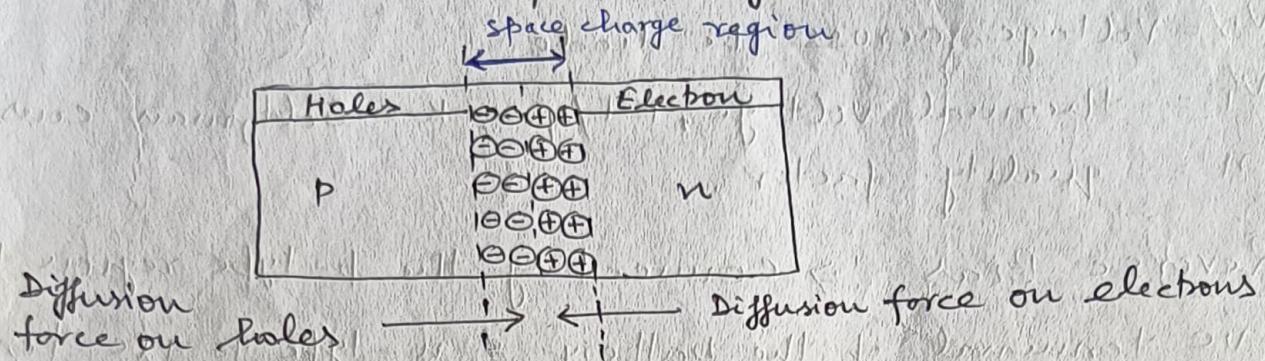


P-N Junction :- A p-n junction is a boundary or interface between two types of semiconductor. P-type contains an excess of holes while n-type contains an excess of electrons. This allows electrical current to pass through the junction only in one direction. P-N junction is created by doping.



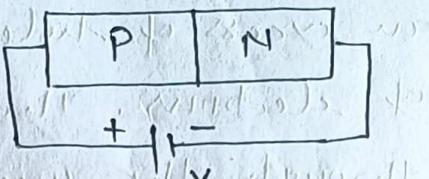
### Biassing Concept of P-N Junction :- (I) Forward Bias

In forward bias p-type is connected with +ve terminal and n-type is connected with -ve terminals.

The battery is connected this way that the holes in p-type region & electrons in n-type region are pushed towards the junction & start to neutralize the depletion zone reducing its width. With increasing forward bias voltage the depletion zone eventually becomes thin enough that the zone's electric field can not counter act charge carrier motion across the p-n junction which as a consequence reduces electrical resistance. The electron that cross the p-n junction into p-type material (or holes that cross into the n-type material) will diffuse into hereby neutral region.

Forward bias cause a force on electrons pushing them from N+ side towards the p+ side.

The ~~Schottkey~~<sup>SchottKey</sup> diode eqn.



$$I = I_s (e^{V_D/nV_T} - 1)$$

$I$  = Diode current,  $I_s$  = reverse bias saturation current

$V_D$  = Voltage across the diode

$V_T = \text{thermal voltage}, kT/q, K = \text{Boltzmann constant}$

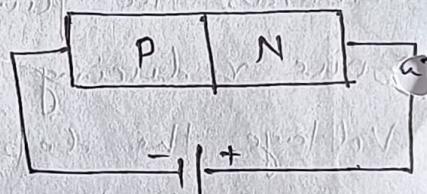
$n$  = quality factor.

Reverse Bias  $\Rightarrow$  connecting the p-type region to the -ve terminal of the battery & n-type to +ve terminal corresponds to reverse bias.

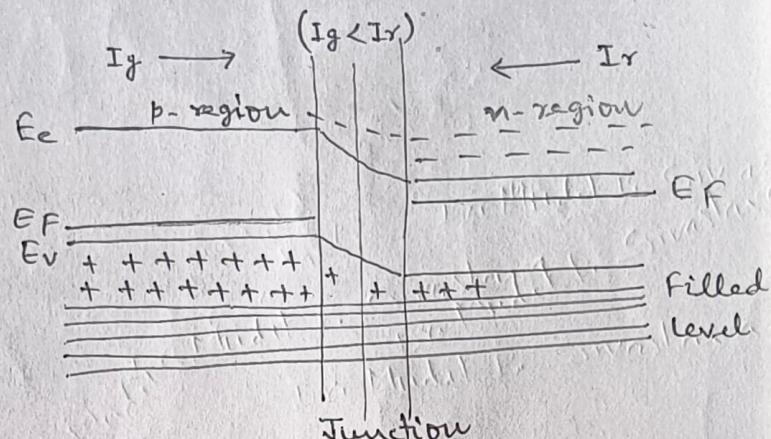
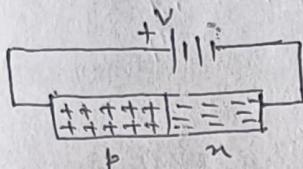
Thus due to reverse bias electrons & holes are pushed and pulled away from junction, this causing the width of depletion layer to increase.

Therefore a very little current will flow until the diode breaks down.

The in width results in the increase in resistance of p-n junction. Thus junction behaving as an insulator.



Forward bias :- Under forward bias the height of potential barrier decreases by an amount  $eV$  as in Fig. 1 (b). Further the recombination current  $I_r$  is increased above its equilibrium value by a factor  $\exp(eV/kT)$  while thermally generated  $e^-$  current  $I_g$  remain same. Thus current increases under F.B.



$$I_r = I_g \exp\left(\frac{eV}{kT}\right)$$

The net current  $I_v$  due to external voltage  $V$  is

$$I_v = I_r - I_g = I_g \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

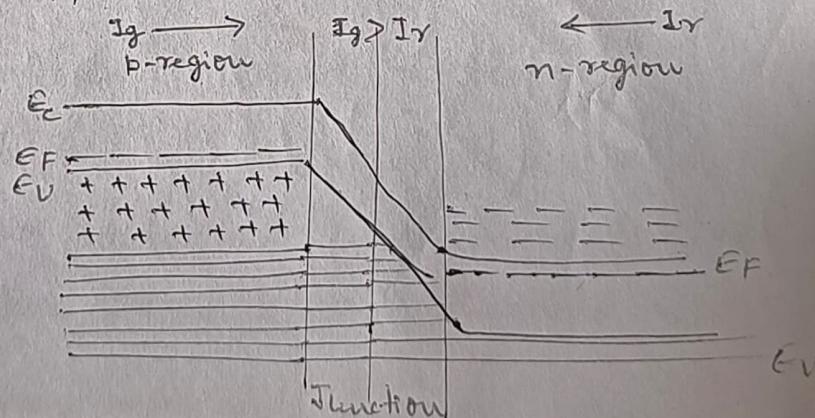
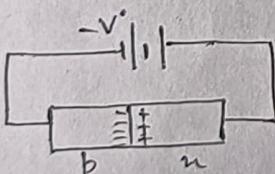
The same is true for hole current in N.B.. The combined current due to holes and  $e^-$  is represented by dark current  $I_o$

$$I_v = I_o \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

Reverse bias :- Under R.B. there is an increase in barrier height by  $eV$  and decrease in value of  $I_r$ , while  $I_g$  remain unaffected. The combined current for R.B.

$$I_v = I_o \left[ \exp\left(-\frac{eV}{kT}\right) - 1 \right] = -I_o$$

The potential  $V$  is increased, the exponential term  $\exp(-eV/kT) \ll 1$  for  $eV \geq 4kT$ . The R.B. current approaches a saturation value  $I_o$ .



## PHOTOCURRENT IN A P-N JUNCTION DIODE -

P-N junction diode is a photo diode that consumes light energy to produce electric current. They are also called as photo detector, a light detector and photo sensor. These diodes are designed to work in reverse-bias condition.

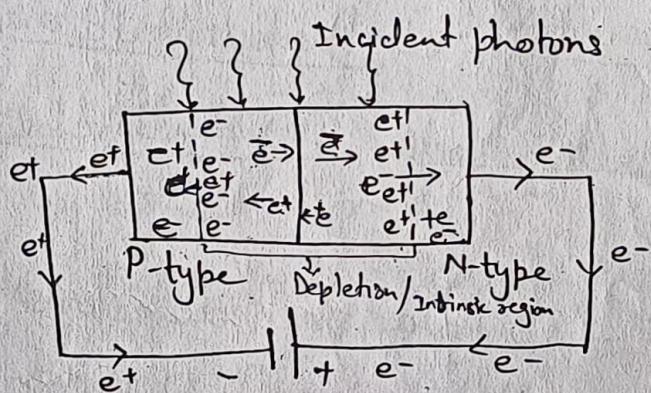
Ex- Solar-cell, a photo-diode which converts solar energy to electric energy



(A photo-diode symbol)

b - bias  
n - reverse biasing

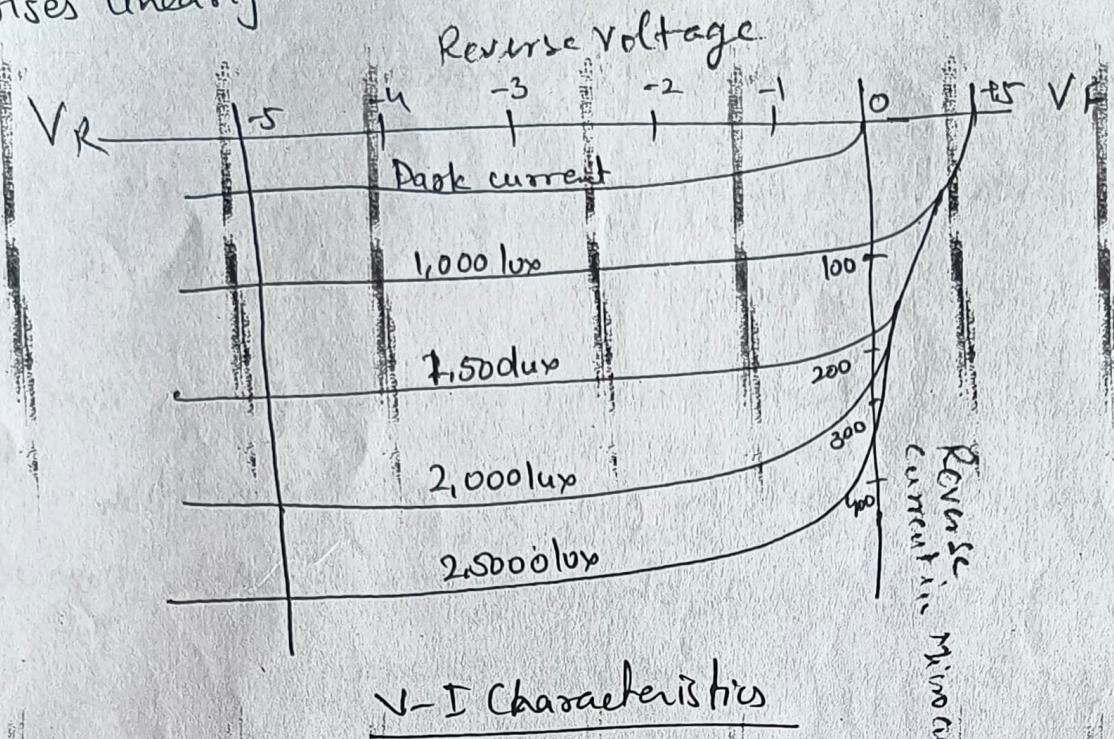
Working -



P-N JUNCTION DIODE

The photo diode continuously operates in reverse bias mode. Photocurrent is nearly independent of reverse bias voltage applied. For zero luminescence, photocurrent is almost zero excluding small dark current. It is of the order of

nan-amperes. As optical power rises, the photo current also rises linearly.



V-I Characteristics

Types - (1) PN photodiode (2) Schottky photo diode  
(3) PIN photodiode (4) Avalanche photodiode.

Modes of Operation - (i) Photo voltaic mode -

(ii) Photo conductive Mode (iii) Avalanche Diode Mode -

Applications - (i) As a photodetectors viz CCD [charge-coupled devices], photo multiplier tubes etc.

(ii) In smoke detectors, CD players, TV & remote controls in VCRs.

(iii) To analyze samples, detectors for computed tomography etc.

(iv) In clock radios, camera light meters, street lights etc.

# Explanation of carrier generation & recombination process :

Carrier Generation (Free e- and holes) :

Process by which free e- and holes are generated in pair is called carrier generation.

In other words, when the e- in the valence band get enough energy, they absorb the energy and jumps to conduction band. The jumped e- is called free e- & the place from where e- is left is called hole. Similarly, two type of charge carriers (e- & holes) are generated.

Recombination (free e- and holes) :

The process by which free e- and holes gets eliminated is called recombination of carriers. When free e- in the conduction band falls into hole in the valence band, the free e- and hole gets eliminated.

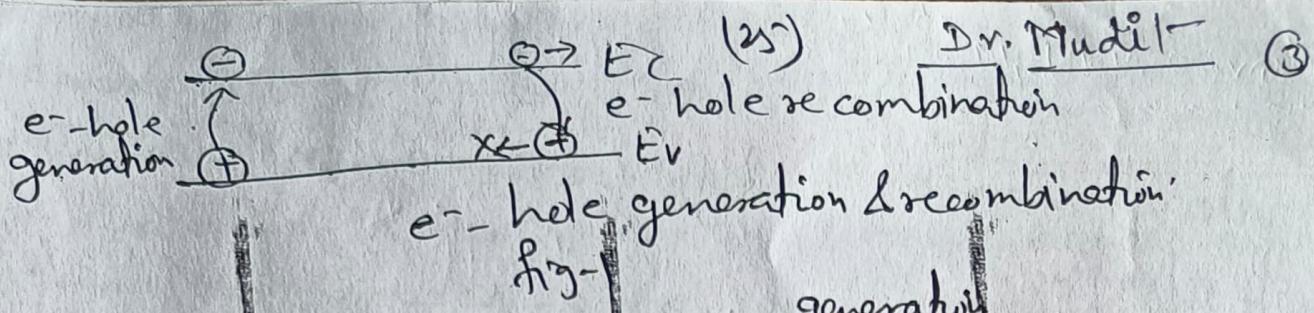
e-hole pair is the fundamental unit of generation and recombination corresponding to an e- transitioning between valence band and conduction

band where generation of  $e^-$  is a transition from the valence band to the conduction band and recombination is a reverse process.

Recombination and generation are regularly happening in semiconductors. With the change (sudden) in temperature, will increase the rate at which  $e^-$  and holes are thermally generated so that their concentrations will change with time until new equilibrium values are reached.

An external excitation such as light can also generate  $e^-$  & holes, creating non-equilibrium condition. Let us first consider the band-to-band generation and recombination and then later on effect of allowed electronic energy states within the band-gap referred as trap/recombination centres.

In equilibrium state  $e^-$  and holes are independent of time. However  $e^-$  and are continually thermally excited from valence to conduction band. At the same time,  $e^-$  and only moving through the crystal in the conduction band may come near to hole & fall into the empty states in the valence band. This rate of generation & recombination should be equal.



Let  $G_{no}$  &  $G_{po}$  be the thermal rates of e- & holes generation given in the units of  $\#/\text{cm}^3 \cdot \text{s}$ .

For direct band-to-band generation, e- & holes are created in pairs, so

$$G_{no} = G_{po} \quad \text{--- (1)}$$

Let  $R_{no}$  &  $R_{po}$  be the recombination rates of e- & holes, in units of  $\#/\text{cm}^3 \cdot \text{s}$ . In direct-band-to-band recombination, e- & holes recombine in pairs, so that

$$R_{no} = R_{po} \quad \text{--- (2)}$$

In thermal equilibrium -

$$G_{no} = G_{po} = R_{no} = R_{po} \quad \text{--- (3)}$$

### ⇒ Excess Carrier Generation and Recombination

When high energy photons are incident on a semiconductor, not only e- is being created in the conduction band but the hole is also being created in the valence band. This additional e- and holes created are called excess e- & hole.

These excess e- & holes are generated by an external force at a particular rate. Let  $g_n'$  be the generation rate of excess e- and  $g_p'$  be the excess holes in units of  $\#/\text{cm}^3\text{-s}$ .

for direct band-to-band

$$g_n' = g_p' \quad \text{--- (4)}$$

$$g_n' = g_p'$$

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$

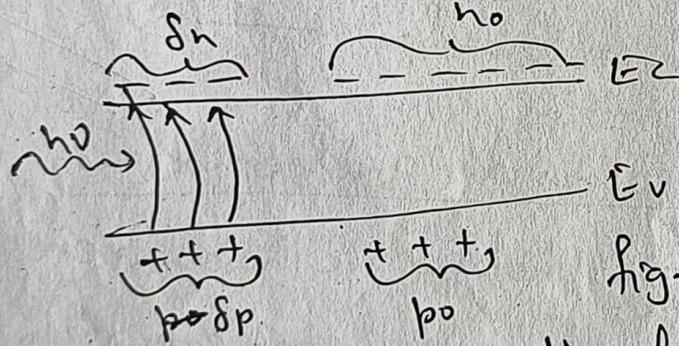
When excess e- and holes are created, concn of e- and holes in the respective bands increases above their thermal equilibrium value.

$$\text{ie } n = n_0 + \delta n \quad \text{--- 5(a)}$$

$$\& \quad p = p_0 + \delta p \quad \text{--- 5(b)}$$

where  $n_0, p_0$  are the thermal equilibrium concn &  $\delta n, \delta p$  are the excess e- & hole concn.

From eqn 5(a) & (b) we know that in non-equilibrium condition  $n_p + h_0 p_0 = n_i^2$



Creation of excess e- & hole densities by photon.

Fig-2

At steady state generation of excess e- & holes will not cause a continual buildup of their carrier concn.

- What is the main factor to control  $R_e$  &  $G_e$ ?
- Ans: temp. Because with increase in temp. concentrations of free e- and holes increases and the rate of recombination is proportional to the product of concentrations of free e- & holes and also rate of

## Introduction to Opto-electronics Integrated Circuits

Opto-electronics is the study of electronic devices and systems that source, detect and control light usually taken as sub-field of photonics.

It is based on quantum mechanical effects of light on electronic materials, especially semiconductors and sometime in the presence of electric fields.

### Opto-electronic Integrated Circuits (OEIC) :-

The best expt. of OEIC is the Monolithic devices. A monolithic device in case of semiconductor is one in which all the components are mounted in a single semiconductor chip.

A monolithic device containing both photonic and electronic devices source, like detectors, modulator etc. on a single semiconductor substrate.

Components :- It consists of active and passive components monolithically integrated on the same substrate. Active components are those which have to be integrated with electronic circuits.

Passive components are those which do not require electric signals for their operations.

Active Components :- Laser, photo-detectors, switches, modulators etc.

Passive Components :- Spectral filters, couplers, lens etc.

Materials - Requirements :- Material should be with nature of transparency and good optical properties, in an appropriate part of spectrum (EMW). It should be feasible to fabricate with low loss thin film waveguides, for optical interconnectors, good electrical, electro-optical & acoustical-optical properties.

Semiconductor materials of III-V and their alloys (i.e., GaAs, InP, InGaAsP, InGaAs — )

Fabrication Technique :- Among the various methods the mostly used ones are

(i) Hybrid Integration :- Combination of best passive and active components from different materials. This improves the individual device performance and provides the flexibility of using different materials.

Limitations :- On the alignment of different optical components, the frequency response of the devices are limited due to relatively higher capacitance as result of parasite effects.

(ii) Monolithic Integration :- All the components are fabricated on a single substrate essentially from the same material. This result the low value of parasite capacitance.

Limitations :- (i) - Poor isolation between components.

(ii) - No possibility of fabrication of inductors.

(iii) - Low power rating

(iv) - Lack of flexibilities

Continuity Equation  $\Rightarrow$  When we consider the overall effect of drift, diffusion and recombination simultaneously in a semiconductor material. The governing eqn. is called the continuity equation.

To derive 1-D continuity equation for  $\bar{e}^s$  consider an infinite sim of slice with thickness  $dx$  located at  $x$  as shown in fig.

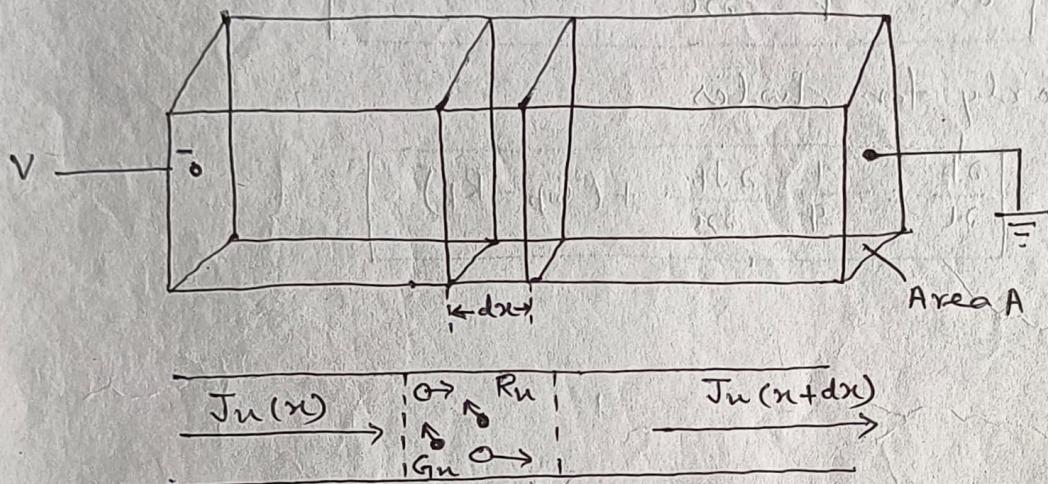


Fig. Current flow & generation and recombination processes in an infinitesimal slice of thickness  $dx$ .

The  $\bar{e}^s$  in the slice may increase due to net current flow into slice and net carrier generation in the slice. The overall rate of electron increases is the algebraic sum of four components; the no. of  $\bar{e}^s$  flowing into slice ' $x$ ' minus the no. of  $\bar{e}^s$  flowing out at  $x+dx$ , plus rate at which  $\bar{e}^s$  are generated minus the rate at which they are recombined with holes in the slice.

The first two components are formed by dividing currents at each side of the slice by the charge of an electron. The generation and recombination rates are designated by  $G_n$  &  $R_n$ . The overall rate of change in number of  $\bar{e}^s$  in the slice is then

(15)

— Dr. Mudit P. Srivastava

$$\frac{\partial n}{\partial t} A \cdot dx = \left[ \frac{J_n(x) A}{-q} - \frac{J_n(x+dx) A}{-q} \right] + (G_n - R_n) A \cdot dx$$

$A$  = cross section area

By using Taylor series yields

$$J_n(x+dx) \approx J_n(x) + \frac{\partial J_n}{\partial x} dx + \dots$$

we finally obtain basic continuity eqn. for electrons

$$\boxed{\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} + (G_n - R_n)}$$

Similarly for holes

$$\boxed{\frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} + (G_p - R_p)}$$

## CONTINUITY EQUATIONS:-

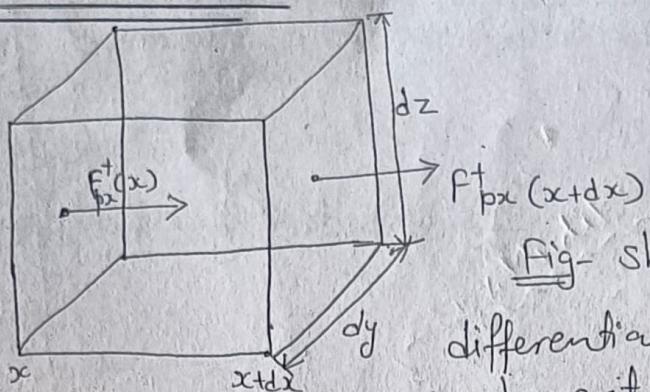


Fig- showing the differential volume of x-component of the hole-particle flux.

The above figure shows the differential volm element of hole-particle flux, in one-direction (1-D) which is entering the element at 'x' and leaving at  $x+dx$ .  $f_{px}^+$  is the hole-particle flux /flow, in holes/cm<sup>2</sup>s.

In x-direction, the particle current density shown can be written as —

$$f_{pxc}^+(x+dx) = f_{pxc}^+(x) + \frac{\partial f_{pxc}^+}{\partial x} \cdot dx \quad \text{--- (1)}$$

(Taylor's expansion having differential length very small to get first two terms significant).

Due to the x-component, the net increase in the ~~net no. of holes/vol~~ no. of holes/time within differential volm element is

$$\frac{\partial p}{\partial t} dx dy dz = [f_{pxc}^+(x) - f_{pxc}^+(x+dx)] dy dz = - \frac{\partial f_{pxc}^+}{\partial x} \frac{dx}{dz} dy dz \quad \text{--- (2)}$$

Generation and recombination rate affects the hole concentration in the differential volume.

Thus, the net increase in the no. of holes/time in the differential volume element is then given by -

$$\frac{\partial P}{\partial t} dx dy dz = - \frac{\partial F_p^+}{\partial x} dx dy dz + g_p dx dy dz - \frac{P}{t_{pt}} dx dy dz \quad (3)$$

where  $P$  = density of holes.

In eqn (3), first term is ~~the~~ on the r.h.s is the increase in the no. of holes/time due to hole flux, second term represents the holes generation and the last term shows the decrease in the no. of holes/time due to recombination of holes, which is given by  $P/t_{pt}$  where  $t_{pt}$  is the carrier life-time at equilibrium and the excess carrier lifetime.

Divide eqn (3) by  $dx dy dz$  b.h.s we get -

$$\frac{\partial P}{\partial t} = - \frac{\partial F_p^+}{\partial x} + g_p - \frac{P}{t_{pt}} \quad || \quad (4)$$

CONTINUITY EQUATION  
(1-D)

Similarly for one dimensional in case of e-

$$\frac{\partial n}{\partial t} = - \frac{\partial F_n^-}{\partial x} + g_n - \frac{n}{t_{nt}}$$

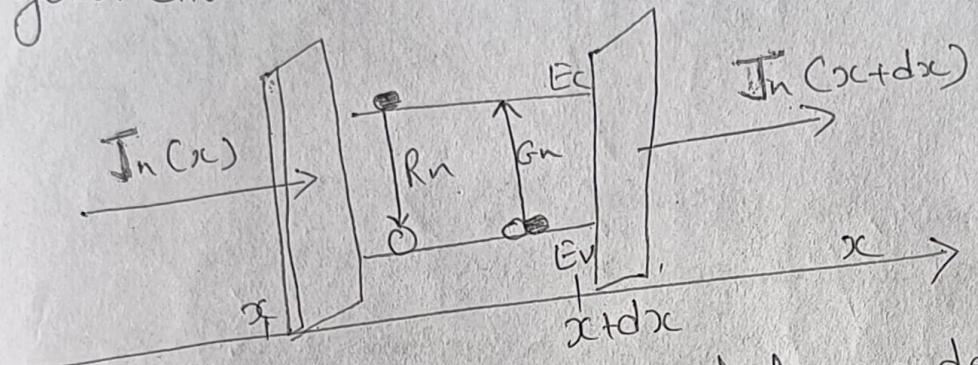
where  $F_n^-$  = e- particle flow/flux electrons/cm<sup>2</sup>-s.



## (25) ①

### CONTINUITY EQUATION (DERIVATION)!

It is the differential form of the conservation of charge equation, plus terms for carrier generation and recombination.



charge is neither created nor destroyed.  
From the above figure -

$$\frac{\partial Q}{\partial t} = I(x) - I(x+dx) \quad \text{--- (1)}$$

where  $Q$  - charge ;  $I$  - current.

Eqn (1) shows, the change in charge / time = current in - current out.

For semiconductor, we consider unbound charge carriers, that can spontaneously appear from the lattice or spontaneously combine into the lattice.

On adding the terms of generation & recombination

$$\frac{\partial Q(\text{unbound})}{\partial t} = I(x) - I(x+dx) + G - R.$$

where  $G$  = generation rate for whole volume.  
 $R$  = recombination rate for whole volume.

Consider that areas and volumes <sup>(26)</sup> are uniform  
 then shrinking the volumes to 0.

$$\cancel{q \frac{\partial n}{\partial t} dx * A}$$

$$q \cancel{\frac{\partial n}{\partial t}} dx \cancel{n} dx \cancel{A} = A \times [J(x) - J(x+dt)] + q G A dx - q R A dx \quad (27)$$

where  $n$  - no. of charge carriers.

$q$  - charge on single carrier.

here  $G$  and  $R$  are numbers/volume.

inspite

Dividing eqn (2) by  $q, A$  &  $dx$ , b.h.s, we get

$$\cancel{q \frac{\partial n}{\partial t}}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} [J(x) - J(x+dt)] / dx + G - R$$

Taking the lim as  $dx \rightarrow 0$  we get.

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J}{\partial x} + G - R \quad \text{or} \quad \frac{\partial P}{\partial t} = -\frac{1}{q} \frac{\partial \Phi}{\partial x} + G - R$$

(for holes)  
(electrons)

When  $J$  is figured out,  $J$  has two components,  
 drift and diffusion.

Drift current = no. of charge carriers times their  
 avg. velocity and avg. vel. is  $\propto \frac{1}{q} \frac{\partial \Phi}{\partial x}$   
 proportional to applied electric field through  
 'mobility term' all times the charge on single  
 carrier.

(3)

$$J_{n\text{ diff.}} = e D_n \frac{\partial n}{\partial x} \quad ; \quad J_{n\text{ drift}} = ne U_n E.$$

$$\text{and } J_{p\text{ diff.}} = -e D_p \frac{\partial p}{\partial x} \quad ; \quad J_{p\text{ drift}} = pe U_p E.$$

We know we now have, equation as (using diffusion current)

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} - \frac{\Delta n}{L_n}$$

where  
 $\Delta n = n_p(x) - n_{p0}$

$$\text{and } \frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \frac{\Delta p}{L_p}$$

$$\Delta p = p_p(x) - p_{p0}$$

for steady state  $\frac{\partial n}{\partial t} = \frac{\partial p}{\partial t} = 0$

$$\text{ie } \frac{\partial^2 n}{\partial x^2} = \frac{\Delta n}{D_n L_n} = \frac{\Delta n}{L_n^2}$$

$$\text{& } \frac{\partial^2 p}{\partial x^2} = \frac{\Delta p}{D_p L_p} = \frac{\Delta p}{L_p^2}$$

where  $L_n$  &  $L_p$  = Diffusion lengths

$$\left. \begin{array}{l} L_n = \sqrt{D_n L_n} \\ L_p = \sqrt{D_p L_p} \end{array} \right|$$

$D_p = D_n$  = Diffusion constt.

## Carrier Transport :- Diffusion & Drift current :-

The flow of current through a semiconductor material is normally referred to as one of two types: drift & diffusion.

**Drift Current :-** When a voltage is applied across the material the electrons experience a force towards +ve terminal and holes towards -ve terminals of battery. The charge carriers ( $e^-$  & holes) encounter collisions with other atoms and ions in their movement may result in a erratic path. The net result however is a drift of carriers towards the +ve terminals. The combined effect of movement of holes and electrons constitute an electric current due to applied voltage which is called a drift current.

$$J_e(\text{drift}) = nevnE \quad \text{--- (1)}$$

$$J_h(\text{drift}) = pe\mu_p E \quad \text{--- (2)}$$

Although  $e^-$  and holes flow in opposite directions, the directions of conventional current flow due to both carriers is in the same direction. Thus total current density is given by

$$J(\text{drift}) = J_e(\text{drift}) + J_h(\text{drift})$$

$$J(\text{drift}) = eE [nue + pue] \quad \text{--- (3)}$$

**Diffusion Current :-** It is possible for the electric current to flow in a semiconductor even in the absence of an applied voltage, provided a concentration gradient exists in the material. A concentration gradient exist if the number of either  $e^-$  and holes is greater in one region of a semiconductor compared to rest of the region.

The direction movement of charge carriers due to their concentration gradient produces a ~~per~~ component of current known as diffusion current.

Consider a long bar of p-type semiconductor with an excess concentration of holes as shown in figure. Now an imaginary surface is drawn y-y' in the semiconductor. The density of holes on left side of y-y' is larger than density of holes on right side. Thus there exist a concentration gradient given by

$$\frac{dp}{dx} = -\frac{(p_0 - p_x)}{x}$$

$p_0$  = concentration of holes at left end of semiconductor bar and may be reformed as an origin plane.

$p_x$  = concentration of holes at imaginary surface y-y'

$x$  = Distance of imaginary surface from origin plane

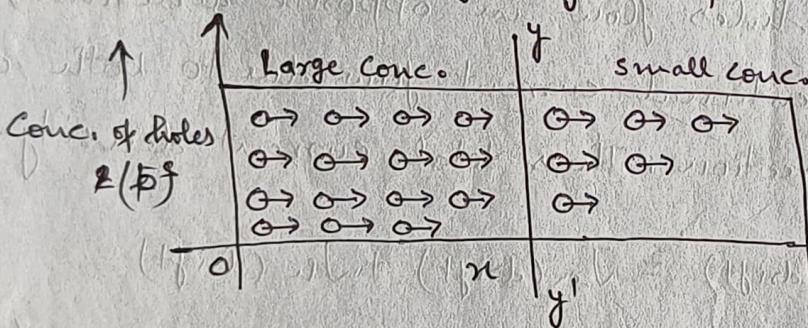


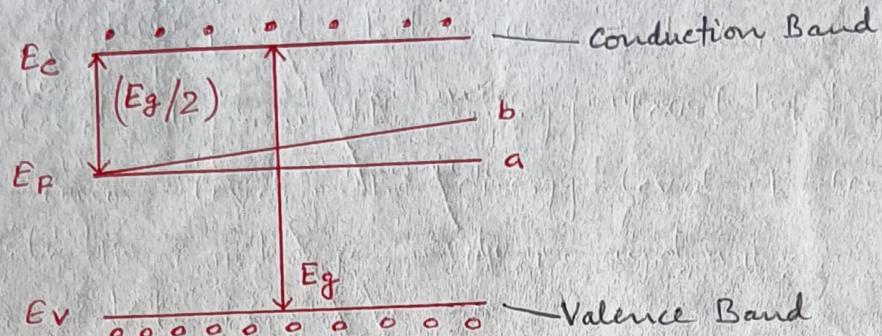
Fig. - Diffusion of holes in a p-type semiconductor

The holes are in a random motion due to their thermal energy. The no. of holes passing through unit area in one sec. is given by

$$P = D_p \frac{dp}{dx} \text{ holes/m}^2/\text{s}$$

where  $D_p$  = holes diffusion coefficient ( $\text{m}^2/\text{s}$ )

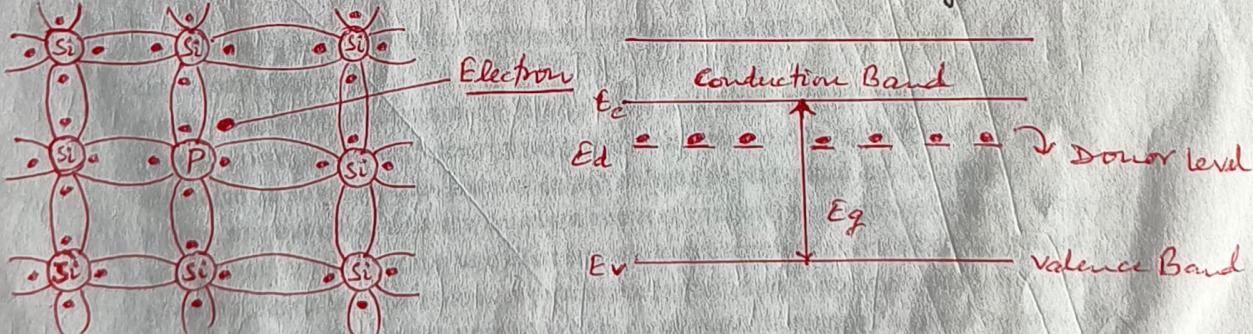
Thus the fermi level is located half way between valence and conduction band and its independent of temperature. Since  $m_A > m_e$ ,  $E_F$  is just above the middle and rise slightly with increase in temperature.



Position of Fermi level in an intrinsic Semiconductor at Various Temperatures, (a) At  $T=0$ , (b) As temp increases  $E_F$  shift

$\Rightarrow$  N-type of Semiconductor !  $\Rightarrow$  When <sup>small amount of</sup> pentavalent impurity such as P, As, Sb is added to the intrinsic semiconductor, n-type semiconductor is formed.

$\Rightarrow$  When fifth column element phosphorus substitute for a silicon atom, four of the five electrons in the outermost orbit of Phosphorus atom take part in tetrahedral bonding with four Silicon atoms. The fifth electron cannot take part and it is loosely bound. It revolve around the +ve charged P ion.



$\Rightarrow$  The electron of phosphorus atom is moving in the electric field of Silicon crystal and not in free space.

$\Rightarrow$  This brings in dielectric constant of crystal into orbit calculation and the radius of electron orbit here turn out to be very

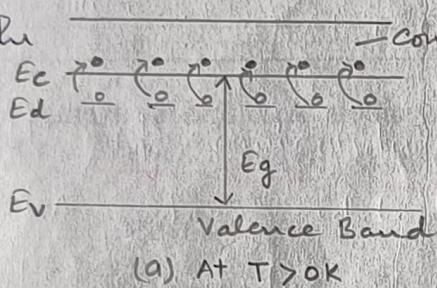
large about  $80\text{ \AA}$ . such large orbit means fifth electron free and is at energy level close to conduction band.

→ At 0K the electronic system is in its lowest state, all the valence electron will be in valence band and all phosphorus atom will un-ionised.

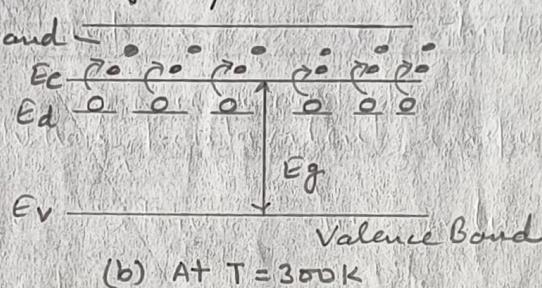
→ In energy level diagram the energy level of fifth electron is called donor level. The energy level of donor atoms are very close to bottom of conduction band.

→ Most of donor level electrons are excited into conduction band at room temperature & become majority carriers.

At 0K



(a) At  $T > 0\text{K}$



(b) At  $T = 300\text{K}$

→ At high thermal energy, in addition to ionization of donor impurity atom, breaking of covalent bond give rise to electron hole pair.

### Fermi Energy:

The fermi energy for n-type semiconductor is

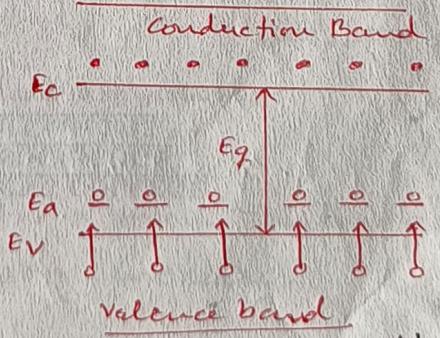
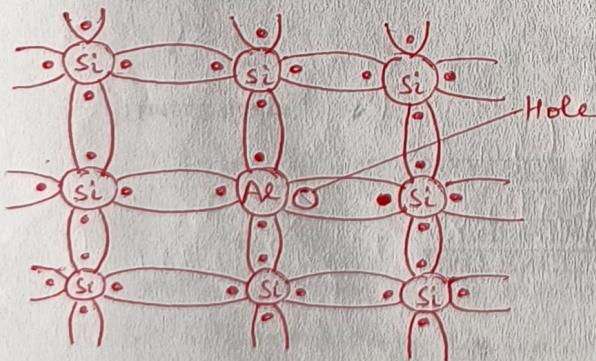
$$E_F = \frac{(E_c + E_d)}{2} + \frac{kT}{2} \log \left[ \frac{N_d}{2 \left( \frac{2\pi m e k T}{h^2} \right)^{3/2}} \right]; \quad \text{At } 0\text{K}, E_F = \frac{E_c + E_d}{2}$$

P-type Semiconductor :  $\Rightarrow$  When trivalent impurity like Al is added to the intrinsic semiconductor, P-type semiconductor is formed.  $\Rightarrow$  Aluminium has three electrons. While substituting for Silicon in the crystal it needs an extra electron to complete the tetrahedral bonds. The extra electron can come out only from one of the neighbouring Si atom, thereby creating a vacant electron site (hole). The Al atom with extra-electron becomes a negative charge and the holes with positive charge can considered to resolve around Aluminium atoms.

$\Rightarrow$  Since the trivalent impurity accepts an electron, the energy level of this impurity atom is called acceptor level. This acceptor level lies just above valence band.

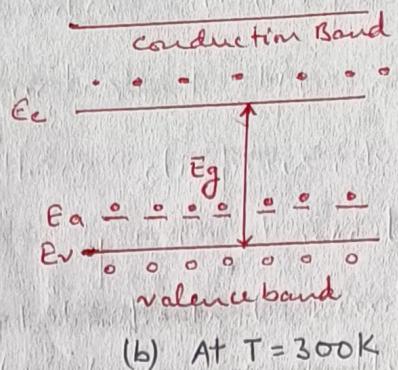
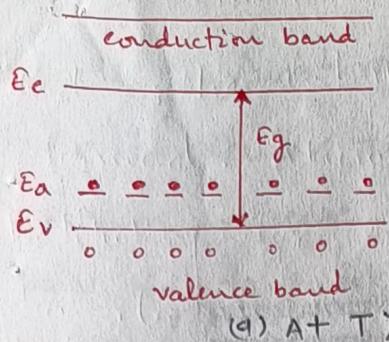
$\Rightarrow$  Even at relatively low temperature, these acceptor atoms get ionized taking electrons from valence bond and thus giving to holes in valence bond for conduction.

$\Rightarrow$  Due to ionization of acceptor atoms, only holes and no electrons are created. If the temperature is sufficiently high, in addition to above process electron and holes pairs are generated due to breaking of covalent bonds. Thus holes are majority carriers and electrons are minority carriers for P-type Semiconductor.



P-type Semiconductor

At.  $T = 0K$



Fermi Energy :

The Fermi energy for p-type semiconductor is

$$E_F = \left( \frac{E_V + E_A}{2} \right) + \frac{kT}{2} \log \left[ \frac{N_A}{2 \left( \frac{2\pi m_e kT}{h^2} \right)^{3/2}} \right]$$

At 0K,  $E_F = \frac{E_V + E_A}{2}$

i.e. at 0K, Fermi level is exactly at the middle of the acceptor level or the top of valence band.

Q: Explain with sketch the variation of Fermi Level and carrier concentration with temperature in case of P and N type semiconductor for high and low doping levels.

Ans:- Variation of Fermi Level with temperature (N-type) :

The Fermi Energy is given by

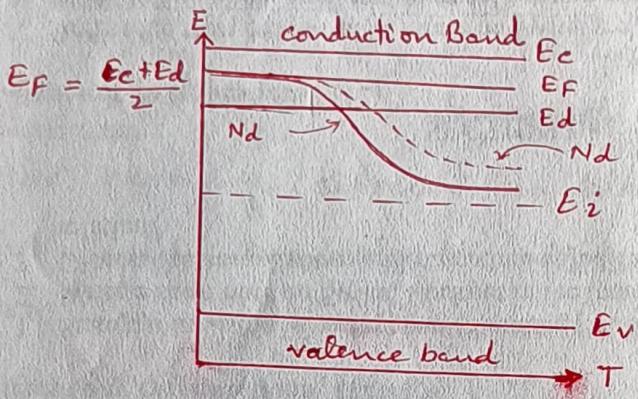
$$E_F = \left( \frac{E_d + E_c}{2} \right) + \frac{kT}{2} \log \frac{N_d}{2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{3/2}}$$

Let  $2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{3/2} = N_x$

$$\begin{aligned} \therefore E_F &= \left( \frac{E_d + E_c}{2} \right) + \frac{kT}{2} \log \left( \frac{N_d}{N_x} \right) = \left( \frac{E_d + E_c}{2} \right) - \frac{kT}{2} \log \left( \frac{N_d}{N_x} \right)^{-1} \\ &= \left( \frac{E_d + E_c}{2} \right) - \frac{kT}{2} \log \left( \frac{N_x}{N_d} \right) \end{aligned}$$

→ As T increases, Fermi level drops. For a given temperature the Fermi level shift upward as concentration increases.

- Above eqn. show that  $E_F$  decreases with increases in temp.
- As the temperature increased, more donor atom are ionized.
- For a particular temperature all donor atom are ionized.
- Further increase in temperature generate electron-hole pair due to breaking of covalent bond, & material behave as intrinsic semiconductor.



{ Variation of Fermi level with donor concentration with temperature.

### Variation of Fermi level with temperature (P-type) :

The fermi energy is given by

$$E_F = \left( \frac{E_v + E_a}{2} \right) - \frac{kT}{2} \log \left[ \frac{N_a}{2 \left( \frac{2\pi m_a k T}{h^2} \right)^{3/2}} \right] = \left( \frac{E_v + E_a}{2} \right) - \frac{kT}{2} \log \left( \frac{N_a}{N_y} \right)$$

where  $N_y = 2 \left( \frac{2\pi m_a k T}{h^2} \right)^{3/2}$

$$E_F = \left( \frac{E_v + E_a}{2} \right) + \frac{kT}{2} \log \left( \frac{N_a}{N_y} \right)$$

- The above eqn. shows that  $E_F$  increases as the temperature increase
- As the temp. increases more & more acceptor atom are ionized
- For a particular temperature all the acceptor atoms are ionized.
- Further increases in temperature generates the electron-hole pair due to breaking of covalent bond & the material behave as intrinsic semiconductor.

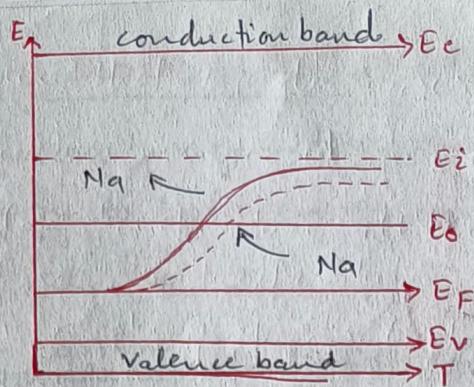
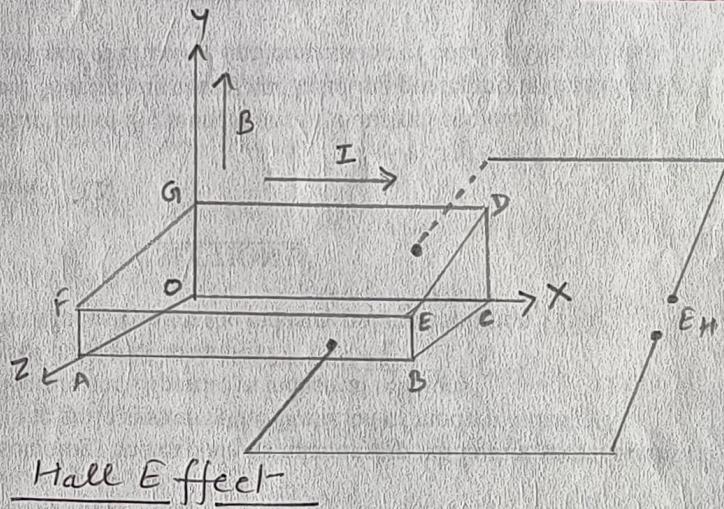


Fig.: Variation of Fermi Level with Acceptor

\* Hall Effect : When a piece of conductor (metal or semi-conductor carrying current) is placed in a transverse magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This is known as Hall Effect. And the generated voltage is called the Hall-voltage.

Explanation :



Explanation : If the Material is N-type Semiconductor / Metal consider a strip is made up of metal or N-type semiconductor, the charge carriers in the strip are electrons. conventional current flow along OX, the electron must be moving along XO. If v is the velocity of electron and -e is the charge of electron, then the force on electron due to magnetic field is

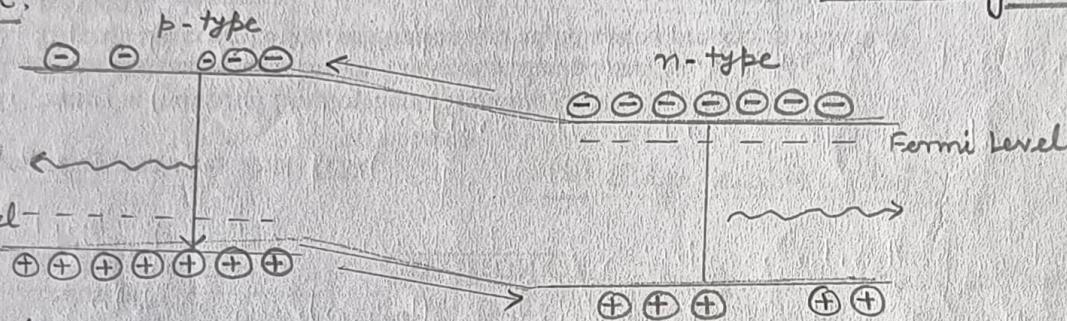
$$F = -B e v$$

which act along OZ. So by deflection electron accumulate at face ABEF.

Light Emitting Diodes (LED)  $\Rightarrow$  LED (light emitting diodes) is a semiconductor p-n junction diode which convert ~~light~~ electrical energy to light energy under forward biasing.

Principle  $\Rightarrow$  When the diode is in forward bias electrons which are majority carriers in 'n'-regions cross the junction and go to 'p'-region and become minority carriers in 'p'-regions.

Likewise holes which are majority carriers in 'p'-region cross the junction and go to 'n'-region and become minority carriers in 'n'-region. This phenomenon is called minority carriers injection.



If biased voltage is further increased these excess minority carriers diffuse from junction and they recombine with majority carriers. So the electrons which are minority carriers in 'p'-region recombine with holes which are majority carriers in 'p'-region and emit light. Similarly holes are ~~majority~~ minority carriers in 'n'-regions recombine with electrons which are majority carriers in 'n'-region and emit light. Thus radiative recombination leads to photon emission.

The no. of radiative recombination is proportional to carrier injection rate and hence current flow through device

$$I = I_0 \left[ \exp\left(\frac{eV}{BkT}\right) - 1 \right]$$

where  $I_0$  = saturation current,  $V$  = forward bias voltage,  $k$  = Boltzmann const  $B$  varies from 1 to 2 depending upon superconductor & temp.

(26)

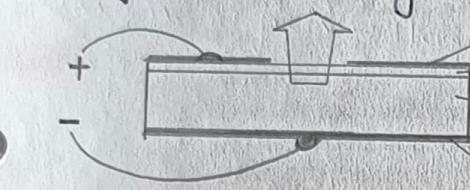
The optical photon emitted due to radiative recombination has the energy very close to bandgap  $E_g$  and frequency of emitted photon is

$$\frac{hc}{\lambda} = E_g$$

### LED Construction :

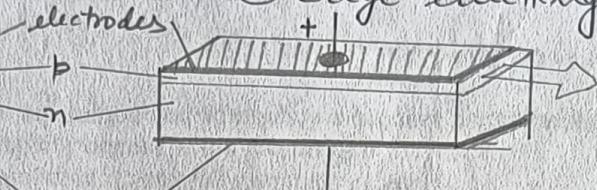
An LED must be constructed such that the light emitted by radiative recombination event can escape the structure. The LED can be of two different type -

#### ① Surface Emitting LED



(a) Surface emitting LED

#### ② Edge emitting LED.



(b) Edge emitting LED

Srivastava

① Surface Emitting LED :> Surface emitting LED can be made such that the bottom edge reflect light back towards the top surface to enhance the output intensity.

② Edge Emitting LED :> In edge emitting LED the <sup>emitted</sup> radiation is relatively direct by side edge. Hence it has higher efficiency.

Although the internal quantum efficiency is 100%, the external efficiencies are much lower. The main reason is that most emitted light radiation strikes the material interface at greater angle than critical angle.

The internal critical angle at semiconductor

$$\sin \theta_c = \frac{n_2}{n_1}$$

$n_1$  &  $n_2$  are refractive index of air = 1 & Semiconductor of group III = 3.5,  $\theta_c = 16^\circ$

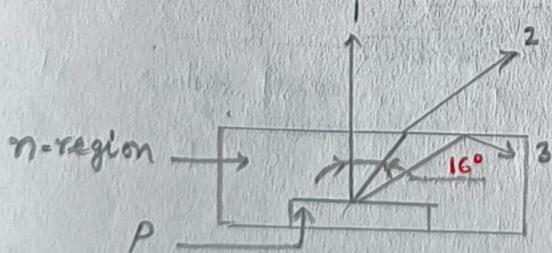
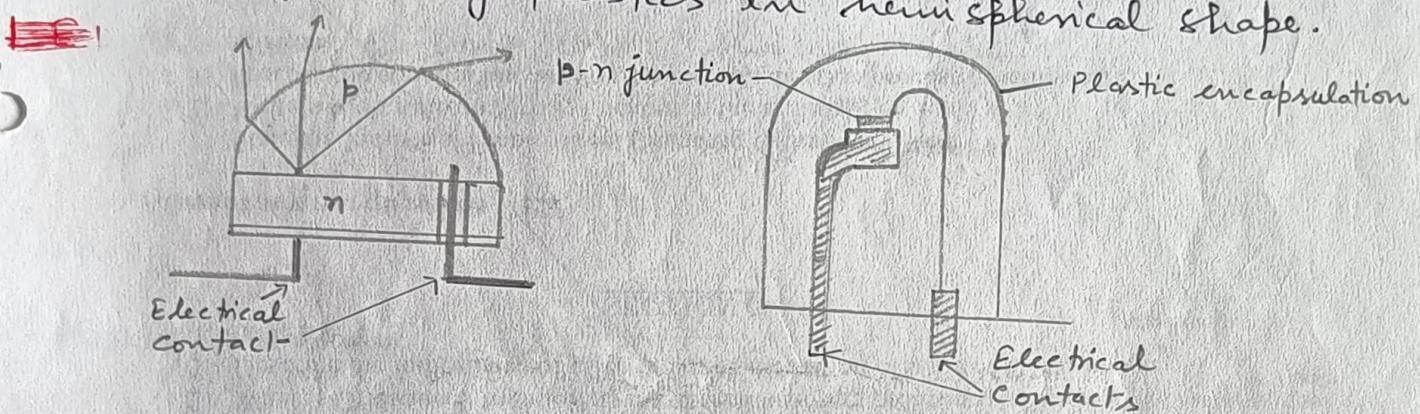


Fig: Critical Angle

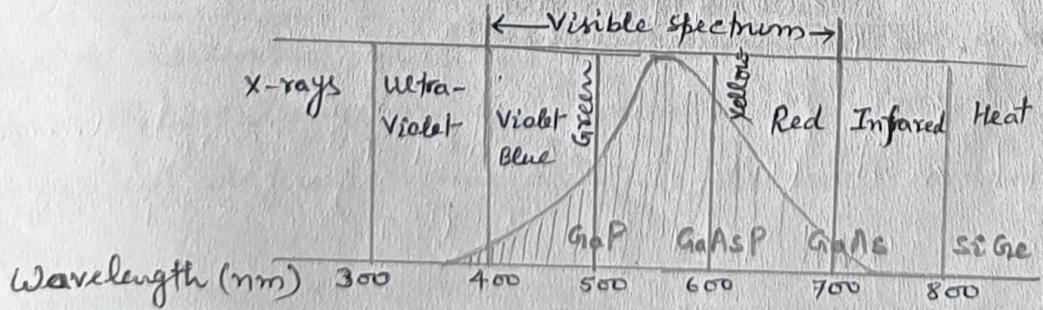
So All striking light rays having angle exceeding  $16^\circ$  suffer total internal reflection and as a result most of ~~reflected~~ emitted light is reflected back inside semiconductor crystal.

Hence to improve the external efficiency loss the semiconductor is given a dome shape. Hemi-spherical domes made from plastics are effective in increasing the external efficiency by a factor 2 or 3. There will be some losses at plastic/air interface but these are easily minimize by molding plastics in hemispherical shape.



### LED Materials :

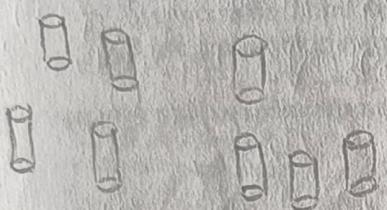
- (1)- The choice of material for an LED is decided by spectral requirement. The most commonly used materials for LED are GaP, GaAs and their related ternary compound  $\text{GaAs}_x\text{P}_{1-x}$ .
- (2)- The band gap radiation of GaP, GaAs & GaAsP is shown in Fig. GaP gives a peak of 560nm is very close to wavelength of eye.
- (3)- The GaP one of the most useful of all visible semiconductor light sources since in addition to green light both red and other colour can be produced by dopant.



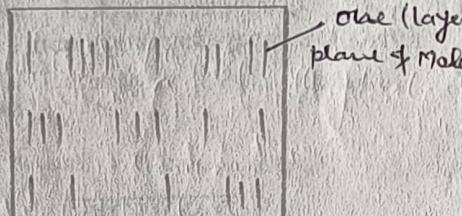
LED Material Properties

Material	Dopant	Bandgap (eV)	Wavelength (Nm)	Quantum Efficiency
GaP	N	2.88	430	0.6
GaP	ZnO	1.80	690	0.2
GaP	N	2.25	550	0.1
GaAs	P	1.88	660	0.2
AlGa	As	1.84	675	0.2

Liquid Crystal Display :⇒ "Liquid crystals are organic compounds that flow like a liquid while maintaining a long range orderliness of a solid. The molecules of liquid crystal compound are in the form of long cigar shaped rods."



(a) Shape of LC molecule



(b) Smectic



(c) Nematic

Types :⇒ Based on orientation of these rods like polar molecule the liquid crystals are classified in three basic types - Smectic, Nematic & Cholesteric.

(i) Smectic :⇒ The smectic phase consists of flat layers of cigar shaped molecule with their long axes oriented perpendicular to the plane of the layer.

(ii) Nematic :⇒ The nematic phase also have molecules with their long axes parallel to each other but they are separated into layers. In nematic mesophase the individual molecules can move freely up and down.

(iii) Cholesteric :⇒ Cholesteric mesophase can be defined as a special type of nematic in which thin layers of mostly parallel molecules have their longitudinal axes twisted (rotated) in adjacent layers at definite angle. This is most ordered phase.

## Semiconductor materials of interest for Optoelectronic devices:

Optoelectronic devices find various applications in telecommunication, military services, medical field and automatic control system. Devices and the material used are as follows:

1- Photovoltaic Cell :- Photo electric transducers generate electric current when exposed to light. A photovoltaic cell consist of many p-n junctions connected in series. One of the junction is very thin, so light can easily pass through it. When light passes, charge carriers such as holes & electrons are produced proportional to incident light.

Solar cells & solar batteries are used in satellites.

Ex. of Materials :- Some common solar cell material semiconductors are, Si - single crystal, Si - polycrystal, Amorphous Si - Ge : H films, GaAs, GaAlAs, GaInP, CdTe thin films.

(2) Photoconducting cells :- LDRs are typical photoconductive cell Ex. Cadmium Sulphide (cds)

(3) Light Emitting Diodes :- A semiconductor diodes that emits narrow-spectrum light when electrically biased in forward direction. Ex. GaAs, AlGaAs, InGaN.

(4) Diode Lasers :- Based on semiconductors (III-V) group. Indium Phosphide, Gallium antimonide & gallium nitride are some examples of compound semiconductor that can be used to create junction diodes that emit light.

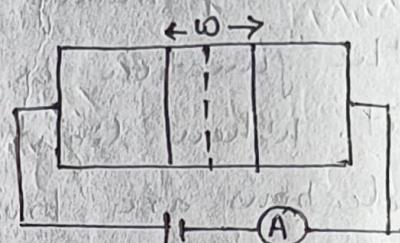
(5) Photo diode & Photo current :- A photodiode is semiconductor device that converts light into an electrical current. Photo-diodes are similar to regular semiconductor diodes except

that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device.

Materials :- Silicon  $\rightarrow \lambda = 190 - 1100$  nm, Indium Gallium Arsenide  $\lambda = 800 - 2600$  nm,

CdTe  $\rightarrow \lambda = 400 - 1700$  nm, Mercury Cadmium Telluride  $= 400 - 14000$  nm

Light creates the carriers that move in the same direction as minority carriers in reverse biased junction (in the darkness).



Therefore under illumination there is a photo current whose direction corresponds to reverse current of the junction. Incident photon flux ( $n/A/\text{sec}$ )  $\phi_0 = \frac{P_{\text{inc}}}{A h \nu (1 - R)}$

where  $R$  = reflection coefficient of top surface

$A$  = Area of device,  $P_{\text{inc}}$  = incident optical power

Drift current density  $J_{dr} = q \phi_0 (1 - e^{-\alpha w})$

In case depletion region is thick enough i.e.  $\alpha w \gg 1$

$$J_{dr \max} = q \phi_0$$

Total Photo current 
$$I_{dr} = A q \phi_0 (1 - e^{-\alpha w})$$

### CLASSIFICATION of LED :-

LED's are p-n junction that can emit spontaneous radiation in UV, visible or IR regions. The visible LED has a multiple of applications as an information link b/w electronic instruments and their uses.

(1) Visible LED :- Multiple application as an information link b/w electronic instruments and their uses.

- (2) White LED's :- Key component in backlight source for liquid crystal flat-panel display & street lamp.
- (3) IR LED's :- Useful in opto-electronic applications. Like opto-isolators, Optical Fiber communications and health care applications.

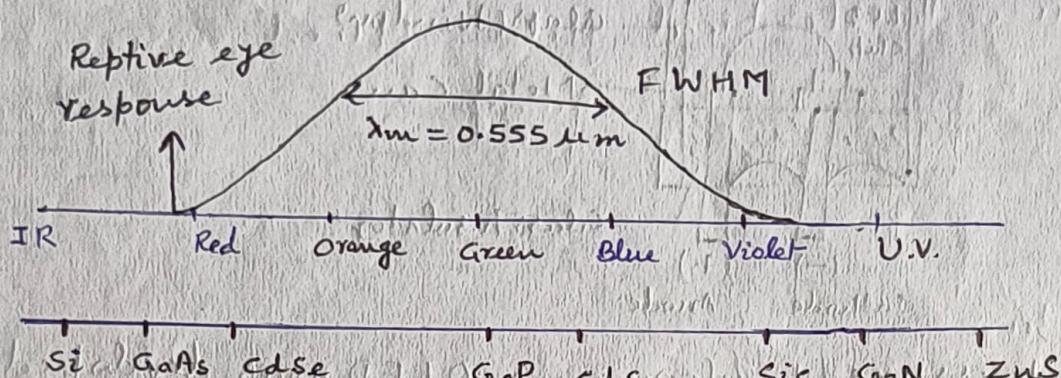


Fig. Eye Response Curve

Materials

InAs SbP / InAs

InAs

GaAs

SiC

GaAs : Si

GaP

SiC

BN

Wavelength

4200 nm

3800 nm

1800 nm

1300 nm

940 nm

690 nm

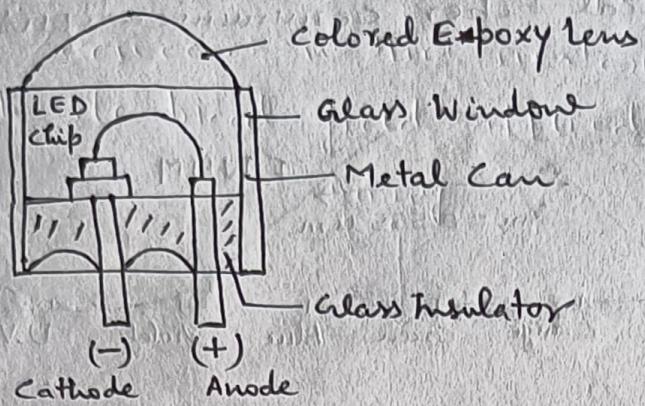
400 - 460 nm

260, 310, 490 nm

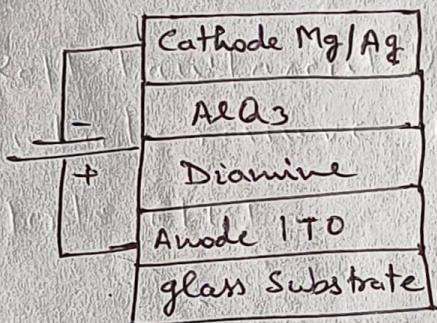
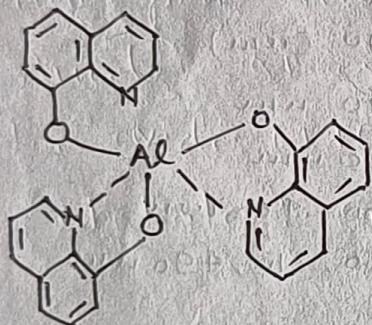
Organic LED :- In recent years certain organic semiconductor have been studied for electroluminescent applications. Organic LED (OLED) is particularly useful for a multicolour large area flat panel display because of its attributes of low power consumption & excellent emissive quality with a wide viewing angle.

OLED's are made from small molecules or polymers. Commonly macro particles/molecules with a molecular weight greater than 10000 atomic mass unit (amu) are called polymers,

whereas higher molecules are referred to small molecules. Usually a polymer light emitting diode is referred to as PLED. Structure of OLED prepared by vacuum deposition technique.



- High pressure/ performance OLED was developed using the concept of multilayer structures. Fig. below shows the molecular structure of two representative organic semiconductors used for a double layer structure. They are the triis (quinolin-8-olato) aluminum ( $\text{Al}(\text{Q}_3)$ ), Aromatic diamine.



200 nm  
75 nm  
75 nm  
30 nm

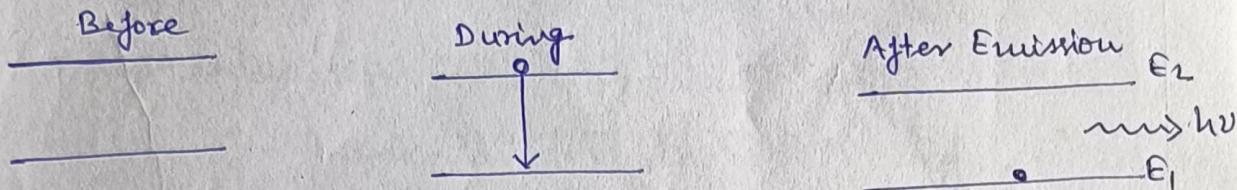
Fig:- Organic Semiconductor & OLED Cross-Section View.

The organic material is electrically conductive due to delocalization of  $\pi - e^-$  caused by conjugation over all or part of molecule & the material therefore acts as organic semiconductor.

Advantages :- Thin low cost display with low driving voltage, wide-viewing angle, high contrast and colour.  
Polymer LEDs are beneficial for printable & flexible displays.  
OLEDs - digital cameras, MP3 players etc.

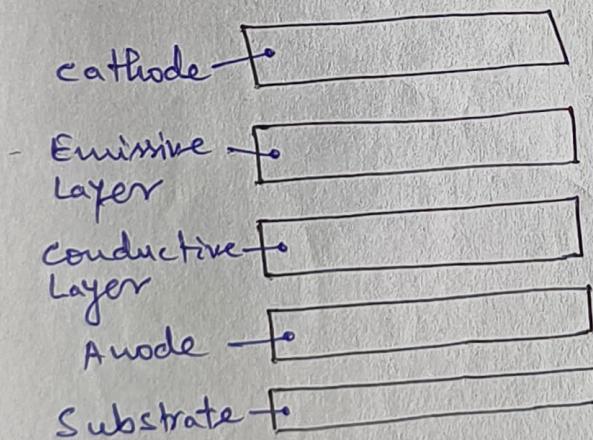
OLED  $\Rightarrow$  Any LED in which organic layers are responsible for emitting light emission.

Principal  $\Rightarrow$  It is based on the principle of Electroluminescence. In this material emits light in response to electrical field applied across it.



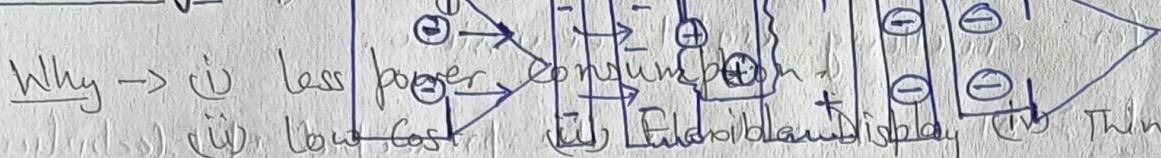
### Structure :-

1. Cathode - It inject electron into the emissive layer.
2. Emissive Layer - It is made of Polyfluorene which transfer  $e^-$  from cathode. Here light is made.
3. Conducting Layer - Made of polyaniline which transfer holes from anode.
4. Anode - It is kept transparent & made up of indium tin oxide (ITO) which removes  $e^-$ .
5. Substrate :- Supports OLED.



Types → (i) Passive Matrix (ii) Active matrix (iii) Transparent  $\oplus$

Working → (i) Emitting (ii) Foldable (iii) White OLED



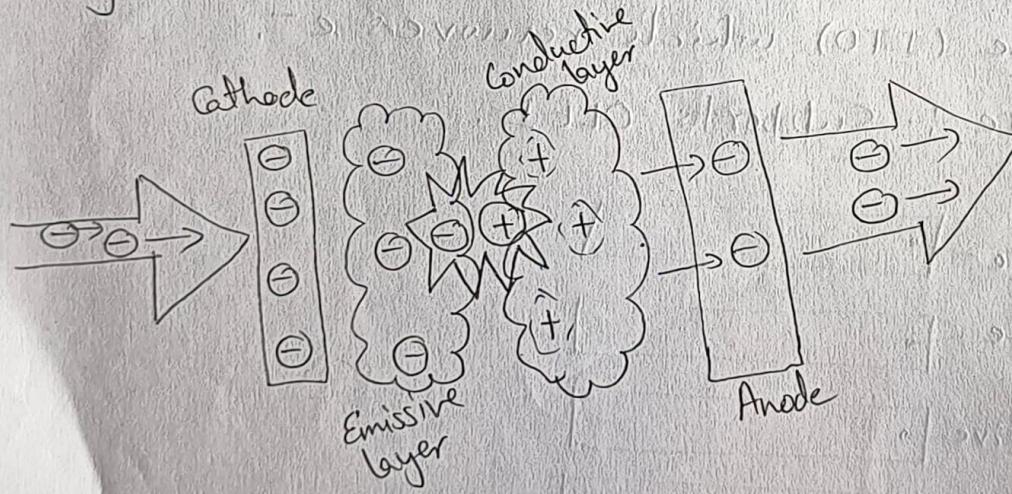
Why → (i) less power consumption  
(ii) low cost  
(iii) Full color display  
(iv) Thin display.

(v) Safer for Environment  
(vi) Better contrast ratio  
(vii) Wider viewing angle.

Drawbacks - (i) ~~less~~ life span  
(ii) Easily damageable  
(iii) Outdoor performance  
(iv) Complex fabrication method

In future - (i) finding cheap way to produce  
(ii) Roll-to-roll manufacturing  
(iii) Increasing efficiency of OLED  
(iv) To increase lifespan of OLED

Working -



Metal Semiconductor junction - Ohmic Contact :- It is the oldest practical semiconductor devices N-S junctions can either be rectifying or non-rectifying. The rectifying metal - semiconductor junction forms a Schottky barrier making a device known as a Schottky diode, while the non-rectifying junction is called an ohmic contact. Metal semiconductor junctions are crucial to the operation of all semiconductor devices. Usually an ohmic contact is desired so that electrical charge can be conducted easily b/w the active region of a transistor & external circuitry. A Schottky barrier is useful as in Schottky diodes, transistors & metal semiconductor field-effect transistors.

Schottky Junction :- When a metal & semiconductor are brought into contact there are two types of junctions formed depending upon the work function of the semiconductor and its relation with the metal

- 1. Schottky Junction  $\phi_m > \phi_{semi}$
- 2. Ohmic contact  $\phi_m < \phi_{semi}$

① VISIBLE LEDs → That generates visible illumination when charged with electrical currents. They are used in many electronic devices as indicator lamps, as rear-window & brake lights, full-color posters, in auto-focus cameras, in TV remote controls and also as light sources in fibre-optic communication systems.

② IR LEDs → The infra-red LED is a special purpose LED emitting infrared rays ranging from 700nm to 1mm wavelength. They are made of GaAs, AlGaAs. They are commonly used as sensors. It works on the photo-coupler or opto-coupler.

③ White LEDs → This displays the white light in colour when all the primary colors mixes well. Secondly, by the use of a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, as similar to ~~flat~~ fluorescent light bulb works.

Methods of mixing colors to get White LED

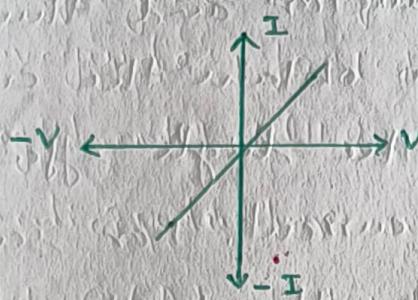
① Blue LED + Green LED + Red LED

② Near-UV/UVLED + RGB phosphor.

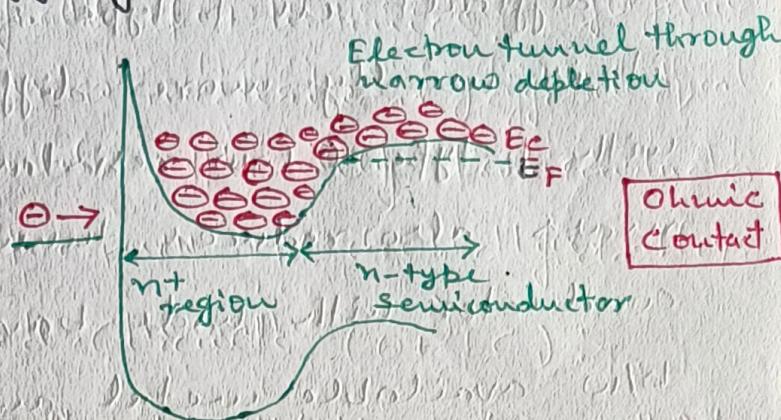
③ Blue LED + Yellow phosphor

## Metal Semiconductor Junction :-

(1) Ohmic contact ;  $\Rightarrow$  Ohmic contact is the contact that gives Linear non-rectifying I-V characteristics.



(a) I-V Characteristics



(b) Band gap diagram of metal  $n^+$ - $n$  metal.

Heavy doping reduces the depletion region or width to such an extent that the  $e^-$  can tunnel through the spiked barrier easily.

Ohmic contact is created by heavy doping and the use of tunnelling to get large current across the interface. Due to heavy doping, the depletion width could be extremely narrow. In fact it is so narrow that even if there is a potential barrier, the  $e^-$  can tunnel through the barrier with ease. The Resistance ( $R$ ) define its quality over a certain area ( $A$ )

the normalized resistance is called the specific contact resistance  $r_c$  which is given by

$$r_c = R \cdot A$$

The resistance can be reduced by using a low Schottky barrier height and doping as heavily as possible. Experimentally we can obtain that heavy doping is difficult in p-type semiconductor and thus it is usually more difficult to obtain the contact with p-type (low resistance). The high effective mass also reduces tunneling current. For semiconductor with wide band-gap, the barrier height b/w available metal and the valence band is much greater than that of conduction band.

Schottky Effect :- Schottky effect is also called as Enhanced Thermionic Emission. Under this effect when an accelerating electric field is applied to a heated material surface, in order to remove the emitted electrons from the surface and to accelerate them to collector, where they constitute the thermionic current. This electric field beside doing this, also lowers the height of potential barrier at the surface and hence e<sup>-</sup> emission increases. This increase in emission depends upon external electric field is called Schottky Effect.

This results in decrease of smallest energy required for the release of e<sup>-</sup> from the surface of the material & thus thermionic current increases.

The above plot shows a straight line.

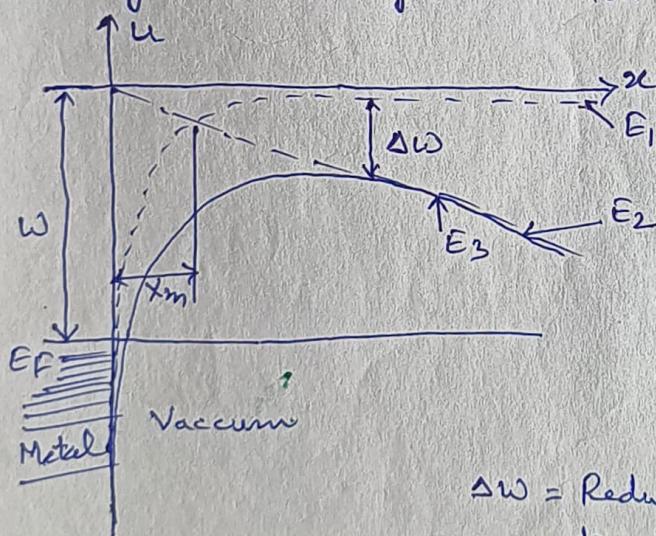
At low anode voltage deviation is due to space charge effect.

At high conductivity, electric line of force at  $90^\circ$  to a surface of a metal. Any charge when placed near the surface of a conductor experience a force arising from polarization of the conducting material. For the distance that are large compared to interatomic distance then the surface can act as a perfect conductor.

Let  $a$  = interatomic distance for an  $e^-$  at  $n \gg a$  in a metal which will be at a distance  $x$ . An attractive force between  $e^-$  is equivalent to that of an equal positive charge, is given by

$$F = \frac{e^2}{16\pi\epsilon_0 x^2}$$

The thermionic emission is the thermally induced flow of charge carrier from a surface or potential barrier.



where  $W$  = Work Function of Metal

$U$  = Potential energy at Surface

$E_1$  = Electron Potential energy in Field

$E_2$  = Electron Potential " in applied Field

$E_3$  = Resultant  $e^-$  Potential Eng

$\Delta W$  = Reduction in Work Function due to applied Field

$E_F$  = Fermi Energy Level

$x_m$  = Distance from height of potential barrier to surface of metal.

Solar Cells:-

Solar cells are useful for both space and terrestrial applications. Solar cells furnish the long-duration power supply for satellites.

P-N junction Solar Cell - It consists of a shallow p-n junction formed on surface, a front ohmic contact strip and fingers, a back ohmic contact that covers the entire back surface and an anti-reflection coating on front surface.

When sun is exposed to solar spectrum, a photon that has energy greater than  $E_g$  contributes an energy  $E_g$  to the cell output. Energy greater than  $E_g$  is wasted as heat.

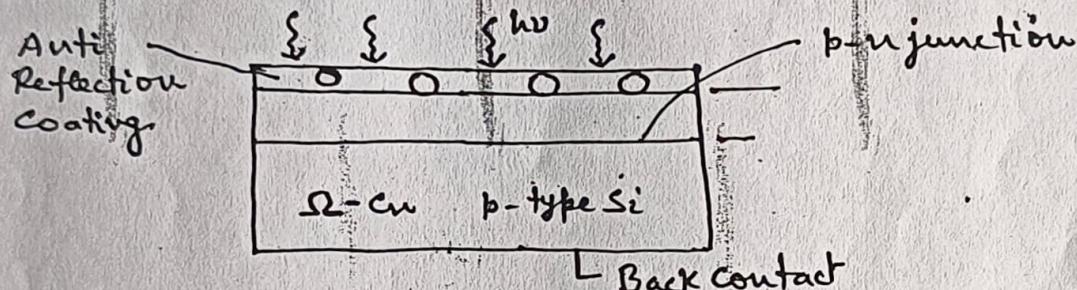


Fig: Silicon p-n junction Solar cell

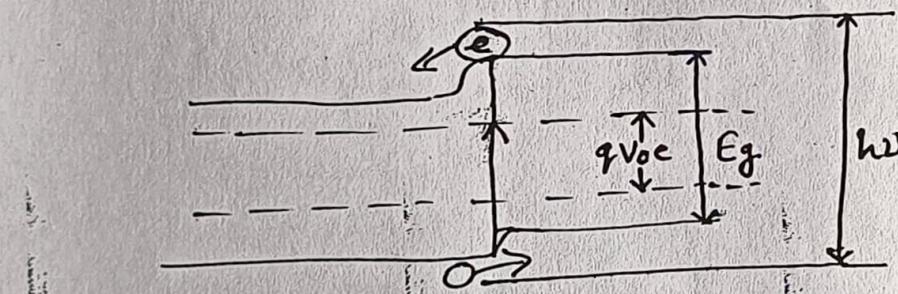


Fig: Energy band Diagram

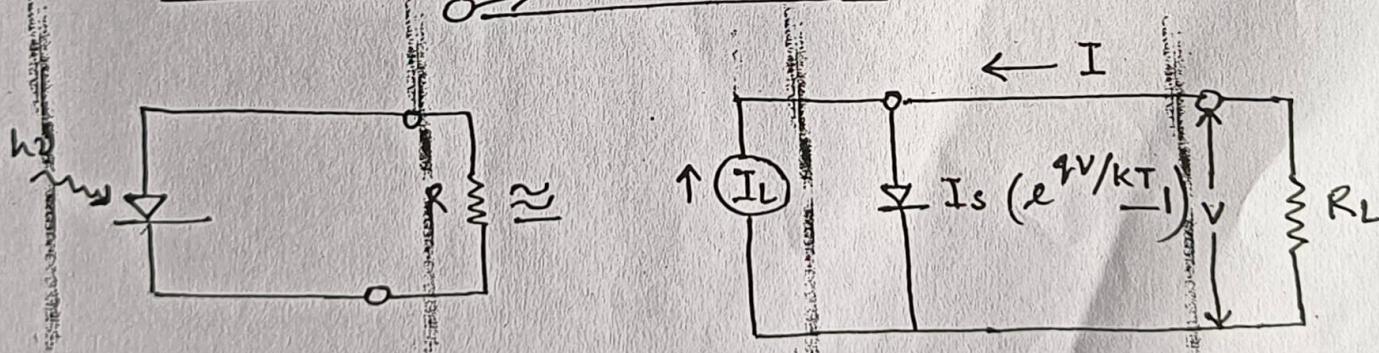


Fig: Idealized equivalent circuit of a Solar cell.

The ideal I-V characteristic of such a device are given by

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

The current through Load  $R_L$  is in opposite direction to the conventional current flow. Thus  $I = -V/R_L$

This current and current in the circuit must satisfy both the I-V characteristic of Solar cell.

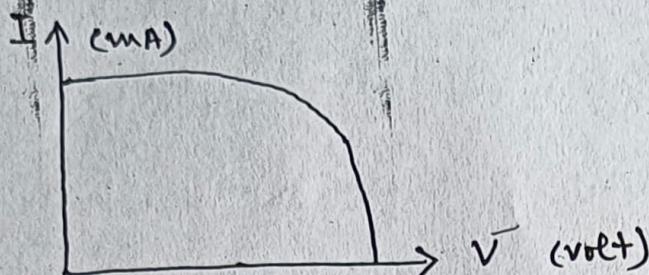


Fig. I-V characteristic curve

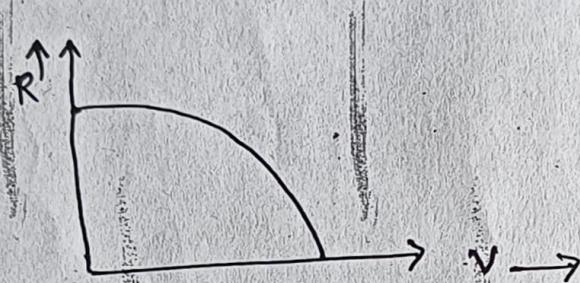


Fig. V-R characteristic of solar cell.

Power consumption efficiency of a solar cell is given by

$$\eta = \frac{I_m V_m}{P_{in}} = \frac{I_L \left[ V_{oc} - \frac{kT}{q} \ln \left( 1 + \frac{qV_m}{kT} \right) - \frac{kT}{q} \right]}{P_{in}}$$

$V_{oc}$  = open circuit voltage

$I_s$  = saturation current

$I_L$  = load current.