

## MODULE - 2

### EXCESS CARRIERS IN SEMICONDUCTORS

→ Excess Carrier in Semiconductor :-

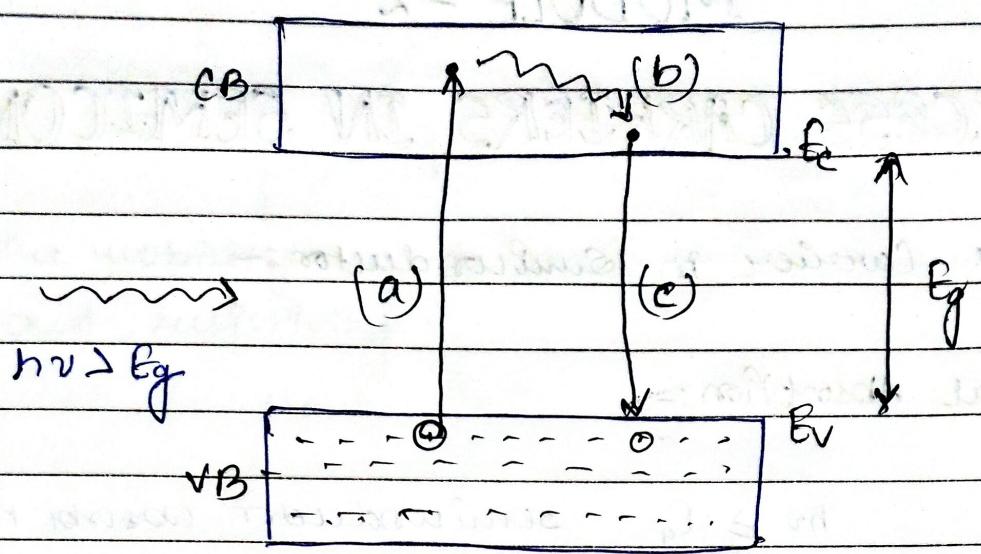
→ Optical Absorption :-

$h\nu \geq E_g$ , semiconductor absorbs the photon.

$h\nu < E_g$ , passes out the photon.

$$E_g = h\nu = hc$$

- This a technique by which band gap energy of any semiconductor can be calculated.
- In this experiment photon of selected wavelength get strike on the semiconductor and relative transmission of various photons are observed.
- Photon having energy  $h\nu \geq E_g$  get absorbed in the semiconductor while photon having energy  $h\nu < E_g$ , get transmitted through the semiconductor.

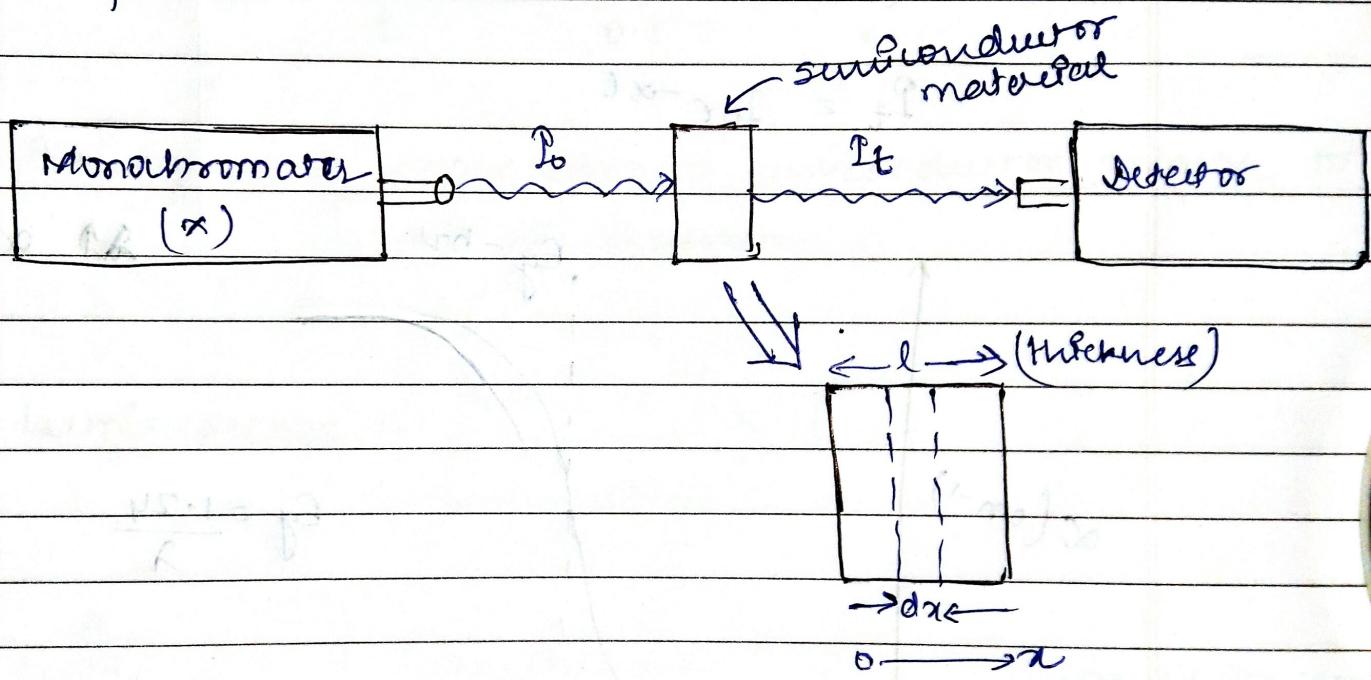


Optical absorption of a photon with  $h\nu > E_g$   
 (electron-hole pairs)

- (a) An E.H.P is created during photon absorption.
  - (b) The excited electron gives an energy to the lattice by scattering event.
  - (c) The electron recombines with the hole in the valence band.
- Under lattice scattering phenomenon, the excited e- loses energy to the lattice in scattering events, until its velocity reaches the normal equilibrium velocity of other conduction band electrons.
- The Electron and hole created by this absorption process are called excess carriers.

→ If a beam of photons with  $\hbar\nu > E_g$  falls on a semiconductor there will be some predictable amount of absorption which can be determined by the properties of material.

→ Ratio of transmitted to incident light intensity is a function of photon wavelength and thickness of sample.



Let a photon of beam of intensity  $P_0$  having unit (Photon/cm<sup>2</sup>-s) is directed to a sample of thickness  $l$ . The beam contains only photon of wavelength  $\lambda$ , selected by monochromator. By considering the probability of absorption within any implemented area, one can easily calculate its intensity at distance  $x$  from the surface.

→ The degradation of intensity is given by,

$$-\frac{dI(x)}{dx} = \alpha I(x) \quad \text{--- (1)}$$

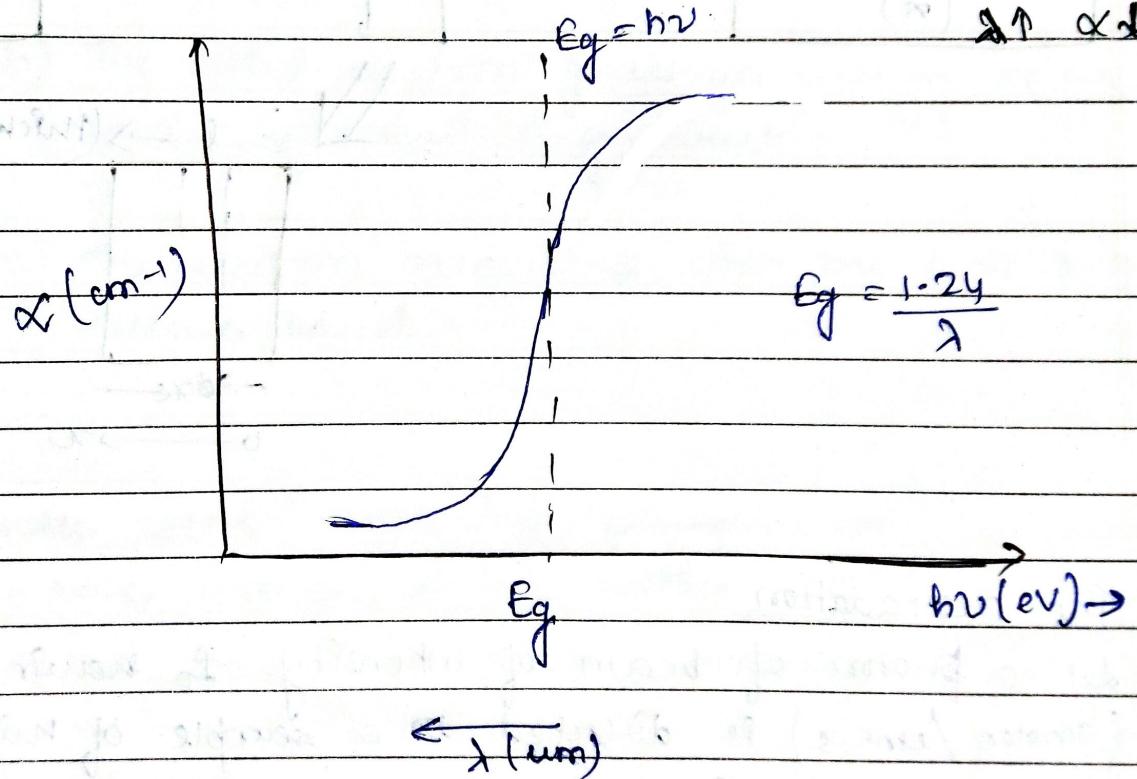
where

$\alpha \rightarrow$  absorption coefficient having unit ( $\text{cm}^{-1}$ ), depends on material and photon wavelength.

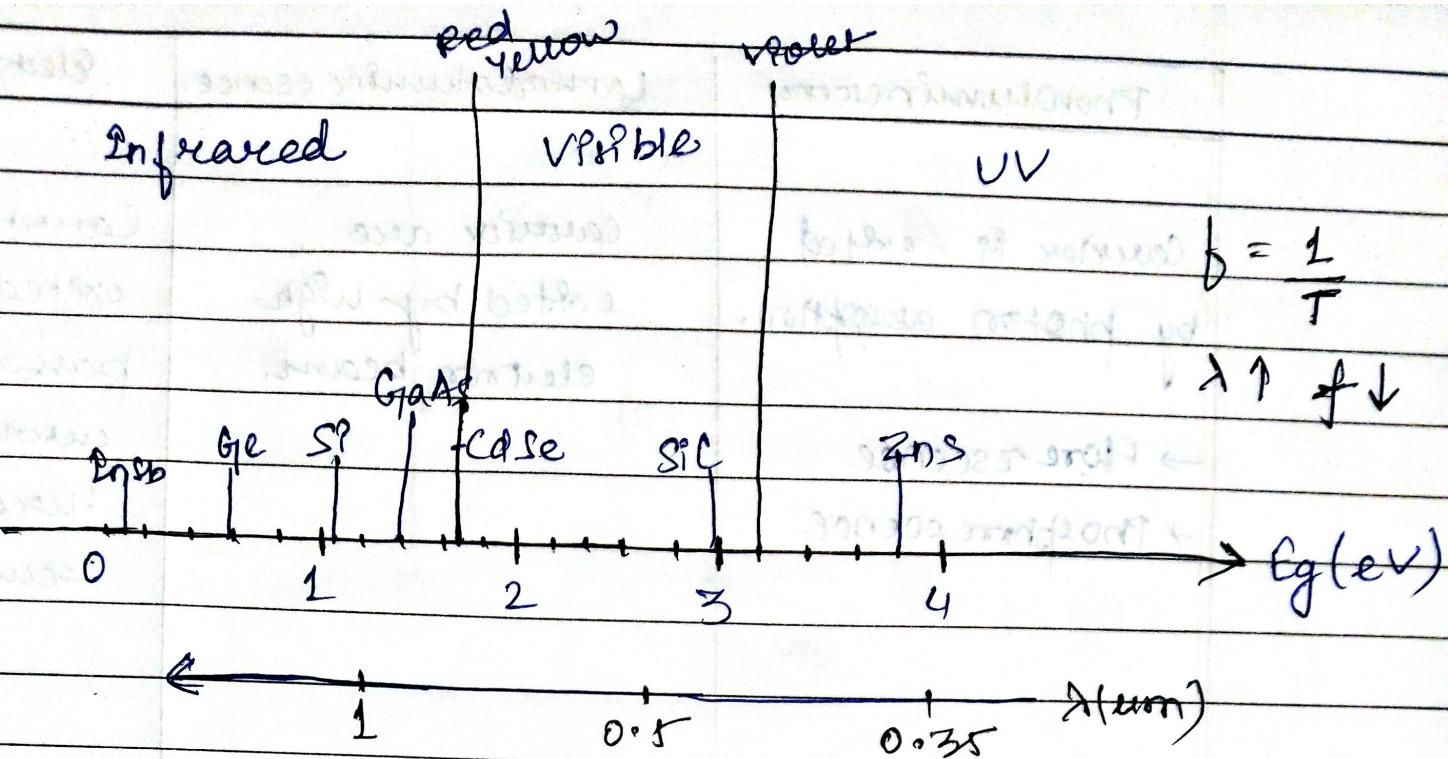
The solution of eqn (1) can be given by,

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

$$I_t = I_0 e^{-\alpha l}$$

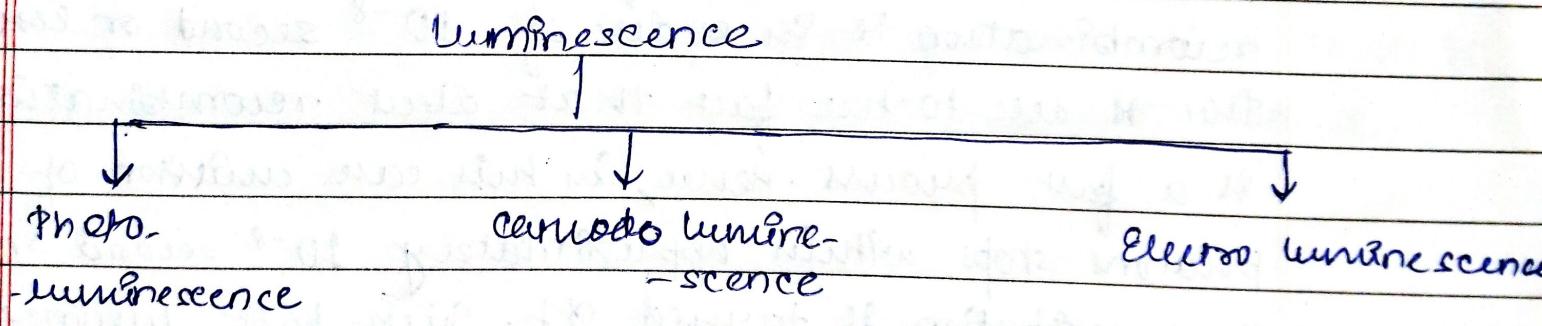


Dependence of optical absorption  $\alpha$  on wavelength of incident light



Bandgap of some common semiconductor relative to the optical spectrum.

⇒ Luminescence :-

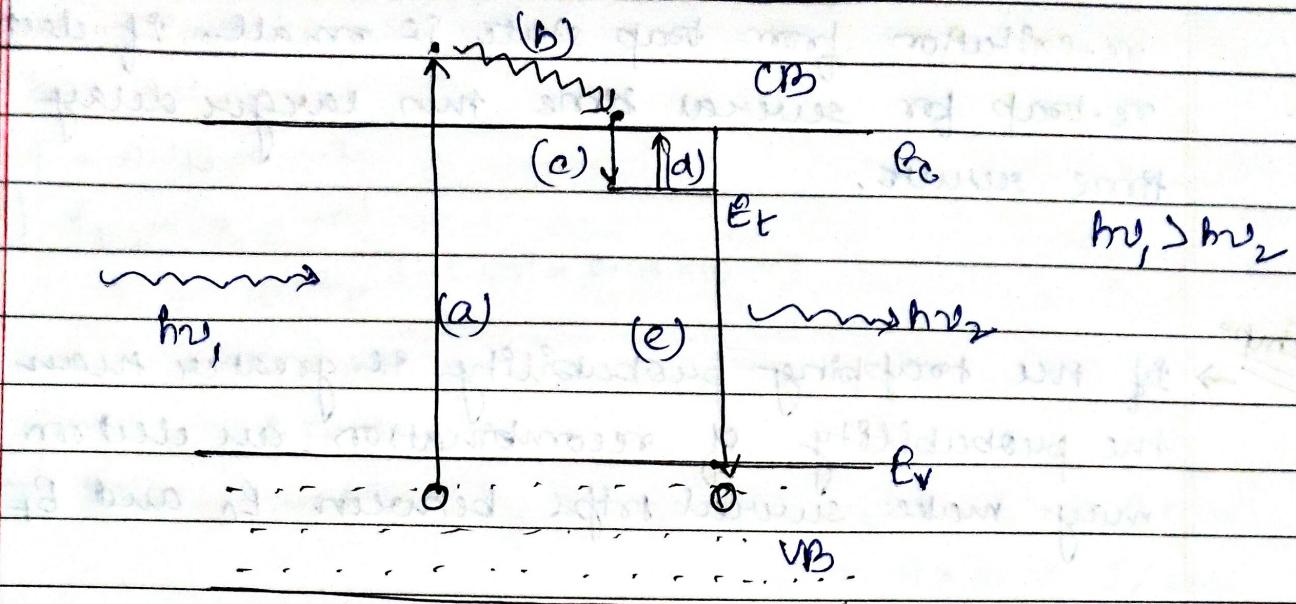


Property of semiconductor for the emission of light is called as luminescence. They are of three types: photoluminescence, cathodo luminescence and electro luminescence.

Photoluminescence	Cathodoluminescence	Electroluminescence
<p>Carrier is excited by photon absorption.</p> <p>→ Fluorescence.</p> <p>→ Phosphorescence.</p>	<p>Carrier are excited by high electron beam.</p>	<p>Carrier are excited by passage of current throughout semiconductor.</p>

⇒ Fluorescence :- Mean life-time EHP in direct recombination is in order of  $10^{-8}$  second or less. This is due to the fact that direct recombination is a fast process. Hence, in this case emission of photons stops within approximately  $10^{-8}$  second or less. After excitation is turned off. Such fast luminescence process is often called as fluorescence.

⇒ Phosphorescence:- In some material emission continue for a longer time of 2 minutes after the excitation is removed. They are very slow process called as phosphorescence and materials are called as phosphors.



Excitation and recombination mechanism in phosphorescence with a trapping level for electron.

→ In the above arrangement, a trapping level  $E_t$  is considered which is very near to the conduction band level and arises due to the impurities of the semiconductor. The main purpose of the trapping level is to capture the electron from the conduction band.

Step (a) and (b) are common step. In step (c) electron got trapped by  $E_t$  and remain there until it can be thermally re-excited to the conduction band as shown in (d). Finally in (e) direct recombination occurs as electron falls to an empty state of valence band giving out  $h\nu_2$ .

The delay time b/w excitation and recombination can be long if the probability of thermal

re-excitation from trap state is small. If electron re-trap for several time then larger delay time results.

Drift

→ If the trapping probability is greater than the probability of recombination, an electron may make several traps between  $E_C$  and  $E_T$ .

→ The colour of light emitted by a phosphor such as  $ZnS$  depends primarily on the impurities present, since many radiative transitions involve impurities levels in band-gap, concepts are applicable in color-television screens.

Q. A  $0.46\text{ }\mu\text{m}$  thick sample of  $\text{GaAs}$  is illuminated with monochromatic light of  $\lambda = 2\text{ }\mu\text{m}$ . The absorption coefficient,  $\alpha = 5 \times 10^{14}\text{ cm}^{-1}$ , the power incident on the sample is  $10\text{ mW}$

(a) Find the total energy absorbed by the sample per second ( $\text{J s}^{-1}$ )

(b) Find the rate of excess thermal energy given by the electron to the lattice before recombination ( $\text{J s}^{-1}$ ).

(c) Find the no. of photons per second, given off from recombination event assuming perfect quantum efficiency.

→ Given:-

$$\alpha = 5 \times 10^4 \text{ cm}^{-1}$$

$$hv = 2 \text{ eV}$$

$$t = 0.46 \times 10^{-4}$$

$$(a) P_t = P_0 e^{-\alpha t}$$

$$= 10^{-2} e^{(-5 \times 10^4 \times 0.46 \times 10^{-4})}$$

$$= 10^{-3} \text{ W}$$

$$= 1 \text{ mW.}$$

$$(b) \text{ Power absorbed by the sample} = (10 - 1) \text{ mW} = 9 \text{ mW}$$

$$= 9 \times 10^{-3} \text{ J/sec.}$$

$$(c) \text{ the fraction of each photon energy unit which is converted to heat H given by } \frac{2-1.43}{2} = 0.285.$$

Thus the amount of energy converted to the heat per second H given by  $0.285 \times 9 \times 10^{-3} \text{ J/sec.} = 2.57 \times 10^{-3} \text{ J/sec.}$

Recombination radiation accounts for  $(9 - 2.57)$

$$= 6.43 \text{ mW at}$$

$$1.43 \text{ eV/photon.}$$

$$\text{That implies } \frac{6.43 \times 10^{-3}}{1.6 \times 10^{-19} \times 1.43} = 2.81 \times 10^{16} \text{ photon/sec.}$$

⇒ Carrier lifetime and photo conductivity :-

→ Carrier lifetime or recombination lifetime is defined as the average time it takes, an excess minority carrier to recombine. It is strongly dependent on the magnitude and type of the recombination process in semiconductor.

→ If the excess carrier arises from optical luminescence the resulting increase in conductivity is called photo conductivity.

⇒ Direct Recombination of Electron and Hole :-

→ Direct recombination occurs spontaneously i.e. the probability that an electron and hole will recombine is constant in time.

→ In the case of carrier scattering, rate of decay of electron at any time  $t$  is proportional to number of electron remaining at  $t$  and no. of holes with some constant of proportionality for recombination  $\alpha_r$ .

→ Net rate of change in the conduction band electron concentration is diff. between thermal generation  $\alpha_g n_i^2$  and recombination rate.

$$\frac{dn(t)}{dt} = \alpha_s n_i^2 - \alpha_r n(t) P(t) \quad (1)$$

↓      ↓  
natural recombination factor

→ Let instantaneous concentration of excess carrier  $\Delta n(t)$  and  $\Delta p(t)$  are equal for a condition of short flash of light.

→ Now from eqn (1), total concentration in terms of equilibrium values  $n_0$  and  $P_0$  and excess carrier concentration,  $\delta n(t) = \Delta P(t)$ , we have,

$$\frac{d\delta n(t)}{dt} = \alpha_s n_i^2 - \alpha_r [n_0 + \delta n(t)] [P_0 + \Delta P(t)].$$

excess electron  
in conduction band.

$$As \ n_i^2 = n_0 P_0,$$

we have

$$\begin{aligned} \frac{d\delta n(t)}{dt} &= \alpha_s n_0 P_0 - \alpha_r [n_0 + \delta n(t)] [P_0 + \Delta P(t)] \\ &= \alpha_s n_0 P_0 - [\alpha_r n_0 P_0 + \alpha_r (n_0 + P_0) \delta n(t) + \delta n^2(t)] \\ &= -\alpha_r [(n_0 + P_0) \delta n(t) + \delta n^2(t)] \quad (II) \end{aligned}$$

$\therefore \delta n(t) = \Delta P(t)$

→ Now consider for low level injection for excess carrier concentration are small  $\delta n^2(t)$  will also be very small and can be neglected.

Also for p-type of material  $P_0 \gg n_0$ , hence  $n_0$  can also be neglected.

$$\frac{d\delta n(t)}{dt} = -\alpha_s P_0 \delta n(t) \quad \text{--- (III)}$$

After solving an equation of exponential decay from the original excess carrier concentration  $\Delta n$  resulted

$$\delta n(t) = \Delta n e^{-\alpha_s P_0 t} = \Delta n e^{-t/T_n} \quad \text{--- (IV)}$$

~~Info~~ → Excess electron in p-type semiconductor recombine with a decay constant  $T_n$ , which is

$$T_n = (\alpha_s P_0)^{-1}$$

is called recombination lifetime or minority carrier life-time.

~~Info~~ → Similarly for n-type semiconductor it would be

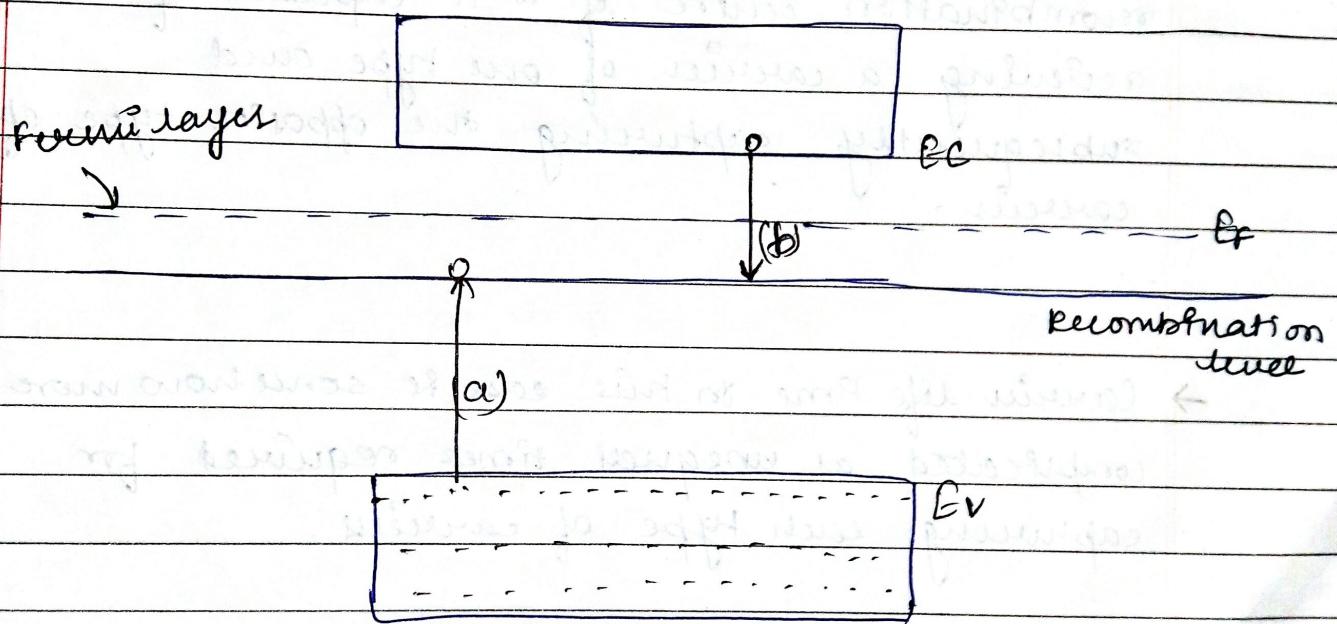
$$T_p = (\alpha_s n_0)^{-1} \quad \text{--- (V)}$$

→ We can conclude that there is a large percentage of change in minority carrier electron concentration and small percentage change in majority hole concentration.

→ More general expression for carrier lifetime is given by

$$T_n = \frac{1}{\alpha_s (n_0 + p_0)} \quad (vi)$$

⇒ Indirect Recombination of Electron and Hole:-  
(Trapping) :-



Capture process at recombination level

- Recombination event in indirect material occurs via recombination level, within the bandgap and resulting energy loss by recombining electron is usually given upto the lattice as heat rather than by emission of photons.
- It involves two simultaneous steps:-

- (a) hole capture.
- (b) electron capture.

(a) hole capture at a field recombination centre.

(b) electron capture at an empty centre.

→ Any impurity or lattice defect can serve as a recombination centre if it is capable of releasing a carrier of one type and subsequently capturing the opposite type of carrier.

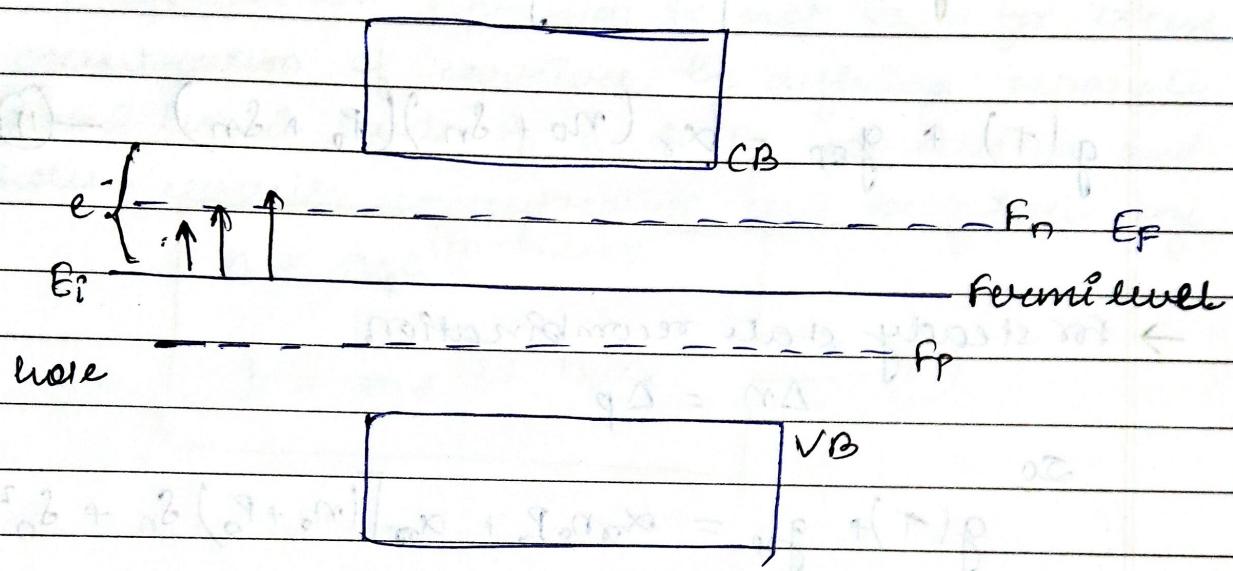
→ Carrier life-time in this case is somehow more complicated as unequal times required for capturing each type of carriers.

→ When a carriers are trapped temporarily at a centre and then it is re-emitted without recombination taking place, the process is called temporary trapping.

→ The recombinations can be slow or fast depending on the average time, the first carrier is freed before second carrier is captured.

→ The effect of recombination and trapping can be measured by a photoconductive decay experiment.

→ Steady state carrier concentration (Quasi Fermi Level) :-



→ Steady state refers to a non-equilibrium condition in which all processes are constant and are balanced by opposite processes.

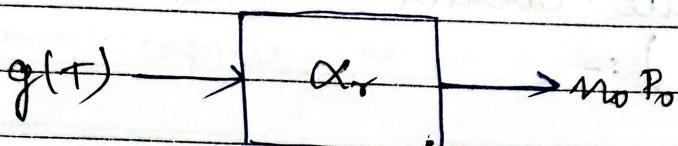
→ A semiconductor at equilibrium experiences thermal generation of EHP at the rate

$$g(T) = g_i$$

This generation is balanced by the recombination rate so that eqm concs of carrier no and  $P_0$  are maintained

$$g(T) = \alpha_s n_0 P_0 = \alpha_s n_p^2 \quad \text{--- (1)}$$

→ Due to emission of steady light and optical generation rate,  $g_{op}$  will be added to the thermal generation and carrier concentration of n and P will increase to a steady carrier.



$$g(T) + g_{op} = \alpha_r (n_0 + \delta_n)(P_0 + \delta_n) \quad (11)$$

→ For steady state recombination,

$$\Delta n = \Delta p$$

So,

$$g(T) + g_{op} = \alpha_r n_0 P_0 + \alpha_r [(n_0 + P_0) \delta_n + \delta_n^2] \quad (11)$$

For low level excitation  $\alpha_r \delta_n^2$  can be neglected and  $\alpha_r n_0 P_0$  will be equal to  $g(T)$ .

Then,

$$g_{op} = \alpha_r [(n_0 + P_0) \delta_n]$$

So,

$$g_{op} = \frac{\delta_n}{T_n} \quad (IV)$$

where

$$T_n = \frac{1}{\alpha_r [(n_0 + P_0) \delta_n]}$$

$\Rightarrow T_n$  = lifetime of electrons.

The excess carrier concentration can be given by

$$\begin{aligned} \text{or } n &= T_n g_{op} \\ p &= T_p g_{op} \end{aligned}$$

(V)

→ The equilibrium expression is not valid for excess concentration of carriers. By defining separate quasi Fermi levels  $F_n$  and  $F_p$ , for electrons and holes carrier concentration can be given by,

$$n = n_{ie} e^{(F_n - E_F)/kT}$$

$$p = n_i e^{(E_F - F_p)/kT}$$

(VI)

→ Quasi Fermi level illustrate dramatically the deviation from equilibrium caused by optical excitation.

→ Quasi Fermi level  $F_n$  and  $F_p$  are steady state analogues of the equilibrium Fermi level  $E_F$ ; when excess carriers are present, the deviation of  $F_n$  and  $F_p$  from  $E_F$  indicates how far the electron and hole populations are from  $n_0$  and  $p_0$ .

→ A given concentration of excess EHP causes a large shift in minority carriers. The quasi Fermi level compared to it that for

majority carriers.

- This concept is very useful in visualising minority and majority carrier concentrations in devices where these quantity values varies with position.

### ⇒ Photoconductive Devices :-

- Devices which changes their resistivity when exposed in light are called photoconductive devices.
- The optical sensitivity of a photoconductor can be evaluated by examining the steady state excess carrier concentration generated by an optical generation rate,  $g_{op}$ . If the mean time re-carrier expands in its respective bands is  $T_n$  and  $T_p$ , we have,

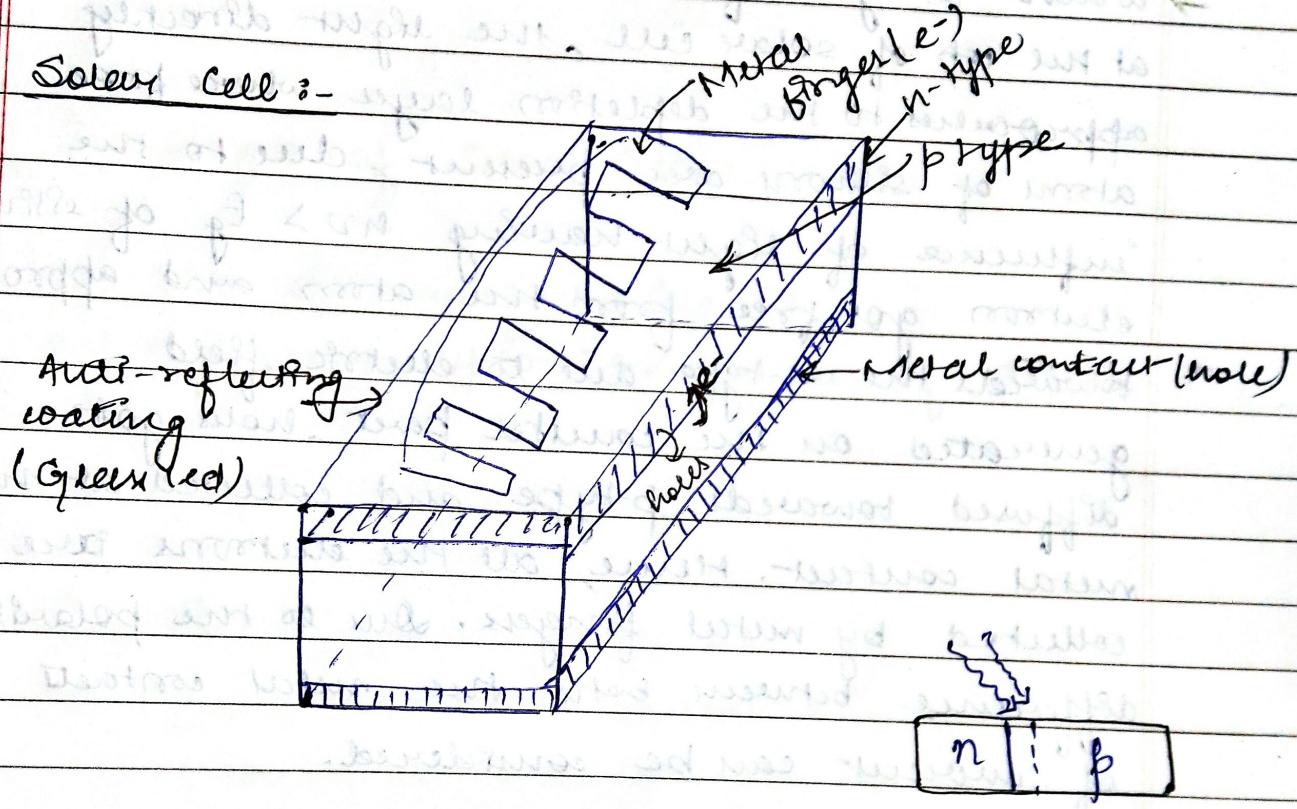
$$\delta_n = T_n g_{op}$$

$$\delta_p = T_p g_{op}$$

- Photocconductivity changes are given by,  
 $\Delta \sigma = g g_{op} (T_n \mu_n + T_p \mu_p)$

→ CdS (Cadmium sulphide) is a commonly used as photoconductor in the visible range and narrow gap material such as InSb ( $E_g = 0.67\text{eV}$ ) and Ge ( $0.18\text{eV}$ ) are useful in infrared portion of spectrum.

⇒ Solar cell :-



→ Solar cell does not require any biasing voltage.

Emf generated is called photovolt. In solar cells, thin <sup>n</sup>-type of semiconductor is sandwiched over a thick p-type of semiconductor. There is an arrangement of metal fingers over the n-type of semiconductor which is covered by a glass led with anti-reflecting coating.

The bottom of p-type silicon diode is attached by a metal contact. Basically solar cell is a transducer which converts solar energy to electrical energy.

→ When a light of  $340 \text{ nm}$  to  $1120 \text{ nm}$  strikes at the top of solar cell, the light directly approaches to the depletion layer where free atoms of silicon are present. Due to the influence of light having  $\lambda > E_g$  of silicon, electron got free from the atom and approaches towards the n-type due to electric field generated on the carrier pair. Now got diffused towards p-type and collected at the metal contact. Hence, all the electrons are collected by metal fingers. Due to the polarity difference between both the metal contacts of current can be considered.

Ans: → For large photovolt, and long life-time heavy doping is required. Also, series resistance of the device, be very small, so that ohmic power loss can be reduced.

Figure of merit or fill factor of a solar cell is given by,

$$\text{FET Factor} = \frac{P_m V_m}{P_{sc} V_{oc}}$$

where

$P_m \rightarrow$  maximum current delivered to the load.

$V_m \rightarrow$  maximum voltage delivered to the load.

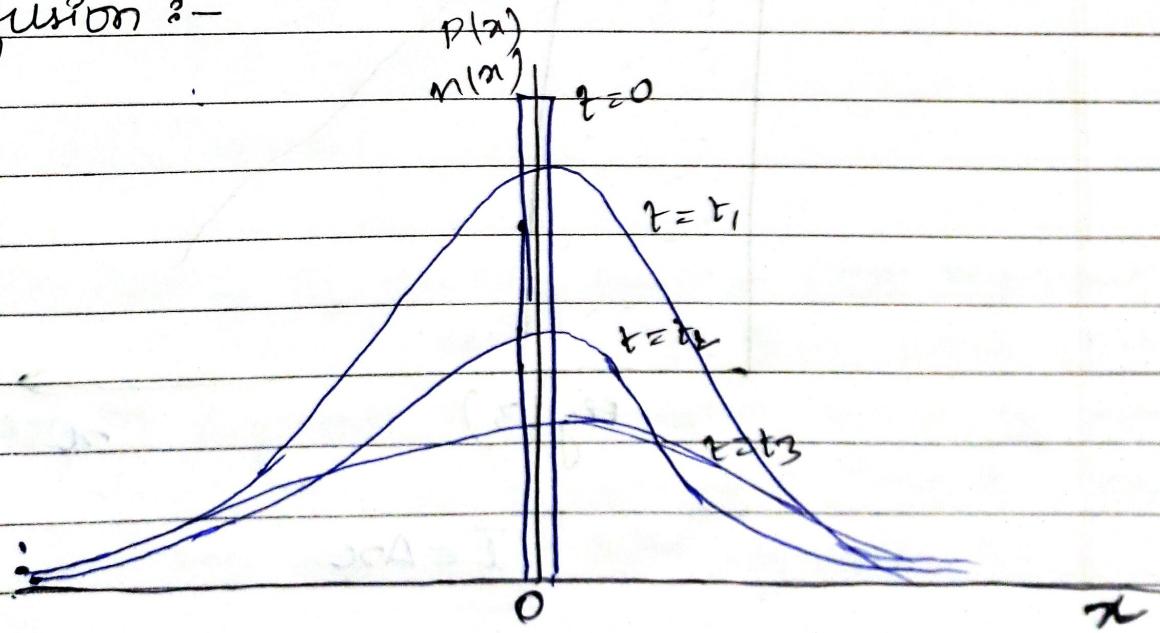
$P_{sc} \rightarrow$  short circuit current.

$V_{oc} \rightarrow$  open circuit voltage.

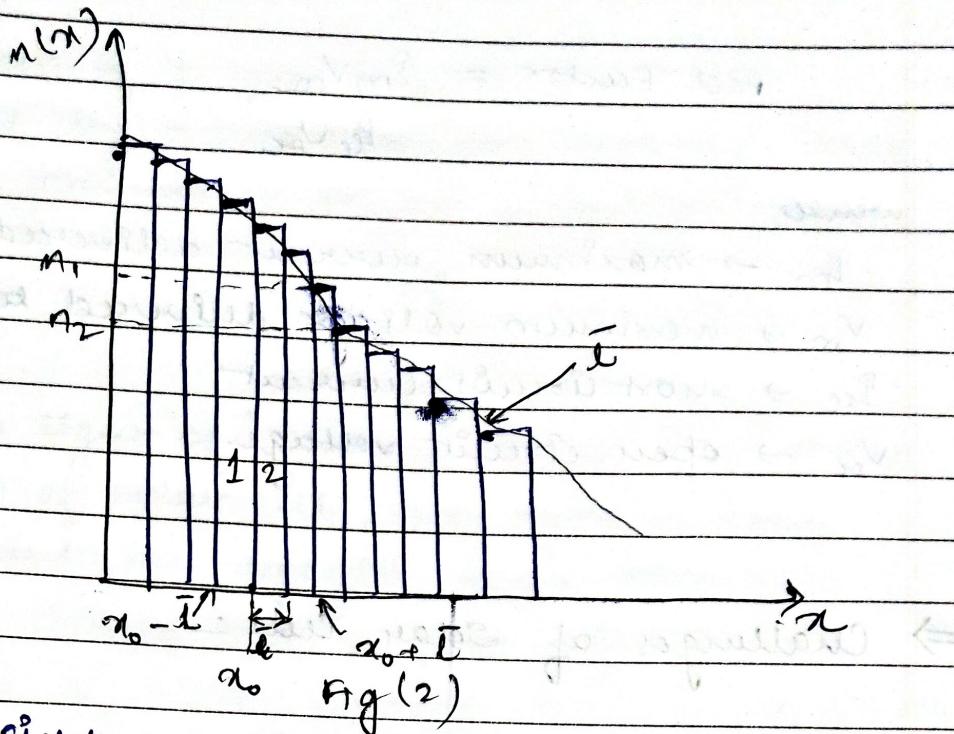
⇒ Challenges of Solar Cell :-

1. High cost of manufacturing.
2. Low efficiency upto 25% in case of silicon.

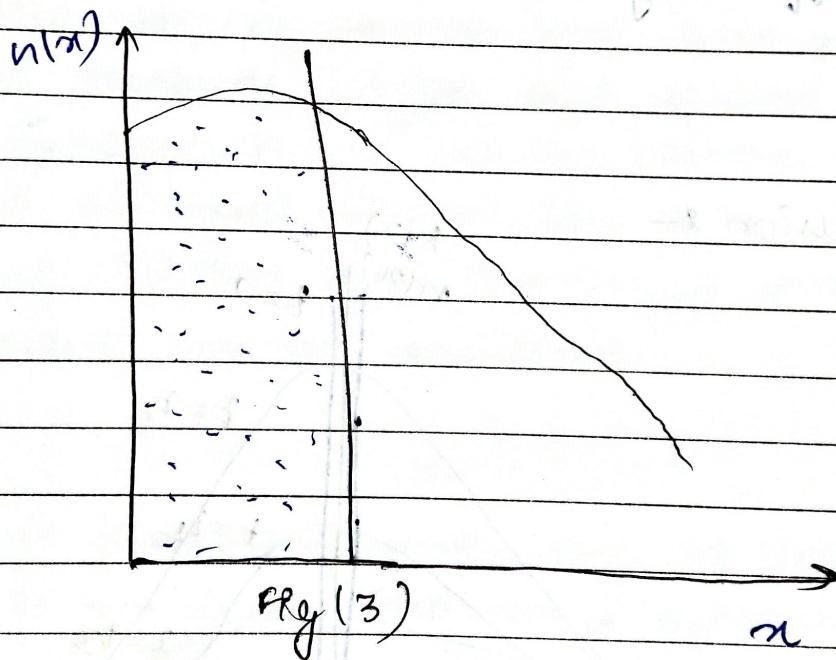
⇒ Diffusion :-



Fpg (1)



→ It obeys Fick's Law.



$$\bar{I} = \Delta x$$

∴

→ When excess carriers are created non-uniformly in a semiconductor, the electron and hole concentration vary with positions in the sample.

Any such spatial variation (gradient) in  $n$  and  $p$ , tends a net motion of the carriers from region of high concentration to region of lower concentration, which is known as diffusion.

→ Diffusion phenomenon is based Fick's law, which suggests that flux of particles is proportional to the gradient of particles.

→ Drift current is due to the motion of charge carriers arises by the force exerted on them by an electric field. whereas, drift velocity is the average velocity of the charge carriers in drift current.

→ Diffusion Process :-

→ As probability of electron passing from segment 1 to 2 or vice-versa is equal. In other words one electron in segment 1 have equal chance of moving left to right and in a mean free time,  $\bar{t}$ , one half of them will move into segment 2.

→ Net number of electron passing through  $\Delta t$  from left to right in 1 mean free time,  $\bar{t}$  is given by,  $\frac{1}{2}n_1 \bar{I}A - \frac{1}{2}n_2 \bar{I}A$ .

where

$A \rightarrow$  Area perpendicular to  $x$ -axis.

the electron flux density  $\phi_n(x_0)$  is given by

$$\phi_n(x_0) = \frac{\bar{l}}{2\bar{t}} (n_1 - n_2) \quad \text{--- (1)}$$

→ As  $\bar{l}$  is very small differential length the difference in electron concentration,

$$(n_1 - n_2) = \frac{n(x) - n(x + \Delta x)}{\Delta x} \bar{l} \quad \text{--- (11)}$$

where,  $x$  is taken at the centre of segment 1 and  $\Delta x = \bar{l}$ . In the limit of  $\Delta x \rightarrow 0$  eqn (1) can be given by

$$\phi_n(x) = \frac{\bar{l}^2}{2\bar{t}} \cdot \lim_{\Delta x \rightarrow 0} \frac{n(x) - n(x + \Delta x)}{\Delta x}$$

$$\Rightarrow \phi_n(x) = \frac{-\bar{l}^2}{2\bar{t}} \cdot \frac{dn(x)}{dx} \quad \text{--- (11)}$$

where

$\frac{dn(x)}{dx} \rightarrow$  carrier gradient

$\frac{\bar{l}^2}{2\bar{t}}$  → electron diffusion coefficient denoted by  $D_n$  having unit  $\text{cm}^2/\text{sec}$ .

→ -ve sign shows direction of decreasing electron concentration.

Hence,

$$\phi_n(x) = -D_n \frac{dn(x)}{dx} \quad \text{--- (11)}$$

$$\phi_p(x) = D_p \frac{dp(x)}{dx} \quad \text{--- } \checkmark$$

→ Hence, current density is given by

$$\begin{aligned} I_n(\text{diffusion}) &= -(-q) D_n \frac{dn(x)}{dx} \\ &= q D_n \frac{dn(x)}{dx} \end{aligned}$$

and,

$$\begin{aligned} I_p(\text{diffusion}) &= -(+q) D_p \frac{dp(x)}{dx} \\ &= -q D_p \frac{dp(x)}{dx} \end{aligned}$$

Electron and holes move together for a carrier gradient but the resulting <sup>electric</sup> current are for opposite direction because of opposing charges of electrons and holes.