

## Module - I

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### Elemental and compound semiconductors:

#### Introduction:

Basically Solids are classified in to 3.

1. Conductors

2. Semiconductors

3. Insulators

This classification is based on conductivity

#### Property.

Conductors: conductivity between  $10^4 - 10^6 \text{ S/cm}^2$ .

Semiconductors: Materials having electrical conductivity between conductors ( $10^4 - 10^6 \text{ S/cm}^2$ ) and insulators ( $10^{-18} - 10^{-8} \text{ S/cm}^2$ ).

They have conductivity between  $10^{-8} - 10^{-3} \text{ S/cm}^2$ .

Conductivity of a semiconductor can be varied by the process of doping. Conductivity can also be varied by changes in temperature, optical excitation and impurity content.

### Elemental and compound semiconductors

#### Elemental SC

→ Composed of single species of atoms.

→ Column IV eg:- Si, Ge

#### Compound SC

→ Composed of two or more species of atoms

##### 1.) Binary SC

It is a compound s.c with two elements.

→ Column III and IV combination.

→ Combination of different column IV elements  
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### List of Binary SCs

| <u>IV</u> group | <u>III</u> - <u>IV</u> compounds           | <u>II</u> - <u>VI</u> Compounds |
|-----------------|--|---------------------------------|
| Si, C           | AlP<br>AlAs<br>AlSb                        | ZnS<br>ZnSe<br>ZnTe             |
| Si, Ge          | GaP<br>GaAs<br>GaSb<br>InP<br>InAs<br>InSb | CdS<br>CdSe<br>CdTe             |

### Ternary SC

→ Compound SC with 3 elements

eg:- GaAsP, AlGaAs

### Quaternary SC

→ Compound SC with 4 elements

eg:- AlGaP, InGaAsP

### Applications:

| Device               | Material       |
|----------------------|----------------|
| Diode, Transistors   | Si, Ge         |
| FETs, Monolithic ICs | Si             |
| LEDs                 | GaN, GaAs, GaP |
| Photo detector       | CdSe, InSb     |
| Solar cells          | Si, GaAs       |
| LASER                | GaAs, AlGaAs   |
| Fluorescent Screen   | ZnS            |

## Types of Semiconductors:

### 1. Intrinsic S.C.

Perfect S.C. with no impurities or lattice defects.

- At 0K, valence band is completely filled and conduction band is empty. So there are no charge carriers at 0K.
- At higher temperature, electron-hole pairs are generated and valence band electrons are excited to conduction band, across the bandgap.
- These Electron-Hole Pairs (EHPs) are the only charge carriers in intrinsic S.C.
- The energy required to break the bond is the  $E_g$  (Bandgap energy).

$n_0$  = Concentration of electrons at thermal equilibrium

$p_0$  = concentration of holes

$n_i$ : Intrinsic carrier concentration

$$n_0 = p_0 = n_i$$

### 2. Extrinsic S.C.

In a SC, charge carriers may be purposely introduced by adding impurities in it. This process is called doping.

$$n_0 \neq p_0 \neq n_i$$

#### a) N-type SC

Majority carrier - Electrons

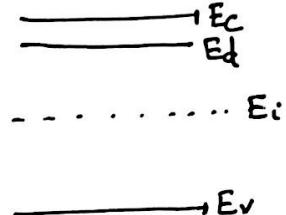
Minority carrier - holes

→ Atoms with 5 valence Es (column V) is added to the Si atom.

e.g.: P, As, Sb

- These N-type dopants are called Donors.
- Donors are neutral at 0K, when occupied by es and become +vely charged when they donate their excess valence es to the CB.
- So at 50-100 K, all of the es in the impurity level are donated to CB. Such impurity level is called donor level.

$$n_0 \gg (n_i, p_0)$$



## b) P type SC

Majority carriers  $\rightarrow$  holes

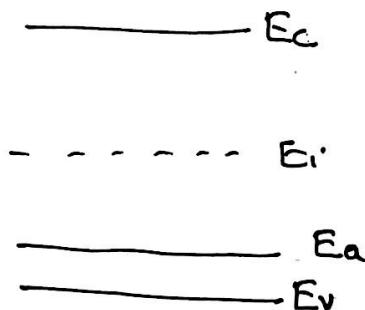
Minority carriers  $\rightarrow$  electrons

- Atoms with 3 valence es (column III) is added to the Si material.

e.g.: B, Ga, Al act as P type dopants

- These P-type dopants are called Acceptors.
- In such material, there is one bond incomplete.
- Thus at 0K, the acceptors are neutral, but at room T, they accept es and becomes -vely charged.
- Thus at 50-100 K, all of the es in the impurity VB ~~level~~ are accepted by the impurity level. This impurity level is called acceptor level.

$$p_0 \gg (n_i, n_0)$$



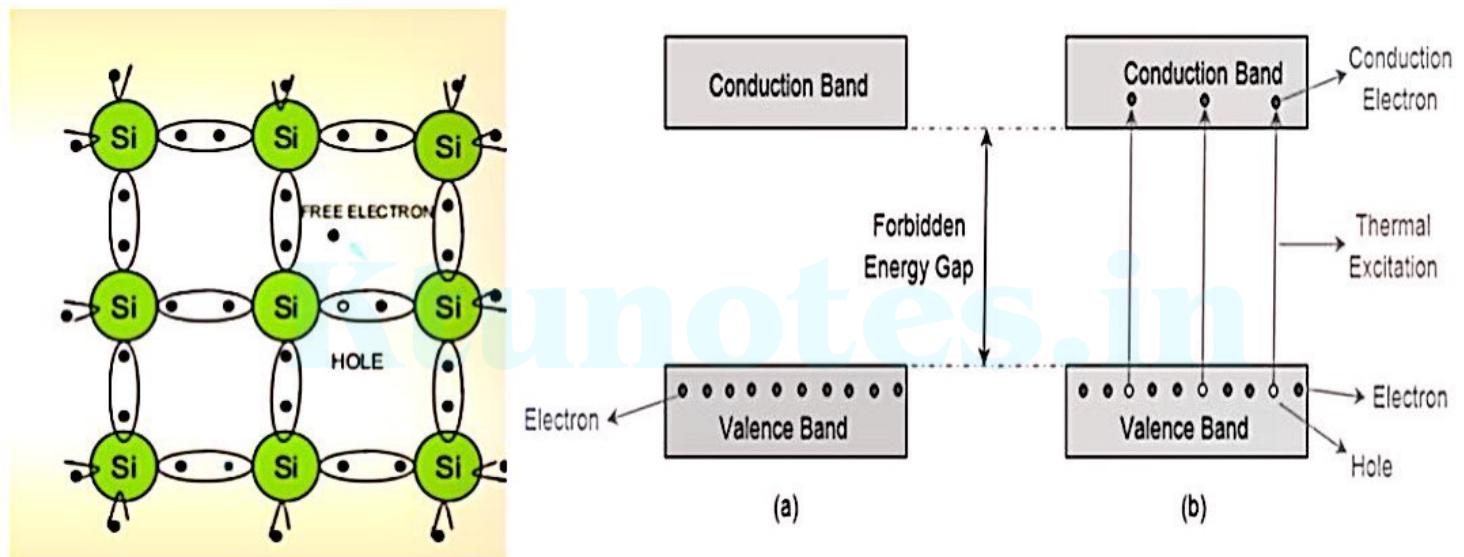
At any given temperature, if steady state carrier concentration is maintained, there is a recombination of electrons and holes (EHPs) at the same rate at which they are generated.

$$\text{Recombination rate } (\gamma_i) = \text{Generation rate } (g_i)$$

At any temperature, the rate of recombination of electrons and holes ( $\gamma_i$ ) is proportional to the equilibrium concentration of holes ( $P_0$ ) and electrons ( $n_0$ ).

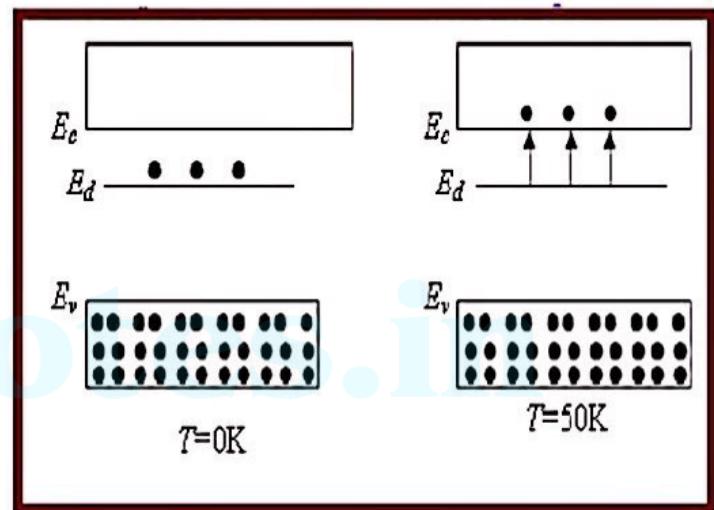
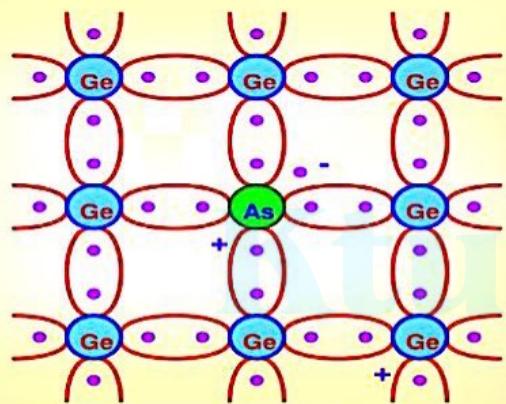
$$\gamma_i = K_r n_0 P_0 = K_r \cdot n_i^2 = g_i$$

where  $K_r$  is the constant of proportionality depending on the recombination mechanism.



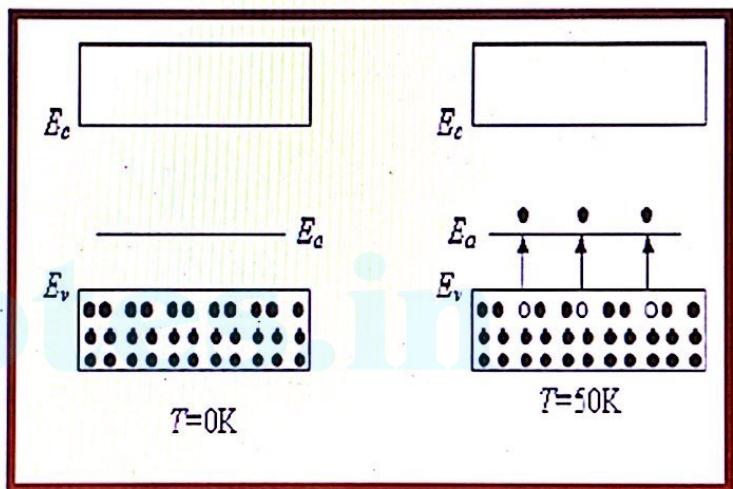
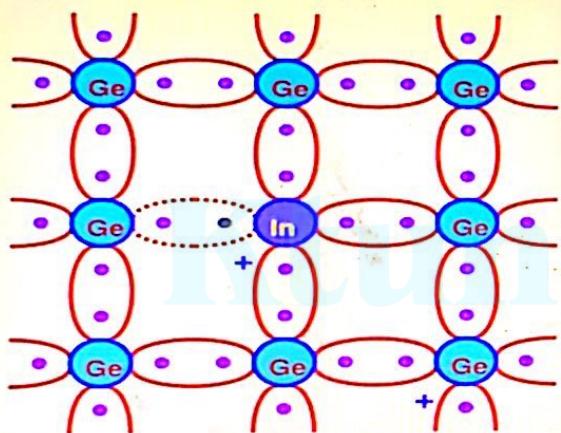
Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K

### N - Type Semiconductors:



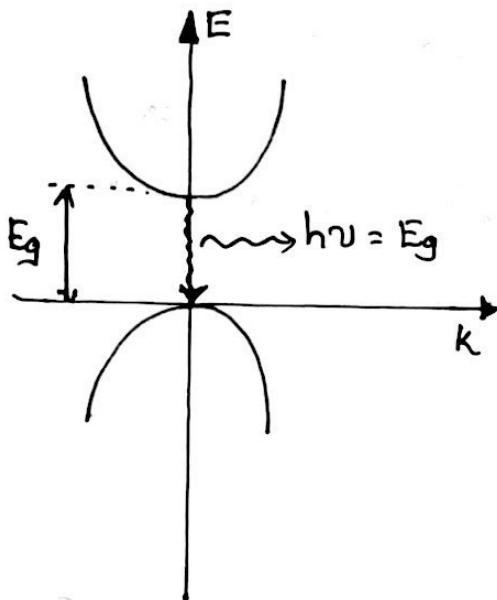
**Fig.** Donation of electrons from donor level to conduction band.

### P - Type Semiconductors:

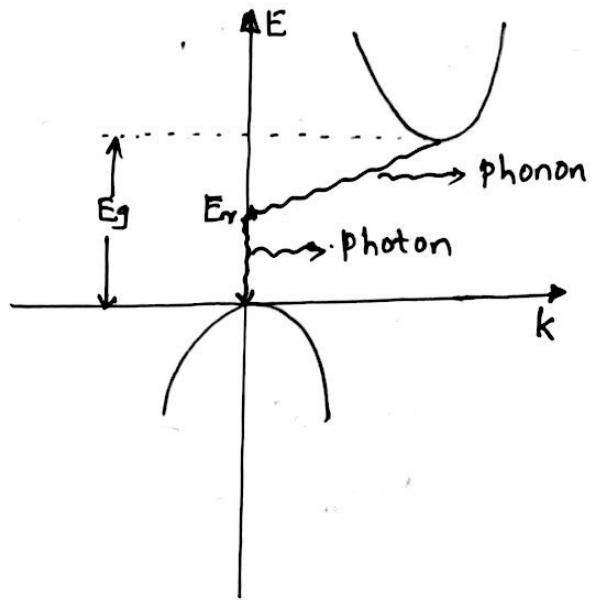


## Direct and indirect semiconductors

### Direct SC



### Indirect SC



### Direct sc

- Minimum energy of  $\bar{e}$  in the CB equals maximum energy of  $\bar{e}$  in the VB.
- ie, They have same momentum value or  $k$  value ( $k=0$ ) for  $\bar{e}$ s in the CB, and holes in the VB.
- $\bar{e}$ s in the CB can easily fall to an empty state in the VB giving off the energy difference  $E_g$  as photon of light w/o change in  $k$  or  $p$  value.

e.g:- GaAs,

Applications : LEDs, Lasers

### Indirect sc

- $\bar{e}$ s in  $CB_{min}$  and  $VB_{max}$  have different values of  $k$ . and thus momentum values are also different ( $p=\hbar k$ )
- So  $\bar{e}$  cannot recombine directly with a hole in the VB by releasing a photon.
- So  $\bar{e}$  in  $CB_{max}$  undergoes a momentum change and

energy change and come to an intermediate position between  $CB_{\min}$  and  $VB_{\max}$  at releasing a phonon.

→ This state is called recombination level ( $E_r$ ) or  $E_f$  or defect level, from where it falls to the  $VB_{\max}$  giving off energy difference as a photon of light.

e.g.: Si, Ge

Applications: Solar cells.

### Relation between Energy (E) and Momentum (P)

$$E = \frac{1}{2}mv^2 \quad \text{--- (1)}$$

We know,  $P = mv \quad \text{--- (2)}$

$$\textcircled{1} \Rightarrow E = \frac{1}{2} \frac{P^2}{m}$$

From DeBroglie eqn,  $\lambda = \frac{h}{P}$

$$P = \frac{h}{\lambda} = \frac{h/2\pi}{\lambda/2\pi}$$

$$\underline{P = \hbar k} \quad \text{where } k = \frac{2\pi}{\lambda}$$

$\hbar$ : angular momentum.,  $k$ : wave vector

$$E = \frac{P^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

$E \propto k^2$  ie,  $E$  vs  $k(P)$  is a parabolic curve, hence both CB and VB are seen to be parabolic.

## Effective Mass

- The movement of an electron in a lattice is different from that of an electron in free space.
- In a crystal lattice there are lots of internal forces due to positively charged ions/protons and negatively charged ions (electrons) which influences the motion in the lattice.
- So the mass of  $\bar{e}$  to be used cannot be that of individual  $\bar{e}$ . It needs to be w.r.t the effect of internal forces.

$$P = mv$$

$$\begin{aligned} E &= \frac{1}{2}mv^2 = \frac{1}{2} \frac{P^2}{m} \\ &= \frac{(\hbar k)^2}{2m} = \frac{\hbar^2 k^2}{2m} \quad \textcircled{1} \end{aligned}$$

Here the mass considered should be the effective mass of  $\bar{e}$ . ( $m_n^*$ )

$$\textcircled{1} \Rightarrow E = \frac{\hbar^2 k^2}{2m}$$

$$\frac{dE}{dk} = \frac{\hbar^2 \cdot 2k}{2m} = \frac{\hbar^2 k}{m} = \frac{P\hbar}{m}$$

$$\frac{dE}{dk} \cdot \frac{1}{\hbar} = \frac{P}{m} = v \quad \textcircled{2}$$

Thus first derivative of  $E$  with respect to  $k$  is related to velocity of the particle ( $v$ )

$$\frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

$$\frac{1}{\hbar^2} \cdot \frac{d^2 E}{dk^2} = \frac{1}{m} \quad \textcircled{3}$$

second derivative of E with respect to k is inversely proportional to mass of the particle.

$$\textcircled{3} \Rightarrow m^* = \frac{\hbar^2}{d^2 E / dk^2}$$

### Equilibrium and steady state conditions:

→ Equilibrium means thermal equilibrium. The solid has one well defined temperature and a constant Fermi energy.

→ Steady state means that the properties of the system do not change with time.

Non equilibrium states can be steady states if there is a source of energy to maintain the non equilibrium condition. Without the source of energy, the system would quickly settle into an equilibrium state.

→ A P-n junction with no voltage applied is in an equilibrium state.

→ The P-n junction diode with a voltage applied across it is in a non equilibrium, but steady state.

**Equilibrium:** Condition of no external excitation (except temperature) and no net motion of charge.

**Steady state:** Non equilibrium state in which all processes are constant and are balanced by opposing processes.

## Fermi Dirac Distribution (FDD)

In order to understand the electrical properties of a semiconductor, it is necessary to understand the number of charge carriers/cm<sup>3</sup> in the material, which is called carrier concentration.

- To obtain the equations for carrier concentration, the distribution of carriers over the available energy states needs to be studied. This is done by using statistical methods.
- ie, studying the property / ~~of~~ behaviour of a group as a whole instead of as an individual particle
- This is done by using Fermi Dirac Distribution Function (FDD).
- It gives the distribution of es over a range of allowed energy levels at thermal equilibrium.

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}} \quad \textcircled{1}$$

where

$f(E)$  : Fermi Dirac Distribution Function

$K$  : Boltzmann's constant  $8.62 \times 10^5 \text{ ev/K}$   
or

$T$  : Absolute Temperature  $1.38 \times 10^{-23} \text{ J/K}$

$E_F$  : Fermi energy level / Fermi level

$f(E)$  gives the probability that the energy level ' $E$ ' is filled by electrons at absolute temperature under thermal equilibrium.

At 0K,

$$\rightarrow \text{when } E > E_F, \quad f(E) = \frac{1}{1 + e^{(E-E_F)/k \cdot 0}} = \frac{1}{1 + e^{\infty}} = \frac{1}{\infty} = 0$$

When  $E < E_F$ ,

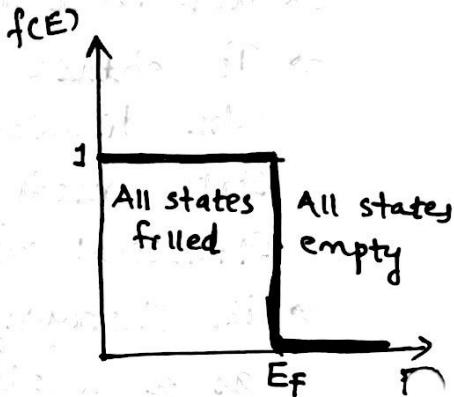
$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}} = \frac{1}{1 + e^{-\infty}} = \frac{1}{1 + \frac{1}{e^{\infty}}} = \frac{1}{1 + 0} = 1$$

So  $f(E > E_F) = 0$

$f(E < E_F) = 1$ .

When  $E = E_F$ ,

$$\Rightarrow f(E = E_F) = \frac{1}{1 + e^{(E_F - E_F)/kT}} = \frac{1}{1 + e^0} = \frac{1}{2}$$



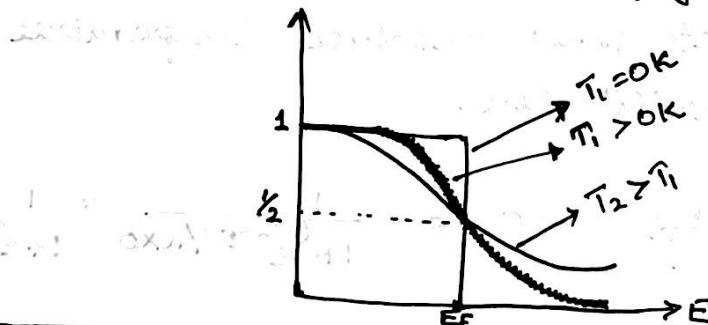
$$\text{atomic units} \Rightarrow 1 = \frac{1}{1 + e^{0/kT}} = \frac{1}{1 + 1} = \frac{1}{2}$$

$$\therefore \text{Probability of finding an electron} = \frac{1}{2}$$

Thus Fermi level ( $E_F$ ) is the energy level at which probability of half being occupied by an electron or the energy level at which the probability of finding the electron is 50%.

At OK, curve takes rectangular distribution implies that, every available states up to  $E_F$  is filled with electrons and all the states above  $E_F$  is empty.

→ At some temperature above OK (say  $T_1$ ), there is some probability of  $f(E)$  that states above  $E_F$  are filled and a corresponding probability  $[1 - f(E)]$  that states below  $E_F$  are empty.



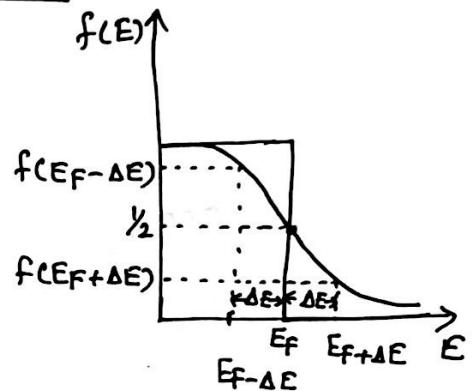
→ Probability  $f(E_F + \Delta E)$  that a state  $\Delta E$  above  $E_F$  is filled is the same as the probability  $[1 - f(E_F - \Delta E)]$  that a state  $\Delta E$  below  $E_F$  is empty.

Prove that

$$f(E_F + \Delta E) = 1 - f(E_F - \Delta E)$$

Proof:

$$\begin{aligned} f(E_F + \Delta E) &= \frac{1}{1 + e^{(E_F + \Delta E - E_F)/kT}} \\ &= \frac{1}{1 + e^{\Delta E/kT}} \end{aligned}$$



Probability  $f(E_F - \Delta E)$  that a state  $\Delta E$  below  $E_F$  is filled,

$$f(E_F - \Delta E)$$

So probability that a state  $\Delta E$  below  $E_F$  is empty

$$1 - f(E_F - \Delta E)$$

$$\begin{aligned} f(E_F - \Delta E) &= \frac{1}{1 + e^{(E_F - \Delta E - E_F)/kT}} \\ &= \frac{1}{1 + e^{-\Delta E/kT}} \end{aligned}$$

$$1 - f(E_F - \Delta E) = 1 - \frac{1}{1 + e^{-\Delta E/kT}}$$

$$= \frac{1 + e^{-\Delta E/kT}}{1 + e^{-\Delta E/kT}} = \frac{e^{-\Delta E/kT}}{1 + e^{-\Delta E/kT}}$$

Divide  $N_r$  and  $D_r$  by  $e^{\Delta E/kT}$

$$\Rightarrow \frac{e^{-\Delta E/kT}}{e^{-\Delta E/kT} + \frac{1}{e^{\Delta E/kT}}} = \frac{1}{e^{\Delta E/kT} + 1}$$

$$\begin{aligned} &= \frac{1}{\frac{1}{e^{\Delta E/kT}} + 1} = \frac{1}{e^{-\Delta E/kT} + 1} \\ &= \frac{1}{1 + e^{-\Delta E/kT}} \\ &= \underline{\underline{f(E_F + \Delta E)}} \end{aligned}$$

## Fermi Dirac Distribution applied to intrinsic and Extrinsic semiconductors

### Intrinsic SC

In Intrinsic SC,

$$\text{No. of } \bar{e}s = \cancel{\text{No. of } \bar{e}s} = \text{No. of holes}$$

$$n_b = p_0$$

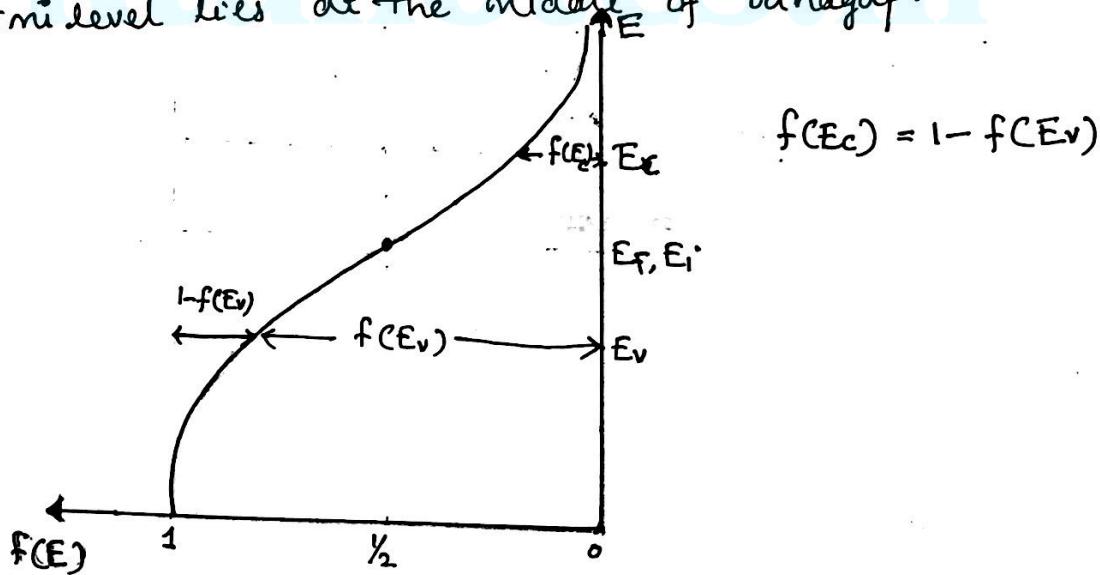
In this case, there is equal no. of states at the edges of CB and VB. ie, there is equal chances of finding an  $\bar{e}$  at CB edge as there is of finding a hole at the VB edge.

$$\begin{aligned} \text{Probability of occupancy in CB} &= f(E_c) \\ \text{Probability of vacancy in VB} &= 1 - f(E_v) \end{aligned}$$

$$f(E_c) = 1 - f(E_v)$$

i.e., Concentration of holes in VB = Concentration of  $\bar{e}s$  in CB

So Fermi level lies at the middle of bandgap.

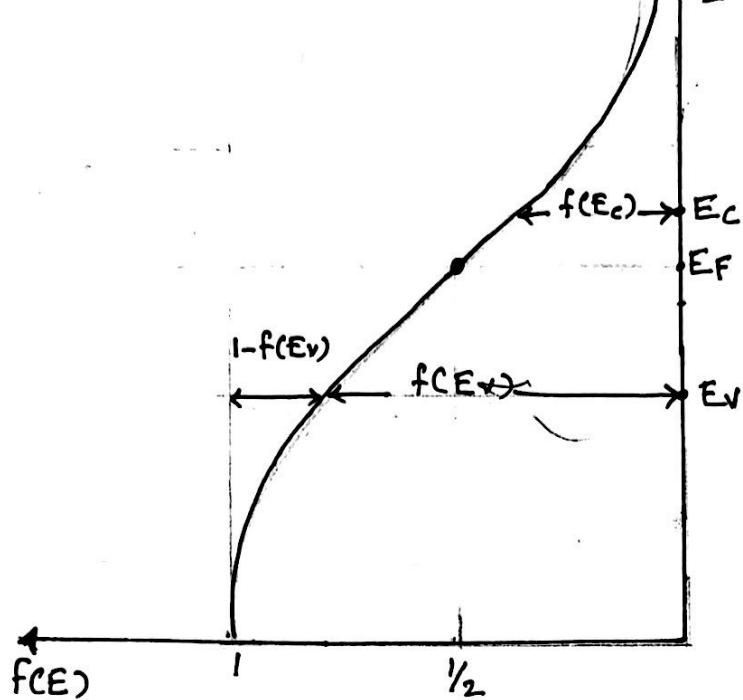


### Extrinsic SC.

#### a) N-type SC

In N-type SC, no. of  $\bar{e}s$  in CB is more compared to hole concentration in VB.

$$\text{So } f(E_c) \gg 1 - f(E_v)$$

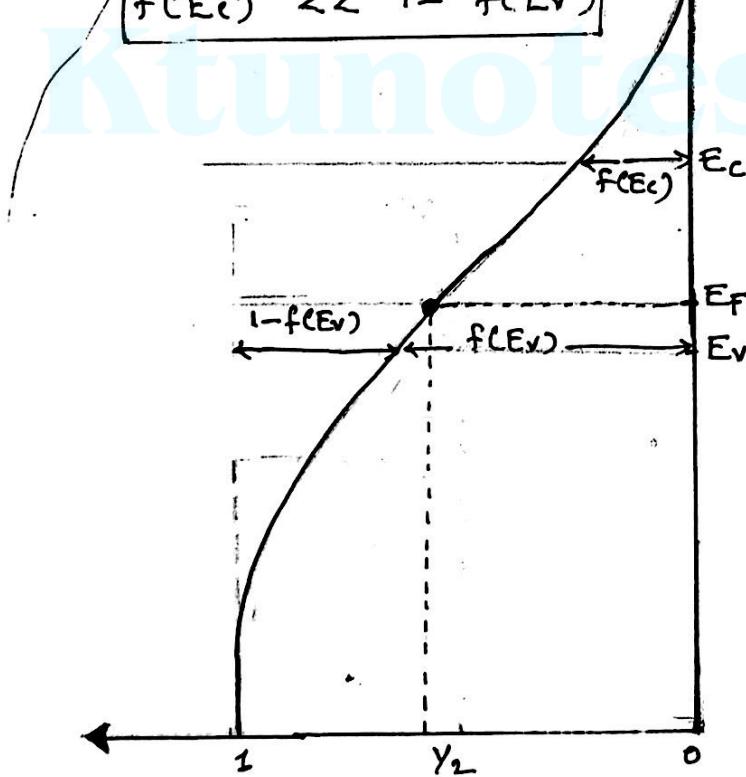


$$f(E_c) \gg 1 - f(E_v)$$

### (b) P type sc

~~concentration of holes in VB is greater than concentration of electrons in CB.~~

$$f(E_c) \ll 1 - f(E_v)$$



$$f(E_c) \ll 1 - f(E_v)$$

## Electron and Hole concentrations at equilibrium ( $n_0, p_0$ )

The Fermi Dirac Distribution can be used to calculate the concentrations of electrons & holes in a SC, if we know the densities of available states in CB and VB.

$$\text{ie, } n_0 = \int_{E_c}^{\infty} f(E) N(E) dE \quad \text{--- (1)}$$

where  $N(E)dE$  is the density of states per  $\text{cm}^3$  in the energy range  $dE$ .  
(DOS)

So number of es per unit volume in the energy range

- $dE$  is the product of DOS and the probability of occupancy.
- Let  $N_c$  be the effective density of states for the distributed electron states in the CB edge.

Then

$$n_0 = N_c \cdot f(E_c) \quad \text{--- (2)}$$

$$\text{We know, } f(E_c) = \frac{1}{1 + e^{-(E_c - E_F)/kT}} \quad \text{--- (3)}$$

$$\text{but } E_c - E_F \gg kT$$

$$\text{③} \Rightarrow f(E_c) = \frac{1}{e^{-(E_c - E_F)/kT}} = e^{-(E_c - E_F)/kT}$$

$$f(E_c) = e^{-\frac{(E_c - E_F)/kT}{e}} \quad \text{--- (4)}$$

$$\text{②} \Rightarrow n_0 = N_c \cdot e^{-\frac{(E_c - E_F)/kT}{e}} \quad \text{--- (5)}$$

$$\text{where } N_c = 2 \left( \frac{2\pi m_n^* kT}{h^2} \right)^{3/2}$$

Concentration of holes in VB is

$$p_0 = N_v [1 - f(E_v)] \quad \text{--- (6)}$$

where  $N_V$  is the effective DOS in the VB.

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$$\begin{aligned}
 1 - f(E_V) &= 1 - \frac{1}{1 + e^{(E_V - E_F)/KT}} \\
 &= \frac{1 + e^{(E_V - E_F)/KT} - 1}{1 + e^{(E_V - E_F)/KT}} \\
 &= \frac{e^{(E_V - E_F)/KT}}{1 + e^{(E_V - E_F)/KT}}
 \end{aligned}$$

Divide Numerator & Denominator with  $e$

$$1 - f(E_V) = \frac{1}{e^{-(E_V - E_F)/KT} + 1}$$

$$\text{But } E_F - E_V \gg KT \quad (E_V - E_F)/KT$$

$$1 - f(E_V) = \frac{1}{e^{-(E_V - E_F)/KT}} = e^{-(E_V - E_F)/KT}$$

$$1 - f(E_V) = \frac{e^{-(E_F - E_V)/KT}}{e^{-(E_F - E_V)/KT}} \quad \textcircled{7}$$

$$\textcircled{6} \Rightarrow P_0 = N_V \cdot \frac{e^{-(E_F - E_V)/KT}}{e^{-(E_F - E_V)/KT}} \quad \textcircled{8}$$

$$\text{where } N_V = 2 \left( \frac{2\pi m_p^*}{h^2} \right)^{3/2} KT$$

Multiply  $\textcircled{5}$  and  $\textcircled{8}$

$$n_0 \cdot P_0 = N_c \cdot e^{-(E_C - E_F)/KT} \cdot N_V \cdot e^{-(E_F - E_V)/KT}$$

$$n_0 P_0 = N_c \cdot N_V \cdot e^{-(E_C - E_V)/KT} \quad \textcircled{9}$$

$$n_0 P_0 = N_c \cdot N_V \cdot e^{-E_g/KT} \quad \textcircled{10} \quad \because E_C - E_V = E_g$$

For intrinsic material,  $E_F$  lies at  $E_i$

$$\textcircled{5} \Rightarrow n_i = N_c \cdot e^{-(E_C - E_i)/KT} \quad \textcircled{11}$$

$$\textcircled{8} \Rightarrow P_i = N_v \cdot e^{-\frac{(E_i - E_v)/kT}{}} \quad \text{--- } \textcircled{12}$$

Multiply \textcircled{11} & \textcircled{12},

$$n_i \cdot P_i = N_c \cdot e^{-\frac{(E_c - E_i)/kT}{}} \cdot N_v \cdot e^{-\frac{(E_i - E_v)/kT}{}}$$

$$n_i \cdot P_i = N_c \cdot N_v \cdot e^{-\frac{(E_c - E_v)/kT}{}} \quad \text{--- } \textcircled{13}$$

$$n_i \cdot P_i = n_i^2 \quad \text{since } n_i = P_i$$

$$\textcircled{13} \Rightarrow n_i^2 = N_c \cdot N_v \cdot e^{-\frac{(E_c - E_v)/kT}{}}$$

$$n_i^2 = N_c \cdot N_v \cdot e^{-\frac{Eg/kT}{}} \quad \text{--- } \textcircled{14}$$

$$n_i = \sqrt{N_c \cdot N_v \cdot e^{-\frac{Eg/2kT}{}}} \quad \text{--- } \textcircled{15}$$

Compare \textcircled{10} and \textcircled{14}, gives

$$n_0 \cdot P_0 = n_i^2 \quad \text{Mass Action Law} \quad \text{--- } \textcircled{16}$$

Compare \textcircled{11} and \textcircled{15}

$$\text{If } N_c = N_v \text{ in } \textcircled{15}, \quad E_c - E_i = \frac{Eg}{2} \quad \text{--- } \textcircled{17a}.$$

i.e. Intrinsic level  $E_i$  is at the middle of bandgap.

$$\text{or } E_p - E_v = Eg/2. \quad \text{--- } \textcircled{17b}$$

$n_0, P_0$  in terms of  $n_i, p_i$

$$\textcircled{5} \Rightarrow N_c = \frac{n_0}{e^{-\frac{(E_c - E_F)/kT}{}}}$$

$$\textcircled{11} \Rightarrow N_c = \frac{n_i}{e^{-\frac{(E_c - E_i)/kT}{}}}$$

$$\text{Equating, } \frac{n_0}{e^{-\frac{(E_c - E_F)/kT}{}}} = \frac{n_i}{e^{-\frac{(E_c - E_i)/kT}{}}}$$

$$\Rightarrow n_0 = n_i \cdot e^{\frac{(E_F - E_P)/kT}{}} \quad \text{--- } \textcircled{18}$$

For  $P_0$ ,

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$$\textcircled{8} \Rightarrow N_V = \frac{P_0}{e^{-(E_F - E_V)/kT}}$$

$$\textcircled{12} \Rightarrow N_V = \frac{P_i}{e^{-(E_i - E_V)/kT}}$$

Equating,

$$\frac{P_0}{e^{-(E_F - E_V)/kT}} = \frac{P_i}{e^{-(E_i - E_V)/kT}}$$

$$P_0 = P_i \cdot e^{(E_i - E_F)/kT}$$

\textcircled{19}

Note :

In \textcircled{18}, when  $E_F = E_i^*$ ,  $n_0 = n_i^*$  <sup>For Intrinsic S.C</sup>  $E_F$  lies at  $E_i^*$ .

As  $E_F$  moves away from  $E_i^*$  towards CB,

$E_F - E_i^* \uparrow$  so  $n_0 \uparrow$  exponentially.

Why  $P_0$  varies from  $P_i$  or  $n_i^*$  to higher values as  $E_F$  moves away from  $E_i^*$  towards VB.

Ques. If the condition  $E_F > E_i^*$  is given, then what will happen?

Ans. In this case,  $E_F - E_i^* > 0$

so  $e^{(E_i^* - E_F)/kT} < 1$

$\therefore P_0 < P_i$

$\therefore n_0 < n_i^*$

$\therefore P_0 < n_0$

$\therefore P_0 < n_i^*$

$\therefore P_0 < P_i$

$\therefore n_0 < n_i^*$

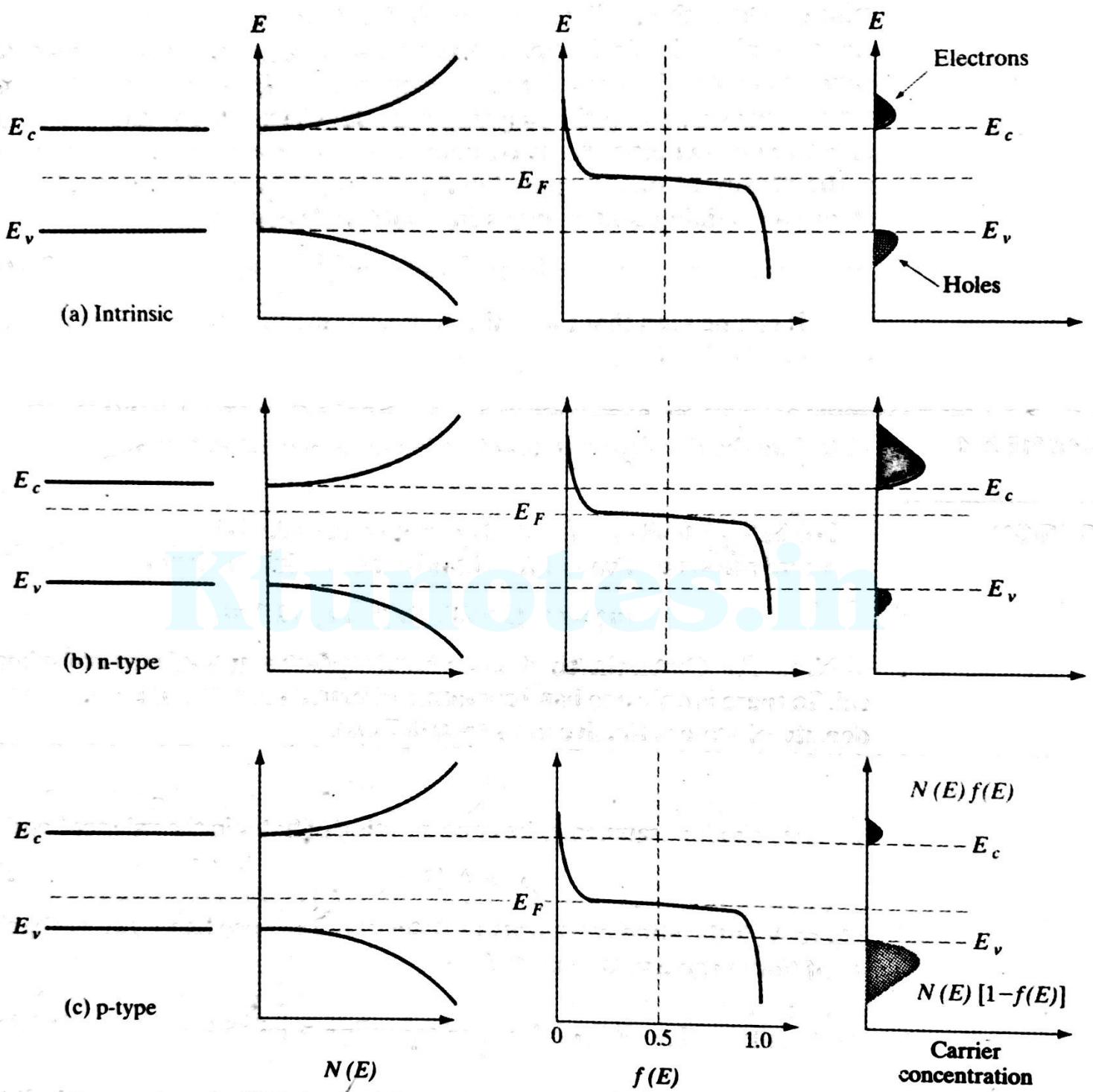


Figure 3-16

Schematic band diagram, density of states, Fermi-Dirac distribution, and the carrier concentrations for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at thermal equilibrium.

## Excess carriers in semiconductors:

Charge carriers in semiconductors which are in excess of their thermal equilibrium value are called excess carriers. They can be generated by

1. Optical excitation
2. Electron bombardment

Consider a semiconductor. A photon of energy  $h\nu$  is incident on it. If  $h\nu \geq E_g$ , the photon is absorbed in the SC, causing excitation of  $\bar{e}s$  from VB to CB. This results in the generation of EHPs. These EHPs in excess of their thermal equilibrium values are called excess carriers.

Optically generated  $\bar{e}$  and hole concentrations are equal.

|                       |
|-----------------------|
| $n = n_0 + \delta n$  |
| $p = p_0 + \delta p$  |
| $\delta n = \delta p$ |

$n$ : Total  $\bar{e}$  concentration

$n_0$ : equilibrium  $\bar{e}$  concentration

$\delta n$ : excess  $\bar{e}$  concentration

$p$ : Total hole concentration

$p_0$ : equilibrium hole concentration

$\delta p$ : excess hole concentration

## Low level injection:

If excess carrier concentration is small compared to the equilibrium majority carrier concentration.

i.e.  $\frac{\delta n, \delta p}{\delta n, \delta p} \ll n_0$  ( $n$  type)

$\frac{\delta n, \delta p}{\delta n, \delta p} \ll p_0$  ( $p$  type)

## High level injection:

$$\underline{\delta n, \delta p \gg n_0} \quad (\text{n type})$$

$$\underline{\delta n, \delta p \gg p_0} \quad (\text{P type})$$

Excess carrier lifetime : Direct recombination

In direct recombination,  $\bar{e}$  from CB falls into a vacant state (hole) in the VB and the difference in energy is released as a photon.

Rate of decay of  $\bar{e}$  at any time  $t$  is proportional to the product of number of  $\bar{e}$ s and number of holes remaining at time  $t$ .

Net rate of change in  $\bar{e}$  concentration,

$$\frac{d n(t)}{dt} = \alpha_r^g n_i^2 - \alpha_r^r n(t) \cdot P(t) \quad \text{--- (1)}$$

(Thermal generation rate - Recombination rate)

But we have

$$n = n_0 + \delta n \quad \text{--- 2(a)}$$

$$P = P_0 + \delta P \quad \text{--- 2(b)}$$

Substitute 2(a) & (b) in (1),

$$\frac{d}{dt}(n_0 + \delta n) = \alpha_r^g n_i^2 - \alpha_r^r (n_0 + \delta n)(P_0 + \delta P)$$

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

$$= \alpha_r^g n_i^2 - \alpha_r^r [n_0 P_0 + P_0 \delta n(t) + n_0 \delta P(t) + \delta n(t) \cdot \delta P(t)]$$

$$\text{But } \delta n(t) = \delta P(t)$$

$$= \alpha_r^2 n_i^2 - \alpha_r [n_0 P_0 + P_0 \delta_n(t) + n_0 \delta_n(t) + \delta_n^2(t)]$$

$$= \alpha_r^2 n_i^2 - \alpha_r [n_0 P_0 + \delta_n(t) [n_0 + P_0] + \delta_n^2(t)] \quad \text{--- (3)}$$

$$\alpha_r^2 n_0 P_0 = \alpha_r^2 n_i^2$$

$\frac{d}{dt} n_0 = 0 \quad \because n_0 \text{ & } P_0 \text{ are equilibrium values}$   
which are constant.

$$\text{③} \Rightarrow \frac{d}{dt} \delta_n(t) = \alpha_r^2 n_i^2 - \alpha_r^2 n_i^2 - \alpha_r \cdot (n_0 + P_0) \delta_n(t) \\ - \alpha_r \cdot \delta_n^2(t)$$

$$\frac{d}{dt} \delta_n(t) = -\alpha_r \cdot (n_0 + P_0) \frac{\delta_n(t)}{\alpha_r} - \alpha_r \delta_n^2(t) \quad \text{--- (4)}$$

Consider low level injection,

$\delta_n(t)$  is small, so  $\delta_n^2(t)$  is also small. neglect

For P type,  $P_0 > n_0$ , neglect  $n_0$ .

$$\text{④} \Rightarrow \frac{d}{dt} \delta_n(t) = -\alpha_r \cdot P_0 \cdot \delta_n(t) \quad \text{--- (5)}$$

$$\text{Soh is } \delta_n(t) = \Delta n \cdot e^{-\alpha_r \cdot P_0 \cdot \delta_n(t)} = \Delta n \cdot e^{-t/\tau_n}$$

$\delta_n(t) = \Delta n \cdot e^{-t/\tau_n}$

--- (6)

$\Delta n$ : Initial excess carrier concentration ( $t=0$ )

$\tau_n = \frac{1}{\alpha_r \cdot P_0}$

= Minority carrier life time  
or

Recombination life time in P type

$\tau_p = \frac{1}{\alpha_r \cdot n_0}$

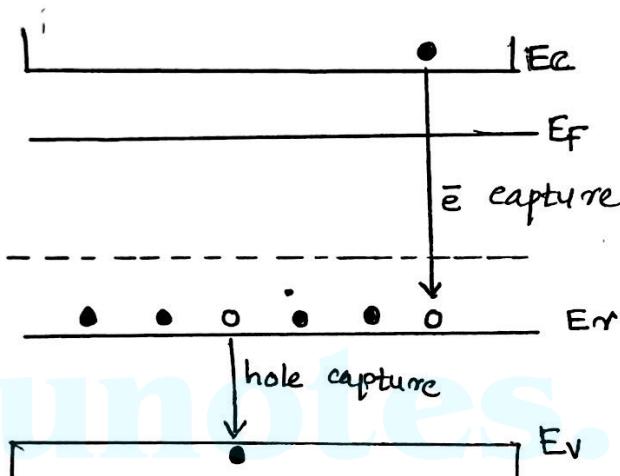
In general,

$\tau_n = \frac{1}{\alpha_r (n_0 + P_0)}$

## Indirect recombination; Trapping

In indirect recombination semiconductors, recombination occurs through recombination levels or centres within the bandgap.

Any impurity or lattice defect can serve as recombination centre, if it is capable of receiving carriers of one type and subsequently capturing the opposite type of carriers, thereby annihilating the pair.



The recombination level  $E_r$  is filled with  $\bar{e}$ s. When excess electrons and holes are created, each electron-hole pair recombines at  $E_r$  in two steps.

### 1. Hole capture:

Falling of an electron from  $E_r$  to the VB leaving behind an empty state in the recombination level  $E_r$  creating heat energy.

### 2. Electron capture

When  $\bar{e}$  in CB falls to an empty state at  $E_r$ , it is called  $\bar{e}$  capture.

## Trapping

Recombination can be delayed if the captured carrier is thermally reexcited back to its original band before the capture of opposite type of carrier ie, If electron capture does not follow immediately after hole capture, the hole is thermally reexcited to the VB.

- This process delays recombination because a hole capture needs to occur again before the recombination can be completed.
- When a carrier is trapped temporarily at a centre and reexcited without recombination, that process is called temporary trapping.

## Steady state Carrier Generation:

At equilibrium,

$$\text{Generation rate} = \text{Recombination rate}$$

$$g(t) = \alpha_r n_i^2 = \alpha_r n_0 P_0 \quad \dots \quad (1)$$

When optical excitation is considered,

$$g(t) + g_{op} = \alpha_r n p \quad \dots \quad (2)$$

$$= \alpha_r (n_0 + \delta n) (P_0 + \delta p)$$

$$= \alpha_r n_0 P_0 + \alpha_r n_0 \delta p + \alpha_r P_0 \delta n + \alpha_r \delta p \delta n$$

$$\therefore \delta n = \delta p$$

$$g(t) + g_{op} = \alpha_r n_0 P_0 + \alpha_r n_0 \delta n + \alpha_r P_0 \delta n + \alpha_r \cdot \delta n^2$$

$$= \alpha_r n_0 P_0 + \alpha_r (n_0 + P_0) \delta n + \alpha_r \cdot \delta n^2$$

$\delta n$  is small, neglect  $\delta n^2$

$$g(t) + g_{op} = \underbrace{\alpha_s n_0 p_0}_{g(t)} + \alpha_r (n_0 + p_0) \delta_n \quad \text{--- (3)}$$

$$\text{So } g_{op} = \alpha_s (n_0 + p_0) \delta_n$$

$$g_{op} = \cancel{\alpha_s} \cdot \frac{\delta_n}{Z_n}$$

$$\boxed{\delta_n = \delta_p = g_{op} \cdot Z_n}$$

Quasi Fermi levels,  $F_n, F_p$

When excess carriers are present, equilibrium fermi level  $E_F$  is meaningless. It does not represent carrier concentration. So separate quasi Fermi levels are defined.

$F_n$  : Excess Fermi level for electrons

$F_p$  : Excess Fermi level for holes

If n type material is considered, it has Fermi level  $E_F$  near the CB.

If excess carriers are added,  $\delta_n = \delta_p$ . Thus  $F_n$  is close to  $E_F$  (or similar to  $E_F$ ), but  $F_p$  is far away from  $E_F$ .

Ec

$\overline{E_F, F_n}$

$\overline{E_i}$

$\overline{F_p}$

$\overline{E_V}$

When excess carriers are present,

the deviations  $F_n$  &  $F_p$  from  $E_F$  indicates how far electrons & holes are

from equilibrium values of  $n_0$  &  $p_0$ .

$$n = n_i e^{(F_n - E_i)/kT} \quad \text{--- (1)}$$

$$P = P_i e^{(E_i - F_p)/kT} \quad \text{--- (2)}$$

$$n_p = n_i P_i e^{(F_n - F_p)/kT}$$

$$\boxed{n_p = n_i^2 \cdot e^{(F_n - F_p)/kT}}$$

Since  $n_i = P_i$