Module 9 : Photo Detectors

Lecture : Principle of Photo Detection

Part-I

Objectives

In this lecture you will learn the following

- Learn about the principle of optical detection.
- Know various optical detectors like photodiodes, p-i-n diodes and avalanche diodes.
- Define figures of merit of the detectors.
- Know about different sources of noise in detectors and the significance of signal to noise ratio.

9.1 INTRODUCTION :

A photodetector is a device which absorbs light and converts the optical energy to measurable electric current. Detectors are classified as

- Thermal detectors
- Photon detectors

Thermal detectors :

When light falls on the device, it raises its temperature, which, in turn, changes the electrical properties of the device material, like its electrical conductivity. Examples of thermal detectors are thermopile (which is a series of thermocouples), pyroelectric detector etc.

Photon detectors :

Photon detectors work on the principle of conversion of photons to electrons. Unlike the thermal detectors, such detectors are based on the rate of absorption of photons rather than on the rate of energy absorption. However, a device may absorb photons only if the energy of incident photons is above a certain minimum threshold. Photon detectors, in terms of the technology, could be based on

- Vacuum tubes - e.g. photomultipliers
- Semiconductors - e.g. photodiodes

For optical fiber applications, semiconductor devices are preferred because of their small size, good responsivity and high speed.

9.2 Physical Processes in Light Detection

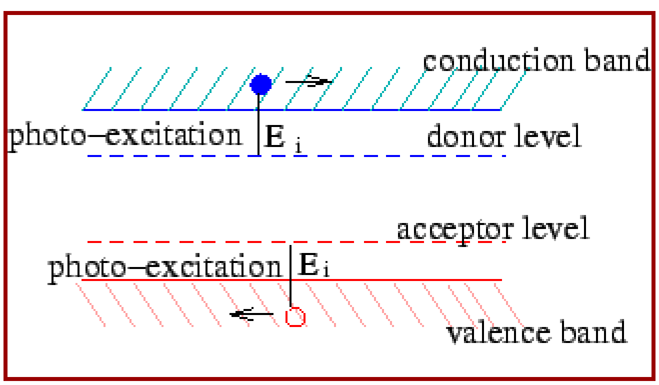
Detection of radiation is essentially a process of its interaction with matter. Some of the prominent processes are

- s smallphotoconductivity
- photovoltaic effect
- photoemissiveeffect

9.2.1Photoconductivity :

A consequence of small band gap (Δ) in semiconductors is that it is possible to generate additional carriers by illuminating a sample of semiconductor by a light of frequency greater than Δ/h. This leads to an increased conductivity in the sample and the phenomenon is known as **intrinsics photoconductivity** . The effect is not very pronounced at high temperatures except when the illumination is by an intense beam of light. At low temperatures, illumination results in excitation of localized carriers to conduction or valence band.

Even when an incident photon does not have sufficient energy to produce an electron-hole paie, it can still produce an excitation at the impurity centres by creating a free electron - bound hole pair (for excitation at donor level) or a free hole - bound electron (for acceptor level). If $E_i$is the impurity ionization energy, the radiation frequency for extrinsic photoconductivity should be at least E_i/h.

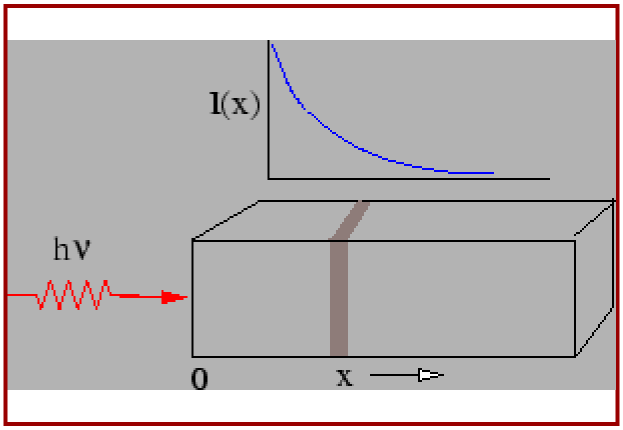


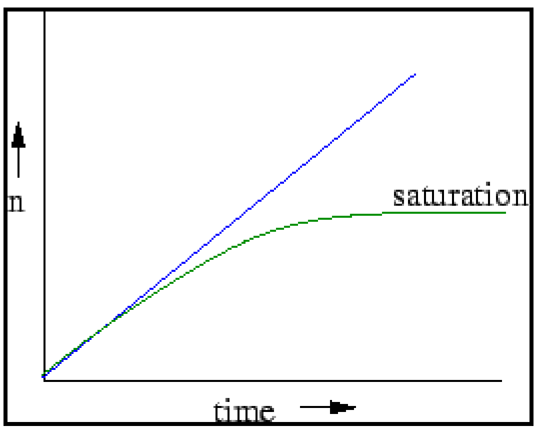
Consider a thin slab of semiconductor which is illuminated by a beam of light propagating along the direction of its length (x-direction). Let Ibe the radiation intensity (in watts/m ^{2}) at a position $x$from one end of the semiconductor. If $\alpha =$absorption coefficient per unit length, the power absorbed per unit length is αI. The change in the intensity with distance along the sample length is given by

$$\frac{dI}{dx} = -\alpha I$$

which has solution

$$I = I_0 e^{-\alpha x}$$

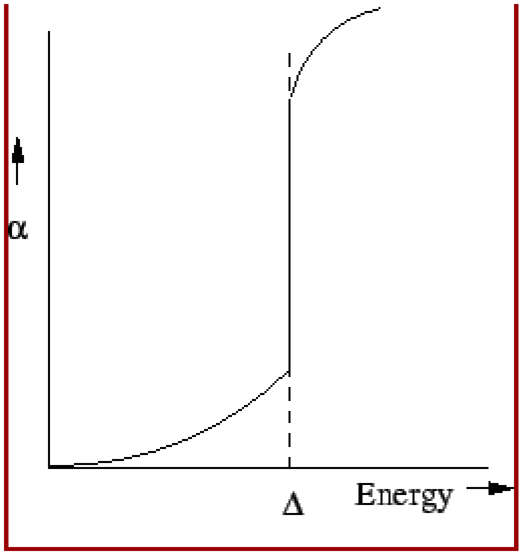




If we define η as the ***quantum efficiency*** , i.e. the fraction of absorbed photons that produce electron-hole pairs, the number of pairs produced per unit time is given by

$$\Delta n = \Delta p = \frac{\eta \alpha I}{h\nu}$$

In principle, the process of illumination will lead to a continued increase in the number of carriers as the amount of energy absorbed (and hence Δn and Δp) will increase linearly with time. However, the excited pairs have a finite life time ($\sim 10^{-7}$ to 10^{-2} s). This results in recombination of the pairs. The relevant life time is that of minority carriers as a pair is required in the process. Recombination ensures that the number of excess carriers does not increase indefinitely but saturates.



Consider an n-type semiconductor. If the recombination life time for the minority carriers is τ_p, the rate of change of carrier concentration is given by

$$\frac{d}{dt}(\Delta p) = \frac{\eta \alpha I}{h\nu} - \frac{\Delta p}{\tau_p}$$

Under steady state condition $d\delta p/dt = 0$, which gives

$$\delta p = \frac{\eta \alpha I_p \tau_p}{h\nu} = \Delta n$$

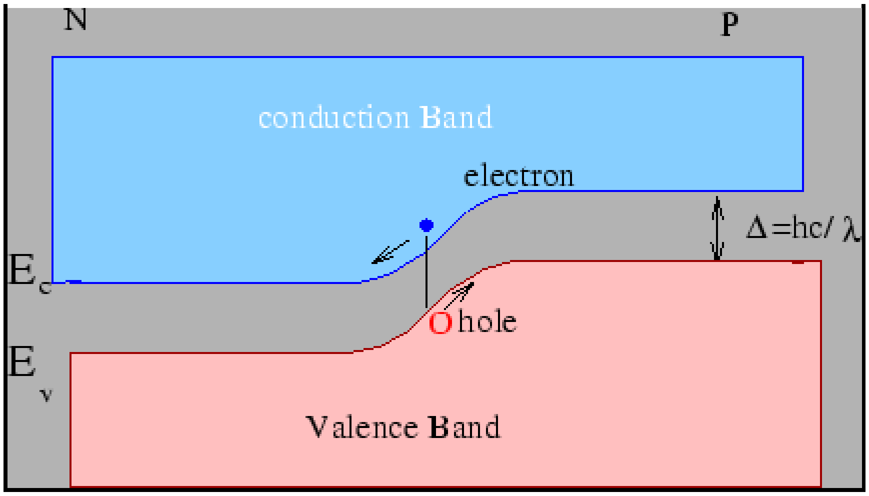
This excess hole density leads to an additional conductivity

$$\Delta \sigma = q\delta n\mu_e + q\Delta p\mu_h$$

9.2.2Photovoltaic Effect :

Photovoltaic effect can occur in a material which has a space charge layer, e.g. in a p-n junction.

A photon of sufficient energy can be absorbed by the detector material to excite an electron from the valence band to the conduction band. The excited electron may be observed through its contribution to the current. A photovoltaic detector can be operated without application of a bias voltage.



9.2.3Photoemissive Process :

In a photoemissive process (also known as **external photoeffect**) incident radiation causes electron emission from photocathode which are to be collected by an anode. Photoemissive detectors have an advantage over other detectors as they have faster speed, higher gain and low noise. However, their spectral range is somewhat limited as the incident photon must have sufficient energy to eject electrons from the photocathode. Photoemissive detectors are, therefore, natural choices in the ultraviolet range.

9.3 Performance Parameters :

The performance of a detector is described in terms of certain **figures of merit** .

Responsivity :

Responsivity of a detector is given as the ratio of the generated photocurrent (I) to the amount of optical power (P_0) incident on the detector

$$\mathcal{R} = \frac{I}{P_0}$$

The unit of responsivity is amperes/watt.

Quantum Efficiency :

A detector is not capable of collecting all the photons and convert them to electron-hole pairs. The number of electrons produced per incident photon is defined as the **quantum efficiency** , which is usually expressed as a percentage

$$\eta = \frac{\text{No. of electrons produced}}{\text{No. of incident photons}} (\times 100\%)$$

If $I =$photocurrent in the external circuit and $P_0 =$the incident optical power (dropping the percentage in the definition,)

$$\eta = \frac{I/q}{P_0/h\nu}$$

Using this in the expression for the responsivity, we get

$$\mathcal{R} = \frac{I}{P_0} = \frac{q\eta}{h\nu} = \frac{q\eta}{hc}\lambda$$

The responsivity, therefore, depends on the wavelength λ. For an ideal photodetector, $\eta = 1$ and $\mathcal{R}$ is linear with λ.

Spectral Response :
The spectral response of a detector is is given by the manner in which the output signal of the detector varies with the change in the wavelength of the incident radiation. As the quantum efficiency depends on the wavelength, the response is not linear as would be the case if $\eta = 1$.

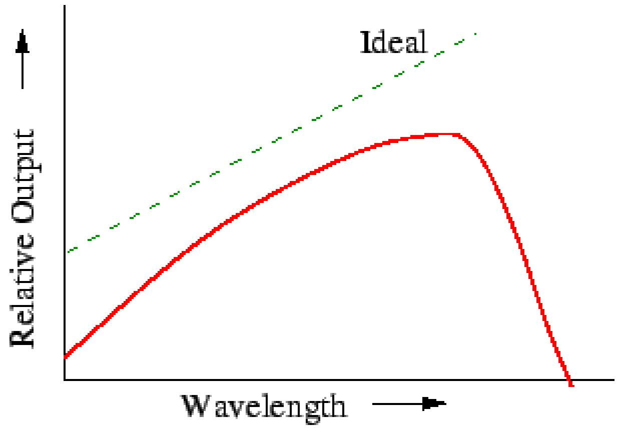
The energy of the photon must be sufficient to excite an electron across the energy barrier Δ. If Δ is in eV, the maximum wavelength that the detector would respond to is

$$\lambda_{\max}\ \ (\mathrm{in\ nm}) = \frac{1240}{\Delta\ (\mathrm{ev})}$$

However, the response does not fall off abruptly to zero for values of λ above the threshold. This is because, due to thermal energy of the molecules, the absorption coefficent α of the material of the device is found to be given by

$$\alpha = \alpha_0 e^{E/\Delta}$$

where E is the incident photon energy. For $\lambda > \lambda_{\max}$, $E < \Delta$ so that the absorption of radiance becomes smaller.



Noise Equivalent Power :

Source of noise in a detector is thermal fluctuation. Charged particles are always in a state of motion. Even when no radiation is incident on a device, a background current, whose magnitude could be in nano-amperes or pico-amperes, is generated. This is known as **dark current** . In order that a detector may be able to differentiate between such random noise and an incoming signal, the power of the signal must be greater than the noise signal. In a detector design, one defines **signal to noise ratio (SNR)** as

$$\mathrm{SNR} = \frac{\text{signal power}}{\text{noise power}}$$

Noise equivalent power (NEP) is an important figure of merit for a detector. NEP is defined as the rms incident power which gives rise to a current (or voltage) whose rms value is equal to the rms value of the current (voltage) due to noise effects.
For a detector, the NEP is usually specified at particular wavelength and temperature. The bandwidth for the incident radiation for the measurement of NEP is generally taken as 1 Hz. Noise power within a bandwidth of Δf is expected to be proportional to Δf itself. Since the current (voltage) is proportional to the square root of the power, the noise current (voltage) is proportional to $\sqrt{\Delta f}$. The unit of NEP is, therefore, watts/ $\sqrt{\mathrm{Hz}}$.(Several texts give the unit of NEP as watt. However, it is more common to use NEP as a misnomer as given here)

Detectivity and Dee Star (D *)

Both these terms are frequently used interchangibly, though some definitions make a difference between the two. D * is essentially the inverse of NEP normalized to unit area of the detector.

$$D^* = \frac{\sqrt{A}}{\mathrm{NEP}}$$

The unit of D * is m-(Hz) $^{1/2}$/w. (Detectivity is often defined as the inverse of NEP.)

Recap

In this lecture you have learnt the following

- Learn about the principle of optical detection.
- Know various optical detectors like photodiodes, p-i-n diodes and avalanche diodes.
- Define figures of merit of the detectors.
- Know about different sources of noise in detectors and the significance of signal to noise ratio.

Part-II

Objectives

In this lecture you will learn the following

- Learn about the principle of optical detection.
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- Define figures of merit of the detectors.
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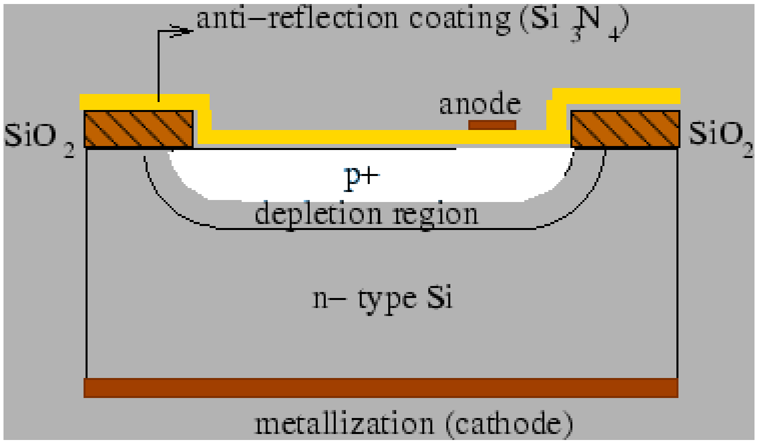
9.4 Photodiode :

A photodiode is a p-n junction diode that can absorb photons and generate either a photovoltage or free carriers that can produce photocurrent. They are used for detection of optical signals and for conversion of optical power to electrical power.
The figure shows a p+n junction diode with a heavily doped p-side. The donor concentration on the n side of the junction is less than the acceptor concentration on the p+ side. The p- layer is very thin and is formed on the front surface of the device by thermal diffusion or ion implantation on an n-type silicon. The active area is coated with an antireflection coating of material (like silicon nitride) so that most of the light falling on the device can be trapped by it. Metallized contacts provide the terminals.



Silicon is the most favoured material for a photodiode. With a band gap of 1.1 eV, its peak sensitivity is in I.R. between 800 to 950 nm. The sensitivity drops at shorter wavelengths. For $\lambda < 700$nm, the light gets absorbed in the p-layer before reaching the junction. Thus in order to increase sensitivity at shorter wavelengths, the width of the p-layer should be smaller.

As p-type regin has an excess of holes and n-type region an excess of electrons, the holes diffuse towards n-side and electrons to the p-side resulting in a built in electric field gradient from n-side to p-side. The built in electric field has a strength such that there is no further movement of charges through the depletion region. The depletion region extends well into the lightly doped n-side.
If the n-side has a donor density $N_d$per unit volume and the p-side an acceptor density of $N_a$per unit volume, equal amount of mobile carriers are annihilated from the two sides leaving fixed charges on the p+ and sides. The charge density distribution is as shown. The condition of charge neutrality requires

$$qN_a x_p = qN_d x_n$$

where $q$is the magnitude of electronic charge and $x_p$and $x_n$are respectively the widths of the depletion region in the p-side and n-side.

One can determine the electric field on both sides by using Gauss's law of electrostatics, $\nabla \cdot \vec{E} = \rho/\epsilon_0\kappa$, where $\kappa$is the dielectric constant and $\rho$is the charge density.

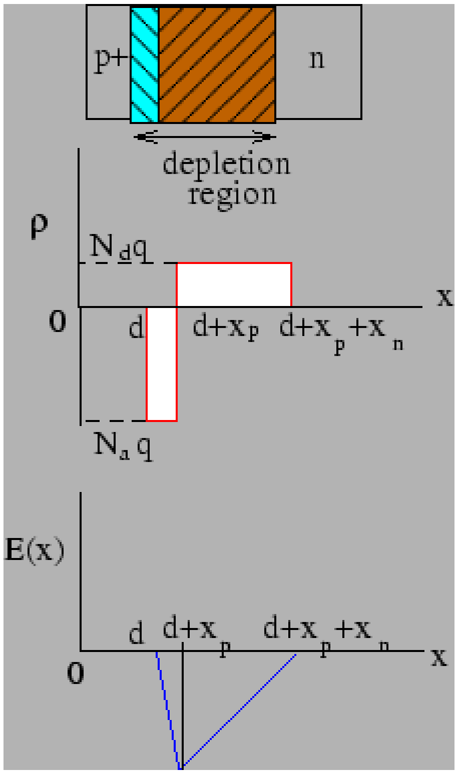
For $d < x < d + x_p$, $\rho = -N_a q$, so that

$$E(x) = \int_d^x \frac{\rho}{\epsilon_0\kappa} dx = -\frac{N_a q}{\epsilon_0\kappa}(x - d)(A)$$

where we have used . For , , so that

$$E(x=d)=0 \qquad d+x_p<x<d+x_p+x_n \quad \rho=N_d q$$

$$E(x)=\frac{N_d q}{\epsilon_0 \kappa}(x-d-x_p-x_n)(B)$$



The maximum magnitude of the field occurs at $x=d+x_p$ and is given by

$$E_0=-\frac{N_a q x_p}{\epsilon_0 \kappa}=-\frac{N_d q x_n}{\epsilon_0 \kappa}$$

The two expressions above for E_0 are equal by the condition of charge neutrality. The negative sign indicates that the direction of the electric field is from n side to the p side.

Built in Potential :

One can obtain an expression for the potential drop across the junction by integrating the electric field

$$V=V(d+x_p+x_n)-V(d)=-\int_d^{d+x_p+x_n} E(x)dx$$

to obtain

$$V = \frac{q}{2\epsilon_0 \kappa}(N_a x_p^2 + N_d x_n^2)(C)$$

Exercise :

Obtain Expression (C) above.

Using the charge neutrality condition $N_a x_p = N_d x_n$ and the total width of the junction $W = x_p + x_n$, we have

$$x_p = \frac{N_d}{N_a + N_d} W$$

$$x_n = \frac{N_a}{N_a + N_d} W$$

We can rewrite Eqn. (C) as

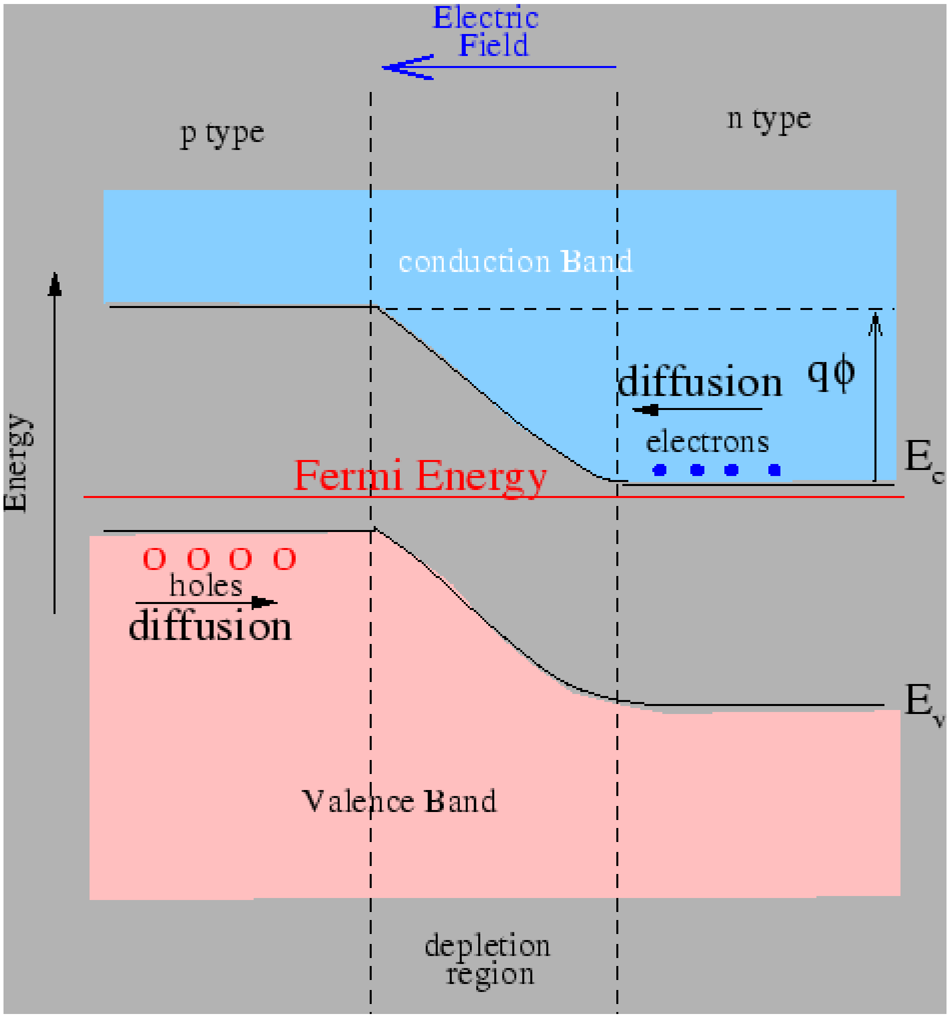
$$V = \frac{q}{2\epsilon_0 \kappa} \frac{N_a N_d}{N_a + N_d} W^2 (D)$$

The junction capacitance per unit area is given by

$$C = \frac{\epsilon_0 \kappa}{W} = \sqrt{\frac{q \epsilon_0 \kappa}{2V_B} \frac{N_a N_d}{N_a + N_d}}$$

Using Eqn. (A) - (D), the magnitude of the maximum electric field E_0 may be expressed as

$$E_0 = \sqrt{\frac{2qV}{\epsilon_0 \kappa} \frac{N_a N_d}{N_a + N_d}} (E)$$



In the absence of an external voltage, the potential difference across the junction is equal to the difference in the Fermi energies of the p-type and n-type semiconductors before they are combined to make the junction. The Fermi energies are given by

$$E_F^p = E_F^i - kT \ln \frac{N_a}{n_i}$$

$$E_F^n = E_F^i - kT \ln \frac{N_d}{n_i}$$

where $E_F^i \simeq \Delta/2$ is the Fermi energy in the intrinsic case and $n_i (= p_i)$ is the intrinsic carrier concentration. Thus the built in potential is given by

$$V_B = \frac{E_F^n - E_F^p}{q} = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2}$$

Example 1 :

A photodiode is made with p-type Ge doped with 10^{23} Ga atoms/m ^{3} and n-type Ge with 10^{22} As atoms/m ^{3}. For Ge, $\kappa = 16$. The intrinsic carrier concentration of Ge at 300 K is given by $n_i = 2.5 \times 10^{19}$. Calculate the width of the depletion layers and the charge transfer per unit area at 300 K.

Solution :

The junction potential is given by

$$V_B = \frac{kT}{q}\frac{N_d N_a}{n_i^2} = 0.369 \text{ V}$$

Substituting the values given in Eqn. (D),

$$W = \sqrt{\frac{2\epsilon_0\kappa}{q}\frac{N_a + N_d}{N_a N_d}V_B} = 0.27\mu m$$

One can check that the widths of the depletion region in p-side is

$$x_p = \frac{N_d}{N_a + N_d} \times W = 0.025\ \mu m$$

and in the n-side is $x_n = 0.245\ \mu$m. The charge transfer per unit area is

$QN_d x_n = 3.9 \times 10^{-4}$C/m ^{2}.

At the junction there are four current densities.

(i) electron diffusion current from n-side to p-side

(ii) hole diffusion current from p-side to n-side

(iii) electron drift current from p-side to n-side due to junction electric field

(iv) hole drift current from n-side to p-side.

(i) and (ii) contribute to current directed from p-side to n-side and are small because the carriers have to over come the junction potential barrier. (iii) and (iv) are small because there are few electrons on the p-side and few holes on the n-side to contribute to drift current. The total current is given by the standard diode equation

$$I = I_s\left(e^{qV/kT} - 1\right)$$

is the reverse saturation current (also known as the **dark current**). It depends on

I_s

junction parameters like the minority carrier lifetime, diffusion coefficient, intrinsic carrier concentration etc. V is the net voltage across the junction which is the algebraic sum of the built in voltage V_B and the applied electric field V_{ext}.

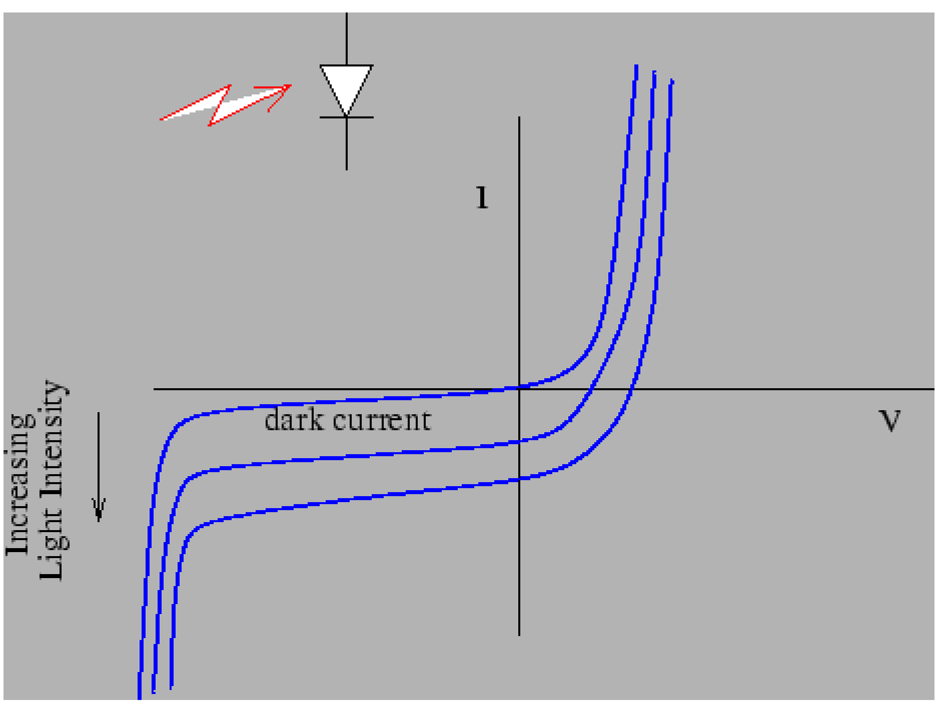
When the junction is illuminated, the diode equation becomes

$$I = I_{opt} + I_s \left(e^{qV/kT} - 1\right)$$

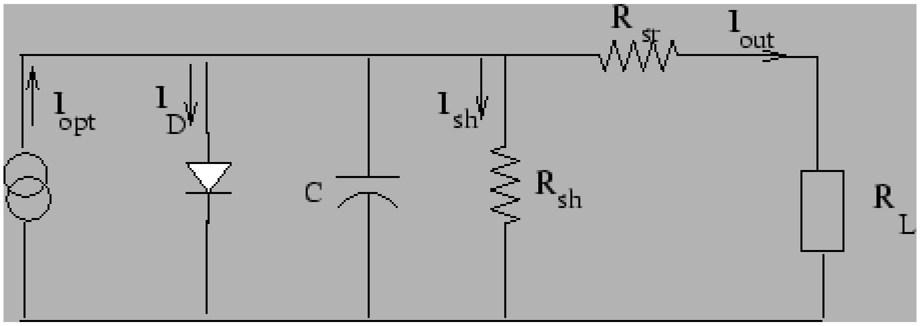
where I_{opt} is the photocurrent. If I_0 is the irradiance (in watts/m^2) falling on an area A of the diode, the optical current I_{opt} is given by the number of charged carriers produced by the light energy available for producing the carriers. If η is the quantum efficiency,

$$I_{opt} = \eta \frac{I_0 A}{hc/\lambda} q$$

which shows that I_{opt} is proportional to the incident light intensity.



The photodiode can be represented by an equivalent circuit shown. The current source is due to the drift current produced by illumination.



The photodiode junction provides an equivalent capacitance and a shunt resistance in the circuit. The series resistance is due to the resistance of other circuit elements like contact resistance, resistance of substrate etc., and may be considered negligible.

Example 2 :

A photodiode is made with p-type Si doped with 10^{23} boron atoms/m^3 and n-type Si phosphorus with 10^{22} As atoms/m^3. The width of the p- side is 1 μm. For Si, $\kappa = 12$. The intrinsic carrier concentration of Si at 300 K is given by $n_i = 1.4 \times 10^{16}$. The index of refraction of Si is 3.5 and the absorption coefficient is $\alpha = 10^6$ m^{-1}. Calculate the quantum efficiency of the photodiode at 300 K.

Solution :

Using Example (1), we can calculate the width of the depletion layer in the p-region to be 0.03 μm, so that the undepleted p-region has a width of 0.97 μm.

The amount of power reflected at the surface is determined by Fresnel coefficient

$$R = \frac{(n-1)^2}{(n+1)^2} = 0.31$$

Thus 0.31 times the incident power P_0 is reflected and $0.69P_0$ is transmitted into the device. The transmitted power is attenuated as it travels through the undepleted p-region of width 0.97μm. The optical power, when it reaches the depletion region is

$$0.69P_0e^{-\alpha x} = 0.69P_0e^{-0.97} = 0.26P_0$$

The power which is converted to electron-hole pair is given by

$$0.26P_0(1 - e^{-0.03}) \simeq 0.008P_0$$

which implies that the efficiency of the device is less than 1%.

Example 3 :

A photodiode has a responsivity of 0.5 A/W at 850 nm. Find the efficiency of the detector.
Solution :
The number of photons per watt is

$$N = \frac{P}{hc/\lambda} = 4.28 \times 10^{18}$$

As the current generated is 0.5 A from 1 Watt of power, the efficiency is (= the number of electrons per photon)

$$\eta = \frac{0.5 \times 1.6 \times 10^{-19}}{4.28 \times 10^{18}} = 0.73$$

Exercise :
In the above example, if the efficiency is taken to be independent of the wavelength, what would be the responsivity at 500 nm ?(Ans. 0.4 A/W)

Exercise :
A p-n junction detector has 50% efficiency at $\lambda = 900$nm. What is the responsivity ? (Ans. 0.36 A/W)

In photoconducting mode, the diode is operated with a reverse bias. In the absence of light, the saturation current is the dark current. As the incident power increases, the magnitude of reverse saturation current also increases. Assuming that the shunt capacitance current is negligible, we have

$$I_{opt} = I_D + I_{out} + I'$$

$$V_{out} = V_D - I_{out} R_{sr}$$

$$V_D = I_{sh} R_{sh}$$

Using the standard equation for diode,

$$I_D = I_s \left[\exp(\frac{qV_D}{kT}) - 1 \right]$$

we see that the diode current saturates for small values of the reverse voltage. , is

I_D

therefore of small value. Since the shunt resistance is large (infinite for an ideal diode), the shunt current I_{sh} is negligible. Thus $I_{out} \simeq I_{opt}$, which imples that the current in the external circuit is proportional to the irradiance.

The efficiency of a photodiode can be increased by increasing the width of the depletion region, so that the probability of pair production increases. However, this would increase response time for the detector as the carrier transit time would increase with the distance travelled. This, in turn, determines the frequency response.

Example 4 :

An ideal photodiode is illuminated with 10 mW of optical power at 900 nm. Calculate the current output when the diode is used in photoconducting mode at 300 K. What is the voltage output if the diode is used in photovoltaic mode ? The reverse bias leakage current is 10 nA.

Solution :

For an ideal photodiode, the shunt resistance is infinite so that the shunt current is zero. Since leakage current under reverse bias is small $I_{out} \simeq I_{opt} = I_0 A\lambda q/hc$. Substituting

$I_0 A = 0.01$ watt and $\lambda = 900$nm, $I_{out} = 7.2$mA.

In the photovoltaic mode, $I_{out} = 0$. Thus,

$$I_{opt} = I_D = I_s \left[\exp\left(\frac{qV_D}{kT}\right) - 1\right]$$

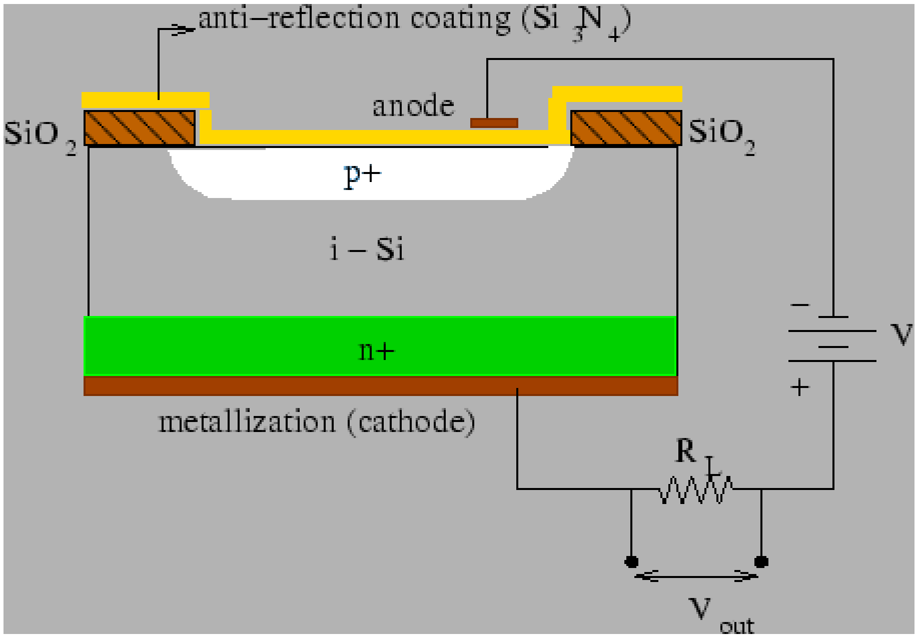
Using $I_{opt} = 7.2$mA, $I_s = 10$nA and $T = 300$, we get $V_D = 0.347$V.

9.5 P-I-N Photodiode :

The width of the depletion layer may be increased artificially, by adding an intermediate intrinsic region.

As the intrinsic region has high resistance, a small reverse bias is good enough to increase the width of the depletion region so that it extends into the n-layer.

A further advantage of a p-i-n diode is that the charge separation in the active region is larger which leads to smaller junction capacitance.

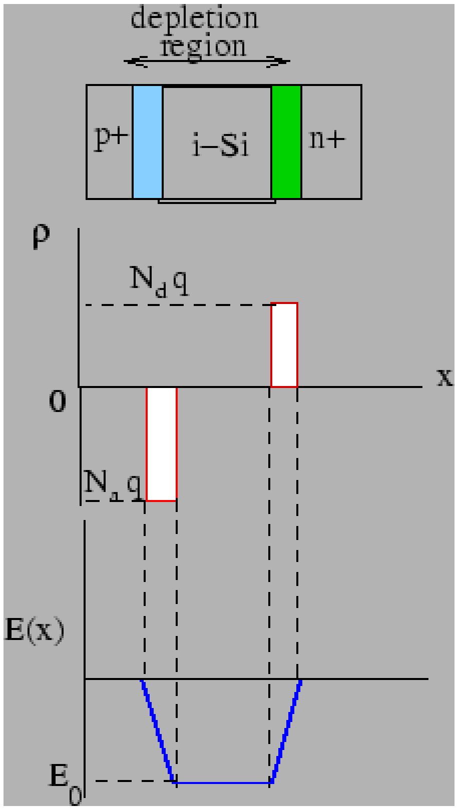


The charge density and the electric field for a p-i-n detector is shown alongside. The electric field in the intrinsic region is uniform and has a magnitude E_0, where, as in the case of the p-n photodiode,

$$E_0 = \frac{N_a q x_p}{\epsilon_0 \kappa}$$

From Eqn. (E) derived for the p-n junction photodiode, replacing V by $V_B - V$, the algebraic sum of the built in voltage V_B and the applied reverse bias V,

$$E_0 = \sqrt{\frac{2q}{\epsilon_0 \kappa}(V_B - V)\frac{N_a N_d}{N_a + N_d}}$$



The width of the depletion region is then given by

$$W = \left[\frac{2\epsilon_0\kappa}{q}(V_B - V)\frac{N_a + N_d}{N_a N_d} + x_i^2\right]^{1/2}$$

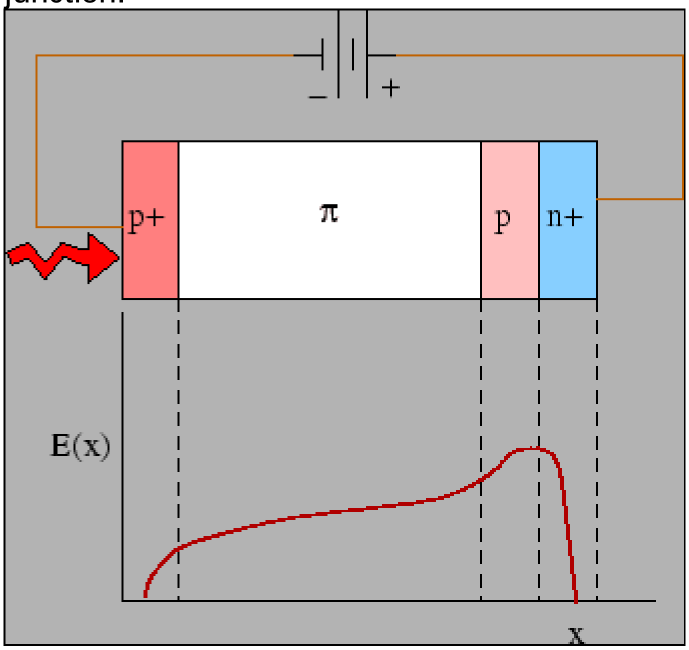
where x_i is the width of the intrinsic layer.

Exercise :
Derive the above expression for W.

Exercise :
A Si p-i-n diode with $N_a = 10^{22}$ atoms/m^3 $N_d = 10^{21}$ atoms/m^3 has an intrinsic i-layer of width 5 μm. Taking the intrinsic carrier concentration of Si to be 1.4×10^{16}/m^3, calculate the width of the depletion region when the diode is operated with a reverse bias of 10 V. (Ans. 6.2μm).

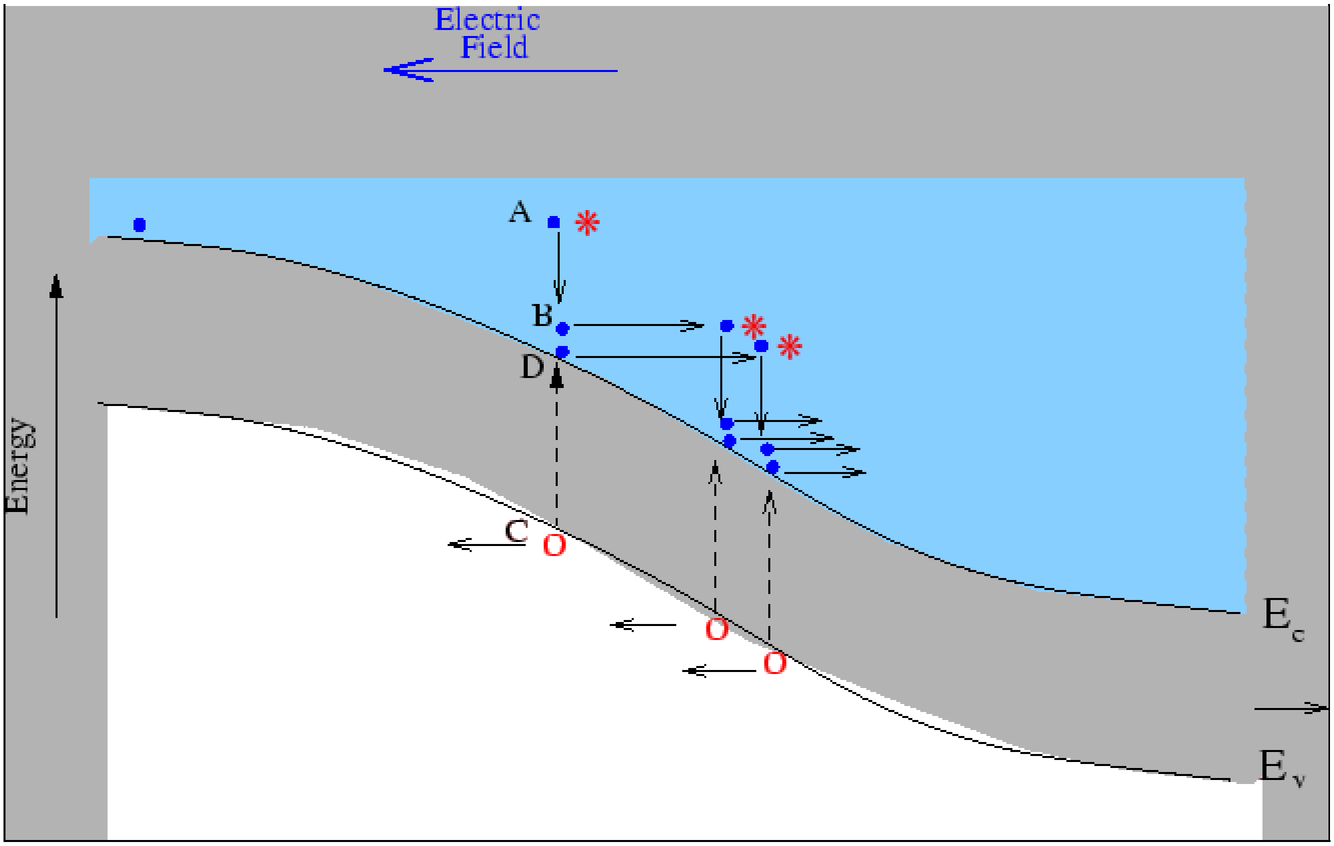
9.6 Avalanche Photodiode (APD) :

A major disadvantage of a p-n or a p-i-n diode is that each photon generates only one pair of electron and hole and there is no internal gain. Amplifying the output current after the detector stage introduces significant noise. One of the ways to deal with this problem is to design a detector with an internal gain (the other is to amplify the optical signal itsdelf). An avalanche photodiode (APD) is a device with internal gain which could be as high as 100. Si - APDs have sensitivities in the range 400 to 1100 nm while Ge-APDs have their spectral sensitivities in 800 to 1550 nm. InGaAs and InP APDs provide better sensitivity and spectral response.
APDs are essentially p-n photodiodes operated under reverse bias near the breakdown voltage. The configuration consists of an n+ layer followed, in sequence, by (i) a thin p-layer, (ii) an intrinsic layer π (in reality, a lightly doped p layer) and (iii) a heavily doped p-layer. The electric field distribution is shown. The field strength is maximum at the n+p junction.



Exercise :

Assuming constant charge densities as was done for the p-n and p-i-n diodes, obtain the electric field distribution for an APD. The electron- hole pair generated by light absorption remain separated by the electric field in the intrinsic region with the electrons drifting towards the lightly doped p-region and holes towards the p+ region. As an electron reach the region of strong electric field, it has a high kinetic energy.
When such an energetic electron collides with the lattice, it may generate a new pair of electron and a hole. Such seceondary carriers may accelerate and create additional pairs leading to an avalanche cascade. In the figure, when the primary electron reaches the point A, it can, by impact, excite an electron from the point C in the valence band to the point D in the conduction band. In doing so, the first electron makes a transition to the point B and the excited electron leaves behind a hole at the point C.



The overall gain is given by a multiplication factor M, which defined as the number of carrier pairs generated from a single pair. Let P be the probability of a single electron (electrons, rather than a holes, are generally responsible for impact ionization) creates an electron hole pair. Empirically, P is given by the formula

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

where V_r is the applied reverse bias, V_{BR} is breakdown voltage and $n(>1)$ is an experimentally determined number. The total number of pairs produced in all generations is

$$M = 1 + P + P^2 + \ldots$$

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

The optimal value of is between 3 and 9.

The responsivity of the APD is therefore increased by the multiplication factor

$$\mathcal{R} = \frac{I_{ph}}{P_0} = M\eta\frac{q\lambda}{hc}$$

Example 5 :

An APD has a quantum efficiency of 50% at a wavelength of 500 nm in the absence of multiplication. If the device is operated with a reverse bias to give a multiplication factor of 8, calculate the responsivity.

Solution :

$$\mathcal{R} = \eta\frac{q\lambda}{hc} = 0.2\ \mathrm{A/W}$$

Hence, with multiplication the responsivity is 1.6 A/W.

Exercise :
In the above example, calculate the photocurrent of the APD if the incident optical power is 4 μW.(Ans. 8 μA)

9.7 Sources of Noise in Detectors :

Detection of signals is impeted by existence of noise which is superposed with the current or voltage output. Some of these noise are inherent to the photon field while some others depend on the circuit used. For photon detectors, there are three primary noise sources.

Dark Noise :
Detection of optical power consists of streams of photons which arrive randomly. The probability of arrival of n number of photons in a given time interval is usually given by a Poission distribution. This causes a random fluctuation of the signal. As the source of noise is statistical, there is no way to reduce or eliminate it. Dark noise, or dark current shot noise is due to thermal generation of e-h paieven in the absence of photo illumination. For large values of reverse bias, an estimate of the dark noise is given by

$$I_{n-d} = \sqrt{2qI_sB}$$

where I_s is the reverse bias saturation current in dark and B is the bandwidth of operation.

Shot Noise :

Shot noise is also associated with the signal (photocurrent) itself because of statistical nature of generation of electron hole pairs due to photon absorption. The signal noise current is estimated by the formula

$$I_{n-s} = \sqrt{2qI_{ph}B}$$

where I_{ph} is the (signal) photocurrent.

Johnson Noise :

Johnson noise arises due to thermal motion of electrons in any resistive element regardless of applied voltage. The noise is intrinsic to all resistors and is not due to poor design or manufacture. The rms value of Johnson noise at a temperature T is given by the formula

$$I_{n-J} = \sqrt{4kTB/R_{sh}}$$

where R is trhe shunt resistance.
Combining the above the noise the signal to noise ratio (Power SNR) is given by

$$SNR = \frac{I_{ph}^2}{I_{n-d}^2 + I_{n-s}^2 + I_{n-J}^2}$$

If the photocurrent is very high, the effect of dark noise and thermal noise may be neglected and the SNR is given by

$$SNR = \frac{I_{ph}^2}{I_{n-s}^2}$$

Example 6 :
A photodetector has a quantum efficiency of 80% at 1000 nm. A radiation of optical power 0.01 watt/m ^{2} at this wavelength is incident on the device which has a receiving area of 1 mm ^{2}. The detector has a dark current of 5 nA and a shunt resistance of 10 ^{8} ohms. If the bandwidth of operation is 100 MHz, calculate the power SNR of the detector.

Solution :
The input power is $P_0 = 0.01 \times 10^{-6} = 10^{-8}$W. The signal current is

$$I_{ph} = \eta \frac{P_0 q\lambda}{hc} = 6.44 \times 10^{-9}\ \mathrm{A}$$

The various noise currents are calculated as follows :

1. Dark Noise :

$$I_{n-d} = (2qI_sB)^{1/2} = (2 \times 1.6 \times 10^{-19} \times 5 \times 10^{-9} \times 10^8)^{1/2} = 4 \times 10^{-10} \text{ A}$$

2. Shot-noise :

$$I_{n-s} = (2qI_{ph}B)^{1/2} = (2 \times 1.6 \times 10^{-19} \times 6.44 \times 10^{-9} \times 10^8)^{1/2} = 4.54 \times 10^{-10} \text{ A}$$

3. Johnson-noise :

$$I_{n-J} = (4kTB/R)^{1/2} = (4 \times 1.38 \times 10^{-23} \times 300 \times 10^8)^{1/2} = 1.28 \times 10^{-10} \text{ A}$$

$$I_{noise} = \sqrt{I_{n-d}^2 + I_{n-s}^2 + I_{n-J}^2} = 6.18 \times 10–10$$

The rms noise is given by

A. The power SNR is

$$SNR = \frac{I_{ph}^2}{I_{noise}^2} = 108$$

Exercise :
Consider an ideal photodiode operating with a bandwidth of 20 MHz. How much optical power is required to get an SNR of 10 ? hfill (Hint : Ideal photodiode has infinite shunt resistance and zero dark current. Ans. $6.8\ \mu$A.)

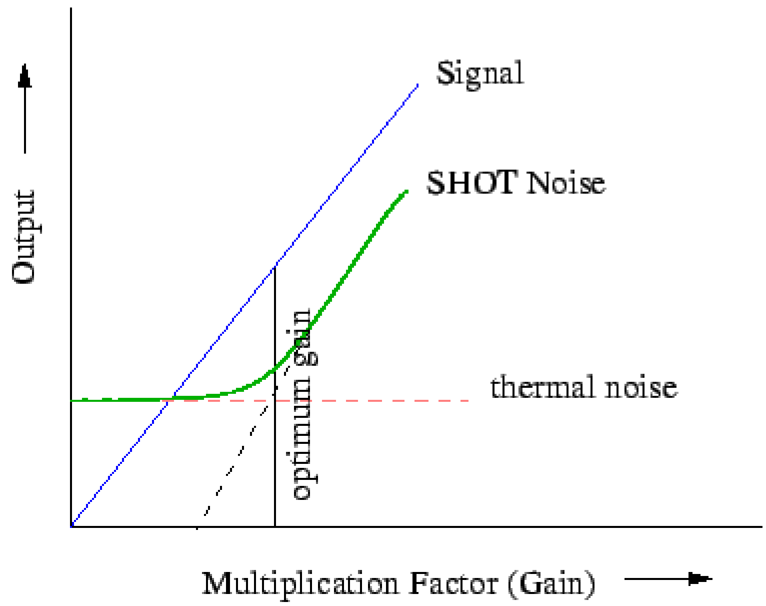
Exercise :
A Si-photodiode receives an optical power of 1 μW at a wavelength of $1\ \mu$W. The quantum efficiency of the photodiode is 0.8 at this wavelength. The detector has a dark current of 10 nA and a shunt resistance of 10^9 ohms. Find the total rms current if the operating bandwidth is 1 MHz. If the photodiode is used with a load resistance of $100\ \Omega$, what would be the primary source of noise ?(Ans. 0.46nA, Johnson noise current 13 nA)

Excess Noise in an APD :
The impact ionization process in an APD is a random process. This makes the multiplication factor itself statistical. M fluctuates about its mean value.

As APD gain increases, the output signal increases linearly. However, the noise current increases as shown alongside. The additional noise arising out of fluctuation in M is known as the **excess noise** . If I_{ph} and I_s are respectively, the photocurrent and the dark currents in the absence of multiplication, an estimate of noise current in APD is given by

$$I_{n-APD} = \left[2q(I_s + I_{ph})M^2 FB\right]^{1/2}$$

where F is known as the excess noise factor. F is to be determined experimentally and is a function of M.



Example 7 :

A Ge-APD has an excess noise factor $F = M^{0.7}$. The APD is biased to operate with a multiplication factor of $M = 5$. The dark current in the absence of multiplication is 25 nA and the operating bandwidth is 50 MHz. If the unmultiplied quantum efficiency is 0.8 and the operating wavelength is 1500 nm, determine the minimum optical power that would give a (power) SNR of 10. Neglect thermal noise.

Solution :

The dark noise current is given by

$$I_{n-d} = (2qI_s M^{2.7} B)^{1/2} = 5.55 \times 10^{-9}\ \mathrm{A}$$

The SNR is given by

$$SNR = \frac{M^2 I_{ph}^2}{[2q(I_{n-d} + I_{ph})M^{2.7}B]} = 10$$

This gives a quadratic equation in I_{ph}

$$I_{ph}^2 - 1.23 \times 10^{-8} I_{ph} - 5.55 \times 10^{-8} = 0$$

$$I_{ph} = 0.47 \times 10^{-4}$$

On solving,

A. Unmultiplied responsivity $\mathcal{R}$ is given by

$$\mathcal{R} = \eta q \frac{I_{ph}\lambda}{hc} = 0.97$$

$$P_0 = I_{ph}/\mathcal{R} = 4.8 \times 10^{-5}$$

Thus

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1. Optoelectronics and Photonics, S.O. Kasap, Prentice Hall, N.J. (2001).
2. Fundamentals of Optoelectronics, C. R. Pollock, Irwin inc. (1995).
3. Optoelectronics - An Introduction, J. wilson ans J. F. B. Hawkes, Prentice Hall International (1983)

Recap

In this lecture you have learnt the following

- Learn about the principle of optical detection.
- Know various optical detectors like photodiodes, p-i-n diodes and avalanche diodes.
- Define figures of merit of the detectors.
- Know about different sources of noise in detectors and the significance of signal to noise ratio.