} → the charge collection time of the carriers in the depleted region of the photodiode

$t_{DIFFUSED}$ → the charge collection time of the carriers in the undepleted region of the photodiode

t_{RC} → the RC-time constant of the diode circuit combination.

• P-I-N Photodiode -

The PN photodiode was the first form of photodiode developed. Its performance is not as advanced as some of the other types and therefore its use is less now than it used to be.

The PIN photodiode is one of the most widely used forms of photodiode today. The PIN photodiode collects the light photons more efficiently than the more standard PN photodiode because of the wide intrinsic area between P and N regions allow for more light to be collected, and in addition to this, it also offers a lower capacitance.

PIN Diode - The diode in which the intrinsic layer of high resistivity is sandwiched between the P and N-region of semiconductor material, such type of diode is known as a PIN diode. The high resistive layer of the intrinsic region provides the large electric field between the P and N regions. The electric field induces because of the movement of the holes and the electrons. The direction of the electric field is from n-region to p-region. The PIN diode is a type of photodetector used for converting the light energy into the electrical energy.

The intrinsic layer between the P and N-regions increases the distance between them. The width of the region is inversely proportional to their capacitance. If the separation between the

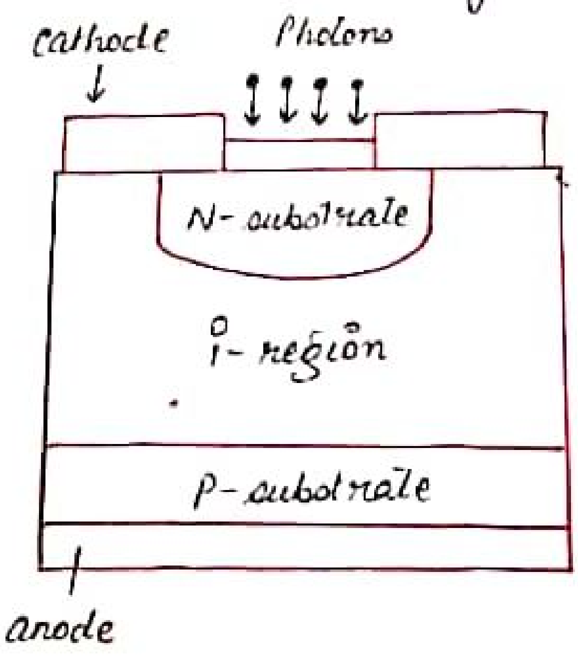
P and N region increases their capacitance decreases. This characteristic of diode increases their response time.

Structure - The diode consists of a p-region and N-region which is separated by the intrinsic semiconductor material. In P-region, the hole is the majority charge carriers while in N-region, the electron is the majority charge carrier. The intrinsic region has no free charge carrier. It acts as an insulator between n and p-type region. The i-region has the high resistance which obstructs the flow of electrons to pass through it.

PIN diode

Working of a PIN diode -

Its working is similar to the ordinary diode. When the diode is unbiased, their charge carrier will diffuse, means the charge carriers of the depletion region try to move to their region.



The diffusion of hole and electrons across the region generates the depletion layer across the NI-region. The thin depletion layer induces across n-region, and thick depletion region of opposite polarity induces across the I-region.

Forward Biased PIN Diode - When the diode is kept forward biased, the charges are continuously injected into the i-region from the P and N-region. This reduces the forward resistance of the diode and it behaves like a variable resistance. The finite quantity of charge stored in the intrinsic region decreases their resistivity.

$$Q = I_F \cdot \tau$$

where,

$I_F \rightarrow$ forward current

$\tau \rightarrow$ recombination time

Reverse Biased PIN Diode - When the reverse voltage is applied across the diode, the width of the depletion layer increases, until the entire mobile charge carrier of the I-region is swept away from it.

The reverse voltage required for removing the complete charge carrier from the i-region is known as the swept voltage. In reverse bias, the diode behaves like a capacitor, the P and N-regions acts as the positive and negative plates of the capacitor, and the intrinsic region is the insulator between the plates.

$$C = \frac{\epsilon A}{w}$$

where,
$A \rightarrow$ junction diode
$w \rightarrow$ intrinsic region thickness

Applications of PIN Diode -

↳ It is used as a high voltage rectifier.

↳ It can also be used as a photodetector i.e converting the light energy into the electrical energy.

- Comparison between PN and PIN Photodiode -

One of the key requirements for any photodetector is a sufficiently large area in which the light photons can be collected and converted. This is achieved by creating a large depletion region - the region where light conversion takes place - by adding an intrinsic area into the PN junction to create a PIN junction.

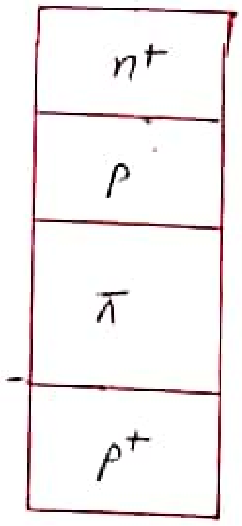
PN Photodiode	PIN Photodiode
(1) A PN-photodiode does not require a reverse bias and as a result is more suitable for low light applications as a result of the improved noise performance.	(1) Reverse bias is required by the PIN photodiode introduces a noise current which reduces signal to noise ratio.
	(2) The reverse bias offers better performance for high dynamic range applications.

(3) The reverse bias required offers better performance for high bandwidth applications as the capacitance between the P and N regions as well as charge storage is small.

- **Avalanche Photodiode - (APD) -**

An avalanche photodiode is highly sensitive semiconductor electronic device that shows photoelectric effect to convert light to electricity. APDs can be thought of photodetectors that provides a built in first stage of gain through avalanche multiplications.

By applying higher reverse bias voltage (100-200V in Si), APD shows an internal current gain effect (around 100) due to Impact Ionisation.



- **Construction** - A commonly used structure for achieving carriers multiplication with very little noise is reached through construction called as Reached through Avalanche Photodiode (RAPD).

It consists of a highly doped p^+ region. A high resistivity p-type material deposited as an epitaxial layer on a p^+ substrate. This is called a π-layer. The π layer is basically an intrinsic material that have some p- doping because of imperfect purification. Then a p type diffusion is made on a high resistivity material. After which, a highly doped n-type layer (n^+ layer) is situated. The configuration is referred to as $p^+ \pi p n^+$ reach through structure.

- Working -

(1) Normally APD operates in fully depletion mode

(2) When light enters in the device through p^+ region, is absorbed in π- material.

(3) This π-material acts as the 'collection region' for the photo generated carriers.

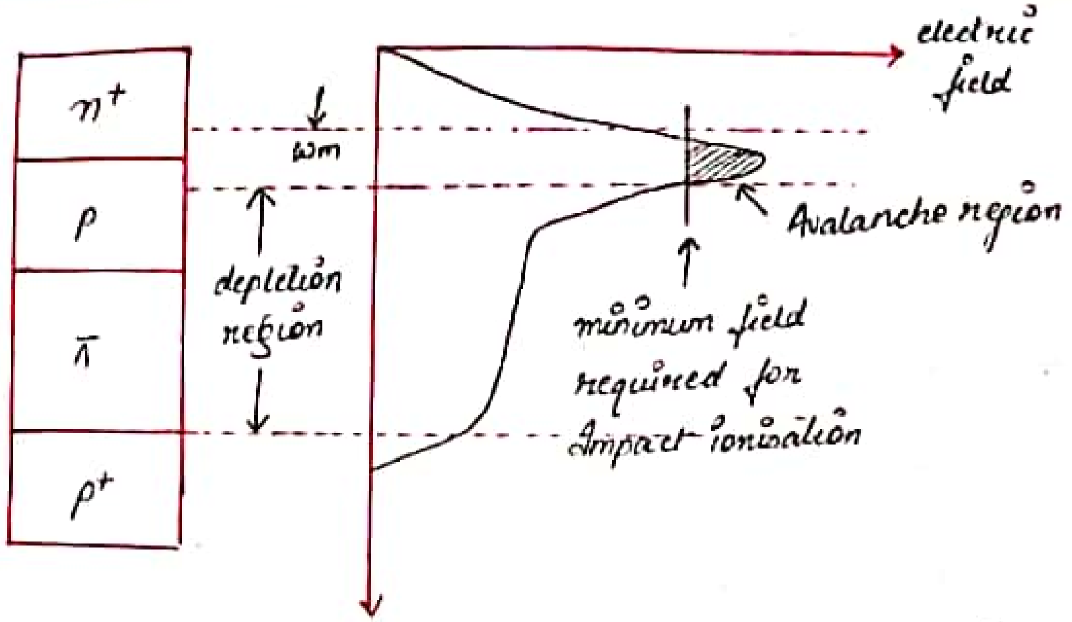
(4) On being absorbed, the photons give up its energy, thereby creating electron hole pairs.

(5) The $e^- h^+$ pairs are separated by the electric field in the π- region.

(6) The photo generated electrons drift through the π-region in pn^+ junction, where a high electric field exists.

(7) In this high electric field region, this $e^- h^+$ pair can gain enough energy so that they ionises bound electrons of valence band by collision with them.

(8) This carrier multiplication mechanism is known as 'Impact Ionisation'



(Reach through avalanche Photodiode structure and electric field in depletion and multiplication regions.)

↳ and the newly created carriers are also accelerated by electric field thus gaining enough energy to show Impact Ionisation. This phenomenon is called Avalanch effect.

The average number of electron and hole pairs created by a carrier per unit distance travelled is called the Ionisation rate.

• <u>Avalanch Photodiode Multiplication Factor</u> -

The avalanche photodiode multiplication factors is given by,

$M = \frac{I_m}{I_p}$, where,

$I_p \rightarrow$ primary photocurrent

$I_m \rightarrow$ total output photocurrent

$$M = \frac{I_p}{\left[1-\left(\frac{V}{V_B}\right)^m\right]} \qquad m \geq 1$$

where. n is the depletion manufacturing
V_B is the breakdown voltage

The overall gain is given by the multiplication factor M, which is defined as the number of carrier pairs generated from a single pair. let P be the probability of a single electron, creates an $e^- h^+$ pair.

$$P = \left(\frac{V_r}{V_{Br}}\right)^n$$

where,
$V_R \rightarrow$ applied reverse biased
$V_{BR} \rightarrow$ bandwidth voltage for $n>1$.

The Total number of pairs produced in all the generation is

$$M = 1 + P + P^2 + P^3 + P^4 + \text{------}$$

This forms a sum of Infinite series i.e $= \frac{a}{1-r}$

$$M = \frac{1}{1-P} = \frac{1}{1 - \left(\frac{V_r}{V_{Br}}\right)^n}$$

- <u>Advantages of APD</u> -

(1) APD has a higher level of sensitivity.

(2) APD has a higher responsivity.

- <u>Disadvantages of APD</u> -

(1) The output is non-linear due to avalanch process.

(2) High internal gain.

(3) Having much higher operating voltage

(4) APD produces much higher level of noise.

• **Parameters of Photodiode** -

(1) Quantum Efficiency (QE) - The quantum efficiency is defined as the fraction of incident photons which are absorbed by photodetector and generated electrons which are collected in the detector terminal.

In other words, Quantum efficiency is defined as the fraction of incident photons which contributes to photocurrent.

$$\eta = \frac{r_e}{r_p} = \frac{\text{electron-hole collected as input per second}}{\text{incident photons per second}}$$

$$\text{Quantum efficiency, } \eta = \frac{R_\lambda \text{ observed}}{R_\lambda \text{ ideal}}$$

$$= R_\lambda \frac{hc}{\lambda q} = 1240 \frac{R_\lambda}{\lambda}$$

where, $h = 6.63 \times 10^{-34}$ Js i.e the Plancks constant

$c = 3 \times 10^8$ m/s i.e the speed of light

$q = 1.6 \times 10^{-19}$ C i.e the electron charge

R_λ is the responsivity in A/w.

λ is the wavelength in nm.

(2) Response Time (T_R) - The time required for the detector output to go from the initial value to a percent of a final value (≅ 99%) is called Response time. In case of an exponential behaviour of the detector T_R, can be related to the Time constant T_c.

OR

The time that photodiode takes for the detector output to change in response to change in the input light intensity. In photodiode detector, a barrier of pn-junction is detected/present to the movement of majority carriers. The response time is thereby significantly improved. Since, the time taken for charge carriers to move through the high field region of the junction (carrier transit time) can be much shorter than the carrier lifetime.

- Various Types of Noise -

Noise is a term generally used to refer to any undesired disturbances that mask the received signal in a communication system.

→ Dark noise

→ Shot noise

→ Thermal or Johnson noise

- Shot Noise - Discrete nature of electrons causes a signal disturbance called Shot noise.

Shot noise is related to the statistical fluctuation or variation in both the photocurrent and dark current. The magnitude of Shot noise is given as the root mean square.

Noise current, $I_{sn} = \sqrt{2q(I_P + I_D).\Delta f}$ ✓

where,

$q = 1.69 \times 10^{-19} C$

I_P = photogenerated current

I_D = photo detector dark current

Δf = noise measurement bandwidth

Shot noise is a dominating source when operating in photo-conductive mode.

- **Thermal Noise** - The shunt resistance in the photo detector has a thermal noise associated with it.

This is due to the thermal generation of carriers or due to temperature variation and temperature random generation of electrons, across the shunt.

The magnitude of thermal noise is given as,

$$I_{jn} = \sqrt{\frac{4 K_B T . \Delta f}{R_{SH}}}$$

where, $K_B = 1.38 \times 10^{-23}$ J/K i.e the Boltzmann constant

T = absolute temperature in degree Kelvin. ($0°c = 273K$)

Δf = Noise measurement bandwidth.

R_{SH} = Shunt resistance of photodiode

This type of noise is dominant current noise in photo voltaic operation mode.