

1/1/08/20  
Monday

## MODULE - I

Elemental and compound semiconductors, Intrinsic and extrinsic semiconductors, Concept of effective mass, Fermions- Fermi Dirac distribution, Fermi level, Doping and Energy band diagram, Equilibrium and steady state conditions, Density of States & Effective density of states, Equilibrium concentration of electrons and holes.

Excess carriers in semiconductors: Generation and recombination mechanisms, excess carriers, quasi Fermi levels.

Generation and recombination mechanisms  
due to carrier trapping and due to  
excitation state trapping due to

(a) Direct emission

(b) Indirect emission

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## Elemental and compound Semiconductors

### Elemental Semiconductors

Semiconductors which are contributed by a single species of atoms are called elemental semiconductors.

e.g.: Silicon, germanium, calcium

### Compound Semiconductors

Semiconductors which are contributed by 2 or more than <sup>atom</sup> different species of atoms is called compound semiconductors.

e.g.: Gallium Arsenide (GaAs)

Aluminum Arsenide (AlAs)

Compound Semiconductors again classified in two types:

1. Binary Compound Semiconductors: consist of two type species of atoms.

eg: Gallium Arsenide ( $\text{GaAs}$ )  
Indium phosphide ( $\text{InP}$ )

2. Pernary compound Semiconductors: consists of 3 elements.

eg: Gallium Arsenide phosphide ( $\text{GaAsP}$ )

Aluminium Arsenide phosphide ( $\text{AlGaP}$ )

## Energy Bands in Solid

When the atoms are brought together the application of Pauli's exclusion principle become important; when two atoms are completely isolated from each other so that there is an attraction of electron wave function between them. They can have identical electronic structure.

On a solid many atoms are brought together. So that different energy levels forms a continuous band of energies.

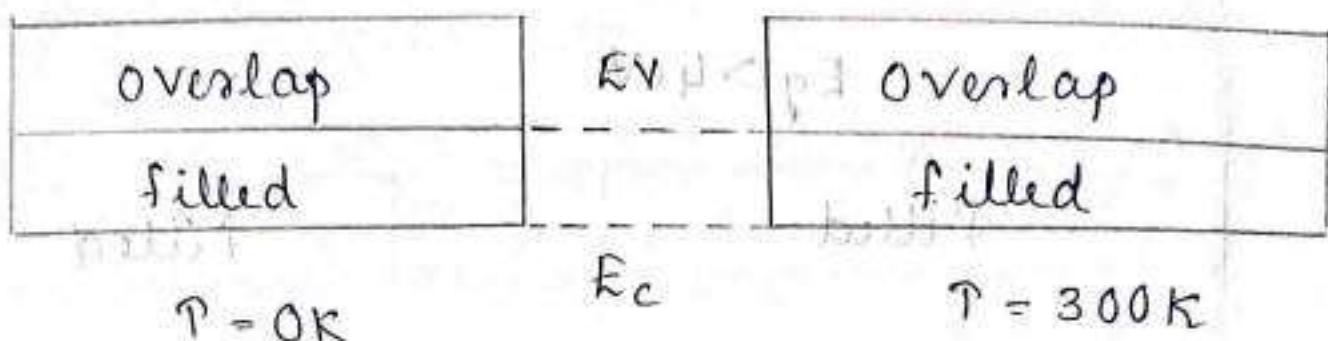
The lower band is called valence band and the upper band is called conduction band.

At 0K valence band is completely filled and conduction band is empty. Of energy equal to the band gap (energy gap b/w valence band & conduction band) is given to an electron in the valence band, it gets excited to valence band conduction band. This creates a vacancy in the valence band. This vacancy is called hole.

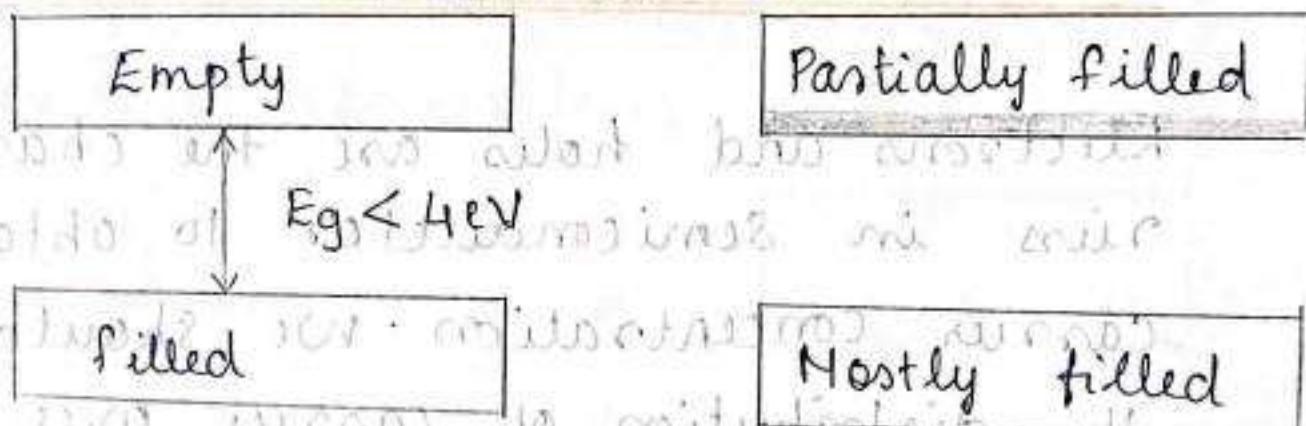
The electrons in the conduction band is called free electrons. These electrons-hole pair is formed. The energy used for this type of generation is called thermal energy and generation process is called thermal generation.

# Energy band diagrams

## Metals

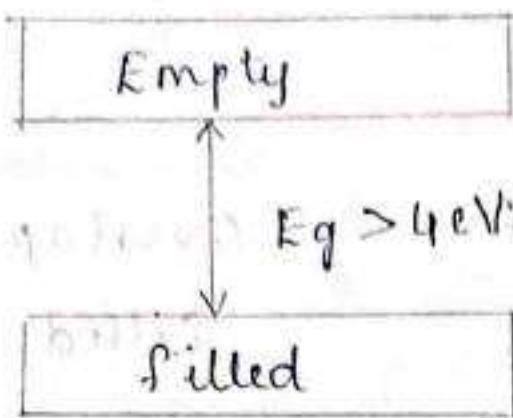


## Semiconductors

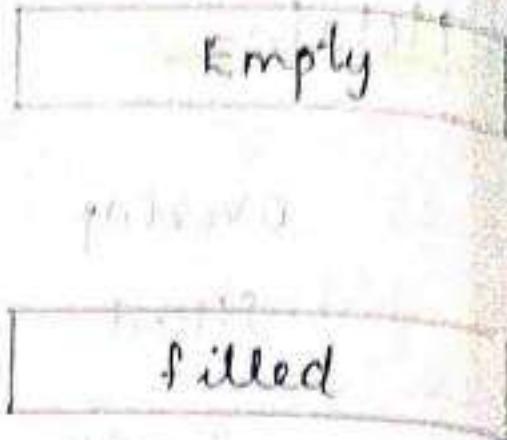


$$\frac{1}{T^2 \sqrt{(T^2 - 1)^2 + 1}} + (A)^2$$

## Insulators



$$T = 0 \text{ K}$$



$$T = 300 \text{ K}$$

## Fermi - Dirac Distribution Function

Elections and holes are the charge carriers in semiconductors. To obtain the carrier concentration we should know the distribution of carrier over available energy level that can be obtained by fermi - dirac distribution function.

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

$f(E)$  : Fermi - dirac distribution

$k$  : Boltzmann constant

$$= 1.38 \times 10^{-23} \text{ J/K}$$

$$= 8.08 \times 10^{-5} \text{ eV/K}$$

$T$  : Absolute temperature @ Kelvin

$E_F$  : Fermi - energy level @ eV

$E$  : Particular energy level

$f(E)$  denotes the probability of electrons or hole at an energy level  $T$  at absolute temperature.

Case - 1 :-

At  $T = 0\text{K}$ ,  $E < E_F$

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

$$= \frac{1}{1 + e^{(E-E_F)/k \cdot 0}}$$

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

case - 2 :-

At T = 0K, E > E\_f

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

$$\lim_{T \rightarrow 0} f(E) = \frac{1}{1 + e^{\infty}} = 0 \quad \left\{ \frac{1}{\infty} = 0 \right.$$

case - 3 :-

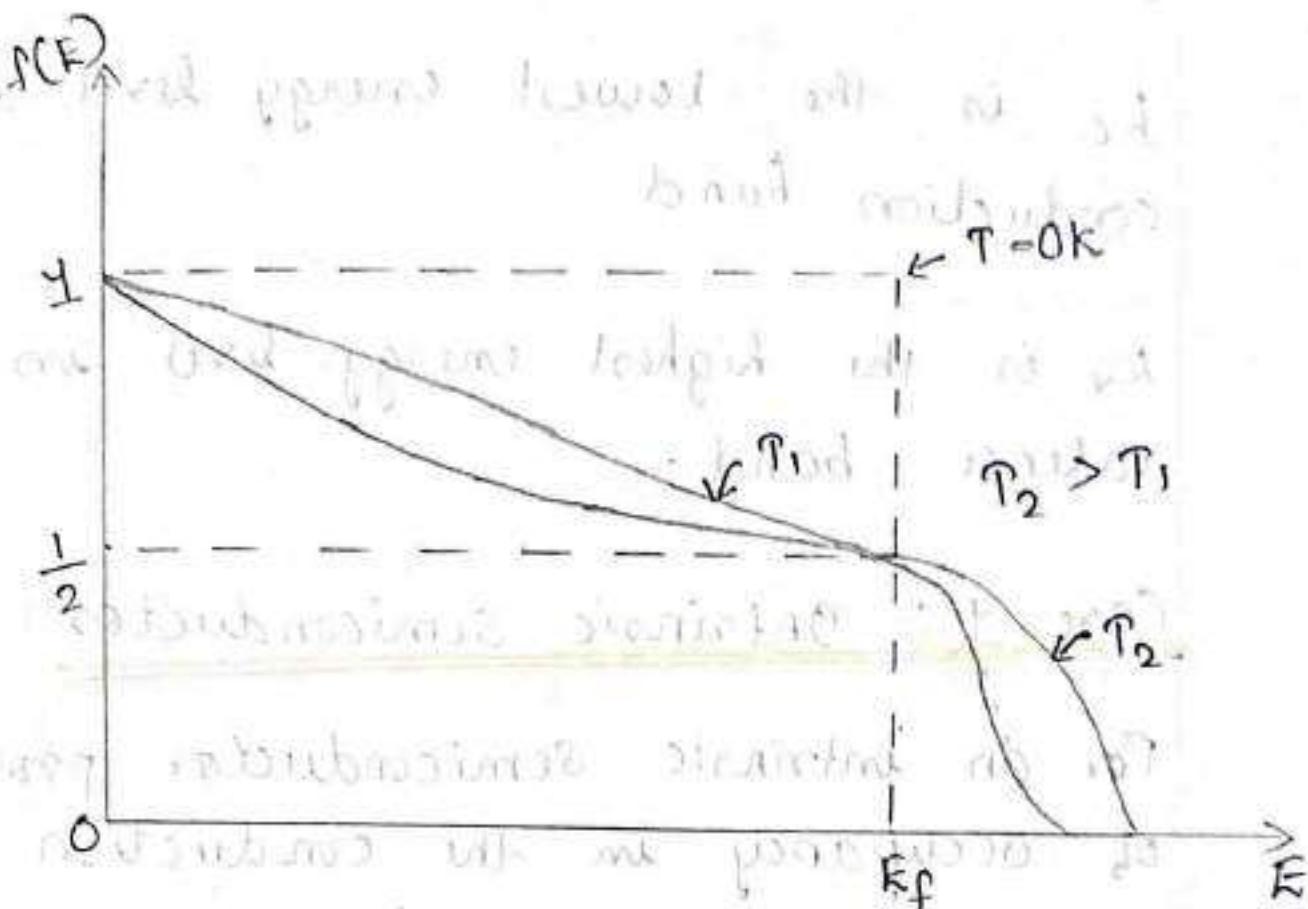
At T ≠ 0K, E = E\_f

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

$$= \frac{1}{1 + e^{0/kT}}$$

$$= \frac{1}{1+1} = \frac{1}{2}$$

i.e., the probability of occupancy of charge carriers at energy level w.r.t is  $\frac{1}{2}$ .



Fermi - Dirac distribution function applied to a semiconductor

$F(E) =$  probability of occupancy of electron, at a particular energy level  $E$

or

probability of occupancy of holes at a particular energy level  $E$

$1 - f(E)$ , is probability of non-occupancy of electronic electrons or holes at particular energy level  $E$

$E_c$  is the lowest energy level in the conduction band

$E_v$  is the highest energy level in the valence band.

### Case I :- Intrinsic Semiconductors

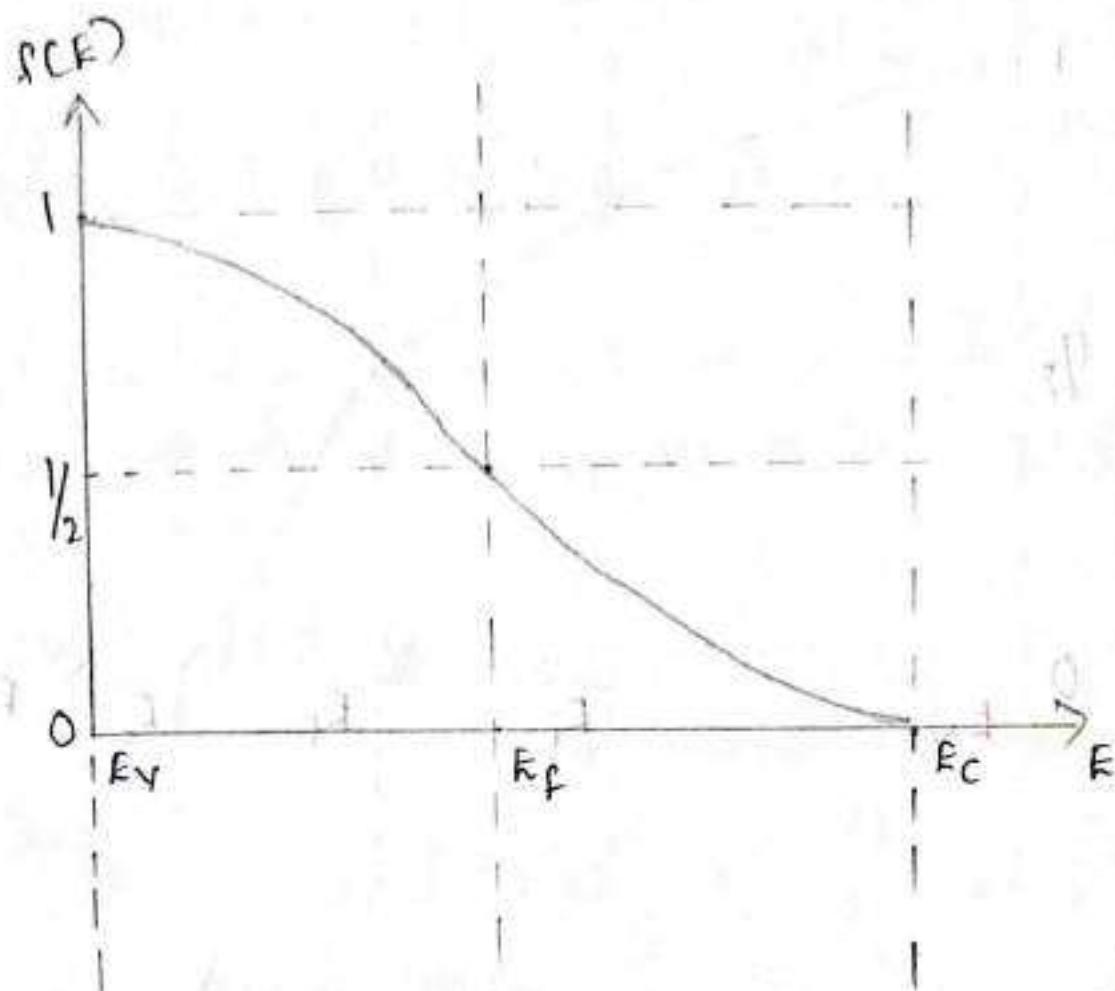
For an intrinsic semiconductor probability of occupancy in the conduction band equals the probability of vacancy in the valence bands

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

i.e.,  $f(E_c) = 1 - f(E_v)$    
 electrons concentration =  $e + \text{concentration}$

for this condition  $E_F$  must be at middle of the band gap. So, it is called intrinsic level

## Distribution of $f(E)$ intrinsic semiconductor



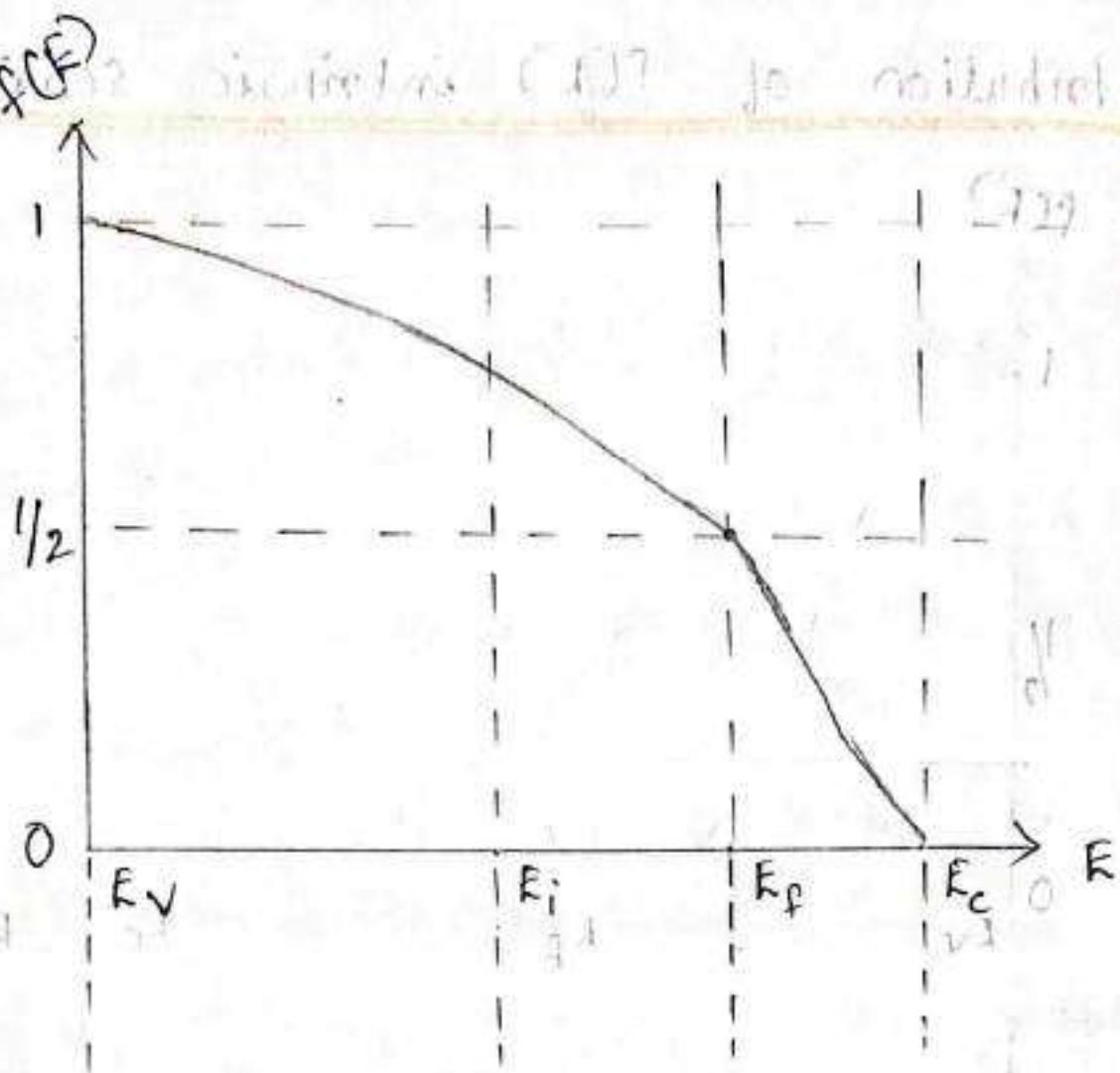
Case 2 : N type semiconductor pentavalent atoms are added

Probability of occupancy in the conduction bands is greater than probability of vacancy in the valence band.

$$f(E_C) > 1 - f(E_V) > \dots$$

$\bar{e}$  concentration  $\gg e^+$  concentration

Here,  $E_f$  level must be nearer to the conduction band.



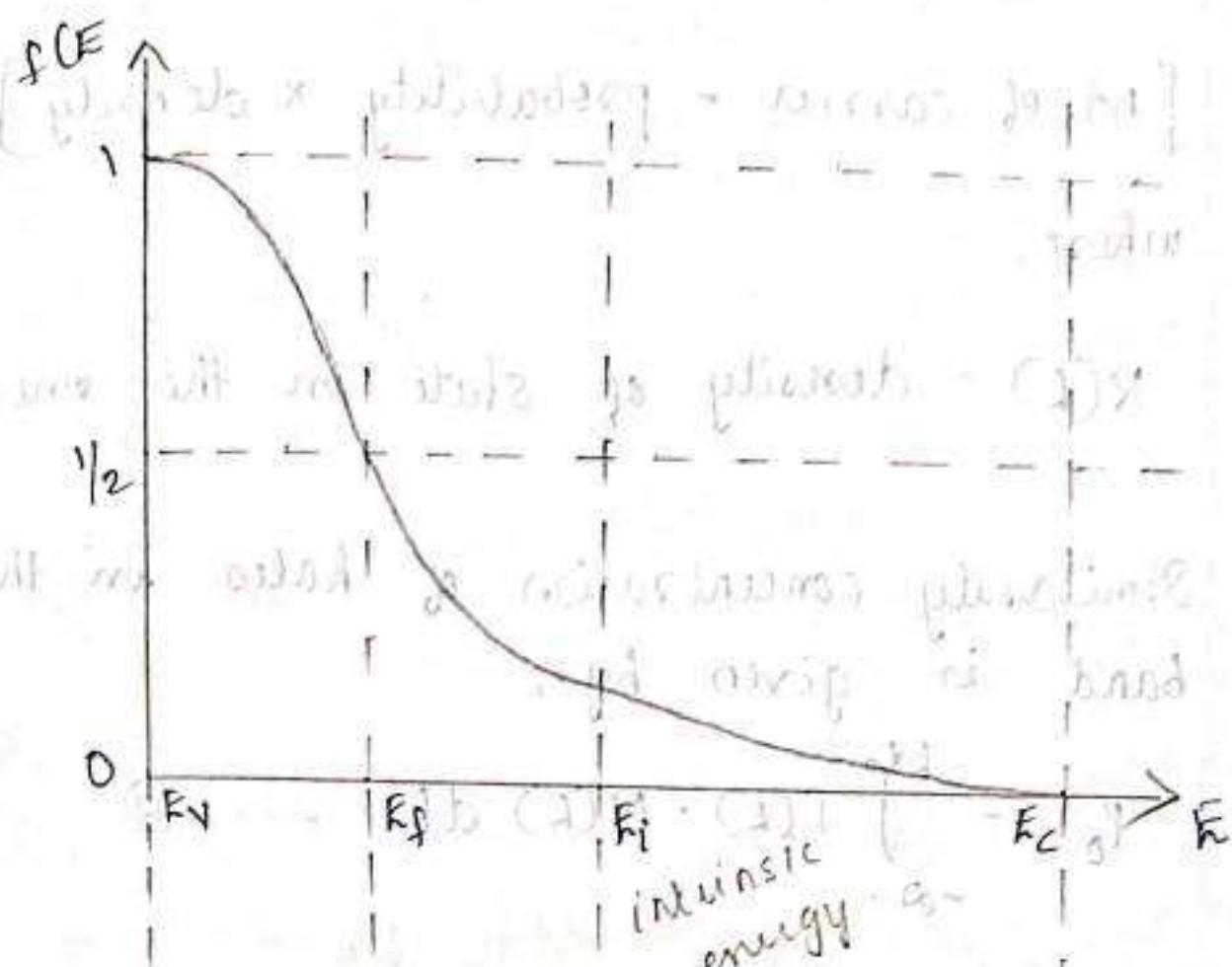
Tetravalent atoms  
are added  
Case 3 :- P type Semiconductor

Probability of occupancy in the conduction band is lesser than probability of vacancy in the valence band

$$f(E_c) \cdot <1-f(E_v)>^n$$

$e^-$  concentration  $\ll e^+$  concentration

Here, the  $E_F$  level must lie at the valence band.



## Electron and hole concentration at equilibrium [Proof of mass-action law]

Perini - Fermi - Dirac distribution function can be used to evaluate electron and hole concentration in a semiconductor.

The concentration of electrons in the conduction band is given by;

$$n_0 = \int_{E=E_C}^{\infty} f(E) \cdot N(E) dE \quad \text{--- (1)}$$

[no. of carrier = probability  $\times$  density]

where,

$N(E)$  = density of state in the energy

Similarly concentration of holes in the valence band is given by,

$$P_0 = \int_{-\infty}^{E_V} f(E) \cdot N(E) dE \quad \text{--- (2)}$$

Since  $f(E)$  become negligibly small, for large values of  $E$  most of electrons occupy states nearer the bottom of the conduction band at equilibrium.

$\therefore$  conduction band electron concentration become,

$$n_0 = f(E_C) \cdot N_C \quad \text{--- (3)}$$

$$f(E_C) = \frac{1}{1 + e^{(E_C - E_F)/kT}} \quad \text{--- (4)}$$

If  $E_C - E_F \gg kT$  then,

$$f(E_C) = \frac{1}{e^{(E_C - E_F)/kT}}$$
$$= e^{-(E_C - E_F)/kT} \quad \text{--- } ⑤$$

∴ ③  $\Rightarrow$

$$n_0 = N_C e^{-(E_C - E_F)/kT} \quad \text{--- } ⑥$$

The effective density of state at the conduction band edge is given by,

$$N_C = 2 \left( \frac{2\pi M_0 * kT}{h^2} \right)^{3/2}$$

where,

$M_0 \rightarrow$  [Effective mass of] electrons in the conduction band.

$h \rightarrow$  Plank's constant

Similarly, the equilibrium concentration holes in the valence band is given by,

$$P_0 = N_V [1 - F(E_V)] \quad \text{--- (8)}$$

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

$$if \quad E_F - E_V \gg kT$$

$$\begin{aligned} 1 - F(E_V) &= e^{(E_V - E_F)/kT} \\ 1 - F(E_V) &= e^{-(E_F - E_V)/kT} \end{aligned} \quad \text{--- (9)}$$

(8)  $\Rightarrow$

$$P_0 = N_V [e^{-(E_F - E_V)/kT}] \quad \text{--- (10)}$$

$$N_V = 2 \left[ \frac{2\pi M p^* k T}{h^2} \right]^{3/2}$$

$$n_0 = N_C e^{-(E_C - E_F)/kT} \quad \text{--- (6)}$$

$$p_0 = N_V e^{-(E_F - E_V)/kT} \quad \text{--- (7)}$$

Intrinsic carrier concentration is given by

$$n_i = N_C e^{-(E_C - E_i)/kT} \quad \text{--- (8)}$$

$$p_i = N_V e^{-(E_i - E_V)/kT} \quad \text{--- (9)}$$

$$n_0 \times p_0 = N_C \cdot N_V e^{-(E_C - E_V)/kT} \quad \text{--- (10)}$$

$$= N_C \cdot N_V e^{-E_g/kT} \quad \text{--- (11)}$$

provided  $(E_C - E_V) = E_g$

[for intrinsic semiconductor  $n_i = p_i$ ]

$$n_i p_i = N_C N_V e^{-(E_C - E_V)/kT} \quad \text{--- (12)}$$

$$n_i^2 = N_C N_V e^{-(E_C - E_V)/kT} \quad \text{--- (13)}$$

(13) and (14)

$$\therefore n_0 p_0 = n_i^2 \quad \text{--- (15)}$$

This relation is known as mass-action law.

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Mars - action Laws states that at a given temperature, the product of equilibrium of electrons or holes in a semiconductor is constant to any doping and equal to the square of the intrinsic carrier concentration at that temperature.

### Equilibrium electron, hole concentration and charge neutrality

Consider a homogeneous non-degenerate Semiconductor with uniform doping  $N_D$  donor/cm<sup>3</sup> and  $N_A$  acceptor/cm<sup>3</sup> under equilibrium semiconductor total +ve charge = total -ve charge ; ie

$$P_0 + N_D^+ = N_o + N_A^+$$

$$N_o - P_0 = N_D^+ - N_A^+$$

This is the charge neutrality equation

$N_D^+$  is ionized donor concentration  
 $N_A^+$  is ionized acceptor concentration

$$N_D^+ = N_D$$

$$N_A^+ = N_A$$

$$N_D - P_0 = N_D - N_A$$

$$N_D > N_A \rightarrow n \text{ type}$$

$$N_D < N_A \rightarrow p \text{ type}$$

donor atom

- n type

acceptor atom

- p type

## Temperature dependents of carrier

concentration -  $(0) \rho_d = (T) \rho_d =$

a) Temperature dependents of intrinsic carrier concentration

We know that,

$$- E_g / 2kT$$

$$N_D \times P_0 = n_i^2 = N_C N_V - e$$

$$n_i = \sqrt{N_C N_V} e^{-Eg / 2kT}$$

Substitute the value of  $N_C$  and  $N_V$

$$n_i = \left[ 2 \left[ \frac{2\pi k T}{h^2} \right]^{3/2} (mn^* m_p^*)^{3/4} \right] e^{-Eg / 2kT}$$

↓  
constant

$$n_i(T) = A T^{3/2} e^{-Eg(T) / 2kT}$$

in Si and Ge bandgap decrease with increase in temperature.

$$-Eg(T) = Eg(0) - b_1 T \quad \text{--- ②}$$

$Eg(0)$  is  $Eg$  at  $T = 0K$

$b_1$  is the rate of decrease of band gap with temperature

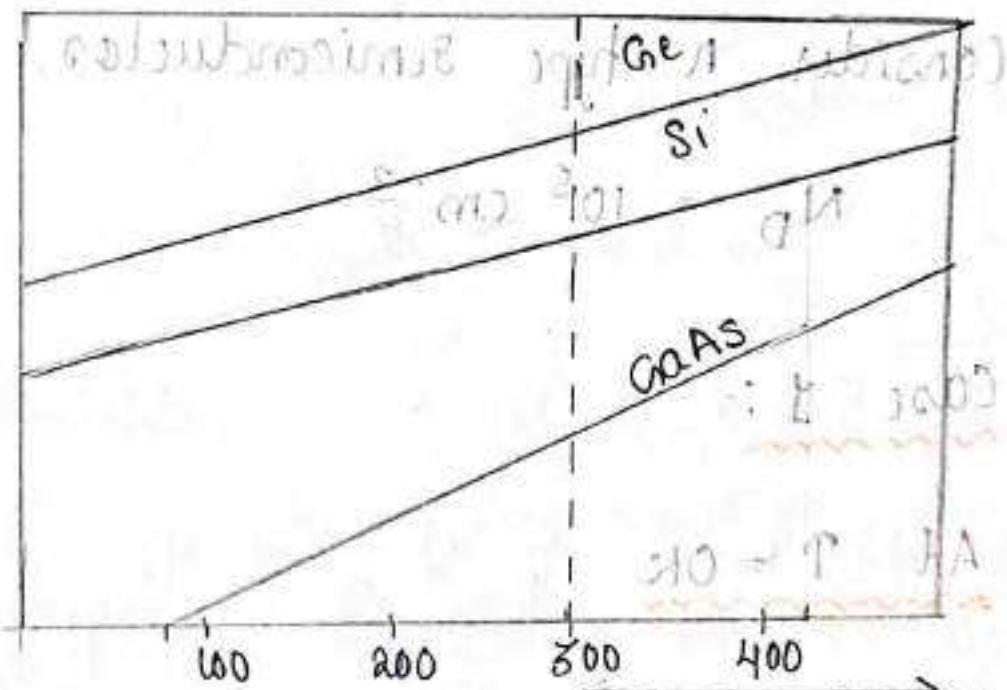
Sub. ② in ①

$$n_i(T) = AT^{3/2} \frac{e^{-Eg(0)} \cdot b_1 T}{2kT}$$

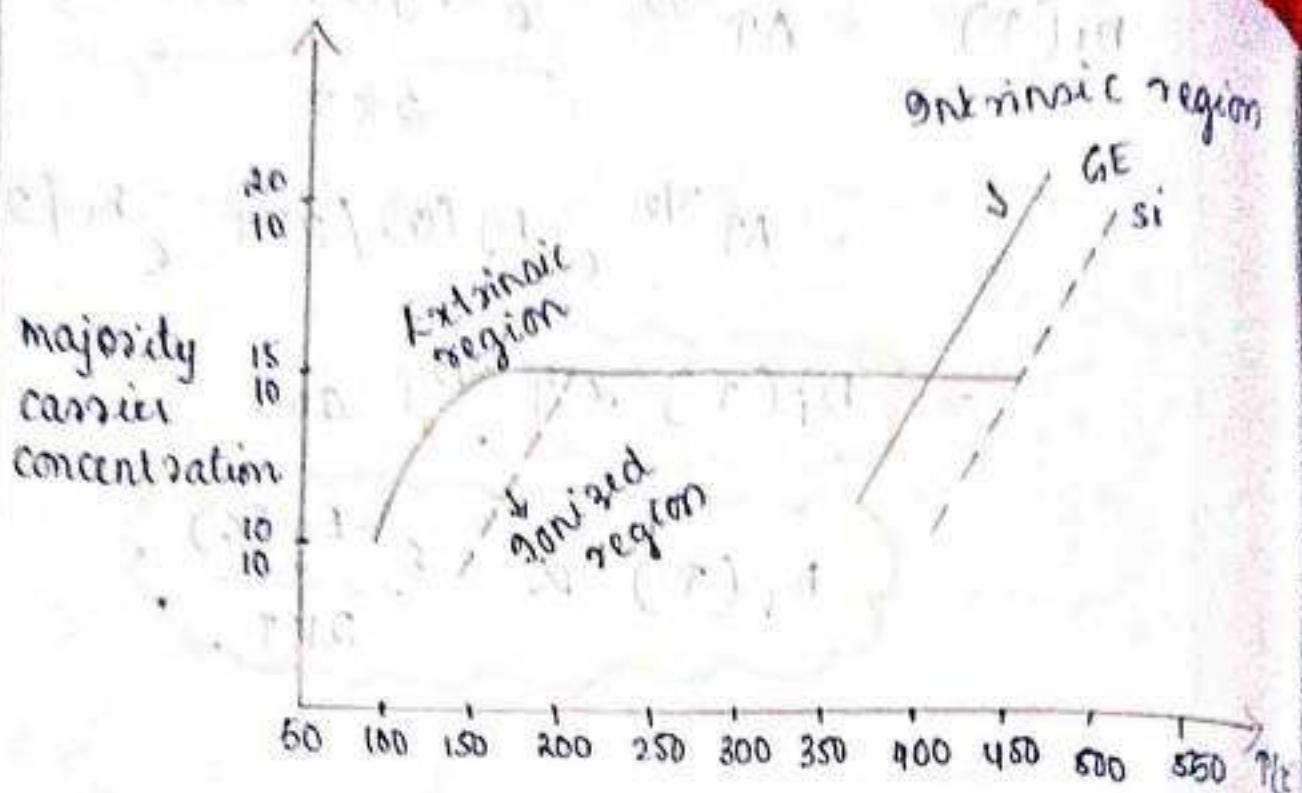
$$= AT^{3/2} e^{-Eg(0)/2kT} \cdot e^{b_1/2kT}$$

$$= n_i(T) \propto T^{3/2} \quad \text{and}$$

$$n_i(T) \propto e^{-Eg(0)/2kT}$$



- b) Temperature dependent of majority carrier concentration in extrinsic carrier concentration



Consider n-type Semiconductors,

$$N_D = 10^5 \text{ cm}^{-3}$$

Case 1 :-

At  $T = 0\text{K}$

No thermal generation, No extrinsic generation (is intrinsic generation zero?)

i.e.,  $n_0 = 0$  (is electron density zero?)

(is electron density zero?)

### Case 2 :-

As temperature increases from 0K to 150 K

Extrinsic generation increases largely, thermal generation increase but negligible

$$n_0 = n_i + N_D^+$$

$$n_0 \approx N_D^+$$

### Case 3 :-

At T = 450K

Extrinsic generation is completed i.e., all donor electrons in conduction band, thermal generation is increases but negligible.

$$n_0 = n_i + N_D^+$$

$$n_0 \approx N_D^+$$

Case 4 :-

At  $T = 300\text{K}$

Thermal generation increases largely

$$n_0 = n_i + N_D$$

Case 5 :-

At  $T > 300\text{K}$

Thermal generation increases more

$$n_0 = n_i + N_D$$

$$n_0 \approx n_i$$

The graph has three regions :-

- i) Ionized region :- Here the majority carrier concentration increases with increase in temperature.

ii) Extrinsic region :- Here the majority carrier concentration is constant while minority concentration is negligible. The device operates satisfactorily in this region. Because, majority carrier concentration remains constant. Hence, conductive remains constant with respect to temperature.

iii) Intrinsic region :- Here the extrinsic property of semiconductor is lost ie, extrinsic will be increases.

## MODULE-2

Carrier transport in a semiconductor

- mobility and conductivity

carrier transport in a semiconductor is mainly by two different mechanism

a) Drift

b) Diffusion