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## Semiconductors

①

- Fermi function: The fermi function  $f(E)$  gives the probability that a given available electron energy state will be occupied at given temperature.

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

where,

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

$E$  = Energy of state

$E_F$  = reference energy called fermi energy

$f(E)$  = Probability of finding  $E$  energy level

$$0 \leq f(E) \leq 1$$

- Variation of  $f(E)$  in case when  $T=0K$

- If  $T=0K$

$$E > E_F$$

$$f(E)=0$$

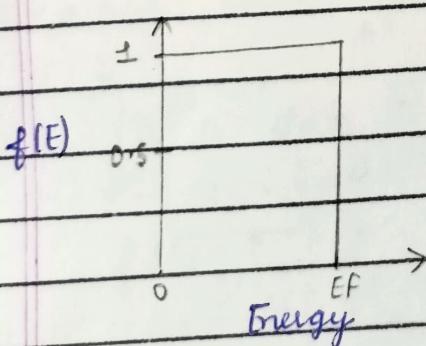
$$E < E_F$$

$$f(E)=1$$

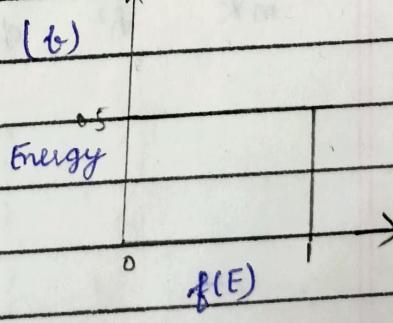
$$E=E_F$$

$$f(E) = \frac{1}{2}$$

(a)



(b)



- If  $T > 0K$

$$E > E_F$$

$$f(E)=0$$

$$E < E_F$$

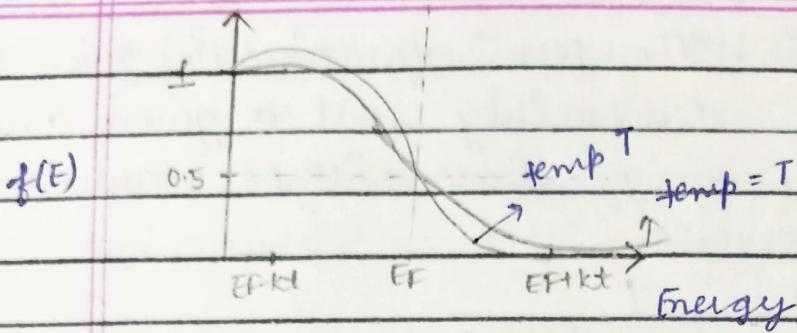
$$f(E)=1$$

$$E=E_F$$

$$f(E)=0.5$$

→ This result is same as case 1. Thus value of fermi factor is  $f(E)$  is 0.5 at any temp.

(2)



Effective mass: Effective mass is denoted by  $m^*$ . It is defined as mass of charged particle in the presence of electric field.

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

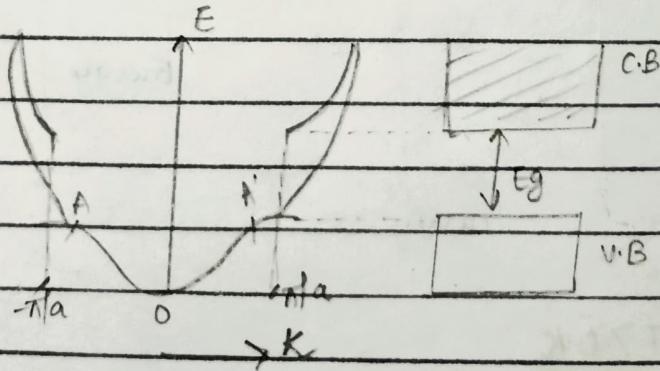
where,  $\hbar$  is reduced plank constant =  $\frac{h}{2\pi} = 1.05 \times 10^{-34}$

$k$  - propagation constant =  $\frac{2\pi}{\lambda}$

$p$  = de Broglie equation

$$p = \frac{\hbar}{\lambda} = \frac{\hbar \times 2\pi}{\lambda} = \frac{\hbar k}{1}$$

$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2E}{dk^2}$$



Observations: If the graph between  $E$  and  $k$  changes concave to convex shape so that

$$\frac{d^2E}{dk^2} = 0, \frac{1}{m^*} = 0, m^* = \infty$$

Between  $\frac{1}{m^*} \text{ of } A \text{ or } A'$  curve is the sol in  $\frac{1}{m^*}$

(3)

+ve or  $m^*$  is also +ve

Beyond pt A and A', graph has -ve curvature  
 $m^*$  is -ve. thus effective mass of electron -ve  
near this region.

# Expression for concentration of free electrons in conduction band for intrinsic semiconductor  
let,  $d\chi$  be the no. of electrons available between the energy interval  $E$  &  $E+dE$  in conduction band.

Then  $d\chi$  is defined as

$$d\chi = (\text{Probability of occupancy}) \times \text{density of states}$$

$$d\chi = f(E) \times z(E) dE \quad \text{--- (1)}$$

$$\# \text{ now } z(E) = \frac{4\pi}{h^3} (2me^*)^{3/2} (E-E_c)^{1/2} dE$$

$$\int_0^\infty \frac{1}{2} e^{-ax} dx = \frac{\sqrt{\pi}}{2a^{3/2}}$$

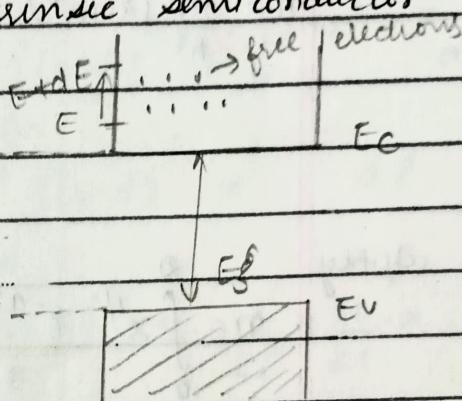
$$f(E) = \frac{1}{1 + e^{(E-E_F)/KT}}$$

$$d\chi = f(E) \times z(E) dE$$

$$= \frac{1}{1 + e^{(E-E_F)/KT}} \times \frac{4\pi}{h^3} (2me^*)^{3/2} (E-E_c)^{1/2} dE$$

$$= e^{-(E-E_F)/KT} \times \frac{4\pi}{h^3} (2me^*)^{3/2} (E-E_c)^{1/2} dE$$

$$= n = \int_{E_c}^\infty d\chi$$



$$n = \frac{4\pi (2me^*)^{3/2}}{\hbar^3} \int_{E_c}^{\infty} (E - E_c)^{1/2} e^{-[E - E_c]/kT} dE \quad (4)$$

$$\text{Now } e^{-[E - E_c + E_F - E_F]/kT} = e^{-[E - E_c]/kT} \cdot e^{-[E_c - E_F]/kT} \downarrow \text{constant}$$

$$n = \frac{4\pi (2me^*)^{3/2}}{\hbar^3} e^{-[E_c - E_F]/kT} \int_{E_c}^{\infty} (E - E_c)^{1/2} e^{-[E - E_c]/kT} dE \quad a = \frac{1}{kT}$$

Put  $E - E_c = x$

when,  $E = E_c = x = 0$

when,  $E = \infty, x = \infty$

apply

$$n = \int_0^{\infty} x^{1/2} e^{-ax} dx$$

$$n = \frac{4\pi}{\hbar^3} (2me^*)^{3/2} e^{-[E_c - E_F]/kT} \frac{\sqrt{\pi}}{2 \left(\frac{1}{kT}\right)^{3/2}}$$

$$n = \frac{2}{\hbar^2} \left( \frac{2me^* \pi kT}{h^2} \right)^{3/2} e^{-[E_c - E_F]/kT} \hookrightarrow n_c$$

# Expression for concentration of holes in valence band for intrinsic semiconductors

let  $dx$  be the no. of holes available between the energy interval  $E$  and  $E + dE$  in valence band. Then  $dx$  is defined as

$dx$  = Probability of occupancy  $\times$  density of state

$$dx = (1 - f(E)) \times z(E) dE$$

here  $1 - f(E)$  is probability of existence of hole

(5)

$$p = \int_{-\infty}^{E_V} dx = \int_{-\infty}^{E_V} (1 - f(E)) \times z(E) dE \quad - (1)$$

$$N_{\text{new}} = 1 - f(E) = 1 - \frac{1}{1 + e^{(E-E_F)/kT}} = \text{new } e^{(E-E_F)/kT} \quad - (2)$$

$$z(E) dE = \frac{4\pi}{h^3} (2m^* h)^{3/2} (E_V - E)^{1/2} dE \quad - (3)$$

$$p = \int_{-\infty}^{E_V} dx = \int_{-\infty}^{E_V} \frac{4\pi}{h^3} (2m^* h)^{3/2} (E_V - E)^{1/2} \cdot e^{(E-E_F)/kT} dE$$

$$p = \frac{4\pi}{h^3} (2m^* h)^{3/2} e^{-EF/kT} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \cdot e^{E/kT} dE$$

$$\text{Now } \frac{(E_V - E)}{kT} = x, \frac{E}{kT} = \frac{E_V - x}{kT}$$

$$dE = -kT dx$$

$$\text{then } E \rightarrow E_V = x \rightarrow 0$$

$$p = \frac{4\pi}{h^3} (2m^* h)^{3/2} e^{(-EF/kT)} \int_0^{\infty} (kTx)^{1/2} e^{(\frac{E_V-x}{kT})} \cdot (-kT) dx$$

$$\text{and } E \rightarrow -\infty, x = \infty$$

$$p = \frac{4\pi}{h^3} (2m^* h k T)^{3/2} e^{(E_V - EF)/kT} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$* \int_0^{\infty} x^{1/2} e^{-x} = \frac{\sqrt{\pi}}{2}$$

$$p = \frac{2}{h^3} \frac{4\pi (2m^* h k T)^{3/2}}{\sqrt{\pi}} e^{(E_V - EF)/kT}$$

$$p = 2 \left( \frac{2m^* h \pi k T}{h^2} \right)^{3/2} e^{(E_V - EF)/kT}$$

$\hookrightarrow N_V$

# Expression for intrinsic carrier concentration whenever a single bond breaks in a semiconductor, then electron-hole-pair is generated. Thus at any temperature  $T$ , the no. of free electrons or holes per unit volume will be equal

$$\begin{aligned} n_i^o &= n \quad - (1) \\ n_i^o &= p \quad - (2) \end{aligned}$$

Multiply (1) and (2), we get

$$\begin{aligned} n_i^{o2} &= np \quad - (3) \\ n &= N_C \cdot [E_C - E_F] / kT \quad - (4) \\ p &= N_V \cdot [E_F - E_V] / kT \quad - (5) \end{aligned}$$

Put (4) and (5) in eq (3)

$$\begin{aligned} n_i^{o2} &= N_C N_V e^{-(E_C - E_V) / kT} \\ n_i^{o2} &= N_C N_V e^{-E_g / kT} \quad [E_g = E_C - E_V] \\ n_i^o &= \sqrt{N_C N_V e^{-E_g / kT}} \quad - (6) \end{aligned}$$

→ Carrier concentration and its dependence with temperature

$$N_C = 2 \left( \frac{2\pi k T}{h^2} \right)^{3/2} \times (m^* e)^{3/2} \quad - (7)$$

$$N_V = 2 \left( \frac{2\pi k T}{h^2} \right)^{3/2} \times (m^* h)^{3/2} \quad - (8)$$

Put (7) & (8) in (6)

$$n_i^{o2} = 4 \left( \frac{2\pi k T}{h^2} \right)^3 (m^* e m^* h)^{3/2} e^{-E_g / kT}$$

$$\text{or } n_i^o = 2 \left( \frac{2\pi k T}{h^2} \right)^{3/2} (m^* e m^* h)^{3/4} \times e^{-E_g / kT}$$

$$n_i^o = 2 \left( \frac{2\pi k}{h^2} \right)^{3/2} (m^* e m^* h)^{3/4} T^{3/2} e^{-E_g / kT}$$

(7)

$$n_i \propto T^{3/2} e^{-Eg/kT}$$

- Conclusion: Intrinsic carrier concentration is independent of energy of fermi level.
- Intrinsic carrier concentration has exponential dependence on band gap energy b/w VB and CB.
- It strongly depend upon temperature  
 $n_i \propto T^{3/2}$

## # Expression for energy of fermi level of an intrinsic semiconductor

→ Concentration of electrons in conduction band of an intrinsic semiconductor is given as

$$n = N_c e^{-(E_c - E_F)/kT} \quad \text{--- (1)}$$

→ Concentration of holes in valence band of an intrinsic semiconductor is given as

$$p = N_v e^{-(E_F - E_v)/kT} \quad \text{--- (2)}$$

$$\text{where } N_c = \frac{2(\alpha m^* e \pi k T)}{\hbar^2}^{3/2} \quad \text{--- (3)}$$

$$N_v = \frac{2(\alpha m^* h \pi k T)}{\hbar^2}^{3/2} \quad \text{--- (4)}$$

We know that  $n = p$

$$N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_v)/kT}$$

taking log both side

$$\ln(N_c) - \left( \frac{E_c - E_F}{kT} \right) = \ln(N_v) - \left( \frac{E_F - E_v}{kT} \right)$$

$$\ln(N_c) - \ln(N_v) = \frac{E_c - E_F}{kT} - \left( \frac{E_F - E_v}{kT} \right)$$

$$\ln\left(\frac{N_c}{N_v}\right) = \frac{E_c - E_F + E_v}{kT}$$

$$RT \ln\left(\frac{N_c}{N_v}\right) = E_c + E_v - \Delta E_F$$

$$\Delta E_F = E_c + E_v - RT \ln\left(\frac{m^*e}{m^*h}\right)^{3/2} \quad \text{using (3) \& (7)}$$

$$E_F = \frac{E_c + E_v}{2} - \frac{3}{4} KT \ln\left(\frac{m^*e}{m^*h}\right) - \textcircled{B}$$

def  $E_g$  = band gap energy

$$E_g = E_c - E_v$$

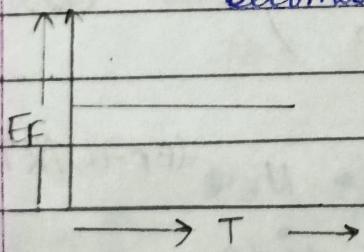
$$\Delta E_V + E_g = E_c - E_v + \Delta E_V$$

$$\Delta E_V + E_g = E_c + E_v \quad \text{put in } \textcircled{B}$$

$$E_F = \frac{\Delta E_V + E_g}{2} - \frac{3}{4} KT \ln\left(\frac{m^*e}{m^*h}\right)$$

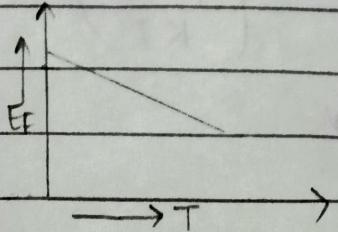
$$\text{or } E_F = E_v + \frac{E_g}{2} - \frac{3}{4} KT \ln\left(\frac{m^*e}{m^*h}\right)$$

- Variation of fermi level with temperature in an intrinsic semiconductor
- There are two cases:  $E_F = E_v + \frac{E_g}{2} - \frac{3}{4} KT \ln\left(\frac{m^*e}{m^*h}\right)$  - ①
- Case 1: If  $m^*e = m^*h$ , then ① becomes  $E_F = E_v + \frac{E_g}{2}$



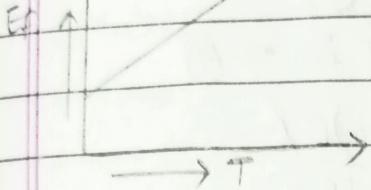
- Case 2: If  $m^*e > m^*h$

$\therefore \ln \frac{m^*e}{m^*h}$  is positive, then  $E_F$  decrease with temperature.



(9)

- Case III : if  $m^*e \geq m^*h$ , i.e.  $\ln\left(\frac{m^*e}{m^*h}\right)$  is negative then  $E_F$  increases with temperature.



- Expression for conductivity of an intrinsic semiconductor and its variation with temperature:

We know that drift velocity of conductor

$$I = nVd eA$$

$V_d$  = drift velocity of electrons

$V_h$  = drift velocity of holes

$$I = I_e + I_h - \textcircled{1}$$

$$I_e = n e V_d eA - \textcircled{2}, I_h = n h V_h eA - \textcircled{3}$$

Put eq \textcircled{2} and \textcircled{3} in \textcircled{1}

$$I = n e V_d eA + n h V_h eA$$

$$I = [n e V_d + n h V_h] eA - \textcircled{4}$$

We know that,

$$V_d \propto E$$

$V_d = \mu e E$  where  $\mu$  is the mobility of charge carrier

$$V_d = \mu e E - \textcircled{5}$$

$$V_h = \mu_h E - \textcircled{6}$$

Substitute the value of  $V_d$  and  $V_h$

$$I = (n e \mu e E + n h \mu_h E) eA$$

$$I = [n e \mu e + n h \mu_h] E eA$$

$$\frac{I}{A} = [n e \mu e + n h \mu_h] eE$$

$\frac{I}{A}$	current density
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(18)

$$J = [n_e e + n_h u_h] e E \quad - (7)$$

Acc. to ohm's law

$$J = \sigma E \quad - (8)$$

Put the value of J in eq- (7)

$$\sigma E = [n_e e + n_h u_h] e E$$

$$\sigma = [n_e e + n_h u_h] e$$

For intrinsic type semiconductor

$$n_e = n_h = n_i$$

$$\boxed{\sigma = [e e + u_h] e n_i}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{(e e + u_h) e n_i}$$

$$\text{we know that } n_i = \sqrt{N_c N_v} e^{-E_g / kT}$$

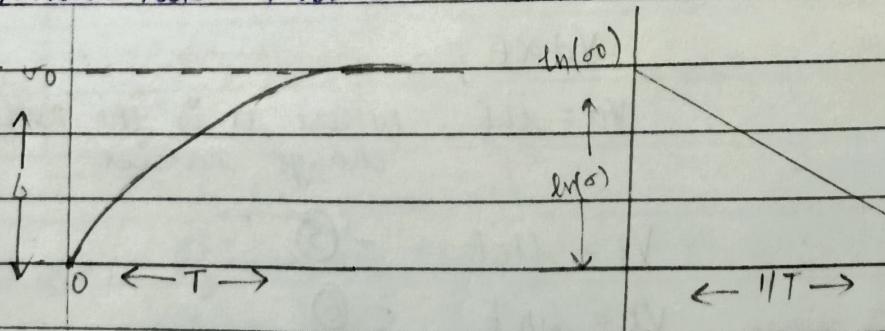
$$\sigma = [e e + u_h] e \sqrt{N_c N_v} e^{-E_g / kT}$$

$$\sigma = \sigma_0 e^{-E_g / 2kT}$$

$$\text{where } \sigma_0 = e (e e + u_h) \sqrt{N_c N_v}$$

- Conductivity of intrinsic semiconductor increases with temperature

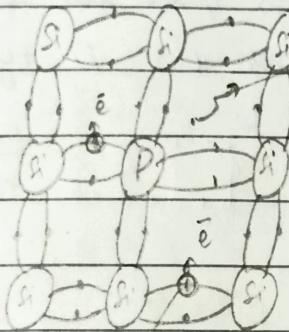
$T=0, \sigma=0$ , at absolute 0K, a semiconductor behave like intrinsic semiconductor.



as  $T$  is increased  $\sigma$  increases and at  $T=\infty, \sigma \rightarrow \sigma_0$  Thus  $\sigma_0$  is max.

(11)

- Energy band diagrams of n-type extrinsic semiconductor and variation of carrier concentration with temperature.

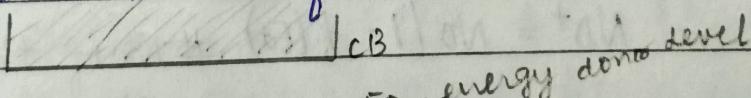


we know that an n-type extrinsic semiconductor is obtained by adding pentavalent impurity in semiconductor sample

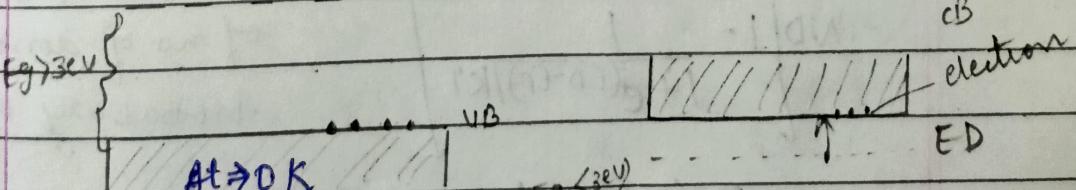
hole

- At  $T=0\text{ K}$  this semiconductor behaves as insulator.
- As we increase the temperature of electrons which is outside the phosphorous will free fast as compared to bounded electron of phosphorous: As more and more temperature is increased the bounded electron leave their place and creates holes in that place.

In this kind of semiconductor near



ED - energy donor level



→ Conduction band empty

$Eg (3\text{eV})$

At  $T > 0\text{ K}$

hole

CB

electron

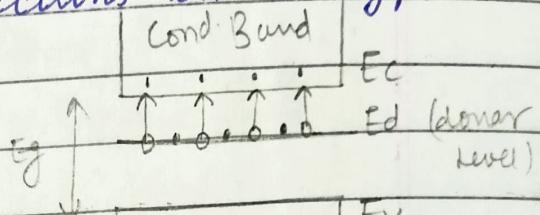
ED

VB

(12)

- Expression for carrier concentration in N-type semiconductor.

→ we know that N-type semiconductors have electrons as majority carriers, so we will be finding the no. of electrons in N-type semiconductor.



- for an N-type semiconductor, the conduction is mainly between conduction band or donor level, so fermi level between Ed and Ec
- let us first find equation of Ef before finding carrier concentration
- let Nd be the no. of donor atoms added per unit volume. As the donor will give its electrons to conduction band it will get positively ionised ie holes formed in donor level will be equal to no. of electrons given to conduction band

$$n = ND^+ = ND \left(1 - f(E_d)\right) \quad \text{# No. of +ve ionised donor atoms is equal to product of no. of donor and probability of holes}$$

$$ND \left[ 1 - \frac{1}{1 + e^{(E_d - E_f)/kT}} \right]$$

$$ND \left[ \frac{e^{(E_d - E_f)/kT}}{1 + e^{(E_d - E_f)/kT}} \right]$$

$$ND \left[ \frac{1}{e^{(E_d - E_f)/kT} + 1} \right]$$

(13)

$$N_D^+ = N_D \cdot e^{(E_D - E_F)/kT} \quad - (1)$$

- now, at low temp. covalent bonds don't break, still conduction band has electrons from donor level, so we can say that

$$N_D^+ = N_c \quad (2)$$

$$N_c = N_c e^{-(E_C - E_F)/kT} \quad - (3)$$

$$N_D \cdot e^{(E_D - E_F)/kT} = N_c e^{-(E_C - E_F)/kT}$$

Taking natural log both sides

$$\ln N_D^+ \frac{E_D - E_F}{kT} = \ln N_c - \frac{E_C - E_F}{kT}$$

$$\ln \left[ \frac{N_c}{N_D} \right] = \frac{E_D - E_F + E_C - E_F}{kT}$$

$$\ln \left[ \frac{N_c}{N_D} \right] = -\frac{2E_F + E_D + E_C}{kT}$$

$$2E_F = E_D + E_C - kT \ln \left[ \frac{N_c}{N_D} \right]$$

$$E_F = \frac{E_D + E_C}{2} + \frac{kT}{2} \ln \frac{N_D}{N_c} \quad - (4)$$

$$E_F = \frac{E_D - E_C + 2E_C}{2} + \frac{kT}{2} \ln \left( \frac{N_D}{N_c} \right)$$

$$E_F = \frac{E_D - E_C}{2} + E_C + \frac{kT}{2} \ln \left( \frac{N_D}{N_c} \right)$$

$$E_F - E_C = \frac{E_D - E_C}{2} + \frac{kT}{2} \ln \left( \frac{N_D}{N_c} \right)$$

divide b.s with  $kT$

$$\frac{E_F - E_C}{kT} = \frac{E_D - E_C}{2kT} + \frac{1}{2} \ln \left( \frac{N_D}{N_c} \right)$$

$$\frac{E_F - E_C}{kT} = \frac{E_D - E_C}{2kT} + \ln \left( \sqrt{\frac{N_D}{N_c}} \right) \quad - (5)$$

(14)

Concentration of electron is given as

$$n = N_c e^{-(E_F - E_C)/kT}$$

$$n = N_c e^{(E_F - E_C)/kT} \rightarrow \text{here put eq(3)}$$

$$n = N_c e^{\left(\frac{E_D - E_C}{2kT} + \ln \frac{N_D}{N_c}\right)}$$

$$n = N_c e^{\left(\frac{E_D - E_C}{2kT}\right)} \times e^{\ln\left(\frac{N_D}{N_c}\right)}$$

$$n = N_c \times \frac{N_D}{N_c} \times e^{\left[\frac{E_D - E_C}{2kT}\right]}$$

$$n = \frac{N_c N_D}{h^2} e^{\left(\frac{(E_D - E_C)}{2kT}\right)} \quad - \textcircled{6}$$

we know

$$N_c = \frac{2(2\pi m^* e k T)^{3/2}}{h^2}$$

$$n = \frac{2 N_c N_D}{h^2} \left(\frac{2\pi m^* k T}{h^2}\right)^{3/4} e^{\left(\frac{E_D - E_C}{2kT}\right)}$$

- Variation of fermi level with temperature and impurity conc. for N-type semiconductor

$$\text{from eq } E_F = \frac{E_D + E_C}{2} + \frac{kT}{2} \ln \frac{N_D}{2(2\pi m^* k T)^{3/2}}$$

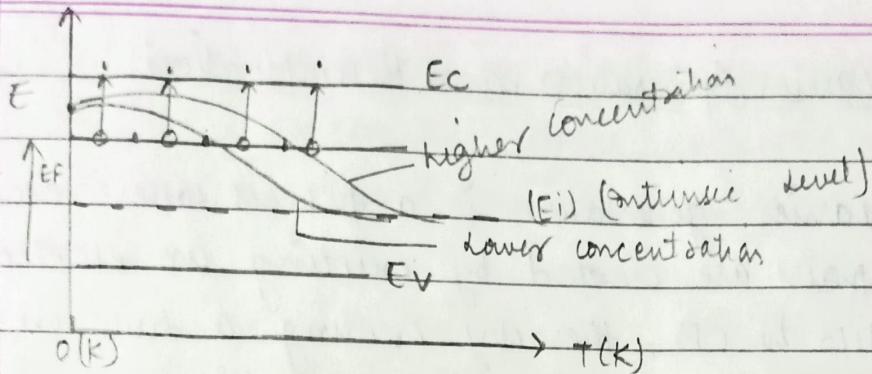
$\rightarrow$  if  $T = 0\text{K}$ , the above eq will reduce to

$$E_F = \frac{E_D + E_C}{2}$$

i.e. fermi level is in the mid of valence & conduction Band.

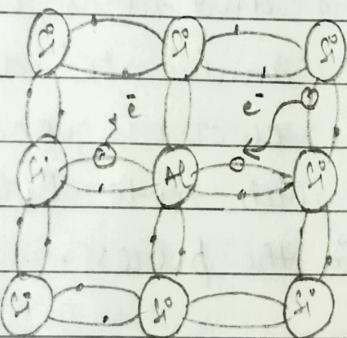
$\rightarrow$  if  $T > 0\text{K}$  i.e. as temperature rises more and more covalent bonds break and e from V.B also move to C.B. i.e. achieve  $n_e = n_h$

(15)



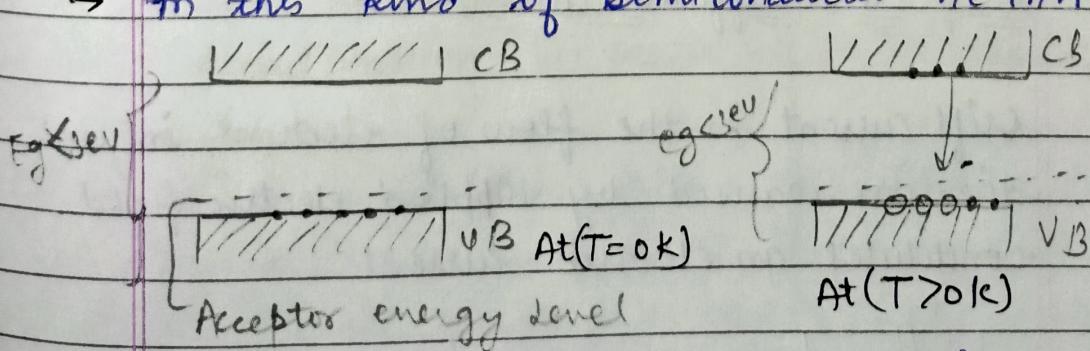
- Energy band diagram of p-type extrinsic Semiconductor:

→



we know that an p-type extrinsic semiconductor is obtained by adding trivalent impurity in semiconductor sample.

- At  $T=0\text{ K}$  this semiconductor behaves as insulator
- If we increase the temperature, electrons get energy, and come from their bond and take the place of nearby electron. This process continues as we increase more and more temperature.
- In this kind of semiconductor  $n < n_h$



Here, conduction band  $\rightarrow e \text{ rare in C.B}$   
Empty  $\rightarrow n < n_h$

## Carrier Generation and Recombination:

- Carrier generation is a process where electron-hole pairs are created by exciting an electron from VB to CB, thereby creating a hole in VB
- ways of carrier generation
  - (i) light absorption
  - (ii) By high energy particle beam bombardment

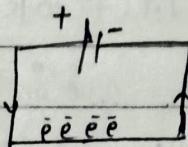
- Recombination of electron and holes is a process by which both carriers 'annihilate' 'destroy' each other. This means electrons occupy the empty states available with hole. Both carriers eventually 'disappear' in the process.

→ Energy released during Recombination can be radiative or non-radiative

- Types: Band to Band Recombination  
Trap assisted Recombination  
Auger Recombination

## Drift and Diffusion currents:

Drift current is the flow of electrons in one direction caused by applied electric field constitutes an electric current



- When electric field is applied to a metal electrons move towards the terminal and then electrons collide

(17)

with atoms, collision take place that collision is inelastic. After collision e gets acceleration and gain velocity in one direction

$$J_d = J_{ed} + J_{hd}$$

$J_d$  = [drift current

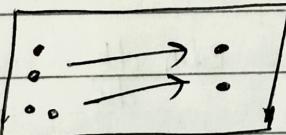
$$J_d = n_e e v_e E + p_h e v_h E$$

[density]

$$J_d = e [n_e v_e + p_h v_h] E$$

→ Diffusion current is the result of gradient of carrier concentration

- charge carriers tend to distribute themselves uniformly throughout the S.C. crystal
- Movement continuous until carriers evenly distributed



• Carrier transport: any process, that is responsible for the movement of charge carriers within a semiconductor is called carrier transport.

(i) Thermal motion (ii) carrier drift (iii) carrier diffusion

(i) → At any given temp above 0K, carriers have thermal kinetic energy  $\frac{1}{2} kT$  per degree of freedom. This thermal energy gives the tendency to charge carriers to move within crystal. During their motion, carrier collide with lattice due to which their direction motion changes. Such kind

of motion is called Brownian motion.

(ii) → The motion of electrons and holes that was random in the absence of electric field tends to acquire an motion and gives rise to drift current given as

$$J_{ed} = n e M_e E$$

$$J_{hd} = p e M_h E$$

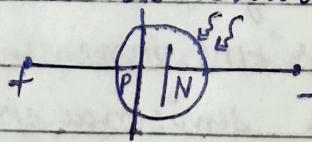
(iii) → The motion of charge carriers due to conc. gradient in a semiconductor is called carrier diffusion is given as

$$J_{ed} = -e D_e \frac{dn}{dx}$$

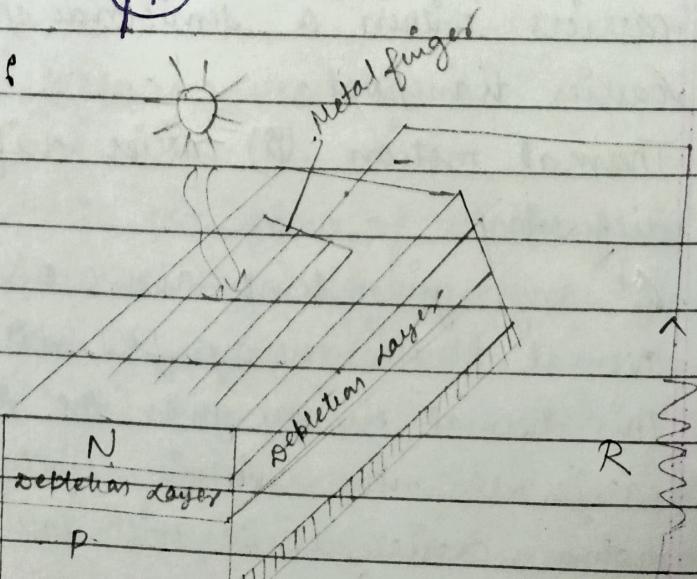
$$J_{hd} = e D_h \frac{dp}{dx}$$

# • Solar cell: It is a P-N junction device which converts solar energy into electric energy.

• Symbol:



• Construction:



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It consists of P-N junction diode in which N-region has small thickness & P has large thickness.

N region made thin, so that light falling on solar cell is reached to depletion layer easily. On the top of N-type layer metallic fingers are deposited and they are made to have enough space between them for the light to reach depletion region through N layer.

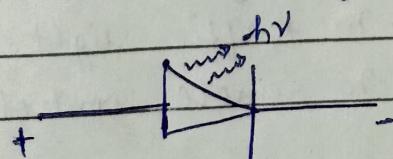
Working: When photons of light fall at solar cell, then electron hole generated in depletion layer. The E-H-P generated moves in opp. direction due to junction field.

The e moves towards N side & hole moves towards P side. They will be collected at the two sides of junction, giving rise to photo voltage between top and bottom metal electrodes. When an external load is connected across metal electrodes a photo current flows.

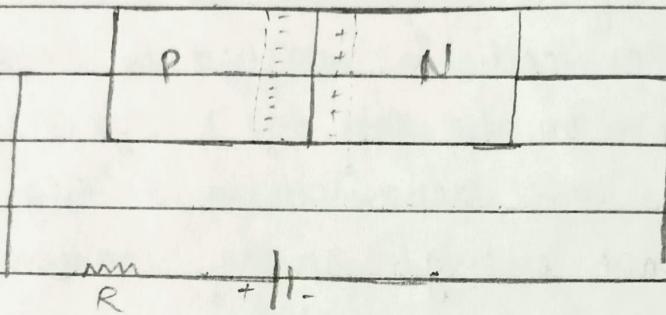
#. LED (Light Emitting diode): It is heavily doped P-N junction diode which converts electrical energy in to light energy.

- This diode emits light under forward biasing

Symbol:



- construction: In this P-N junction diode is connected from a battery through resistance R which controls the brightness of light emitted.



→ Working: When P-N junction is forward biased, electrons and holes move towards opp. side of junction. Therefore excess minority carrier on the either side of junction boundary, recombine with majority carriers near the junction.

On recombination of a hole, the energy is given out in the form of light. The released energy is nearly equal to energy gap.

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

$$\lambda = \frac{hc}{Eg} \rightarrow \text{This is the wavelength of emitted light}$$

- Advantages: long life, low operation voltage, less power consume

- uses of led:
  - in Burglar - alarm system
  - in traffic light
  - in remote control