Semiconductor theory

Introduction

Atomic Structure

All the materials are composed of very small particles called atoms. An atom consists of a central nucleus of positive charge around which small negatively charged particles called electrons revolve in different orbits.

1. **Nucleus :** It is the central part of an atom. It contains protons and neutrons. A proton is a positively charged particle. While the neutron has the same mass of the proton, but has no charge, that is, the nucleus of an atom is positively charged. The sum of protons ans neutrons constitutes the entire weight of an atom and is called atomic weight, and electrons have negligible weight as compared to protons or neutrons.
2. **Extra Nucleus :** It is the outer part of an atom and contains electrons only. An e^- is a negatively charged particle having negligible mass. The charge on an e^- is equal but opposite to that on a proton. Therefore, an atom is neutral as a whole. The number of electrons or protons in an atom is called atomic number.

   The e^- in an atom revolves around the nucleus in the different orbits. The number of e^- in any orbit is given by $2n^2$, where n is the number of the orbit.

   The first orbit contains $= 2 \times 1^2 = 2$ e^-s

   The third orbit contains $= 2 \times 3^2 = 18$ e^-s

   .... etc.

   The last orbit cannot have more than 8 e^-s and the last but one orbit cannot have more than 18 e^-s.

Atomic Structure of Copper

Copper atomic weight = 64

Atomic number = 29

Number of protons = e^-s = 39 and number of neutrons = 64 - 29 = 35

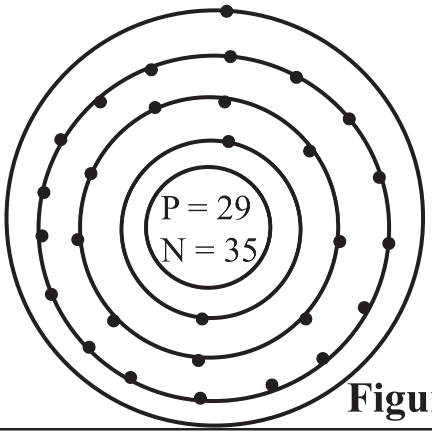


Figure 1 Structure of copper atom

It has 29 e^-s that are arranged in different orbits as follows.

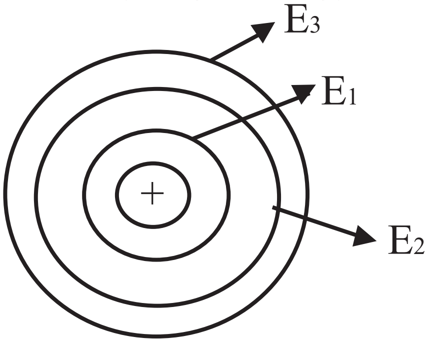
$Cu \rightarrow 29 \Rightarrow 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^1$

Therefore, the number of Valence e^-s in Cu is equal to one.

Some of the important properties of an electron are as follows.

1. Charge on an $e^- = 1.602 \times 10^{-19}$ C = q
2. Mass of an e^- $m = 9 \times 10^{-31}$ kg
3. Radius of an $e^- = r = 1.9 \times 10^{-15}$ m

An e^- moving around the nucleus posses two types of energies : kinetic energy due to its motion and potential energy due to its motion and potential energy due to the charge on the nucleus. The total energy of the electron is the sum of the two energies. The energy of an e^- increases as its distance from the nucleus increases. Thus, an e^- increases as its distance from the nucleus increases. Thus, an e^- increases as its distance from the nucleus increases. Thus, an e^- in the second orbit has more energy than the e^- in the first orbit. Therefore, the e^- in the last orbit possesses very high energy as compared to the inner orbits.



Energy = K.E + P.E

For any atom, the energy of an nth orbit is given by

$$E_n = \frac{-13.56}{n^2} \text{ eV}$$

If $n = 1 \Rightarrow E_1 = -13.56$ eV

$n = 2 \Rightarrow E_2 = -3.5$ ev, etc.,

$\Rightarrow E_1 < E_2 < E_3 \ldots\ldots. E_n$

Valence shell will have the highest energy.

The electrons in the outermost orbit of an atom are known as valence electrons. The outermost orbit can have a maximum of 8 electrons. For a stable atom, the number of valence e^- is equal to 8.

Materials classified based on the conductivity (number of valence e^-) are of three categories : insulators (>4 e^-s), semiconductors (4 e^-s), and conductors (< 4e^-s).

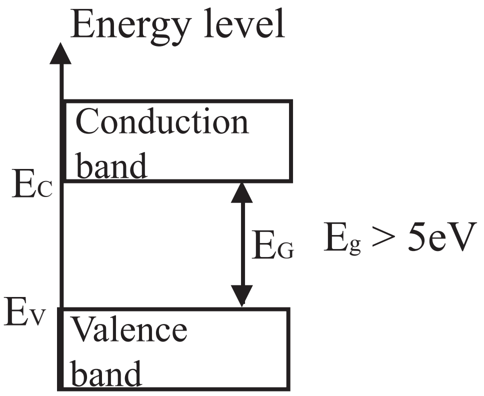
1. When the number of valence electrons of an atom is less than 4, the material is usually a metal and a conductor. For example, Cu, Al, sodium,

Mg, Cl, and gold.

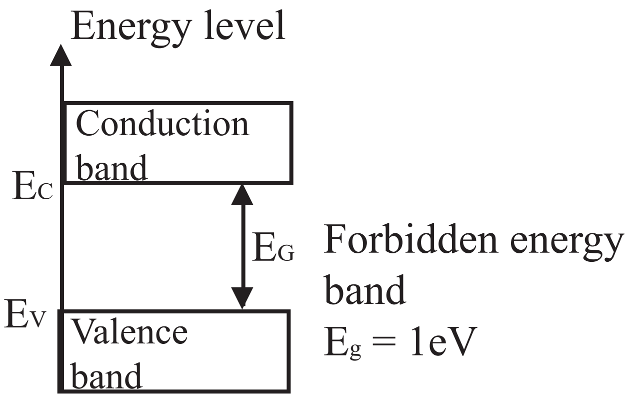
2. When the number of valence electrons of an atom is 4, the material has both metal and non-metal properties and it is called a semiconductor. For example, Si and Ge.
3. When the number of valence electrons of an atom is more than 4, the material is usually a non-metal and an insulator. For example, N, sulphur, neon, Br, As etc, and wood, plastic, mica, etc.
   (a) The resistance of a good conductor increases with an increase in the temperature, that is, it is a positive temperature coefficient (PTC).
   (b) The resistance of a good conductor increases with an increase in the temperature, that is it is a positive temperature coefficient (PTC).
   (c) Insulators also have NTC.

Energy Band Diagrams

1. Insulators



2. Semiconductors



3. Conductors

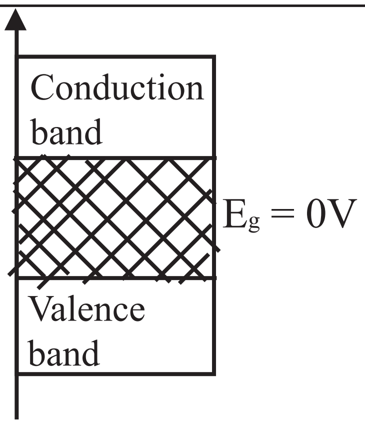


Figure 2 : Energy band diagrams

In an insulator, the conduction band is practically empty and the valence band is full, and therefore, enormous energy would be required to push electrons from the valence band into conduction band, that is, the forbidden energy gap. It is not possible in the normal working temperatures. Hence, an insulator cannot conduct even if a strong electric field is applied.

Insulators => Ionic bond

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator. The valence band is not saturated. Since there are only four e^- and the conduction band is practically empty at low temperatures (insulator).

However, with the increase in temperature, more and more valence electrons are jumped into the condition band. This increases the conductivity of the materials, that is, at high tempertaures, a semiconductor behaves like a good conductor.

Semiconductor => Covalent bonds

In conductors, the valence and conduction band overlap (i.e, $E_G = 0$), and therefore, a large number of free electrons are available even at low temperatures.

=> Conductors => Metalic bond

Intrinsic and Extrinsic Semiconductors

Intrisic Semiconductor

Intrisic semiconductor is a semiconductor material in its purest form, for example silicon and germanium. Both Si and Ge are tetravalent (IV th group), and they are crystal line. Each atom is shared by the four surrounding atoms, as shown in the figure.

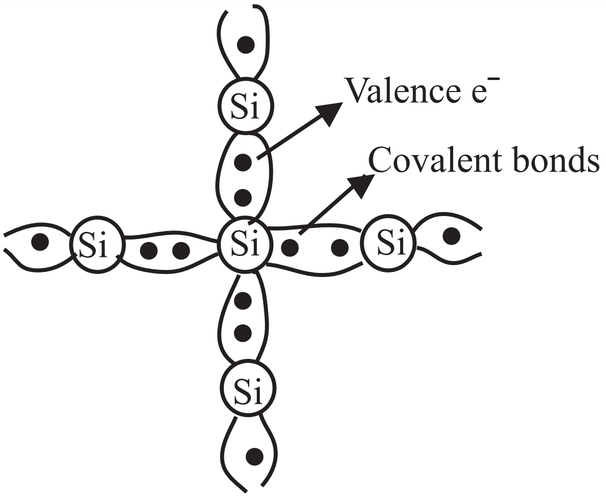


Figure 3 Crystalline structure of Si

At low temperatures, the covelent bonds are intact and the valence electrons are strongly bound to the parent atoms, that is, no free e^-s are available for conduction at room temperature. As temperature increases, the valence e^- acquires energy and create e^- hole pairs or some of the covalent bonds break; further, these free e^-s contribute to conduction. When a covalent bond breaks, a hole is created in the crystal lattice. A hole is nothing but missing electron, and hence, it represents a positive charge.

If the temperature is further increased, it creates more and more new e-hole pairs. This means the conductivity of the material increases with the temperature increases, but the total conductivity is poor.

Extrinsic Semiconductors

The conductivity of a pure semiconductor material can be increased by the addition of a small amount of suitable impurity to a semiconductor. The process of adding impurities to a semiconductor is known as doping.

The purpose of adding impurity is to increase either the number of free e^-s or holes in the semiconductor crystal. Depending on the type of impurity added, extrinsic semiconductor are divided into n-type semiconductors and p-type semiconductors.

n-type Semiconductor

When a small amount of pentavelent impurity is added to a pure semiconductor, it is known as n-type semiconductor.

The addition of pentavalent impurity provides a large number of free e^- s in the semiconductor crystal. For example, P, As, antimony, and Bi (Vth group elements).

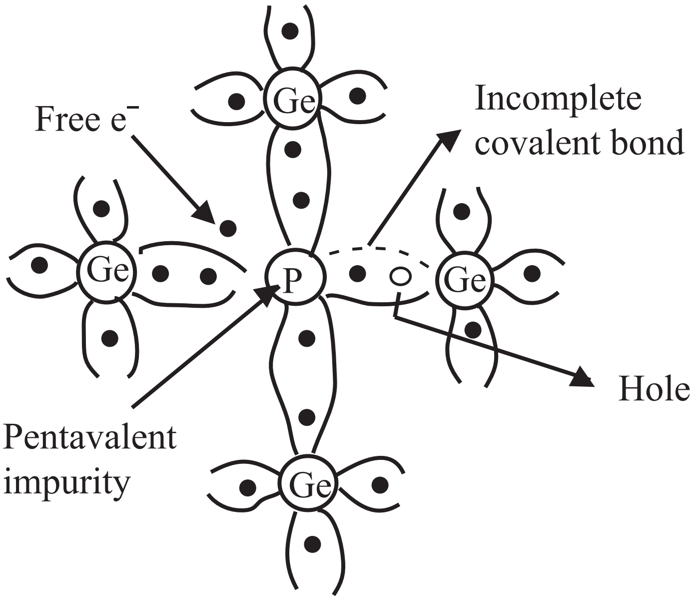


Figure 4 : Crystalline structure of N-type semiconductor

Such impurities are known as donor impurities because they donate or provide free e^-s to the semiconductor crystal. In N-type semiconductor, e^-s are majority charge carriers and holes are the minority charge carriers.

P-type Semiconductor

P-type semiconductor is formed by doping pure Si or Ge with trivalent impurities such as B, indium, gallium, or Al. In P-type semiconductor, holes (which are present in large numbers) are majority charge carriers and e^- s are minority charge carriers.

The acceptor atoms can be represented as negative ions. In extrinsic semiconductor, conduction is due to both majority and minority charge carriers.

Fermi-Dirac Function

The probability of occupation f(E) of an energy level (E) by an electron is given by

$$f(E) = \frac{1}{1 + \exp(E - E_F)/KT}$$

where K is Boltzmann constant in eV/°K.

The Fermi level represents the energy state with 50% probability of being filled, if no forbidden band exists. Therefore, if $E = E_F$, then $f(E) = 1/2$ for any temperature.

Case (i) : At T = zero (0°K)

$$F(E) = \frac{1}{(1 + e^{\infty})} = 0;\ \text{when } E > E_F$$

$$F(E) = \frac{1}{1 + e^{-\infty}} = 1;\ \text{when } E < E_F$$

Intrinsic semiconductor acts like an insulator at 0ºK.

Case (ii) : For T > 0ºK

$$F(E) = 0 \text{ when } E >> E_F$$
$$F(E) = 1 \text{ when } E << E_F$$

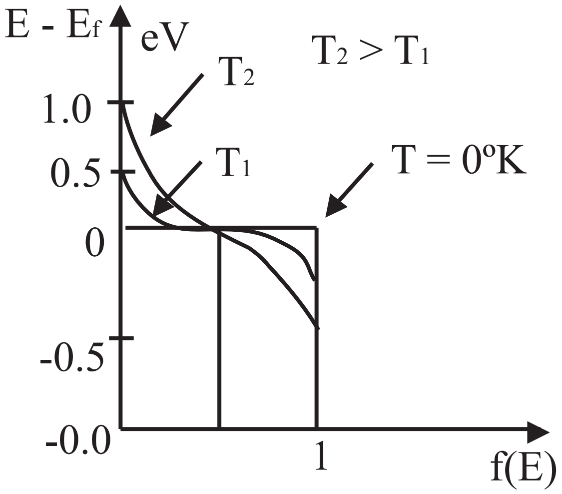


Figure 5 Fermi-Dirac distribution function f(E)

The concentration of free electrons n and the concentration of free holes is p.

$$\therefore n = N_C\, e^{-(E_C - E_F)/KT}$$
$$p = N_V\, e^{-(E_F - E_V)/KT}$$

Fermi Level In An Intrinsic Semiconductor

In the case of intrinsic material, the crystal must be electrically neutral.

$$n_i = P_i$$
$$N_C \,.\, e^{-(E_C - E_F)/KT} = N_V \,.e^{-(E_F - E_V)/KT}$$
$$\Rightarrow E_F = \frac{E_C + E_V}{2} - \frac{KT}{2} \,.\, \ln\left(\frac{N_C}{N_V}\right)$$

If the effective mass of a free electron and hole are same, then

$$N_C = N_V$$
$$E_F = \frac{E_C + E_V}{2}$$

In intrinsic semiconductor, the Fermi level lies in the middle of the forbidden energy band.

Donor Impurities

If pentavalent substances (phosphorous, antimony, As) are added as impurities to a pure germanium or Si, four of the five valence electrons of the impurity atoms will occupy covalent bonds and the fifth e^- will be available as a carrier of current. These impurities donate excess electron carriers, and hence, these are called donor or N-type impurities.

Acceptor Impurities

If a trivalent impurity (B, Al, Ga, In) is added to an intrinsic semiconductor, only three covalent bonds are filled, and the vacancy in the fourth bond constitutes a hole. These impurities are known as acceptor or P-type impurities.

Acceptor ion is indicated by a '-ve' sign because after this atom accepts an electron, it converts into a negative -ion.

Fermi level in an N-type material is given by

We know $n = N_C\,.e^{-(E_C - E_F)/KT}$

But $n \approx N_D$

$$N_D = N_C\,.e^{-(E_C - E_F)/KT}$$

$$E_{Fn} = E_C - KT\,.\,\ln\left(\frac{N_C}{N_D}\right)\text{eV}$$

Where

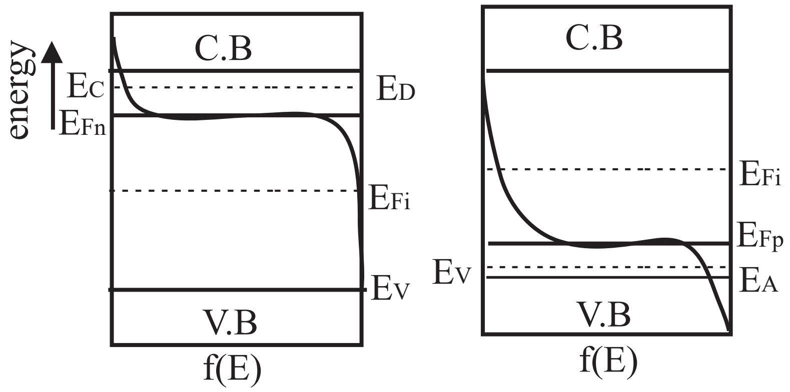
N_D => concentration of donor atoms

N_C = effective density states

The Fermi level in a P-type material is given by

$$E_{Fp} = E_v + KT.\,\ln\left(\frac{N_V}{N_A}\right)\text{eV}$$

Where N_A => concentration of acceptor atoms



(a) N-type (b) P-type

Figure 6 Positions of semiconductor Fermi levels in an extrinsic semiconductor

From the above mentioned figure, it shows the Fermi level in N-type semiconductor is just below the conduction band (E_c), and in p-type semiconductor, the Fermi level lies just above the valence band (E_V .)

Energy Band Gap (E_G)

Energy required to break a covalent bond, that is, it is the difference between the conductance band (E_C) to valence band energy (E_V). The energy gap decreases with the increase in temperature and is given by

$$E_G(T) = E_{G0} - \beta T$$

where β = Constant

$\beta_{Si} = 3.6 \times 10^{-4}$ eV/ºk and $\beta_{Ge} = 2.23 \times 10^{-4}$ eV/ºk

E_{Go} = energy gap at 0ºK

E_{go} = 1.21 eV for Si

E_{go} = 0.785 eV for Ge at 0ºK

and

E_G = 1.1 eV for Si

E_G = 0.72 eV for Ge at room temperature (300K)

Drift and Diffusion Currents

The flow of charge, that is, current through a semiconductor material is of two types, namely drift and diffusion. Since the net current flows through a PN junction, diode has two components : drift current and diffusion current.

Drift Current

When an electric field is applied across the semiconductor material, the charge carries attain a certain drift velocity v_d , which is equal to the product of the mobility of the charge carriers and the applied applied electric field intensity E. This means the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

Drift velocity $V_d = \mu E$ m/s

E = applied electric field intensity in V/cm

∴ The drift current density

$$J = J_n + J_p = (n\,\mu_n + p\,\mu_p)qE \text{ A/cm}^2$$

Diffusion Current

It is possible for an electric current to flow in a semiconductor even in the absence of the electric field, provided a concentration gradient exists in the material. A concentration gradient exists if the number of either e^-'s holes is greater.

In one region of a semiconductor as compared to the rest of the region, that is, diffusion current flows in semiconductor because of unequal distribution of charge carriers

Diffusion current density due to holes, J_P is given by

$$J_P = -q \cdot D_P \cdot \frac{dp}{dx} \text{ A/cm}^2$$

Diffusion current density due to electrons is given by

$$J_n = +q \cdot D_n \cdot \frac{dn}{dx} \text{ A/cm}^2$$

Where

$\frac{dn}{dx}$ => concentration gradient of e^{-}'s

$\frac{dp}{dx}$ => concentration gradients of holes

Note :

$$J_{n(diff)} = (-q) \cdot D_n \left(-\frac{dn}{dx}\right)$$

$= q\, D_n \cdot dn/dx$ => i.e, $J_{n(diff)}$ => +Ve sign

$$J_{P(diff)} = (+q) \cdot D_P \left(-\frac{dp}{dx}\right)$$

$= q\, D_P \cdot dp/dx$ => i.e, $J_{P(diff)}$ => -Ve sign

The total current in a semiconductor is the sum of drift current and diffusion current.

$$J = I/A \text{ A/cm}^2$$

That is, for a P-type semiconductor, the total current per unit area is given by

$$J_P = \left(p\mu_P\, qE - q\, D_P \cdot \frac{dp}{dx}\right) \text{A/cm}^2$$

Similarly, the total current density for an N-type semiconductor is given by

$$J_n = \left(n\mu_n\, qE - q\, D_n \cdot \frac{dn}{dx}\right) \text{A/cm}^2$$

Einstein Relationship for Semiconductors

The equation which related the mobility (μ) and the diffusion coefficient (D) is known as the Einstein relationship. The relationship is expressed as

$$\frac{D_o}{\mu_n} = \frac{D_p}{\mu_p} = \frac{KT}{q} = V_T$$

where

$$V_T = \frac{T}{11{,}600}$$

$V_T = 26$ mV ; At $T = 300°K$

Diffusion Length (L)

The average distance that an excess charge carries can diffuse its life time (τ) is called the diffusion length L, which is given by

$$L = \sqrt{D\tau}$$

where

$$D = \mu V_T$$

$$\therefore L_n = \sqrt{\mu_n . V_iT.\tau_n}$$

$$L_P = \sqrt{\mu_p . V_T . \tau_p}$$

Carrier Lifetime

In a pure semiconductor, the number of holes is equal to the number of free electrons. However, due to thermal agitation, it continues to produce new hole-electron pairs, while other e^- - hole pairs disappear as a result of recombination. On an average, an electron (a hole) will exist for τ_n (τ_p)s before recombination. This time is called the mean life time of the electron and hole.

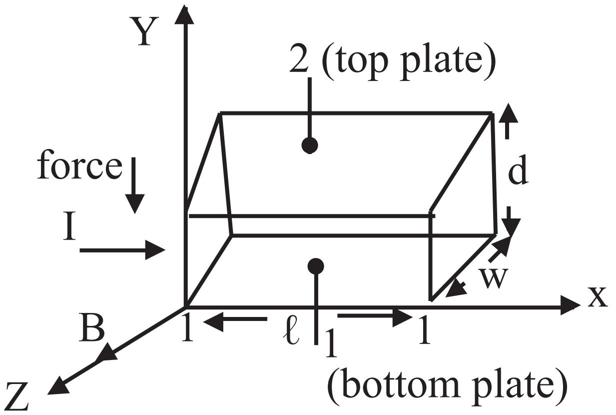
It ranges from few nanoseconds to hundreds of microseconds and depends on the temperature and impurity concentration in the semiconductor material. ‘Gold’ is extensively used as recombination agent.

Consider an N-type semiconductor having thermal equilibrium concentration p_{no} and n_{no} of holes and electrons. When the specimen is illuminated by light, as a result of this radiation, the new electron -hole pairs generate. Therefore, the hole and electron concentration will increase by the same amount.

$$\overline{P_{no}} - p_{no} = \overline{n_{no}} - n_{no}$$

Hall Effect

If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, then an electric field E is induced in the direction perpendicular to both I and B. This phenomenon is known as the Hall effect. This is used to determine whether a semiconductor is N-type or P-type and to find the carrier concentration.



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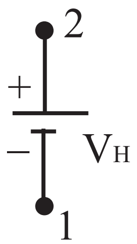
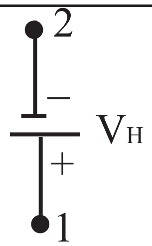


n-type semiconductor



p-type semiconductor

Under the equilibrium condition, the electric field intensity E is due to the Hall effect must exist a force on the carrier charge q, which balances the magnetic force.

That is,

$$qE = B.q.V_d$$

$$E = B.\ V_d \qquad (1.1)$$

Where

V_d => drift velocity

E => electric field due to Hall Effect

$$E = \frac{V_H}{d}$$

where d is the distance between the surfaces 1 and 2

The current density $J = nq\ \mu_n\ E = \dfrac{I}{A}$

$$J = \rho V_d = \frac{I}{wd}$$

where ρ => charge density

$$V_H = Ed = B.d.V_d \qquad (1.2)$$

Substituting $V_d = \dfrac{J}{\rho}$

$$V_H = B.d.\frac{J}{\rho} = \frac{B\ .\ d}{\rho}\ \frac{I}{Wd}$$

$$V_H = \frac{B.I}{\rho.W}$$

Where 'ρ' → charge density

The Hall coefficient, R_H is defined by

$$R_H = \frac{1}{\rho} = \frac{1}{n\ .\ q}$$

=> for n-type semiconductor

$$\therefore V_H = \frac{R_H\ .\ B.\ I}{W}$$

The Hall coefficient (R_H) for a p-type semiconductor is positive and -Ve for n-type semiconductor.

Note :

Hall voltage V_H is positive for n-type and negative for p-type semiconductor.

$$\sigma = \mu\rho \; ; \; \mu = \sigma R_H$$

$$\mu = \frac{\ell}{d}\left(\frac{V_H}{B.\, V_d}\right)$$

Theory of P-N Junction Diode

Introduction

In a piece of semiconductor material, if donor impurities are introduced into one side and acceptors into the other side of a single crystal of semiconductor, a P-N junction is formed. The plane dividing into the two halves or zones is called P-N junction shown in below figure.

The donor ion is represented by a plus sign because, after this impurity atom 'donates' an electron, it becomes a positive ion. The acceptor ion is indicated by a minus sign because, after this atom 'accepts' an electron, it becomes a negative ion.

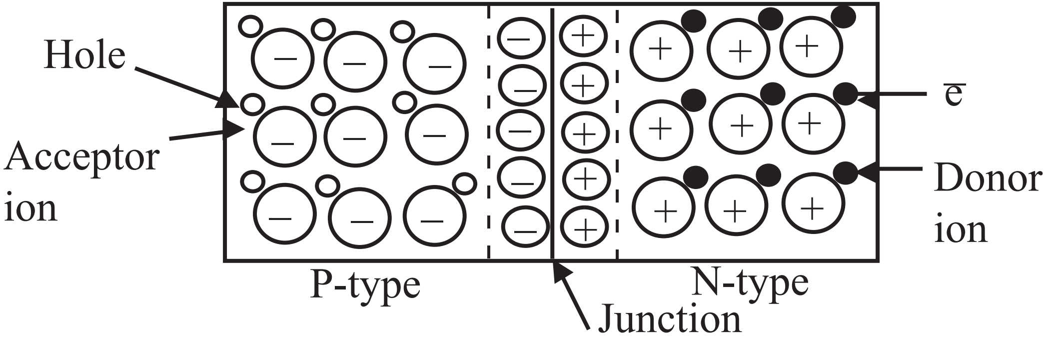
The N-type material has high concentration of free electrons, whereas P-type material has high concentration of holes. At the junction, the free electrons to diffuse over to the p-side and holes to the n-side, this process is called diffusion.

The general shape of the charge density depends upon how the diode is doped. The region of the junction is depleted of immobile charges, and it is called the depletion region, the space-charge region or the transition region.

The space-charge density (ρ) is zero at the junction. It is positive to the right (n-side) and negative to the left (p-side) of the junction.

The field intensity curve is proportional to the integral of the charge density curve. this is known as Poisson's equation.

$$\frac{d^2V}{dx^2} = -\rho l \varepsilon$$



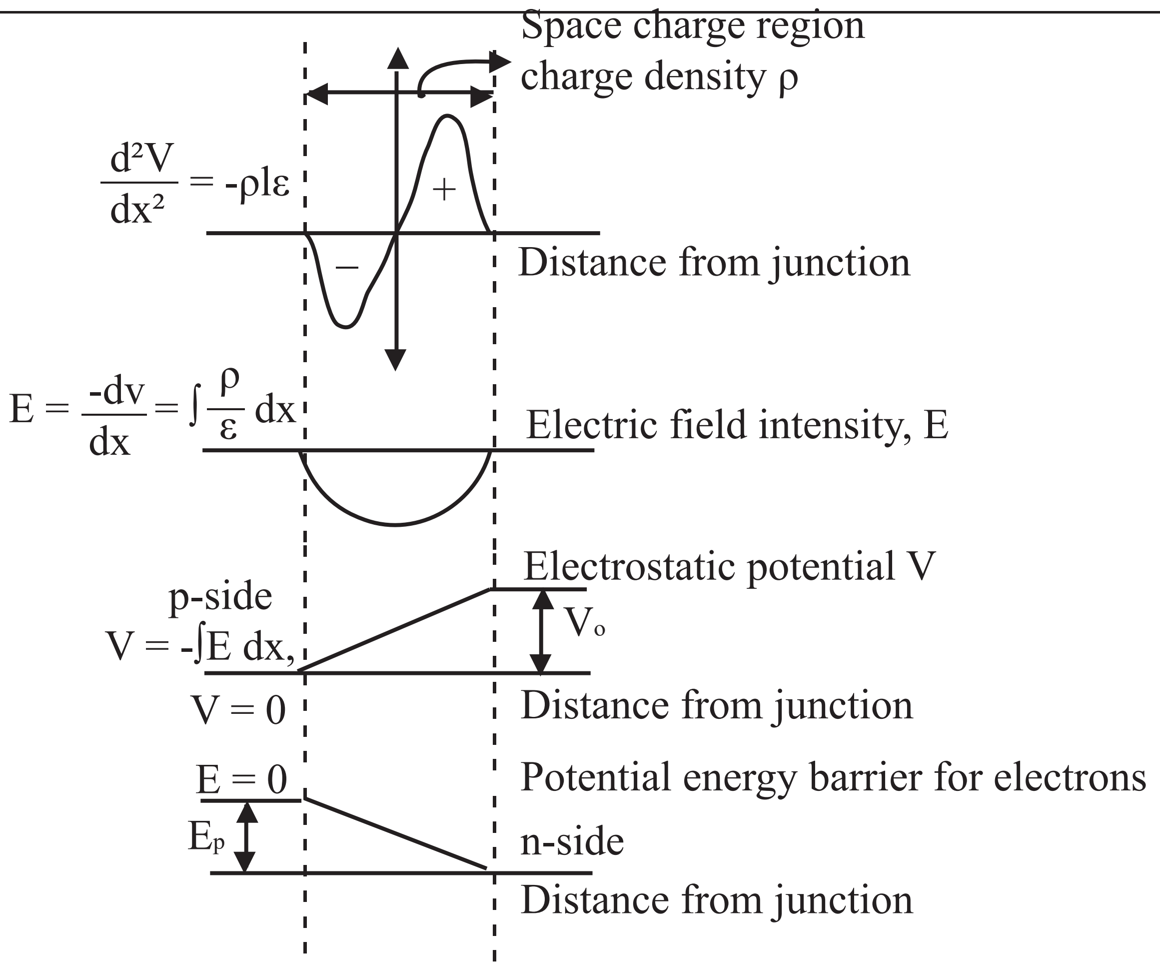


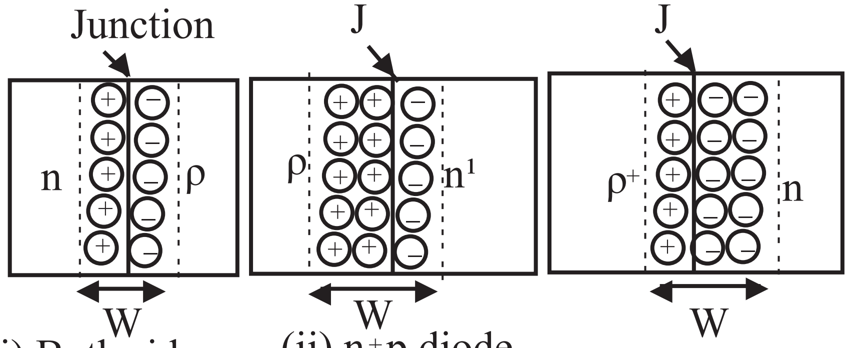
Figure 1 : A schematic diagram of a P-N junction including the charge density, electric field intensity, and potential energy barriers at the junction

The barrier potential of P-N junction mainly depends on the following factors :

1. The type of semiconductor used.
2. The concentration of impurity
3. The temperature

Effect of Doping on Depletion Region

The width of the depletion region depends on the amount of doping on n-side and p-side.



(i) Both sides equally doped (p-n diode) $(W_n = W_p)$

(ii) n^+p diode $(W_n << W_p)$ $W = W_p$ $(W = W_n + W_p)$

(iii) p^+n diode $(W_n >> W_p)$ $W = W_n$

The depletion region penetrates more into the lightly doped side.
The relation between the impurity concentration and depletion width is

$$\boxed{W_p \,.\, N_A = W_n \,.\, N_D}$$

Biasing of P-N Junction Diode

Applying external dc Voltage to any electronic device is called biasing.

Forward Biasing of P-N Junction Diode

When the P-N junction is forward biased as long as the applied voltage is less than the barrier potential, there cannot be any conduction.

When the applied voltage becomes more than the barrier potential, the negative terminal of the battery repels electrons and positive terminal repels holes. Thus, the applied voltage overcomes the barrier potential and hence reduces the width of depletion region.

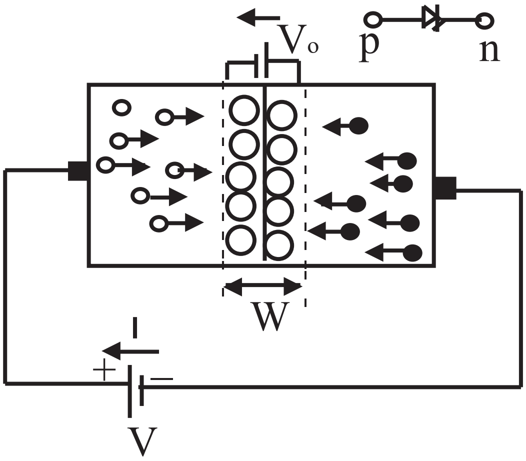


Figure 2 P-N junction under forward bias

Reverse Biasing

If p-side of a P-N junction is connected to the negative terminal, and the n-side is connected to the positive terminal of a battery, since the holes in the p-region are attracted towards the negative terminal, and the electrons in the n-region are attracted towards the positive terminal. There can be no diffusion of charge carriers through the junction, and hence, there is no conduction.

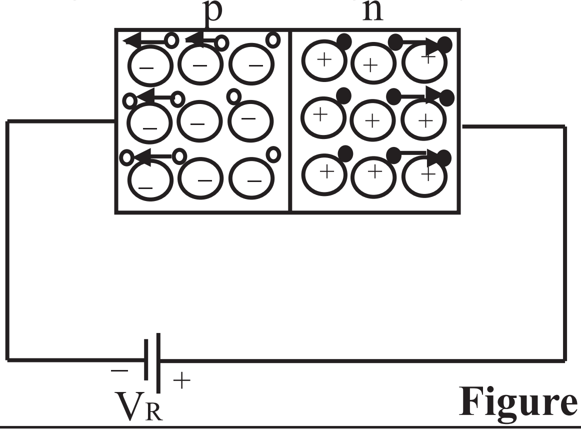


Figure 3 :P-N junction under reverse bias

The applied reverse bias voltage established an electric field in the same direction as the field due to the barrier potential with the result the width of the depletion region increases, and the junction offers high resistance.

A small reverse current of the order of µA or nA flows through the reverse biased P-N junction. This is due to the applied voltage acts as forward bias for the minority charge carriers. This current gets stabilized to a steady magnitude and is quite independent of the bias voltage and this is also called as reverse saturate current (I_s or I_o).

The reverse saturation current is temperature dependent and it is almost doubles for every 10ºC rise of temperature.

$$\boxed{\therefore I_{o2} = I_{o1} \cdot 2^{(T_2 - T_1)/10} \text{ Amps}}$$

Electrons forming covalent bonds of the semiconductor atoms in the P - and N-type regions may absorb sufficient energy form heat and light to cause breaking of some covalent bonds. hence, $\bar{e}$ - hole pairs are continually produced in the both regions. Under the reverse bias condition, the thermally generated electrons in the N-region attracts towards the '+ve' terminal and holes towards '-ve' terminal of the battery. The magnitude of reverse saturation current mainly depends upon junction temperature because the major source of minority carriers is thermally broken covalent bonds.

Energy band Structure of an Open-Circuited P-N Junction

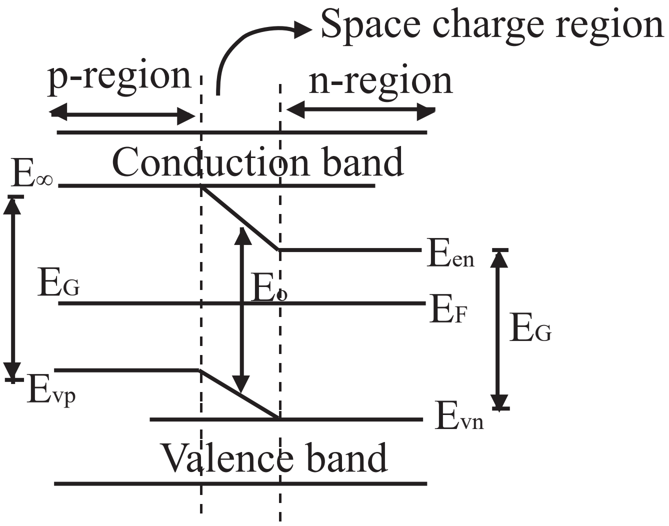


Figure 4 : Energy band structure

The energy band structure of a P-N junction is shown above figure, where the fermi level E_F is closer to the conduction band E_{cn} . In N-type material, and it is closer to the valence band E_{vp} in the P-type material.

The total shift in the energy level E_o is given by

$$E_o = E_{cp} - E_{cn} = E_{vp} - E_{vn}$$

This energyoE(in eV) is potential energy of the electrons at the P-N junction, and it is equal to qv_o (in V).

Where V_o → contact potential (in volts)

(or)

Contact difference of potential

(or)

The barrier potential

Contact Potential V_o

Energy band gap $E_G = KT\ln \dfrac{N_c \, . \, N_v}{n_i^2}$ eV

$$E_o = KT \ln\left[\frac{N_A \, N_D}{n_i^2}\right] eV$$

We know $E_o = qV_o$

$$\therefore \text{Contact potential } V_o = \frac{KT}{q} \,.\ln \left[\frac{N_A \, . \, N_D}{n_i^2}\right] \text{volts}$$

$$\boxed{\therefore V_o = V_T \, . \, \ln \left[\frac{N_A \, . \, N_D}{n_i^2}\right] v}$$

The alternative expression for E_o is as follows : $n_n = N_D$

$n_n \, . \, P_n = n_i^2$ For N-type materials

$$P_n = \frac{n_i^2}{N_D}$$

and $n_p \, . \, p_p = n_i^2$ at $p_p = N_A$ for p-type

$$\therefore n_p = \frac{n_i^2}{N_A}$$

$$\therefore E_o = KT \ln\left[\frac{P_{Po}}{p_{no}}\right] = KT \ln\left[\frac{n_{no}}{n_{po}}\right]$$

Diode Current Equation

$$\boxed{I = I_o \left[e^{V_d/\eta V_T} - 1\right] \text{Amp}}$$

Where v = external voltage applied to the diode, η = constant, 1 for Ge and 2 for si

$$V_T = \frac{KT}{q} = \frac{T}{11{,}600} \, V$$

I_o => reverse saturation current. It is represented by $I_o = A.q$

$$\left[\frac{D_p}{L_p \,.\, N_D} + \frac{D_n}{L_n \,.\, N_A}\right] n_i^2$$

Note :

When the diode is reverse biased, its current equation may be obtained by reverse the sign of the applied voltage v, (-ive). Then, the diode current with reverse bias is $I = I_o$

$$\left[e^{-V_d/\eta V_T} - 1\right] \text{Amp}$$

V-I Characteristics of P-N Junction Diode

Forward-Biased P-N Junction

As the applied voltage is increased beyond cut in voltage, the junction readily conducts, and the forward current. It rapidly rises with further increase in v_p . These are shown in the below figure.

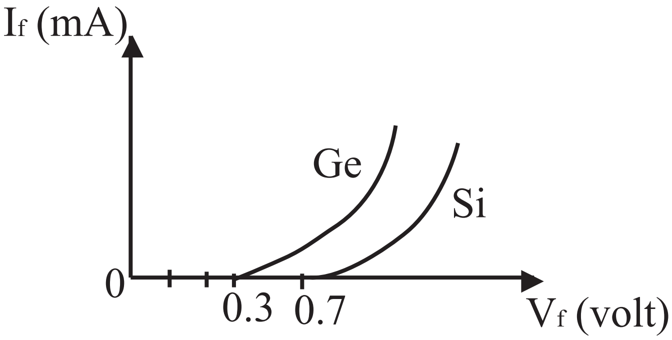


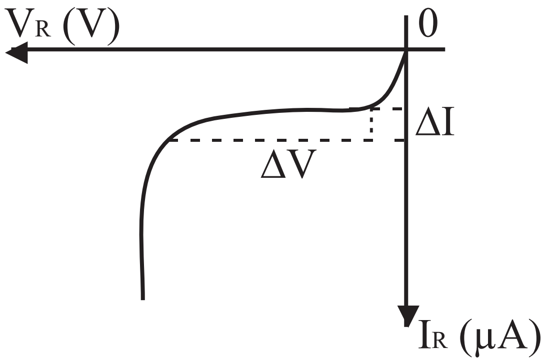
Figure 5 V-I characteristics of P-N diode

Forward resistance of the junction diode is

$$R_f = \frac{\Delta V_f}{\Delta I_f}\ \Omega \Rightarrow R_f \Rightarrow \text{is small}$$

Reverse-Biased P-N Junction

When P-N junction is reverse biased, the depletion region widens, and as a result, the junction offers very high resistance.



Breakdown in P-N Junction Diodes

The junction breakdown is due to the following two factors. They are as follows :

(i) Zener effect
(ii) Avalanche effect

Avalanche Effect

As the reverse voltage increases, the minority charge carriers acquires more kinetic energy, so its drift velocity increases.

They acquire sufficient energy, from the applied potential to produce new carriers by removing valance electrons from their bonds.

These new carriers will in turn collide with other atoms and will increase the number of electrons and holes available for conduction. Thus, charge carriers increase at a very rapid, and at breakdown voltage, the minority carrier current rises rapidly, causing the breakdown of the junction. This phenomenon is formed as avalanche effect.

It is a positive temperature coefficient.

Zener Effect

Practical diodes are heavily doped, the depletion layer is very thin, and hence, the potential gradient is quite high. Increase in reverse bias increases the potential gradient, even if the initially available carriers do not acquire sufficient energy to disrupt bonds, it is possible to initiate breakdown by a direct rupture of the bonds because of the existence of strong electric field. This phenomenon is known as Zener effect.

The Zener effect is in diodes with breakdown voltages below about 6V, and the operating voltages in avalanche breakdown are from several volts to several 100 volts with power rates up to 50 W.

$$(V_A > 6V)$$

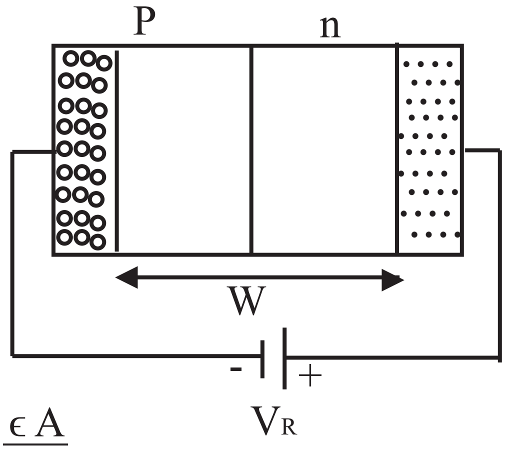
It has a negative temperature coefficient.

P-N Junction Capacitances

In a P-N junction, there is a depletion region in between P-type and N-type semiconductor, the depletion region is totally devoid of charge carriers, and hence, it acts as a dielectric in between two oppositely charged surfaces. A practical junction diode possesses two types of capacitances:

Transition or Space Charge or Depletion Capacitance (CT)

Under reverse-biased condition, the majority carriers move away from the junction, thereby uncovering more immobile charges. Hence, the width of the space charge layer at the junction increases with reverse voltage.



$$\Rightarrow C_r = \frac{\epsilon A}{W}$$

Where A → Surface area of the junction

W → width of the depletion layer

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right]V_j}$$

Diffusion Capacitance (C_D)

When a P-N junction is forward biased, the capacitance of the junction is much larger than its transition capacitance.

Diffusion capacitance may be defined as the rate of change of charge with voltage.

$$C_D = \frac{dQ}{dV}$$

$$i = \frac{dq}{dt} \Rightarrow dQ = \tau.dI$$

$$C_D = \tau.\frac{dI}{dv}$$

We know $I_D \simeq I_o \, . \, e^{\left(\frac{V_d}{\eta V_T}\right)}$

$$\frac{dI}{dV} = \frac{I}{\eta V_T} = g$$

$$\therefore C_D = \frac{\tau I}{\eta V_T} \text{ or } C_D = \tau g$$

Where $g = 1/r = \frac{I_f}{\eta V_T}$

Application of P-N Diode

1. Rectifiers in DC power supplies.
2. Switching circuits
3. Clamping and clipping circuits, used as wave shaping circuits used in computers, radar, radio and TV receivers.
4. Demodulation circuits.

The same P-N junction with different doping levels finds special applications as follows.

1. Zener diodes in voltage regulators.
2. Varactor diodes in tuning sections of radio and TV receivers.
3. Detectors (APD, PIN photo diode)
4. LED and LCD's in digital displays.
5. LASER diodes in optical communication.

Tunnel diodes used as a relaxation oscillators at microwave frequencies.

Zener Diode

When the reverse voltage reaches breakdown voltage in normal P-N diodes, the current through the junction and the power dissipation at the junction will be high such an operation is destructive and the diode gets damaged.

As diodes can be designed with adequate power dissipation capabilities to operate in the breakdown region, one such diode is known as zener diode. It is a heavily doped than the ordinary diode.

In forward bias, the operation of zener diode is the same as normal P-N diode.

While under reverse biased condition, breakdown of the junction occurs, it depends on the concentration of doping. If the diode is heavily doped, depletion layer will be very thin and breakdown occurs at lower reverse voltage and further breakdown voltage is sharp.

The sharp increasing current under breakdown conditions are due to the following mechanisms.

1. Zener breakdown
2. Avalanche breakdown

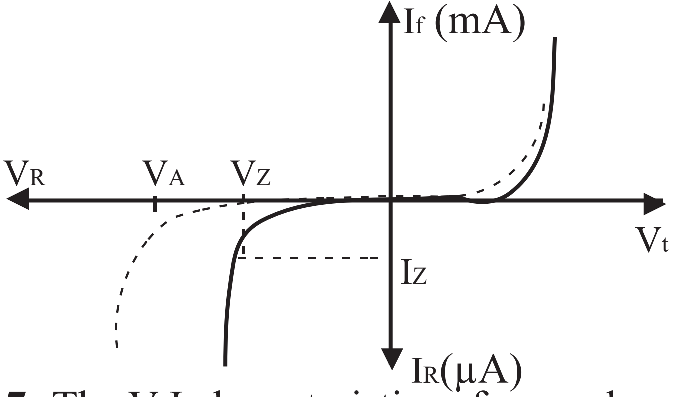
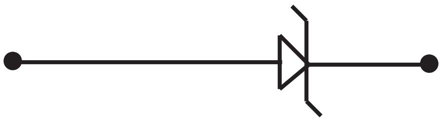


Figure 7 : The V-I characteristics of an avalanche, or Zener diode

Symbol



Example 3

Consider an asymmetrical Si junction, with $N_A = 10^{19}\ cm^{-3}$ and $N_D = 10^{17}\ cm^{-3}$. If the cross-sectional area of the junction is $10\mu m^2$, determine its transition capacities with no applied bias. ($n_i = 1.45 \times 10^{10}$)

Solution :

$$C_T = \frac{\text{‘}\varepsilon\text{’}A}{W}$$

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right]V_j}$$

$$V_j = V_o = V_T \ln\left[\frac{N_A \,.\, N_D}{n_i^2}\right] V$$

$$V_j = 0.94 \text{ volts},.\ \varepsilon_s = 11.9\ \varepsilon_o^{\,si}$$

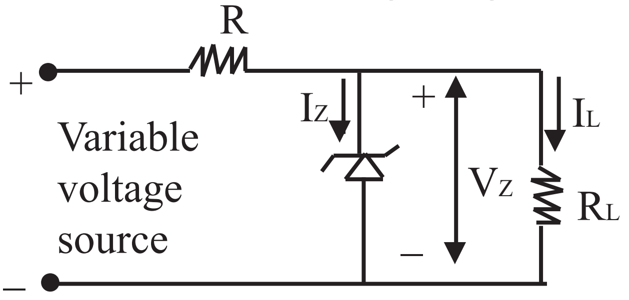
$$W = \sqrt{\frac{2 \times 11.9 \times 8.85 \times 10^{-12}}{1.6 \times 10^{-19}} \times \left[\frac{1}{10^{19}} + \frac{1}{10^{17}}\right] . (0.94) \times 10^{-6}}$$

$$W = 11.17\ \mu m$$

$$C_T = \frac{11.9 \times 8.85 \times 10^{-12} \times 10 \times 10^{-12}}{11.17 \times 10^{-6}}$$

$$= 9.428 \times 10^{-17}\ F$$

Zener Diode as a Voltage Regulator



A zener diode, under reverse bias breakdown condiction, can be used to regulate the voltage across the load irrespective of the supply voltage or load current. The voltage across the zener diode remains constant even if current through it changes by large extent.

Zener breakdown occurs and current I_Z flows through it. A current I_L flows into the load R_L.

$$V_Z = I_L \,.\, R_L$$

$$V_Z = V_L$$

The current through R is, $I = I_Z + I_L$

If the supply voltage now increases, more current is drawn from the supply. Since the zener diode is operating in the breakdown region, its current I_Z

increases and I_L remains same (V_Z = constant)

If P_Z denote the power rating of the zener diode

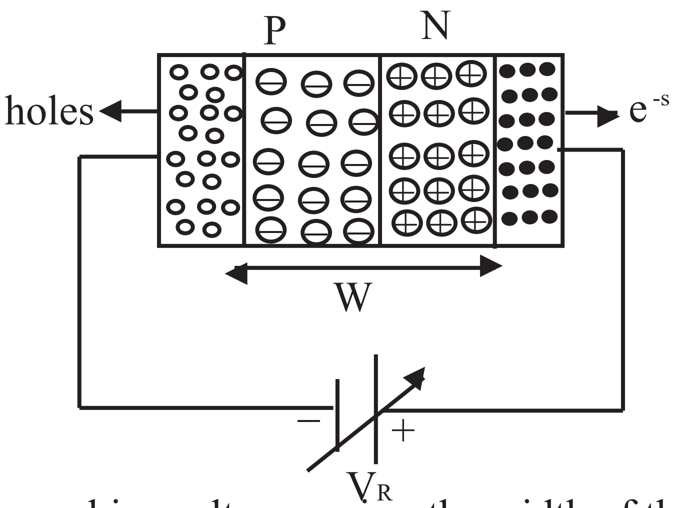
$p_Z = V_Z . I_{Z(max)}$ watts,

If the load resistance decreases, more current flows into the load; if the load resistance increases, the load current decreases. That is, the load is parallel to the zener diode operations with a constant breakdown voltage.

Varactor Diode

The varactor diode also called as a varicap or tunning or voltage variable capacitor diode, it is a lightly doped diode.

The diodeis reverse-biased, a depletion region is formed, shown in below figure.



If the reverse bias voltage varies, the width of the depletion region also varies.

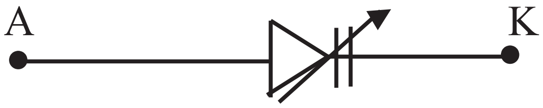
If V_R increases, the width of the depletion layer 'W' becomes wider.

$V_R \alpha W$

This depletion region is devoid of majority carriers and acts like an insulator preventing conduction between the N and P region of the diode, which separates the two plates of a capacitor.

$$C_T = \frac{\varepsilon A}{W} F$$

The capacitances is inversely proportional to the distance between the plates (C_T a l/W)



Circuit symbol of varactor diode

Applications

1. Varactor diode are used in FM radio and TV Receivers AFC circuits.
2. Self-adjusting bridge circuits and adjustable band pass filters.
3. Tuning circuits of LC resonant circuits in µW frequency multipliers and in very low noise µw parametric amplifiers.

Tunnel Diode

The tunnel or Esaki diode is a thin-junction diode which exhibits negative resistance under forward bias.

An ordinary P-N junction diode has an impurities concentration of 1 : 10^8 atoms. In this, the amount of doping is 1 in 10^3 atoms.

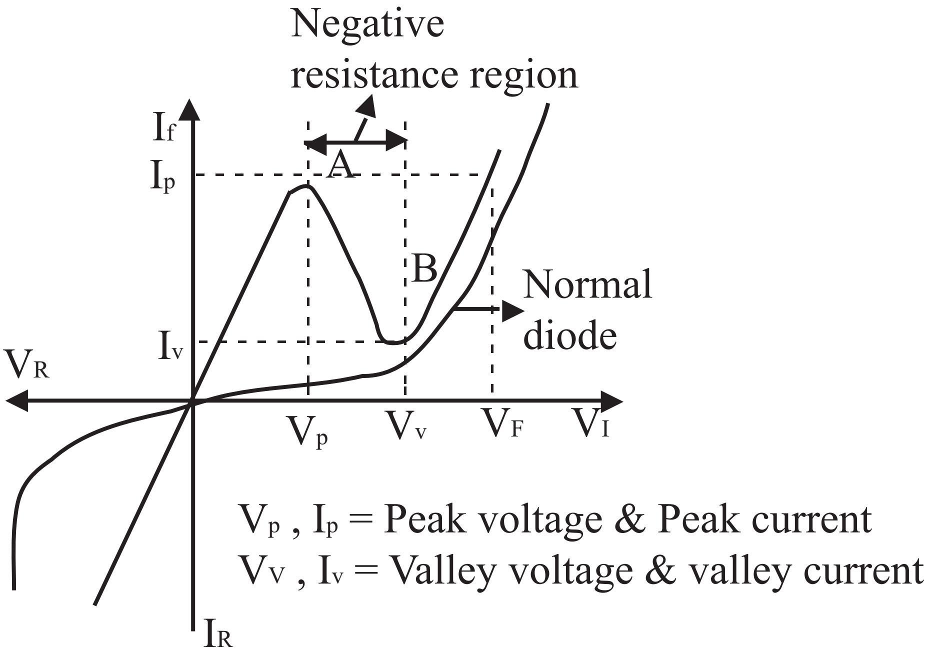


Figure 8 : V-I characteristics of tunnel diode

Operation : When the semiconductor is very highly doped, the fermi level goes above the conduction band for N-type and below valance band for P-type material. These are called degenerate materials.

Under Forward Bias

Step 1 : At zero bias there is no current flow.

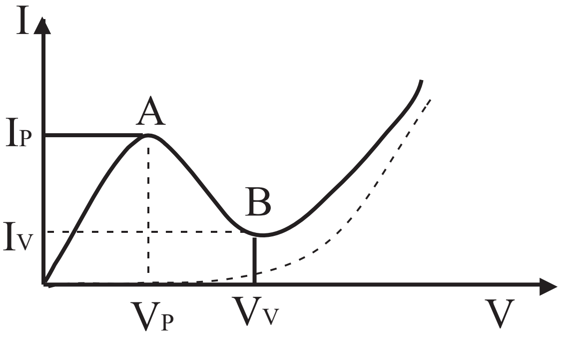
Step 2 : A small forward bias is applied. The potential barrier is still very high with no noticeable injection and forward current through the junction. However, electrons in the conduction band of the N-region will tunnel to the empty states of the valance band in P-region. This will create forward bias tunnel current.

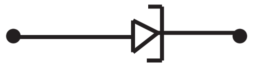
Step 3 : With a large voltage, the energy of the majority of $\overline{e}$ in the N-region is equal to the empty states (holes) in the valence band of P-region. This will produce maximum tunnelling current.

Step 4 : As the forward bias continuous to increase, the number of $\overline{e}$'s in the n-side that are directly opposite to the empty states in the valance band (In terms of their energy) decreases. That is, decrease in the tunnelling current will start.

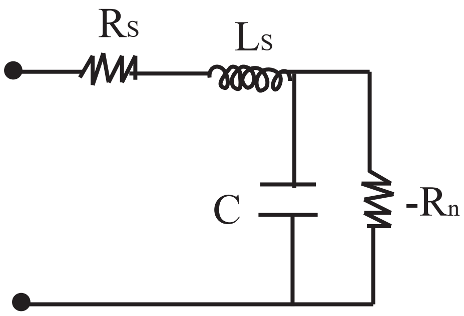
Step 5 : As more forward voltage is applied, the tunnelling current drops to zero. However, the regular diode forward current due to electron - hole injection increases due to lower potential barrier.

Step 6 : With further voltages increases, the tunnel diode V-I characteristics is similar to that of a normal P-N diode.





(a) Symbol



(b) Tunnel diode circuit

Applications :

1. High-speed switch
2. High -frequency oscillator
3. The most commonly available tunnel diodes are made from Ge or GaAs.

Note :
It is the difficult to have a high ratio of peak to valley current $\frac{I_P}{I_V}$ with Si

Example 6

The reverse bias breakdown of high speed Si transistors is due to

(a) Avalanche breakdown mechanism at both the junctions.
(b) XZener breakdown mechanism at base-collector junction.
(c) Zener breakdown mechanism at base-emitter junction
(d) All the above.

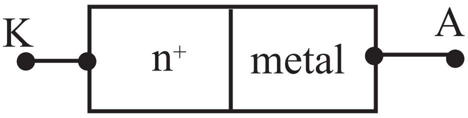
Solution : (c)

Schottky Diode

1. Schottky diode are high current diodes used in high frequency and fast

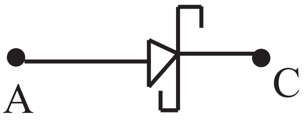
switches applications.

2. A Schottky diode is formed by joining a doped N-type with a metal such as gold silver or platinum.
3. It means that it has a metal-to-semiconductor junction rather than P-N junction.



(a)

Figure 9 : Schottky diode structure



(b) Symbol

4. The forward voltage drop is 0.3 V
5. There are only majority carriers with no reverse leakage current.
6. The metal conductor has many conduction band electrons and N-type is also heavily doped.
7. When forward bias applied, the N-type electrons move across to the metal region and rapidly loss energy. The process is very fast which makes Schottky diodes ideal for fast switches applications.
8. It is also called hot carrier diode.

Pin Diode

1. The PIN diode consists of heavily doped P and N regions, which are separated by intrinsic material.
2. In reverse bias, the PIN diode acts like a capacitance.
3. When forward bias applied, it acts like a current controlled variable resistance.

OPTOELECTRONIC DEVICES

Introduction

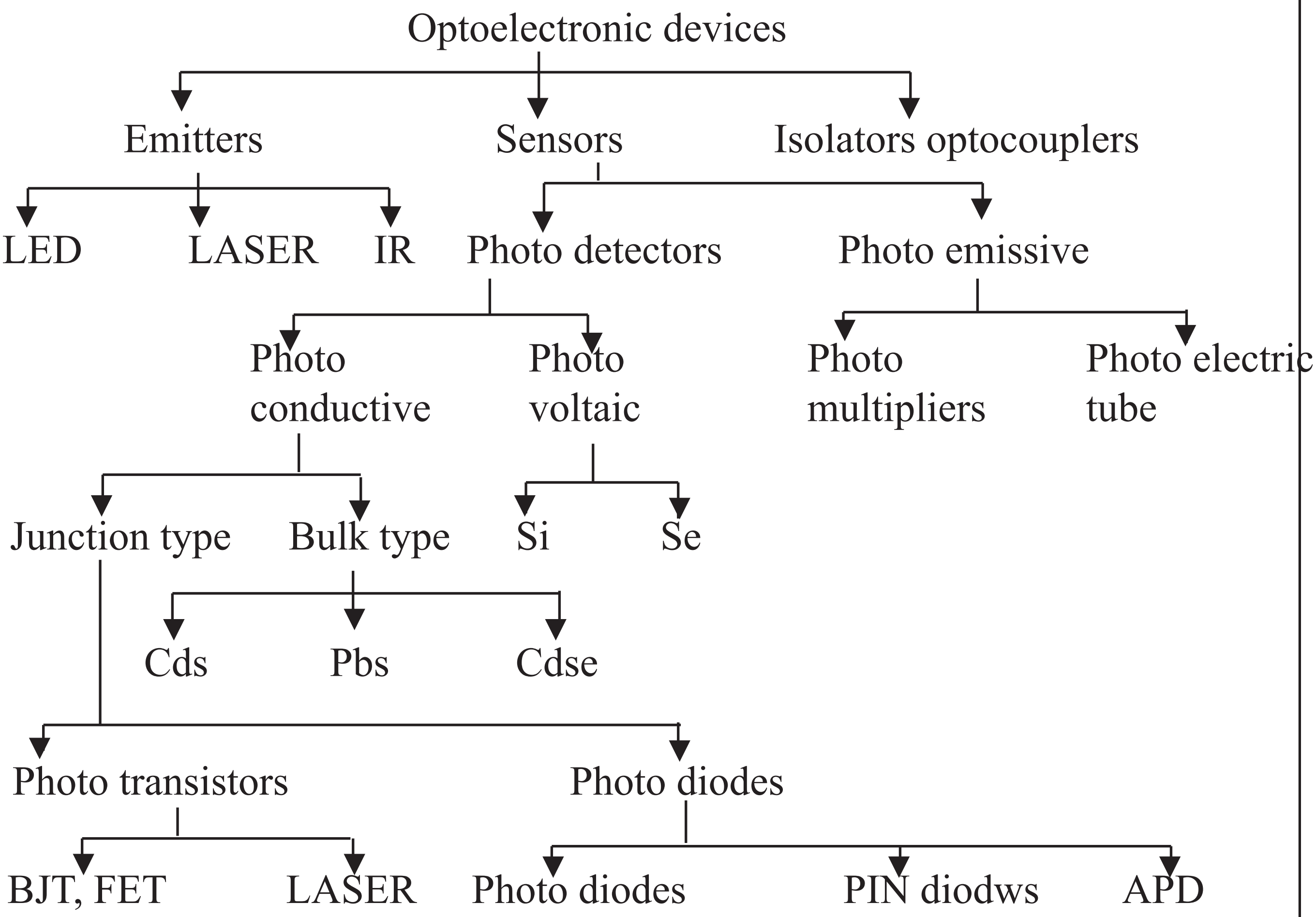
Optoelectronics is the technology that combines optics and electronics and the devices based on this technology are known as optoelectronic devices.

These devices are broadly classified as follows :

1. Devices that convery optical radiation into electrical energy such as photovoltaic device or solar cell.
2. Devices that detect optical signals through electronic processes such as photodetectors.

3. Devices that convert optical energy optical radiation such as light-emitting diodes and the LASER diodes.
   - The devices that convert electrical energy into optical radiations are known as emitters.
   - Photo detectors are the semiconductor devices that can be used to detect the presence of photons and convert optical signals into electrical signals.

The photo conductors in which the photons-generates excess electron-hole pairs. It changes the conductivity of a semiconductor.



According to the Quantum theory, light consists of discrete packets of energy called photons.

$$\therefore E = hv = \frac{hC}{\lambda} = hf$$

Where h is plank's constant

$h = 6.625 \times 10^{-34}$ Js

λ → wave length in meters

C → Light velocity

$$E_G \leq \frac{1.24\text{eV}}{\lambda(\mu\text{m})}$$

In a forward bias p-n junction, electrons and holes both cross the junction. In this process, some electrons and holes recombine with the results that electrons lose energy; the amount of energy lost is equal to the energy band gap of semiconductor E_G .

At room temperature, the value of E_G is

For Si => $E_G = 1.1$ eV
Ge => $E_G = 0.72$ eV
GaAs => $E_G = 1.43$ eV
and INAS => $E_G = 0.36$ eV

Photo Conductivity

If radiation falls upon a semiconductor , its conductivity increases. This is called photoconductive effect. Radiant energy supplied to the semiconductor causes covalent bonds to be broken, and new electron-hole in excess of those generated thermally are created. These increased current carriers decrease the resistance of the material, and hence, such a device is called a photoresistor or photoconductor.

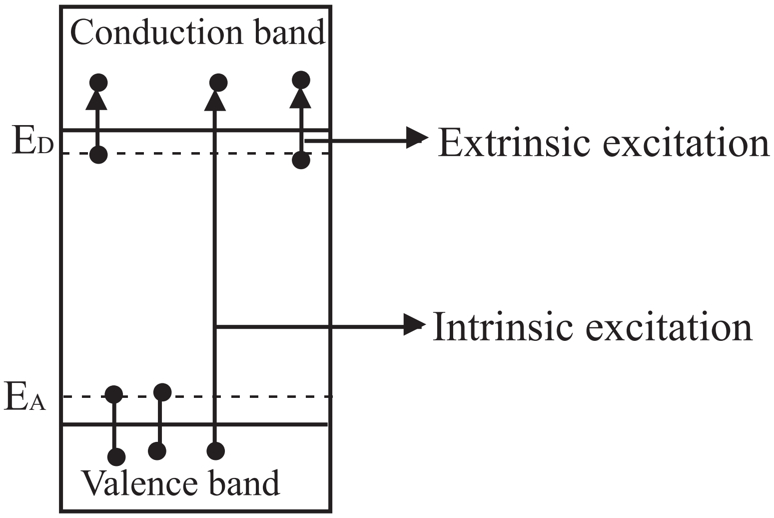


Figure 1 : Photo excitation in a semiconductor

In the above figure, the energy band diagram of a semiconductor having both acceptor and donor impurities is shown. If photons of sufficient energies are illuminated on this specimen, then following transitions are possible.

1. An electron-hole pair can be created by a high-energy photon-what is called intrinsic excitation. i.e, the excitation takes place directly from valance band to conductor band. This is known as intrinsic excitation.
2. A photon may excite a donor electron into conduction band or a valance electron may go into an acceptor state. These transitions are known as impurity excitations.

The minimum energy of a photon required for intrinsic excitation is the forbidden energy gap E_G of the semiconductor material.

$$\lambda = \frac{1.24}{E_G\,(\text{eV})}\ \mu\text{m}$$

For Si, $E_G = 1.1$ eV and $\lambda = 1.13\ \mu$m

For Ge, $E_G = 0.72$ eV => $\lambda = 1.73\ \mu$m at room temperature.

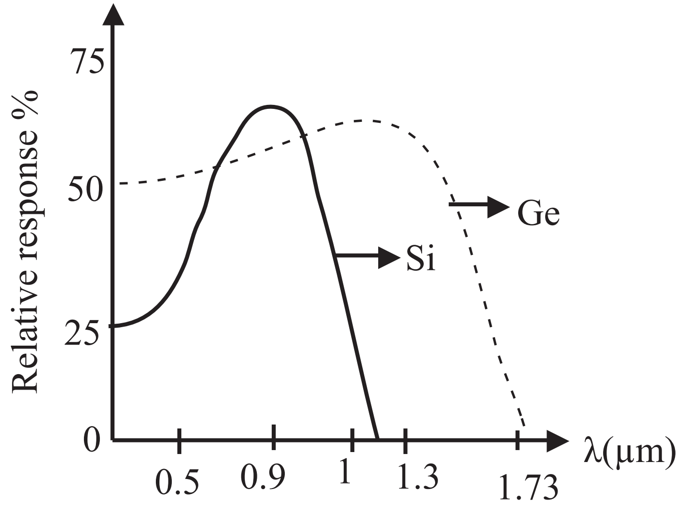


Figure 2 Relative response of Si and Ge

Solved Examples

Example 1

The longest wavelengt that can be absorbed by Si, which has the band gap of 1.12 eV, is 1.1 μm. If the longest wave length that can be absorbed by another material is 0.87 μm, then the band gap of this material is

(a) 1.425 eV (b) 0.85 eV

(c) 0.706 V (d) 1.23 eV

Solution

We know $E_G = \dfrac{1.24\ \text{eV}}{\lambda(\mu\text{m})}$

Given λ 0.87 μm

So $E_G = \dfrac{1.24\ \text{eV}}{0.87} = 1.425$ eV

Photodiode

If a junction diode is reverse biased, then conduction occurs due to the minority charge carriers only. The reverse, saturation current is practically of constant magnitude, which is irrespective of the applied reverse bias. If the temperature of the junction increases, then evidently the reverse saturation current also increases as new electron-hole pairs are created due to incident thermal energy ; the same effect is caused with incident light also.

V-I Characteristics

Photodiode operates in the reverse bias mode, there is an arrangement by which light is allowed to fall on the particular surface across the junction through a window, the diode is kept enclosed within a plastic container. Except for the surface that receives the radiant energy, the other sides are painted black.

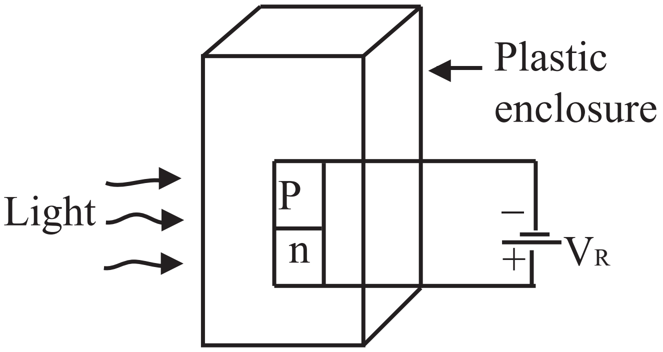
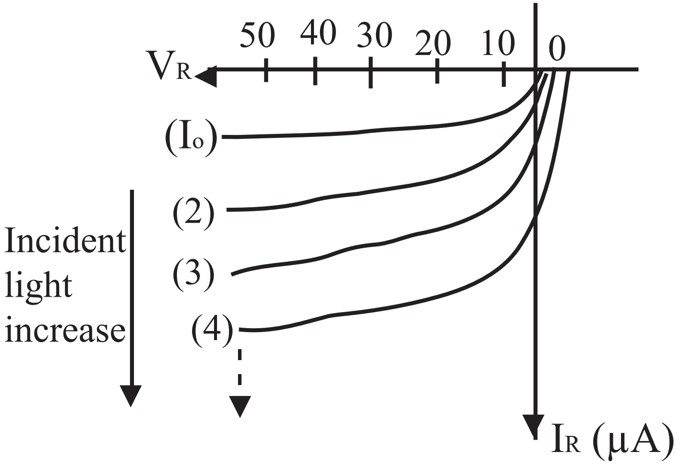
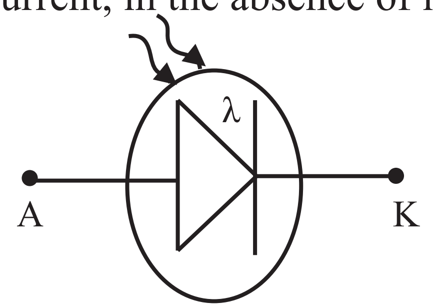


Figure 3 : Structure of a photodiode

When light which consists of photons, is incident on the junction surface, additional electron-hole pairs are created due to the fact that valence electrons acquire energy from the photons. This has the effect of increasing the reverse current. It depends on the incident photon energy at the junction. The V-I characteristic of a photodiode is as shown below.



Where I_0 is teh dark current, in the absence of incident light or photon energy.



Photodiode symbol

Typical values of the parameter of a photodiode

Diode forward resistance $R_f = 100\ \Omega$

Reverse resistance $R_r = 50\ n\Omega$ and $C_T = 10$ pF

Applications

1. Optoelectronic applications. They are used in light operated switches, light detection systems, for reading of sound track on films, and for counting objects in a production line.
2. They are used in high-speed reading of computer punched cards and tapes.

Avalanche Photodiode

Avalanche photodiode is also a photodetector. A photodiode will produce less amount of current, which is not sufficient to drive some circuits. An avalanche photodiode (APD) gives more output current when compared to a photodiode. The 'impact ionization' takes place in APD's

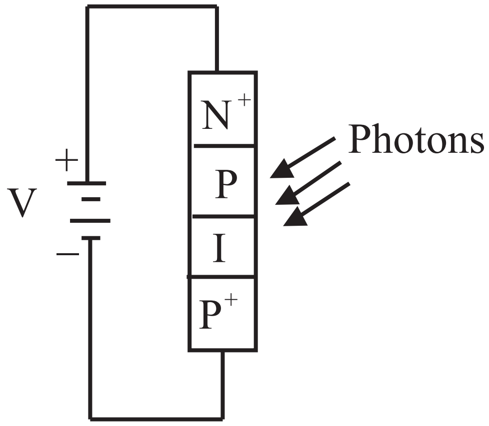


Figure 4 : Structure of an APD

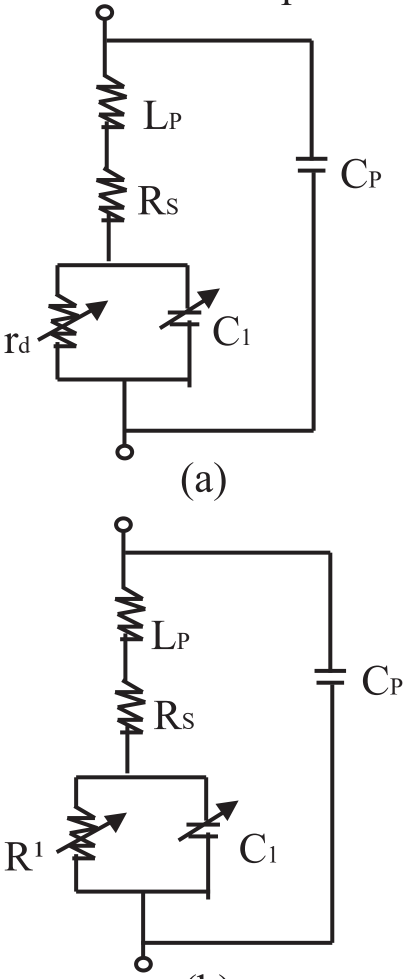
Pin Photodetectors

A PIN diode is composed of three sections. A high resistivity intrinsic layer is sandwiched between P- and N- regions. The high resistance of the intrinsic layer provides the posibility of larger electric field between the P- and N- regions, and therefore, electron-hole pair generation is enhanced by enebling PIN diode to process even very weak input signals. Because of more seperation between P- and N- regions, the capacitance C_{pn} is reduced because the capacitance decreases with the increase in seperation of P- and N-regions. It allows the diode a faster response time, thereby making it suitable for use as a microwave switch.

PIN diode

PIN diode in the forward bias mode offers a variable resistance-decreasing with the increase in forward current. For larger d.c current, it will appear like a short. In reverse bias mode, it offers infinite resistance.

The equivalent circuit of a PIN diode at d.c or low frequency operation is similar to a conventional P-N junction in Figure (a). Here L_p and C_p represent the package inductance and capacitance respectively. C_j represents the junction diode capacitance. However, the effect of junction capacitance may be neglected for most of the applications of PIN diodes under forward bias operation. Since the dynamic resistance is very large and $C_I = C_T$ under reverse bias operation. The effect of dynamic resistance can be neglected and therefore, the PIN diode behaves simply as a parallel plate capacitor of capacitance C_T in its reverse bias operation.



(a)

(b)

High frequency model

At high frequency, C_1 represents the capacitance of the I region, which is approximately equal to C_T and depends on the geometry of the I region. R_I is the effective RF resistance of the I region and represents the value at the operating frequency of the RF signal.

When a light intensity of wavelength λ is incident on the photodiode, if energy $E_g < hv$ of PIN diode, then an output current 'I_p' in response to the incident light is produced.

$$\text{Efficiency } \eta = \frac{\text{No. of } e^{-} \text{ - hole pairs generated}}{\text{No. of photons incidented}}$$

$$\eta = \frac{(I_p / q)}{(P_0 / hf)}$$

$$\text{Response } R = \frac{I_p}{P_0} = \frac{\eta q}{hf} \text{ A/watt}$$

$$\text{Maximum wave light } \lambda_{max} (\mu m) = \frac{1.24}{E_G \text{ (eV)}}$$

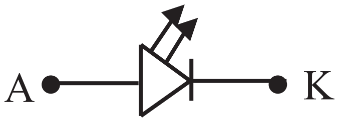
Where,
P_o → incident optical power
I_p → photocurrent generated in PIN diode
∴ The main drawback of photodiode is the low output current.

Light Emitting Diodes

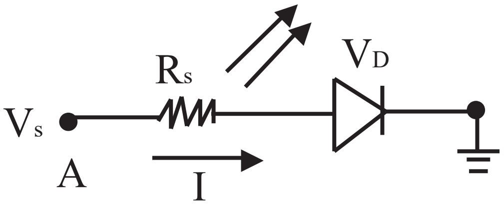
The operation of light emitting diodes (LED) is based on the phenomenon of electro luminance, which is the emission of light from a semiconductor under the influence of an electric field. The recombination of charge carriers takes place in a forward P-N junction as the electron crosses from the N-region and recombines with the holes existing in P-region. Free electrons are in the conduction band, whereas holes are in the valence band. Therefore the electrons are at high energy levels than holes. For the electrons to recombine with holes, they must give some of their energy. Typically, these electrons give up energy in the form of heat and light. In silicon and germanium diodes, most of the electrons give up their energy in the form of heat. However, with GaAsP and GaP semiconductors, the electrons give up their energy by emitting photons. If the semiconductor is translucent, then the light will be emitted and the junction becomes a source of light, that is LED. i.e. the electrons are at high energy levels than the holes. In the process of recombination of the electrons to holes, they must give energy in the form of heat and light but these are constructed by using direct band gap semiconductors. Hence, they are dissipated energy in the fomr of light.

- In Si and Ge diodes (indirect band gap S.C), most of the electrons give up their energy in the form of heat.
- In GaAsP, GaAs, GaP, and InP semiconductors, the electrons give up their energy by emitting photons (direct band gap S.C).
- LEDs operate the forward biasing with a current of 20 mA.

These enit no light when reverse biased. In fact, operating LEDs in reverse direction will quickly destroy them.



(a) LED symbol



(b) LED circuit

$$I = \frac{V_S - V_D}{R_S}$$

- LEDs are forward biased P-N junctions, which emit ‘Spontaneous radiation’.
- The colour of the emitted light depends on the type of material used, which is given below.

Colour	Construction	Typical forward voltage V_t (volts)
Amber	Al Gap	2.1
Blue	GaN	5
Red	GaAsP	1.8
Green	GaP	2.2
Yellow	AlGaP	2.1
White	GaN	4.1

The visible wavelength ranges from 0.45 μm to 0.7 μm (energy 2.8 eV to 1.8 eV)

Applications

LEDs are used in remote controls, as display devices in designing optocouplers.

The LED emits light of a particular colour because the band gap of the semiconductor material used in the fabrication of the diodes is equal to energy hv of the light photon.

Liquid Crystal Displays

1. LCDs opearte on the principle of dynamic scattering of light.
2. Power dissipation is in the order of μW.
3. Response time is in m sec.
4. Its operating life time is 50,000 + hours.
5. These are used as display devices.

Example 2

Photons of energy 1.5 × 10   Joules are incident on photodiode that has a responsibility of 0.7 A/W. If the optical power level is 10μW, then the photocurrent generated is

(a) 70 ηA (b) 7μA

(c) 6.5 μA (d) 6.5 ηA

Solution

We know that responsibility $R = \frac{I_p}{I_0}$

$$\therefore I_p = R \cdot I_0 = 0.7 \times 10\ \mu \frac{A}{W}$$

$$= 7\mu A$$

Photovoltaic or Solar Cells

These cells are semiconductor junction devices used for converting radiation energy into electrical energy. These cells generate a voltage proportional to electromagnetic radiation intensity and are called the photovoltaic cells. Selenium and Si are the most widely used materials for solar cells.

- The working principle of solar cell is 'Photovoltaic effect'.
- Popularly used solar cells are se cells, Ni-cd cells, and pbs cells.
- Ni-cd cells are rechargeable cells used in satellites.
- These are used in automatic traffic signal lighting.
- These are generally operated under open circuit condition. It can be operated in forward biased condition and has cut in voltage equal to zero.

Laser

Laser is the short form of 'Light Amplification by Stimulated Emission of Radiation'. A laser emits radiation of essentially one wavelength or a very narrowband of wave lengths. This means that the light has a single colour, that is, monochromatic.

In a laser, the atoms are struck by photons (or packets of energy) that are exactly similar to the photons of energy emitted when recombination occurs. This triggers energy emission and the result is two identical photons for each recombination : the incident photon and the emitted photon. The photon produce further emission of similar photons, which in turn generate more similar photons. The result is emission of energy in the form of a beam of coherent light.

- LASER light is referred to as coherent light as opposed to light made up of a wide band of wavelengths, which is termed as incoherent.
- LASERs are fabricated with direct band gap materials having larger carrier

life time.

- Emission in LASER is both spontaneous and stimulated.
- Population inversion occurs in LASER. These are highly directional.

The primary requirement is the population inversion, that is, the higher energy level is more populated than the lower energy level.

Unique Characteristics of LASER Light

The beam of LASER light produced by the diode has the following unique characteristics :

1. It is coherent, that is, there is no path difference between the waves comprising the beam.
2. It is monochromatic, that is, it consists of one wavelength and hence one colour only.
3. It is collimated, that is, light waves travel parallel to each other.

Note :

	Diode	**Operating bias**
1.	Photodiode, APD	Reverse bias
2.	LED, LASER, and solar cells	Forward bias