

### ➤ Optical Receivers:-

In the past few decades, there have been tremendous advances in opto-electronic integrated circuits (OEICs), primarily because of their widespread use in optical communication systems. Among OEICs, some of the key drivers have been high performance, low cost, and small size of photoreceivers. And in photoreceivers and optical receivers, the photodetector and preamplifiers are critical components. The photodetector's function is to convert light (photons) or radiant energy into charge carriers, electrons and holes, which can then be processed, stored, or transmitted again.



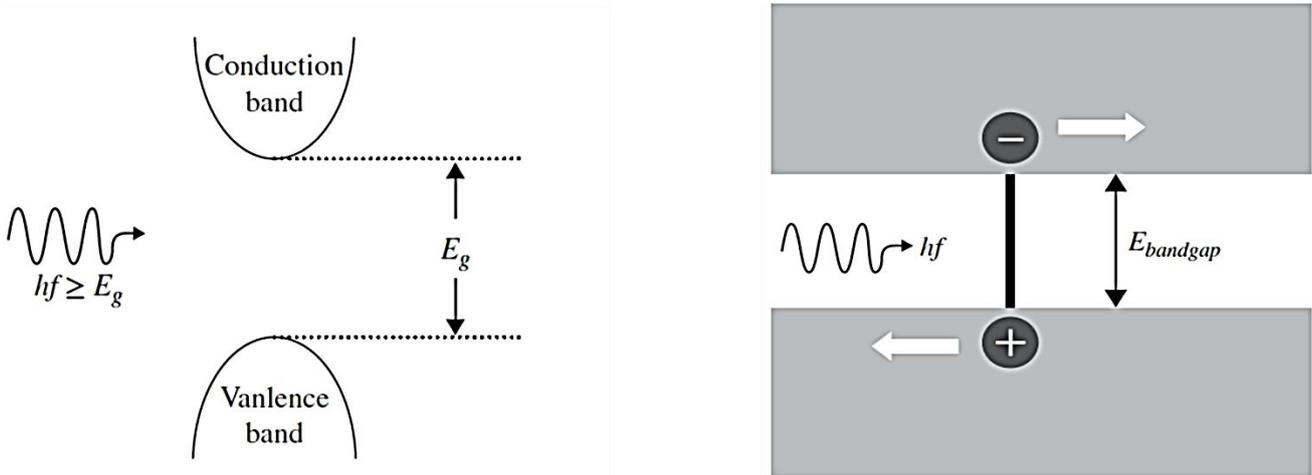
Simple schematic representation of a typical optical detector system

A photodetector is a device in which an electron–hole pair is generated by photon absorption. In the case of lasers, electrons and holes recombine (stimulated emission) and their energy difference appears in the form of light. In other words, an electron and a hole annihilate each other to create the photon. In the case of photodetectors, the reverse process takes place. A photon with energy  $hf > E_g$ , where  $E_g$  is the band-gap energy, is annihilated to create an electron–hole pair. The photon energy ( $E_{ph}$ ) decreases as the wavelength ( $\lambda$ ) increases according to:

$$E_{ph} = hf = \frac{hc}{\lambda},$$

where  $h$  = Planck's constant ( $6.626 \times 10^{-34}$  J · s),  $c$  = speed of light,  $f$  = frequency of light (Hz), and  $\lambda$  = wavelength of light (m). If the energy  $E_{ph}$  of the incident photon is greater than or equal to the band-gap energy  $E_g$ , an electron makes a transition from the valence band to the conduction band, absorbing the incident photon. The wavelength  $\lambda_{co}$  at which the absorption coefficient  $\alpha$  becomes zero is called the *cutoff wavelength*. If the incident wavelength  $\lambda$  is greater than  $\lambda_{co}$ , the photodiode will not absorb light. This is because, if  $\lambda > \lambda_{co}$ ,

$$f < f_{co} = \frac{E_g}{h}.$$



**Photon absorption in a semiconductor, with energies equal to or greater than the band gap.**

Therefore, the energy of the photon ( $\propto f$ ) will not be adequate to excite an electron into the conduction band if  $\lambda > \lambda_{co}$ , and such a photon will not be absorbed. The equation above may be rewritten as:

$$\lambda_{co} = \frac{hc}{E_g}$$

$$\lambda_{co} = \frac{1.2}{E_g(\text{eV})} (\mu\text{m}).$$

In a silicon photodiode,  $\lambda_{co} \approx 1.1 \mu\text{m}$ , so at  $1.1 \mu\text{m}$ , the photon energy is just sufficient to transfer an electron across the silicon energy band gap, thus creating an electron-hole pair, as shown in figure above. As this *cutoff wavelength* is approached, the probability of photon absorption decreases rapidly.

Semiconductor	Bandgap (eV) at 300 K	Cutoff wavelengths $\lambda_{co}$ ( $\mu\text{m}$ )
Silicon	1.12 (indirect)	1.1
Germanium	0.66 (indirect)	1.85
GaAs	1.42 (direct)	0.87
GaSb	0.73 (direct)	1.7
AlAs	2.16 (direct)	0.57
InAs	0.36 (direct)	3.5
InP	1.35 (direct)	0.92
$\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$	1.15 (direct)	1.08
$\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$	0.75 (direct)	1.65

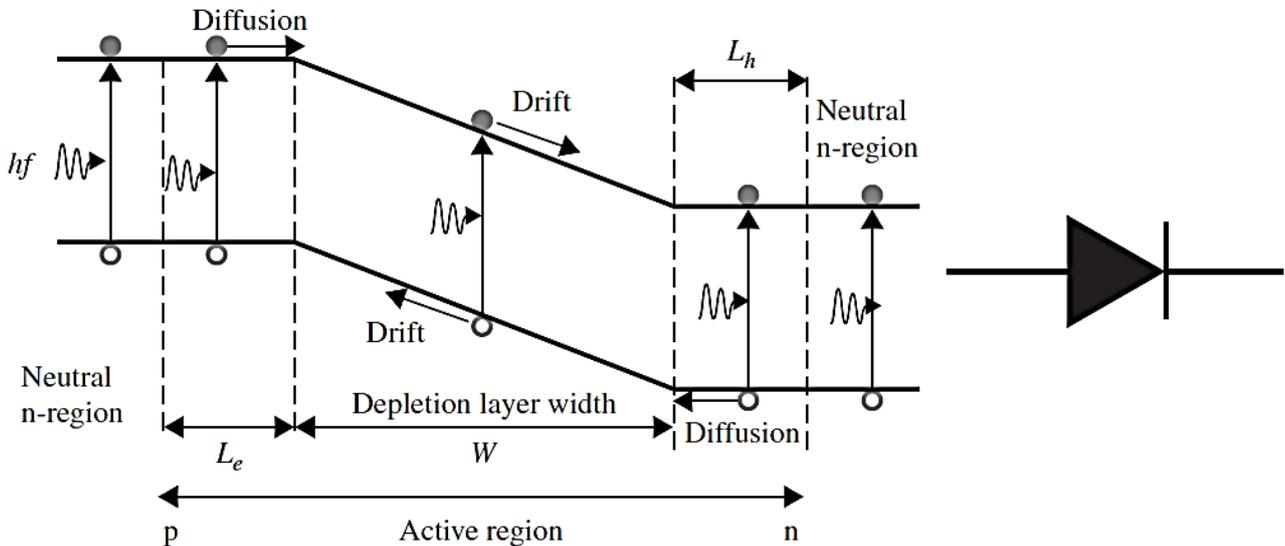
**Some common semiconductor materials used in photodetectors with their  $E_g$  and  $\lambda_{co}$  values.**

**Quantum Efficiency**

In a semiconductor photodetector, when a photon of energy  $E_{ph} \geq E_g$  is absorbed, an electron-hole pair (ehp) is formed. Then, a photocurrent is produced when the photon-generated electron-hole pairs (eph) are separated in an applied electric field, with electrons moving to the n-region and holes to the p-region (Figure below). However, the photons of appropriate wavelength do not always generate ehps, nor are all ehps collected at the respective terminals. Therefore, quantum efficiency QE (or  $\eta$ ) is defined as the probability that a photon incident on the photodetector generates an ehp (photocarrier) that contributes to the photodetector current and is given by:

$$\eta = \frac{\text{number of photocarriers that contribute to the photocurrent}}{\text{number of incident photons}}$$

Note that  $0 < \eta \leq 1$ , that is, the maximum value of  $\eta$  in a photodetector without gain is 1 or 100%, which means that each incident photon generates an ehp. The QE depends on the photon wavelength, type of semiconductor, and structure of the photodetector.



**Photoexcitation and energy-band diagram of a pn photodiode and its symbol.**

The mean number of photons,  $N_{ph}$ , in an optical wave of energy  $E$  and frequency  $f_0$  is:

$$N_{ph} = \frac{E}{hf_0}$$

Therefore, the mean number of photons per unit time, or *photon rate or photon flux*, is given by:

$$\frac{N_{ph}}{T} = \frac{E}{Thf_0} = \frac{P}{hf_0}.$$

If the incident optical power on the photodetector is  $P_I$ , the mean number of photons incident per unit time, or *photon incidence rate*, is:

$$R_{incident} = \frac{P_I}{hf_0}.$$

Let the number of photocarriers generated be  $N_{PC}$ . Not all the photocarriers contribute to the photocurrent, as some of them recombine before reaching the terminals of the photodetector. Let  $\zeta$  be the fraction of photocarriers that contribute to the photocurrent. Where  $q$  is the electron charge, the effective photocarrier generation rate may be written as:

$$R_{gen} = \frac{\zeta N_{PC}}{T} = \frac{I_{PC}}{q},$$

Therefore the equations above can be rewritten as:

$$\begin{aligned} \eta &= \frac{\text{photocarrier generation rate}}{\text{photon incidence rate}} \\ &= \frac{I_{PC}/q}{P_I/hf_0} = \frac{I_{PC}}{P_I} \frac{hc}{q} \frac{1}{\lambda_0}. \end{aligned}$$

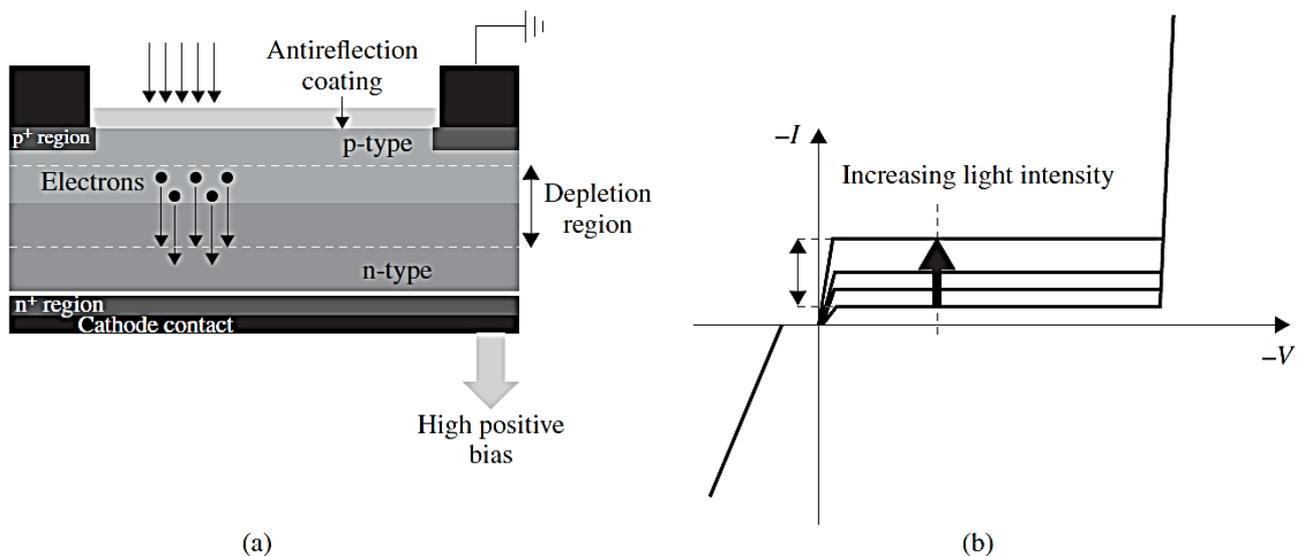
From this equation, it is noted that  $\eta$  is inversely proportional to wavelength  $\lambda_0$ . However, at short wavelengths,  $\eta$  decreases due to surface recombination because most of the light is absorbed very close to the surface.

For example, if the absorption coefficient  $\alpha = 10^5$  to  $10^6$   $\text{cm}^{-1}$ , then most of the light is absorbed within the penetration distance  $1/\alpha = 0.1$  to  $0.01$   $\mu\text{m}$ . At these distances, close to the surface, the recombination lifetime is very short, so the majority of photogenerated carriers recombine before they can be collected at the terminals. This gives rise to the short-wavelength limit in the quantum efficiency of the photodetector.

However, with careful surface treatment, it may be possible to extend the short-wavelength limit to lower values of wavelength  $\lambda$ .

An example of a simple pn-homojunction photodetector operating in the photoconductive mode is shown in figure below. That, the main absorption or photoactive region is the depletion region, where the electric field sweeps the photogenerated electrons to the n-side and holes to the p-side. This results in a photocurrent that is a drift current flowing in the reverse direction, that is, from the n-side (cathode) to the p-side (anode), and this is the main contribution to the total photocurrent.

In addition, if ehps are generated within one diffusion length of the depletion region boundaries, they can also contribute to the photocurrent. For example, the photogenerated minority carriers -holes on the n-side and electrons on the p-side- can reach the depletion boundary by diffusion before recombination happens. Once they reach the depletion region, they will be swept to the other side by the electric field. Thus, there is also a diffusion current flowing in the reverse direction and contributing to the photocurrent.



(a) Schematic representation of a simple photodiode with coating of reflectivity  $R_p$ . Note that only electrons are shown moving toward the n-type semiconductor from the depletion. An equivalent number of holes move in the opposite direction.

(b) Typical reverse-bias characteristics where the photocurrent increases with light levels.

In contrast, in the bulk **p- or n-regions**, although the generation of ehps occurs by photon absorption, they do not contribute to the photocurrent. This is because there is negligible electric field to separate photogenerated charges and hence they recombine randomly.