# Optical Detectors

The basic detection process in an intrinsic absorber is illustrated in Figure 3.11 which shows a $p$–$n$ photodiode. This device is reverse biased and the electric field developed across the $p$–$n$ junction sweeps mobile carriers (holes and electrons) to their respective majority sides ($p$- and $n$-type material). A depletion region or layer is therefore created on either side of the junction. This barrier has the effect of stopping the majority carriers crossing the junction in the opposite direction to the field. However, the field accelerates minority carriers from both sides to the opposite side of the junction, forming the reverse leakage current of the diode. Thus intrinsic conditions are created in the depletion region.
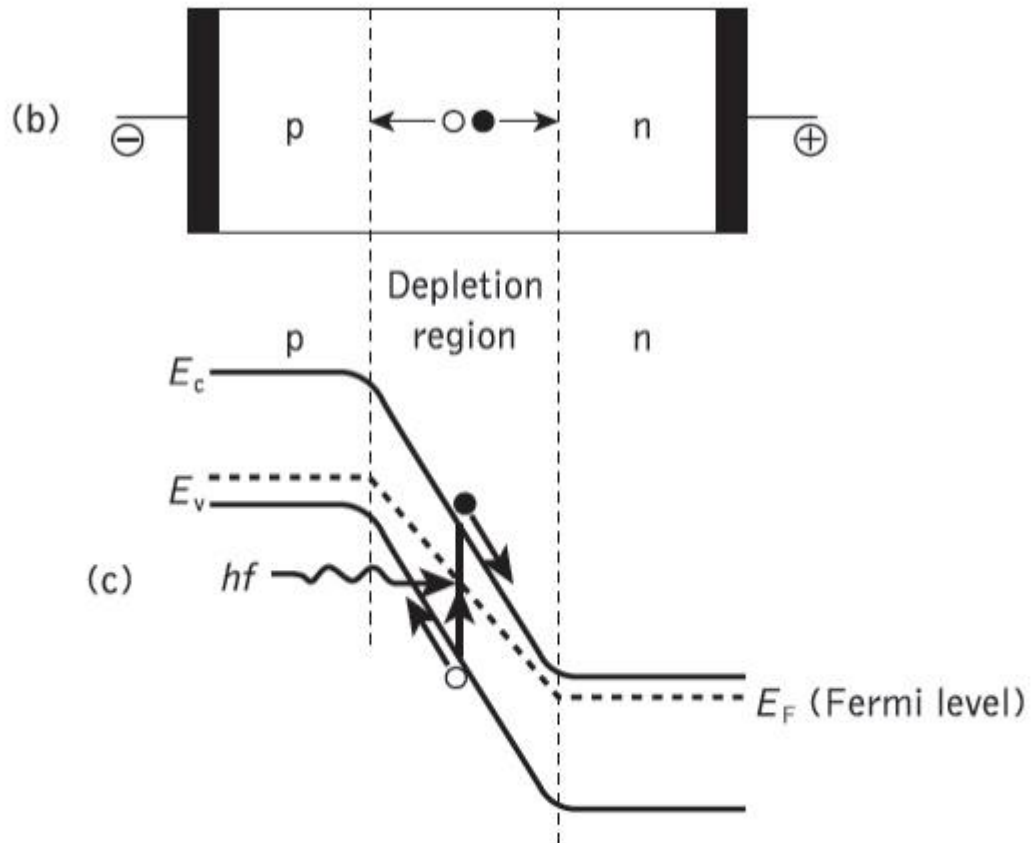


(a)
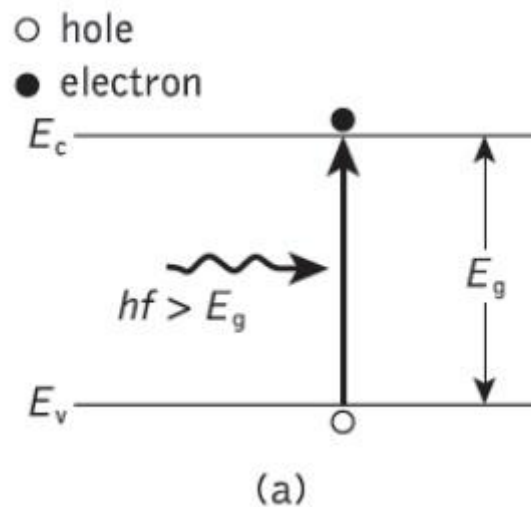
**Figure 3.11** Operation of the *p–n* photodiode: (a) photogeneration of an electron–hole pair in an intrinsic semiconductor; (b) the structure of the reverse-biased *p–n* junction illustrating carrier drift in the depletion region; (c) the energy band diagram of the reverse-biased *p–n* junction showing photogeneration and the subsequent separation of an electron–hole pair

[Source: htpp://img.brainkart.com]

## 1. PIN Photo Detectors

In order to allow operation at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary. To achieve this the *n*-type material is doped so lightly that it can be considered intrinsic, and to make a low resistance contact a highly doped *n*-type (n+) layer is added. This creates a *p–i–n* (or PIN) structure, as may be seen in Figure 3.12 where all the absorption takes place in the depletion region.
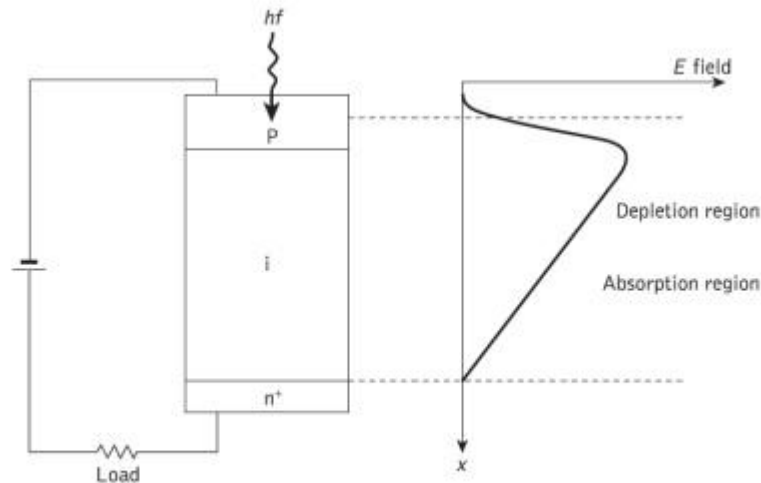
**Figure 3.12** The *p–i–n* photodiode showing the combined absorption and depletion region

[Source: htpp://img.brainkart.com]

Figure 3.13 shows the structures of two types of silicon *p–i–n* photodiode for operation in the shorter wavelength band below 1.09 μm. The front-illuminated photodiode, when operating in the 0.8 to 0.9 μm band (Figure 3.13(a)), requires a depletion region of between 20 and 50 μm in order to attain high quantum efficiency (typically 85%) together with fast response (less than 1 ns) and low dark current (1 nA). Dark current arises from surface leakage currents as well as generation– recombination currents in the depletion region in the absence of illumination.
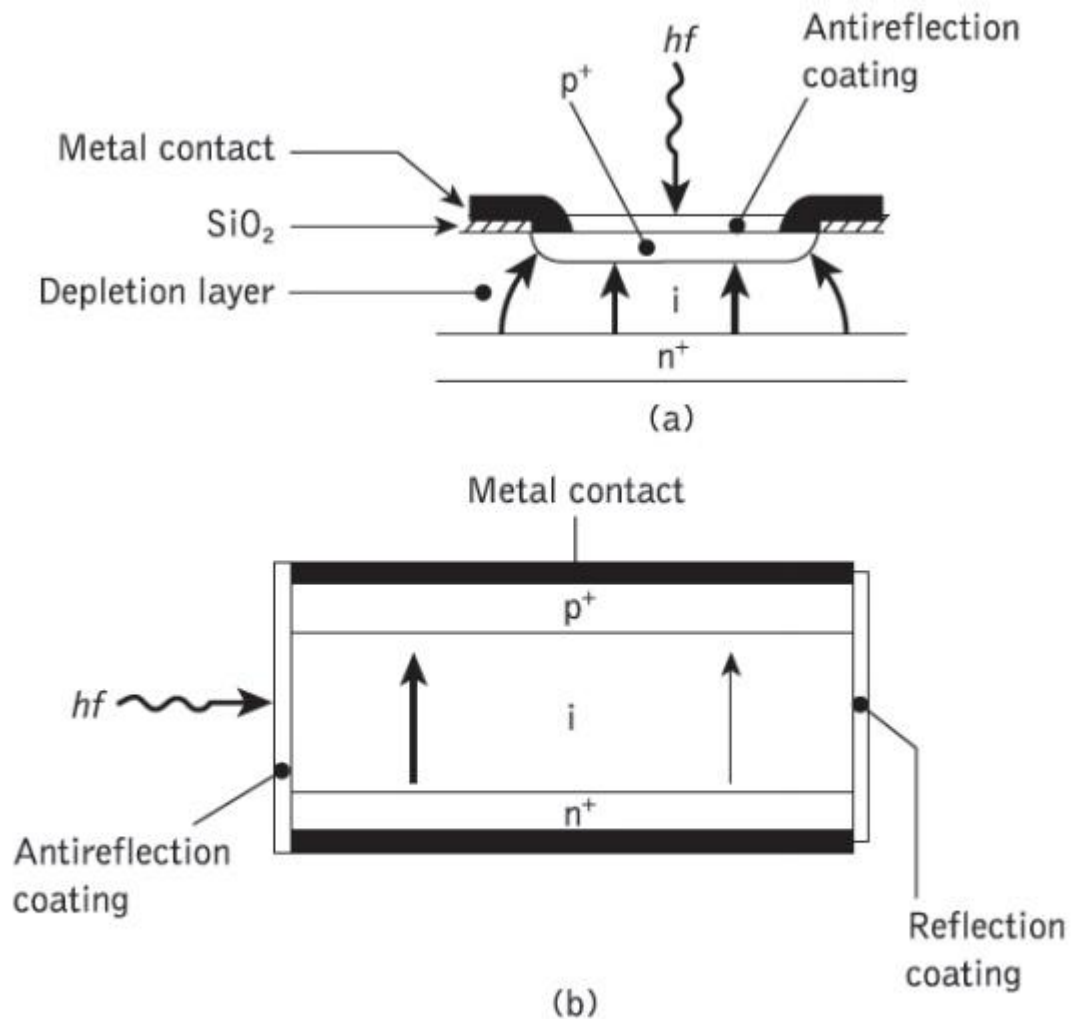
**Figure 3.13** (a) Structure of a front-illuminated silicon *p–i–n* photodiode. (b) Structure of a side-illuminated (parallel to junction) *p–i–n* photodiode

[Source: htpp://img.brainkart.com]

The side-illuminated structure (Figure 3.13(b)), where light is injected parallel to the junction plane, exhibits a large absorption width ( 500 μm) and hence is particularly sensitive at wavelengths close to the bandgap limit (1.09 μm) where the absorption coefficient is relatively small. Germanium *p–i–n* photodiodes which span the entire wavelength range of interest are also commercially available, but as mentioned previously the relatively high dark currents are a problem (typically 100 nA at 20 °C increasing to 1 μA at 40 °C).

The favoured material is the lattice-matched In0.53Ga0.47As/InP system which can detect at wavelengths up to 1.67 μm. A typical planar device structure is shown in Figure 3.14(a) which requires epitaxial growth of several layers on an *n*-type InP substrate. The incident light is absorbed in the low-doped *n*-type InGaAs layer generating carriers, as illustrated in the energy band diagram Figure 3.14(b). The discontinuity due to the homojunction between the n+-InP substrate and the n-InGaAs absorption region may be noted. This can be reduced by the incorporation of an *n*-type InP buffer layer.
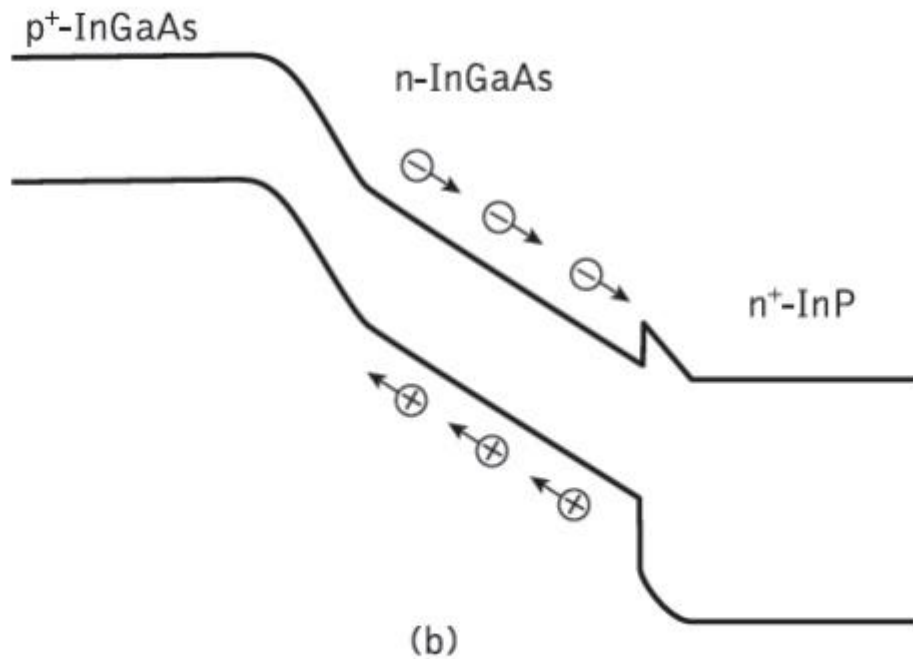


(a)
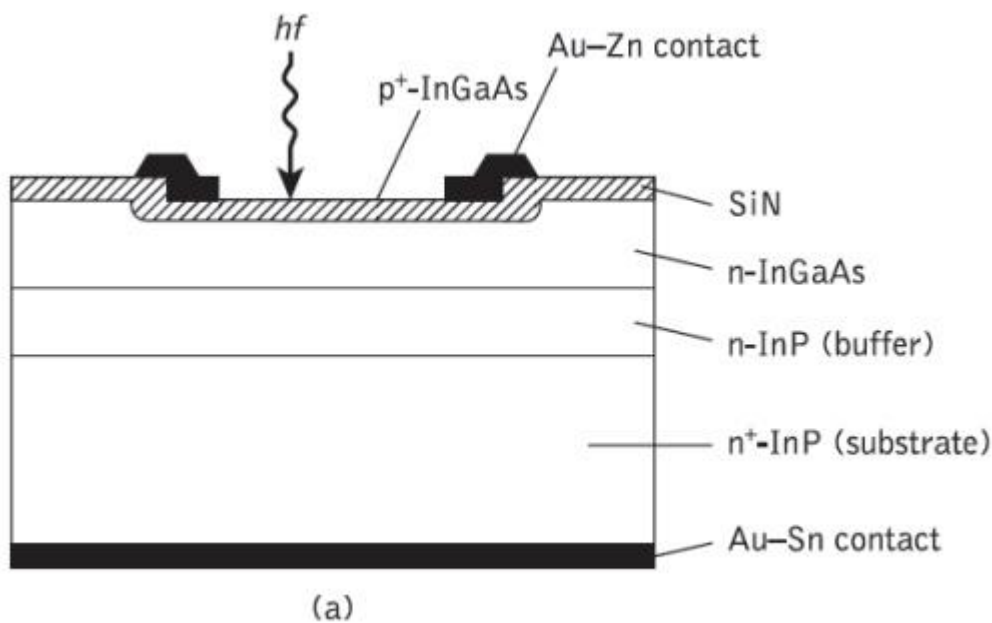
**Figure 3.14** Planar InGaAs *p–i–n* photodiode: (a) structure; (b) energy band diagram showing homojunction associated with the conventional *p–i–n* structure

[Source: htpp://img.brainkart.com]

The top entry* device shown in Figure 3.14(a) is the simplest structure, with the light being introduced through the upper p+-layer. However, a drawback with this structure is a quantum efficiency penalty which results from optical absorption in the undepleted p+- region. In addition, there is a limit to how small such a device can be fabricated as both light access and metallic contact are required on the top. To enable smaller devices with lower capacitances to be made, a substrate entry technique is employed. In this case light enters through a transparent InP substrate and the device area can be fabricated as small as may be practical for bonding.

## 2. Avalanche Photodiodes

The second major type of optical communications detector is the avalanche photodiode (APD). This has a more sophisticated structure than the *p–i–n* photodiode in order to create an extremely high electric field region

(approximately $3 \times 105$ V cm$-1$), as may be seen in Figure 3.15(a). Therefore, as well as the depletion region where most of the photons are absorbed and the primary carrier pairs generated, there is a high-field region in which holes and electrons can acquire sufficient energy to excite new electron–hole pairs.
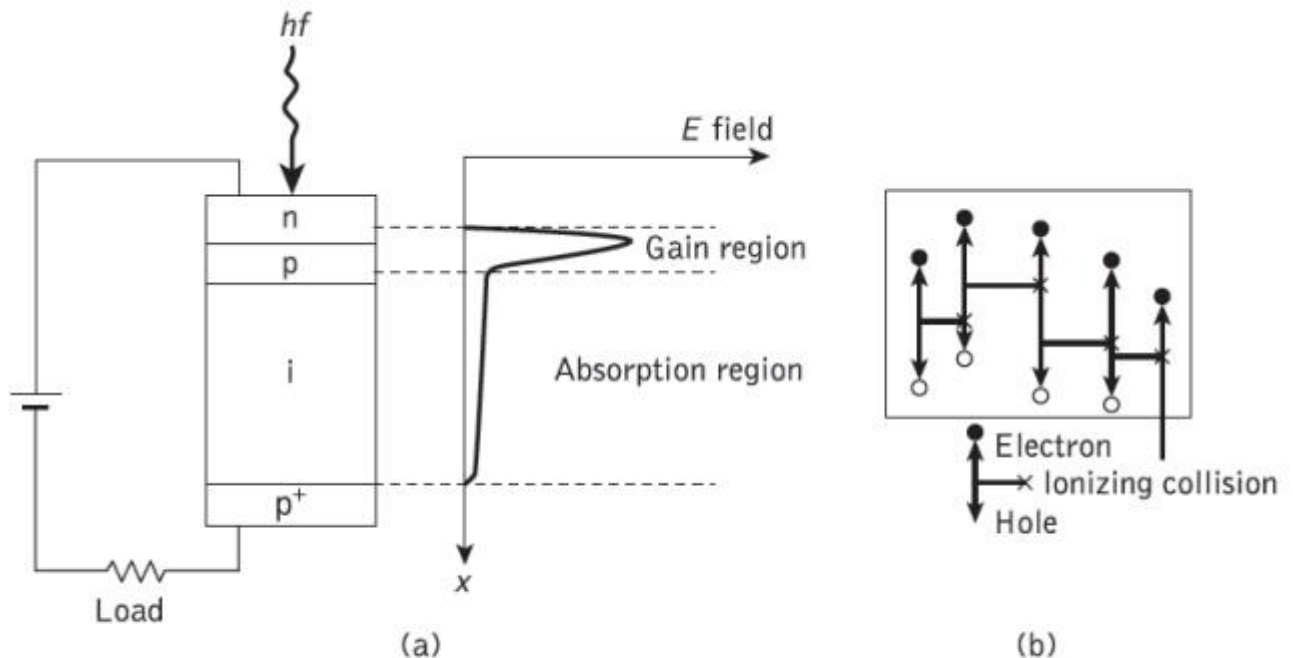


**Figure 3.15** (a) Avalanche photodiode showing high electric field (gain) region. (b) Carrier pair multiplication in the gain region of an avalanche photodiode

[Source: htpp://img.brainkart.com]

This process is known as impact ionization and is the phenomenon that leads to avalanche breakdown in ordinary reverse-biased diodes. It often requires high reverse bias voltages (50 to 400 V) in order that the new carriers created by impact ionization can themselves produce additional carriers by the same mechanism as shown in Figure 3.15(b). More recently, however, it should be noted that devices which will operate at much lower bias voltages (15 to 25 V) have become available.

Carrier multiplication factors as great as 104 may be obtained using defect-free materials to ensure uniformity of carrier multiplication over the entire photosensitive area. However, other factors affect the achievement of high gain within the device. Micro plasmas, which are small areas with lower breakdown

voltages than the remainder of the junction, must be reduced through the selection of defect-free materials together with careful device processing and fabrication.

In addition, excessive leakage at the junction edges can be eliminated by the use of a guard ring structure as shown in Figure 3.16. At present silicon, germanium and InGaAs APDs are generally available.Operation of these devices at high speed requires full depletion in the absorption region. 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 electric fields in excess of 104 Vm−1, all the carriers drift at saturation-limited velocities. In this case the response time for the device is limited by three factors.

These are:

(a) the transit time of the carriers across the absorption region (i.e. the depletion width)

(b) the time taken by the carriers to perform the avalanche multiplication process

(c) and the $RC$ time constant incurred by the junction capacitance of the diode and its load.
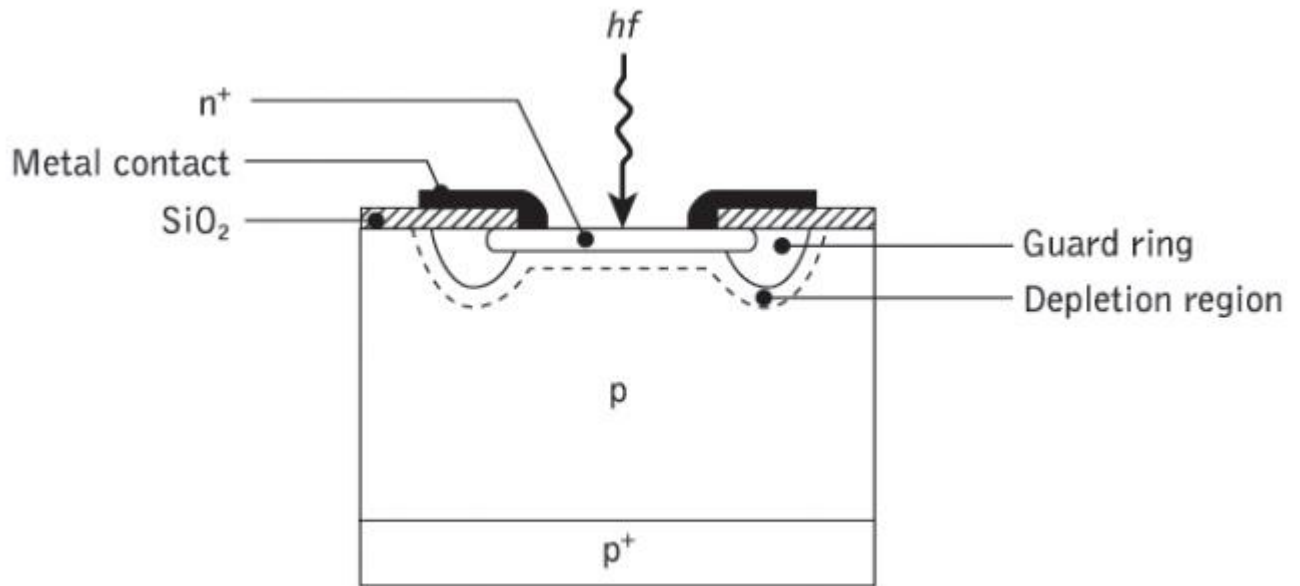
**Figure 8.16** Structure of a silicon avalanche photodiode (APD) with guard ring

[Source: htpp://img.brainkart.com]

At low gain the transit time and $RC$ effects dominate giving a definitive response time and hence constant bandwidth for the device. However, at high gain the avalanche build up time dominates and therefore the device bandwidth decreases proportionately with increasing gain. Such APD operation is distinguished by a constant gain–bandwidth product. Often an asymmetric pulse shape is obtained from the APD which results from a relatively fast rise time as the electrons are collected and a fall time dictated by the transit time of the holes traveling at a slower speed. Hence, although the use of suitable materials and structures may give rise times between 150 and 200 ps, fall times of 1 ns or more are quite common and limit the overall response of the device.

# Photo detector Noise & S/N Ratio Calculation:

Detection of weak optical signal requires that the photodetector and its following amplification circuitry be optimized for a desired signal-to-noise ratio.

It is the noise current which determines the minimum optical power level that can be detected. This minimum detectable optical power defines the **sensitivity** of photo detector. That is the optical power that generates a photocurrent with the amplitude equal to that of the total noise current (*S/N=1*)

$$\frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

# 1. Signal Calculation:

Consider the modulated optical power signal *P(t)* falls on the photodetector with the form of

$$P(t) = P_0[1 + ms(t)]$$

Where *s(t)* is message electrical signal and *m* is modulation index. Therefore the primary photocurrent is (for pin photodiode *M=1*):

$$i_{\text{ph}} = \frac{\eta q}{h\nu} MP(t) = I_P[\text{DC value}] + i_p(t)[\text{AC current}]$$

The root mean square signal current is then

$$\left\langle i_s^2 \right\rangle = \left\langle i_p^2 \right\rangle M^2 = \sigma_s^2$$

$$\left\langle i_p^2 \right\rangle = \sigma_p^2 = \frac{m^2 I_P^2}{2} \quad \text{for sinusoidal signal}$$

## Noise Sources in Photo detectors:

The principal noises associated with photo detectors are:

1- Quantum (Shot) noise: arises from statistical nature of the production and collection of photo-generated electrons upon optical illumination. It has been shown that the statistics follow a Poisson process.

2- Dark current noise: is the current that continues to flow through the bias circuit in the absence of the light. This is the combination of bulk dark current, which is due to thermally generated e and h in the *pn* junction, and the surface dark current, due to surface defects, bias voltage an surface area.

• In order to calculate the total noise presented in photodetector, we should sum up the root mean square of each noise current by assuming that those are uncorrelated.

• Total photo detector noise current=quantum noise current +bulk dark current noise + surface current noise

## Noise calculation:

Quantum noise current (lower limit on the sensitivity):

$$\langle i_Q^2 \rangle = \sigma_Q^2 = 2qI_P BM^2 F(M)$$

$B$: Bandwidth, $F(M)$ is the noise figure and generally is

$$F(M) \approx M^x \quad 0 \le x \le 1.0$$

Bulk dark current noise:

$$\langle i_{DB}^2 \rangle = \sigma_{DB}^2 = 2qI_D BM^2 F(M)$$

Surface dark current noise

$$\langle i_{DS}^2 \rangle = \sigma_{DS}^2 = 2qI_L B$$

The total rms photodetector noise current is:

$$\langle i_N^2 \rangle = \sigma_N^2 = \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle$$
$$= 2q(I_P + I_D)BM^2 F(M) + 2qI_L B$$

The thermal noise of amplifier connected to the photodetector is:

$$\langle i_T^2 \rangle = \sigma_T^2 = \frac{4k_B TB}{R_L}$$

# 2. S/N Calculation:

Having obtained the signal and total noise, the signal-to-noise-ratio can be written as:

$$\frac{S}{N} = \frac{\langle i_P^2 \rangle M^2}{2q(I_P + I_D)BM^2 F(M) + 2qI_L B + 4k_B TB/R_L}$$

Since the noise figure *F(M)* increases with M, there always exists an optimum value of *M* that maximizes the S/N. For sinusoidally modulated signal with *m=1* and *F(M) = Mx*

$$M_{opt}^{x+2} = \frac{2qI_L + 4k_BT/R_L}{xq(I_P + I_D)}$$

# Photodetector Response Time

The response time of a photodetector with its output circuit depends mainly on the following three factors:

1- The transit time of the photocarriers in the depletion region. The transit time depends on the carrier drift velocity and the depletion layer width $w$, and is given by:

$$t_d = \frac{W}{v_d}$$

2- Diffusion time of photocarriers outside depletion region.

3- $RC$ time constant of the circuit

$$B = \frac{1}{2\pi R_T C_T}$$

$$R_T = R_s \parallel R_L \quad \text{and} \quad C_T = C_a + C_d$$