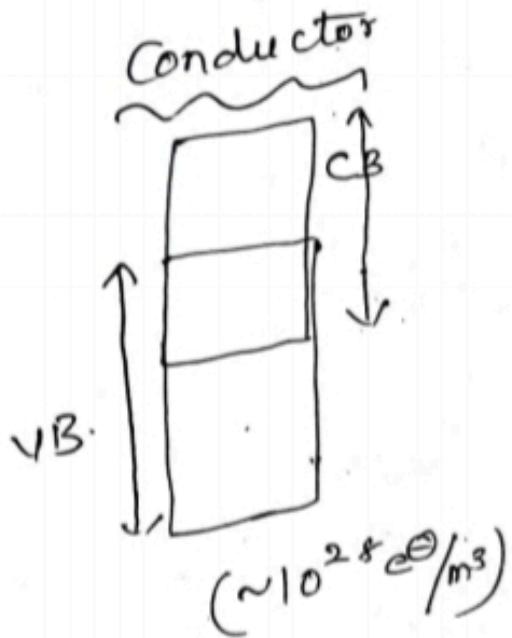
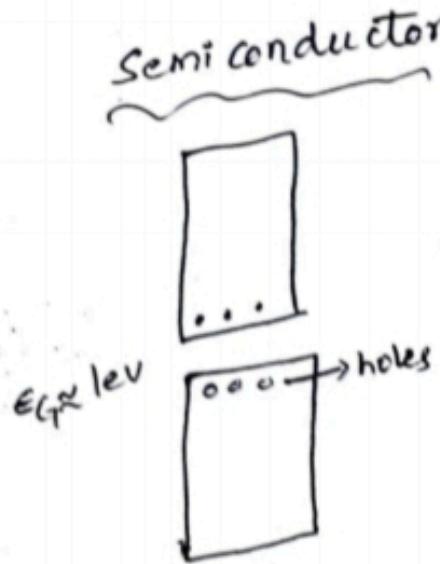
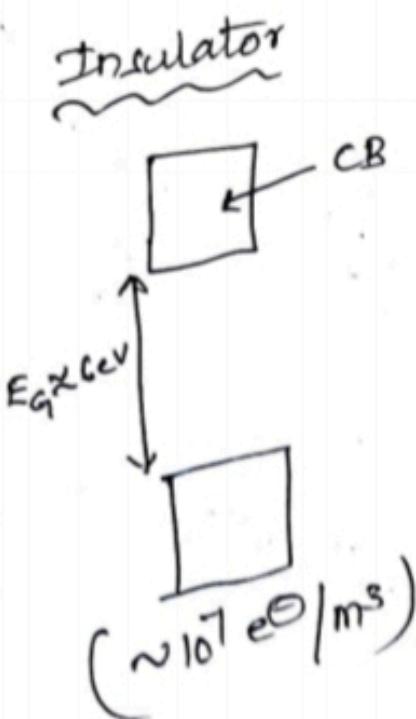


EDCUNIT-7SEMI CONDUCTOR PHYSICSBAND THEORY OF CRYSTALS

- \* 3D arrangement of atoms in a crystal
- \* Due to less interatomic spacing and covalent bonds, a large number of closely spaced discrete energy levels called Valency band are occupied by valence electrons.
- \* Valency band  
Conduction band  
forbidden energy gap - free from any discrete energy levels



At 0°K

$$E_g \approx 0.785 \text{ eV (Ge)}$$

$$E_g \approx 1.21 \text{ eV (Si)}$$

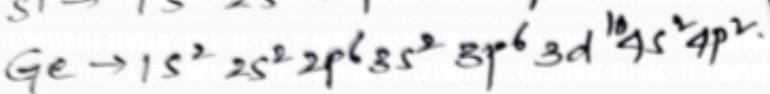
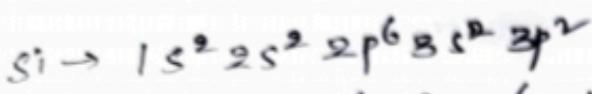
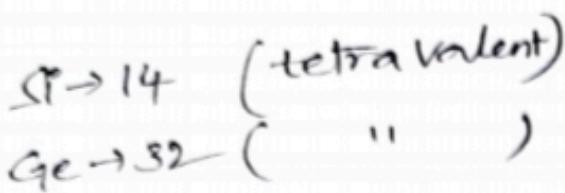
Intrinsic (in pure semiconductor)

Extrinsic (in impure)  $\rightarrow E_g$  has new levels because of impurity.

At room

$$(Si) \quad E_g = 1.1 \text{ eV}$$

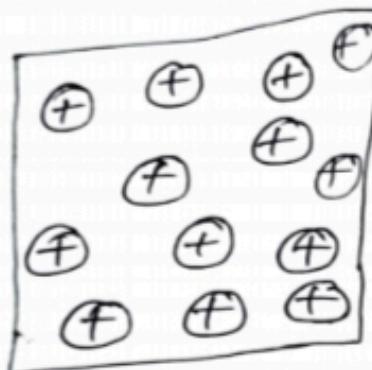
$$(Ge) \quad E_g = 0.72 \text{ eV}$$



### mobility and conductivity in metals

metals  $\rightarrow$  electron gas

- Random  $\oplus$  movement gives zero current - collisions
- Avg. distance b/w two collisions is mean free path



- External field  $E$  (force on unit positive charge at any point in electric field is called electric field intensity)
- Steady state speed  $v$ .

$$v = \mu E$$

$\mu \rightarrow$  mobility ( $\text{cm}^2/\text{volt}\cdot\text{sec}$ )

$$E \rightarrow v/m$$

current density  $\rightarrow$  current per unit area

$$J = nev$$

$n \rightarrow e\Theta s/m^3$  (concentration)

$J \rightarrow \text{amp}/m^2$

$$J = neve$$

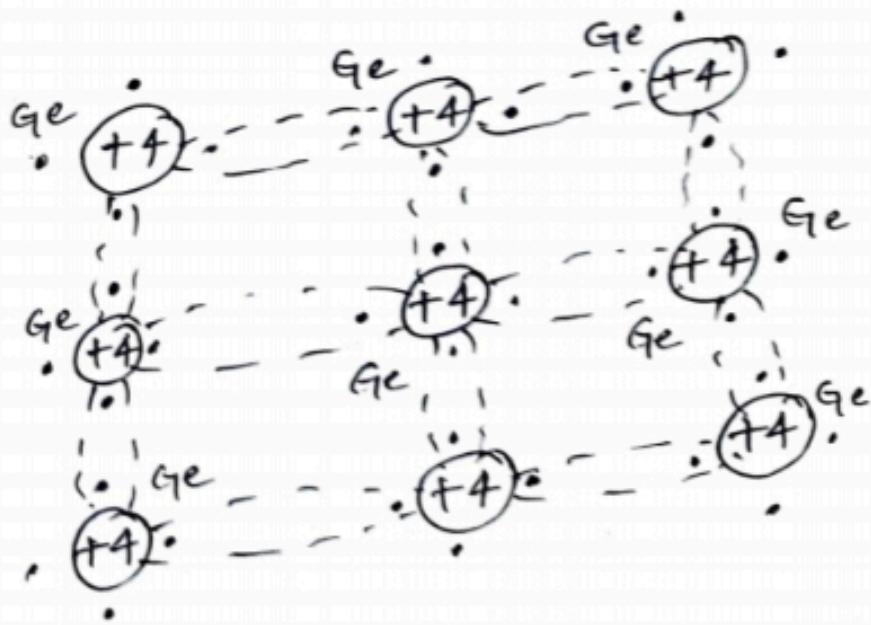
$$\boxed{J = \sigma E} \rightarrow \text{ohm's law}$$

$$\boxed{\sigma = nev}$$

$\sigma \rightarrow$  conductivity  $\rightarrow (\Omega^{-1} \text{m}^{-1})$

power dissipated  $\rightarrow$  ion-e<sup>-</sup> collision  
 $JE = \sigma E^2$  (watt/m<sup>3</sup>)

e<sup>-</sup>s and holes in an intrinsic semiconductor (pure)

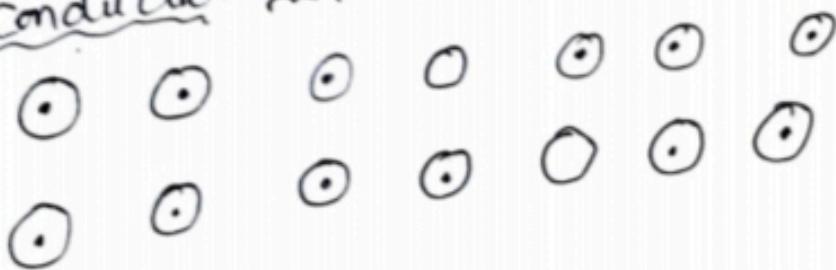


- At 0 K, insulator
- At room temp, free e<sup>-</sup>  $\rightarrow$  conduction
- At room temp, free e<sup>-</sup>  $\rightarrow$  conduction  
    (Semi conductor)  
    e<sup>-</sup> move from VB  $\rightarrow$  CB due to temp rise.

- \* Absence of  $e^-$  in a covalent bond (or) empty valency energy level is called "hole"
- \*  $e^-$  movement is opposite to hole movement  
 $e^-$  from one bond fills hole and repeats
- \* holes in VB (no free  $e^-$ )  
 $e^-$  in CB } constitutes current.

\* Recombination and generation happens

hole conduction in VB



$e^-$  - hole movement

hole  $\rightarrow$  positive charge carrier

Conductivity of a semi conductor ( $\sigma$ ) :-  
 with  $e^-$  and hole pair, conductivity is due to both of them.

current density :-

$$J = (n\mu_n + p\mu_p)eE = \sigma E$$

$\mu_p, \mu_n \rightarrow$  Mobility of hole and  $e^-$

For intrinsic semiconductor

$$n_p = n_e = n_i$$

(or)

$$P = n = n_i$$

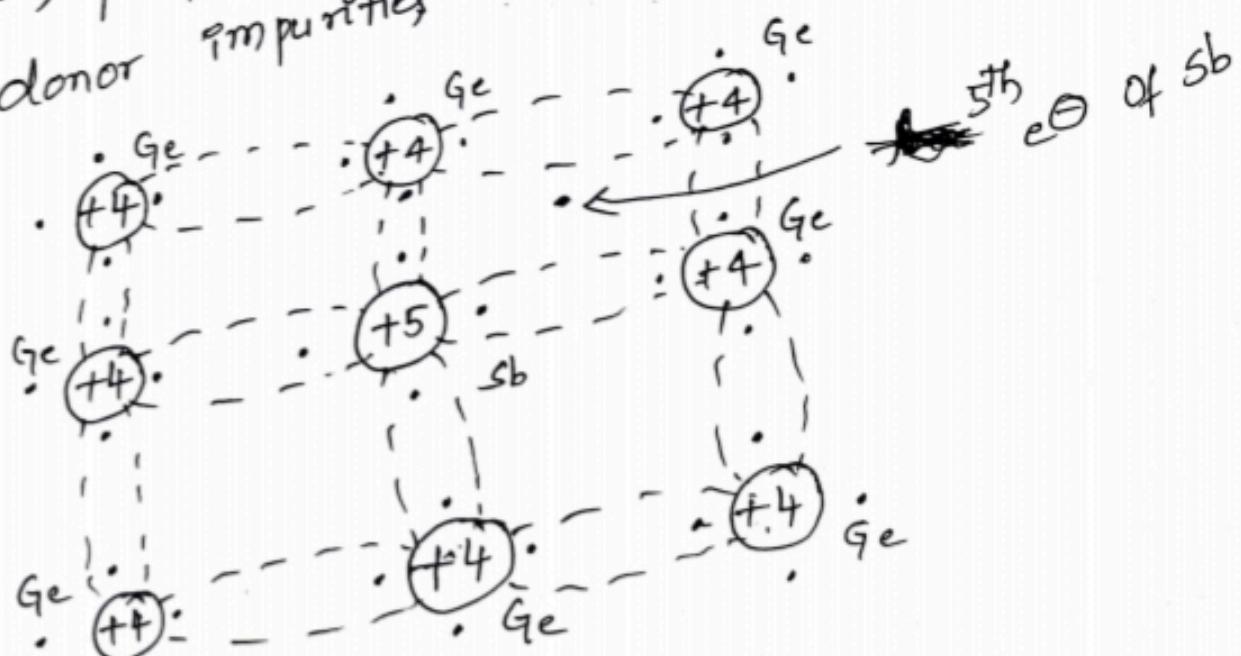
$$\frac{\mu_n > \mu_p}{\text{Ge, } \mu_n = 3800, \mu_p = 1800}$$
$$\text{Si, } \mu_n = 1300, \mu_p = 500$$

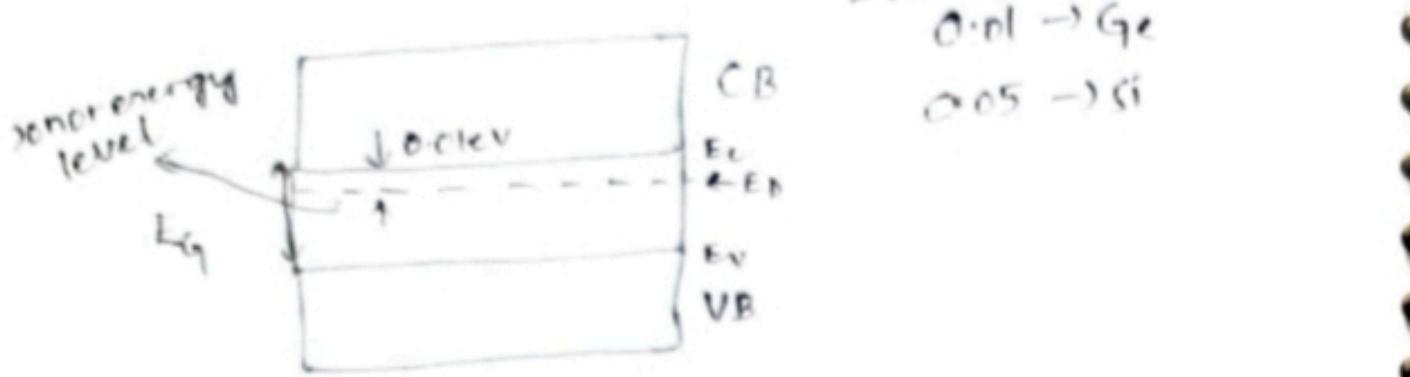
for Ge, conductivity raises approx. 6(8) % per degree rise in temperature.

for metals, resistance raises  $0.4\%/\text{ }^{\circ}\text{C}$  - collisions  
" semi conductors, resistivity decreases with raise of temperature.

Extrinsic semiconductor :-  
A pure Semiconductor when added a trivalent (or) a pentavalent impurity becomes an extrinsic Semiconductor.

Donor (or) pentavalent impurity ( $n$ -type)  
Bismuth, phosphorous, arsenic, antimony ( $\text{Sb}$ ) are generally donor impurities

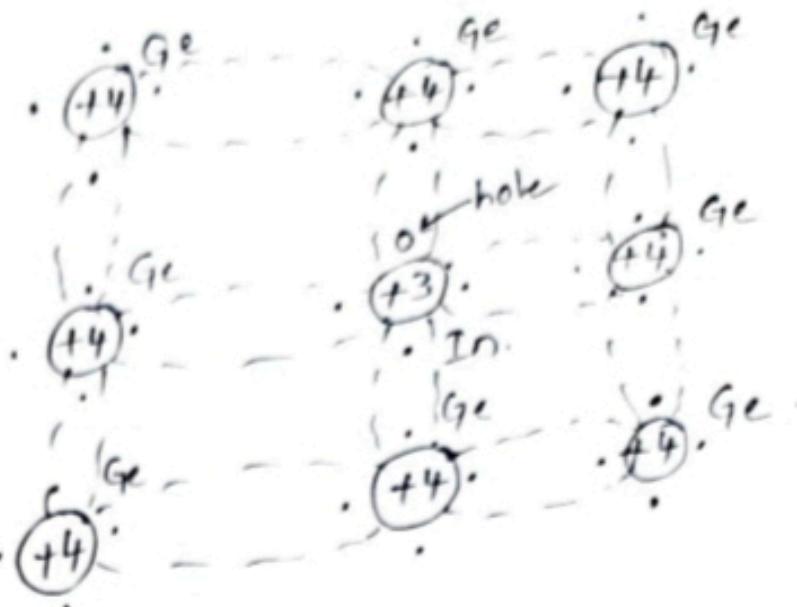




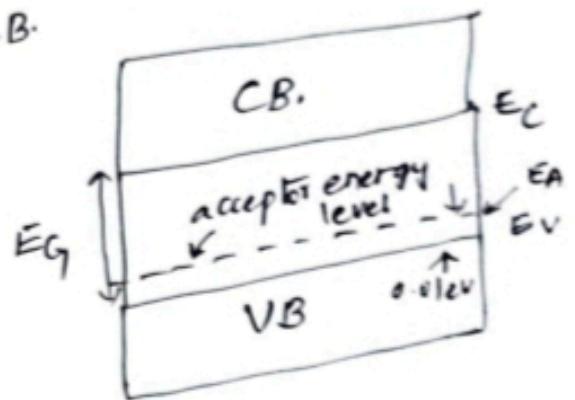
- \* The pentavalent impurity causes a free  $5^{\text{th}}$   $e^{\text{th}}$  which is not in any covalent bond and needs just one  $e^{\text{th}}$  to enter conduction band
  - \* It forms a new energy level called "donor energy level" near to CB.
  - \* The no of  $e^{\text{th}}$  raises in an n-type semiconductor and holes decrease because of recombination (and opposition force in CB.)
- Acceptor (Or) trivalent impurity :- (p-type)

\* When a trivalent impurity (boron, gallium or indium) is added to an intrinsic semiconductor  $3e^{\text{th}}$  will form 3 covalent bonds and leave one covalent bond short of an  $e^{\text{th}}$ .

The vacancy in 4th bond constitutes a hole. Such holes accept  $e^{\text{th}}$  and such impurities are acceptor impurities and it becomes a p-type semiconductor.



- \* The acceptor impurity will form an acceptor energy level near to valency band and  $e\Theta_A$  can move easily to acceptor level and form holes. large number of holes in VB but no  $e\Theta_A$  in CB.



- \* So acceptor makes p-type carrier holes (majority carriers) extrinsic semi conductor " "
- \* " donor (minority majority -  $e\Theta_A$ ) " n-type " "
- \*

charge densities in a semi conductor :-

\* In an intrinsic <sup>extrinsic</sup> semi conductor ...

$$n_p = n_i^2 \quad (\because n = p = n_i)$$

for extrinsic semiconductor :-

since the semiconductor is electrically neutral.

let  $N_D$  is concentration of donor atoms.  $N_D$  positive charges ions constitute  $N_D$  positive ~~ions~~ ( $/m^3$ )

Total =  $N_D + P$ . (positive charge density)

similarly  $N_A$  acceptor ions make  $N_A$  negative charges ~~ions~~ ( $/m^3$ )

$$\text{Total} = N_A + n$$

Since semiconductor is electrically neutral.

$$N_D + P = N_A + n$$

( $\because$  positive charge density = -ve charge density)

In n-type  $\Rightarrow N_A = 0$ ,  $n \gg p$ .

$$\Rightarrow [n \approx N_D]$$

$$\Rightarrow [n_n \approx N_D]$$

Concentration  $P_n$  of holes in 'n'-type is obtained from  $n_n P_n = n_i^2$

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

Similarly for p-type

$$P_p \approx N_A$$

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

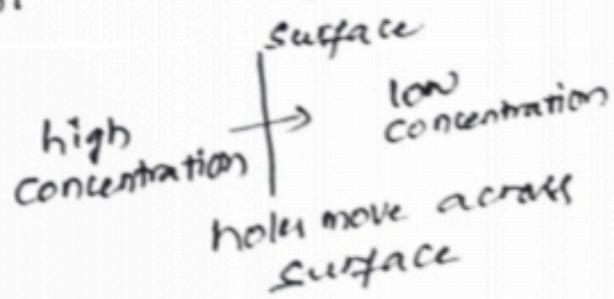
$$n_p P_p = n_i^2$$

Drift and Diffusion:

Diffusion:

Due to non-uniform concentration of charged particles in a semiconductor, the charges move from a region of greater concentration to a region of smaller concentration.

for eg. the concentration of holes 'p' varies with distance 'x' and concentration gradient is  $dp/dx$  (density of carriers)



This constitutes a current and diffusion hole-current density  $J_P$  ( $\text{amp}/\text{cm}^2$ )

$$J_p = -e D_p \frac{df}{dx}$$

$D_p$  → diffusion constant for holes (cm<sup>2</sup>/sec)

For e<sup>θ\_h</sup>

$$J_n = e D_n \frac{dn}{dx}$$

$D, \mu$  are statistically thermodynamic phenomena.

$$\boxed{\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T}$$

$$V_T = \frac{kT}{e} = \frac{T}{11,600} \quad (\text{Voltage eq. of temperature})$$

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

At room temp.,  $\mu = 39 D$  ...

Drift:-

When an electric field is applied across the semiconductor, the charge carriers attain a certain drift velocity  $v_d$

$$v_d = \mu E$$

$\mu$  → mobility of charge carrier

The holes move toward -ve terminal and e<sup>θ\_s</sup> to +ve terminal of

$E$  → electric field intensity V/cm

battery

→ this combined effect of movement of charge carriers under the influence of external electric field constitutes a current called drift current. The drift current density due to charge carriers such as free  $e^-$ s and holes are the current passing through a  $1\text{cm}^2$  area perpendicular to direction of flow.

drift current density due to free  $e^-$ s

$$J_n = n e u_n E \quad \text{Amp/m}^2$$

$$\text{Due to holes, } J_p = p e u_p E \quad \text{Amp/m}^2$$

$n, p \rightarrow e^-$  and hole concentration ( $1/\text{m}^3$ )

$u_n, u_p \rightarrow$  mobility ( $\text{m}^2/\text{V-sec}$ )

$e \rightarrow$  charge of  $e^-$ .

The Hall effect:

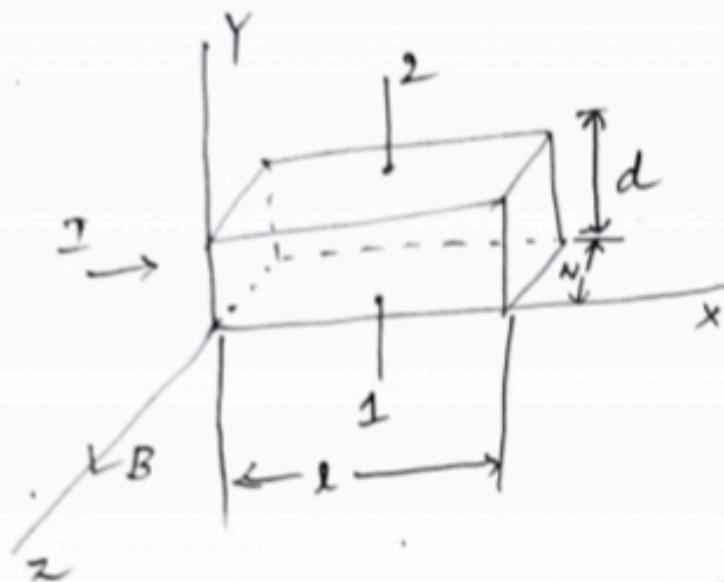
If a specimen (metal or semiconductor) carrying a current  $I$  is placed in a transverse magnetic field  $B$ , an electric field  $E$  is induced in the direction perpendicular to both  $I$  and  $B$ . This phenomenon is called as Hall effect. It is used to determine

1) type of a semiconductor (p-type or n-type)

2) carrier concentration

3) conductivity and mobility ( $\mu$ )

\* If I is in +ve X and 'B' is in the Z,  
then a force will be exerted in the -ve Y on  
the current carriers



\* If the semiconductor is n-type, current is because of electrons and they are forced towards negative 'Y' i.e. side 1 will be at negative potential than side 2.

a potential  $V_H$ , Hall voltage appears between surfaces 1 and 2.

\* In the equilibrium state the electric field intensity due to the Hall effect must exert a force on the carriers which balances magnetic force

$$eE = Bev \quad (\text{v} \rightarrow \text{mean drift speed})$$

$e \rightarrow$  magnitude of charge on carrier

$v \rightarrow$  drift speed

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

$d \rightarrow$  distance b/w 1 and 2

also  $J = PV = \frac{I}{wd}$

$J \rightarrow$  current density

$P \rightarrow$  charge "

$w \rightarrow$  width of specimen in direction of magnetic field

$$\Rightarrow V_H = Ed = BVd$$

$$= \frac{BJd}{P}$$

$$\Rightarrow \boxed{V_H = \frac{BT}{PW}} \quad \text{---(1)}$$

\* \* : 'P' can be measured from others from above equation

if carriers are  $e^{\circ}s$ ,  $P = ne$   $\hookrightarrow e^{\circ}$  concentration

" " holes,  $P = pe$

now Hall Coefficient

$$R_H = \frac{1}{P}$$

( $\because$  from (1))

Hence  $R_H = \frac{V_H w}{BI}$

if conduction is primarily to charges of one sign, relation b/w  $\sigma$  and  $R_H$

\* conductivity  $\boxed{\sigma = PR}$  ( $\mu \rightarrow$  mobility)

( $\therefore$  in terms of  $R_H$ )

\*  $\Rightarrow \boxed{\mu = \sigma R_H}$

$R_H = \frac{3\pi}{8P}$  for random thermal distribution in speed of particles

## Fermi-Dirac function:

The equation  $f(E)$  is called the Fermi-Dirac probability function, and specifies the fraction of all states at energy  $E$  (ev) occupied under conditions of thermal equilibrium.

From quantum statistics it is found that

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

where  $K$  = Boltzmann constant, ev/ $^{\circ}\text{K}$

$T$  = temperature,  $^{\circ}\text{K}$

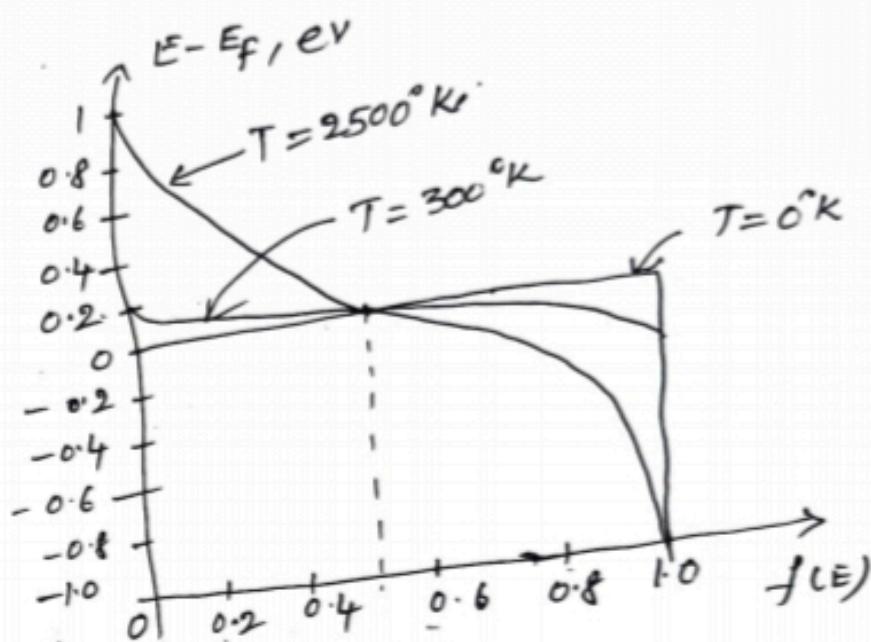
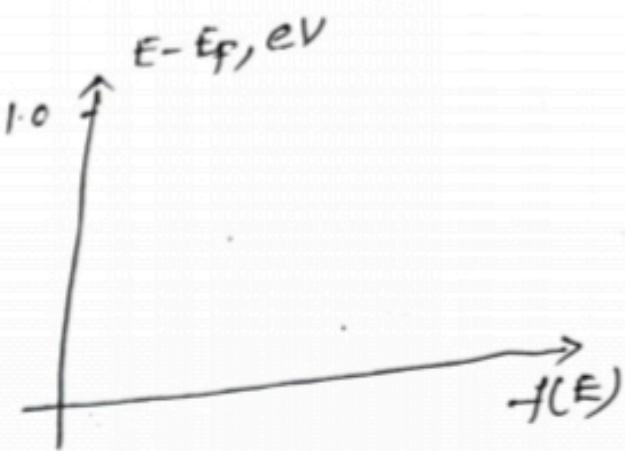
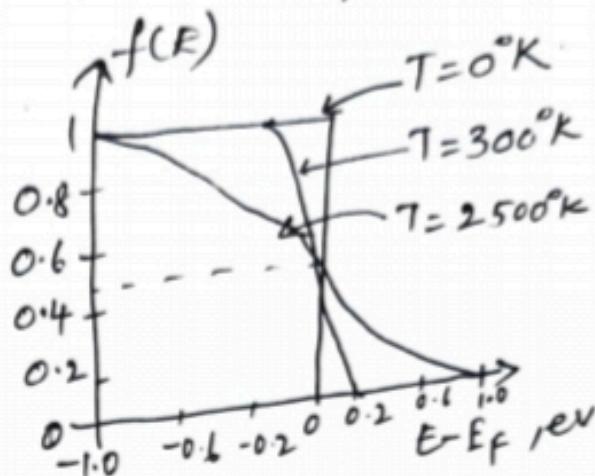
$E_F$  = Fermi level (or characteristic energy for crystal, ev.)

• The "Fermi level" represents the energy state with 50 percent probability of being filled if no forbidden band exists.

• The Fermi-Dirac distribution function  $f(E)$  gives the probability that a state of energy  $E$  is occupied.

If  $E = E_F$  then  $f(E) = \frac{1}{2}$  for any value of temperature.

Observe graphs  $E - E_F$  vs  $f(E)$  and  $f(E)$  vs  $E - E_F$



when  $T = 0^\circ K$ , two possible conditions exist:

(1) If  $E > E_F$ , the exponential term becomes infinite and  $f(E) = 0$ .

$\Rightarrow$  there is no probability of finding an occupied quantum state of energy greater than  $E_F$  at absolute zero.

(2) If  $E < E_F$ , the exponential becomes zero and  $f(E) = 1$ . All quantum levels with energies less than  $E_F$  will be occupied at  $T = 0^\circ K$ .

- \* There are no e<sup>⊖</sup>s at 0°K which have energies in excess of E<sub>F</sub>. i.e. Fermi energy is the maximum energy that any electron may possess at absolute zero.

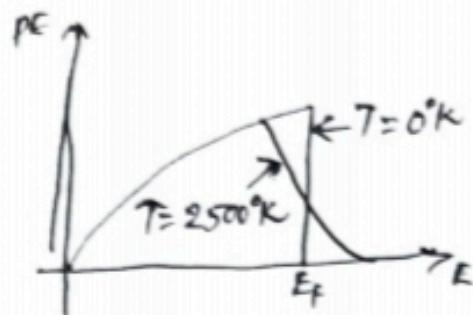


Fig: Energy distribution in metallic tungsten at 0 and 2500°K.

- \* Because of Pauli exclusion principle, no two e<sup>⊖</sup>s have the same energies even at 0°K (so only 0 to E<sub>F</sub> levels)
- so the area under the curve is total no of particles/m<sup>3</sup>. Two areas are equal ( $\therefore$ )
- \* Imp inference is that the distribution function changes only very slightly with temperature even temp diff is large (2500°K), curve change is less. e<sup>⊖</sup>s with lower energies at 0°K will be undisturbed and e<sup>⊖</sup>s with higher will have much more higher energies because of temp.

Fermi level in a semi conductor -

\* No of  $\Theta_s$  in conduction band

$$n = N_c \exp(-(E_c - E_F)/kT) \quad (1)$$

$N_c$  → effective state density

$$\text{at } 300K, N_c = 1.02 \times 10^{19} \text{ cm}^{-3} \text{ for Ge}$$

$$= 2.8 \times 10^{19} \text{ cm}^{-3} \text{ for Si}$$

$N_c$  gives the concentration of free  $\Theta_s$  in a semi conductor at absolute temp  $T$  and it is hypothetical density of  $\Theta_s$  states placed at the bottom of conduction band energy  $E_c$  after multiplication with fermi function  $f(E_c)$

\* Concentration of hole in VB

$$p = N_v \exp[-(E_F - E_v)/kT] \quad (2)$$

when multiplication with  $[1 - f(E_v)]$ , gives

hole concentrations in a semi conductor

for intrinsic ... since the crystal must be electrically neutral.  $N_c, N_v \rightarrow$  hypothetical electron state density placed at top of energy band level  $E_v$ , after mul. with  $1 - f(E_v)$ , gives conc. of holes in a sc @  $T$  (absolute from (1) & (2) ...

$$\Rightarrow N_c \exp[-(E_c - E_F)/kT] = N_v \exp[-(E_F - E_v)/kT]$$

Take log on both sides

$$\ln \frac{N_c}{N_v} = \frac{E_c + E_v - 2E_F}{kT}$$

Hence

$$E_F = \frac{E_c + E_v}{2} - \frac{kT}{2} \ln \frac{N_c}{N_v}$$

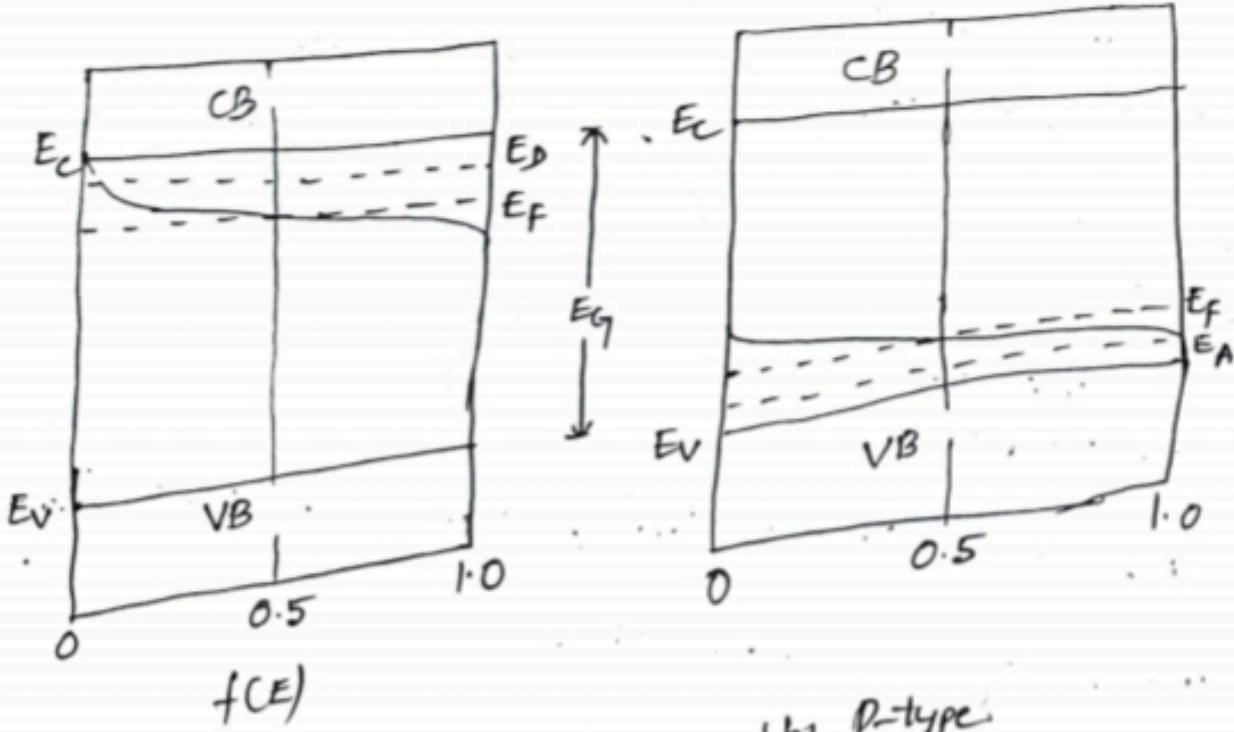
If effective masses of atom and e<sup>-</sup> are the same,  $N_c = N_v$

$$\Rightarrow \boxed{E_F = \frac{E_c + E_v}{2}} \quad \text{--- (A)}$$

At  $T=0^\circ\text{K}$ , even  $N_c \neq N_v$ , 'A' is valid.

Hence the fermi level lies in the center of the forbidden energy band.

Fermi level in an extrinsic semiconductor: ( $E_F$ )



position of  $E_F$ : (a) n-type

(b) p-type

\* In intrinsic semi conductor,  $E_F$  lies in the middle of energy gap, indicating equal concentration of free  $e^-$  and holes.

\* If the donor impurity is added to crystal, then, at a given temperature and assuming all donor atoms are ionised, the first  $N_D$  states in the CB are filled. Hence it is more difficult for the  $e^-$  from VB to bridge the  $E_F$  by thermal agitation (repulsion).

\*  $e^-$ -hole pairs thermally generated for that temp will be reduced since  $E_F$  is a measure of probability of occupancy of allowed energy states, it is clear that  $E_F$  must move closer to CB to indicate that many of the energy states in that band are filled by donor  $e^-$ . and fewer holes exist in VB.

\* If the temp of n-type (or p-type) semiconductor is raised to a large extent high level (somehow), new  $e^-$ -hole pairs form, finally making  $e^-$ s in CB and holes in VB almost equal. So the semiconductor becomes intrinsic and  $E_F$  moves to the centre of energy gap.

To calculate position of fermi level in n-type -

we have  $n = N_c \exp [-(E_c - E_F)/kT]$

Substitute  $n \approx N_D$  ( $\because$  n-type)

$$N_D = N_c \exp [-(E_c - E_F)/kT]$$

$$\Rightarrow E_F = E_c - kT \ln \frac{N_c}{N_D}$$

Similarly for p-type ..

$$E_F = E_v + kT \ln \frac{N_V}{N_A}$$

If  $N_A = N_D$  ..,

$$E_F = \frac{E_c + E_v}{2} - \frac{kT}{2} \ln \frac{N_c}{N_V} \quad (\because \text{intrinsic})$$

The Continuity equation :-

\* if we disturb the equilibrium concentration of carriers in a semiconductor, the concentration of holes and electrons will vary with time.

\* the carrier concentration in the body of a semiconductor is a function of both time and distance.

\* we will derive the differential equation which gives this relationship.