Phy I

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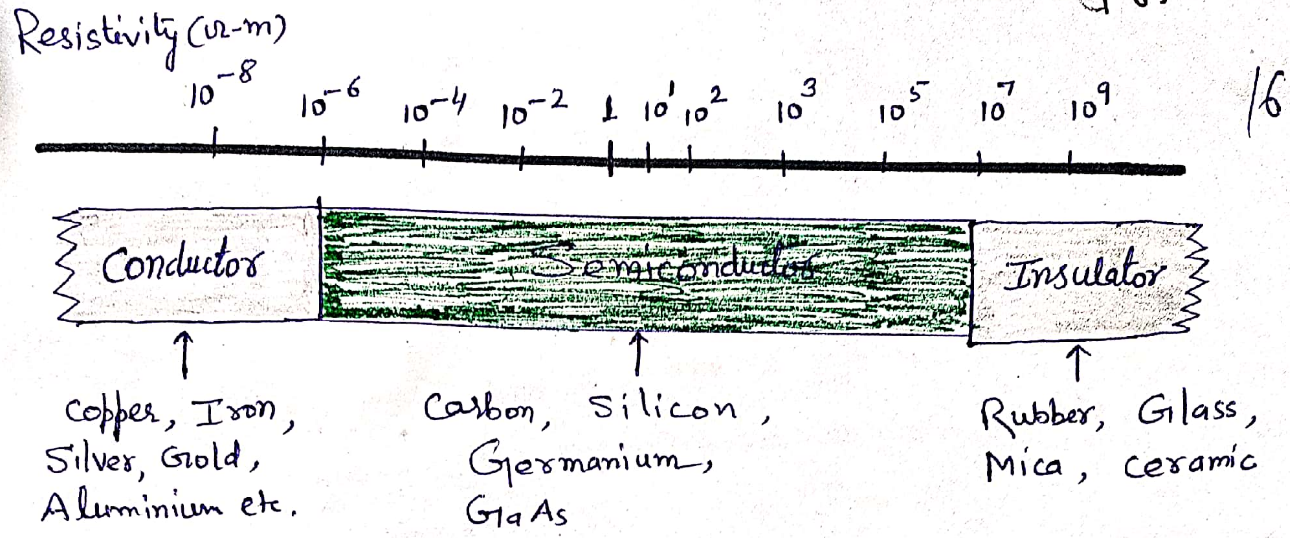


Semiconductors:- The substances which have electrical properties (resistivity or conductivity) in between conductors and insulators are known as Semiconductors.

Ex: Silicon, Germanium.

Semiconductors have very few "free electrons" because their atoms are closely grouped together in a crystalline pattern called a "crystal lattice" but electrons are still able to flow, but only under special conditions.

Properties :-

1. They have resistivity less than insulators & more than conductors.
2. The resistance of Semiconductor decreases with increase in temperature & vice versa i.e. they have negative temp coefficient of resistance (α)
3. When suitable impurity is added to a semiconductor, then its current conducting properties change appreciably.
4. They are extensively used in electronic circuits.

Conduction in Semiconductors :- The conduction in Semiconductors is due to the flow of electrons and holes. The band gap or the forbidden gap is about 1eV. b/w VB and C.B.

Types of Semiconductors :-

1. Intrinsic Semiconductors or pure Semiconductors.
2. Extrinsic semiconductors or Impure Semiconductors.

*** Intrinsic Semiconductors :-** Semiconductors in an extremely pure form is known as intrinsic semiconductors. In these Semiconductors, electrons and holes are solely created by thermal excitation.

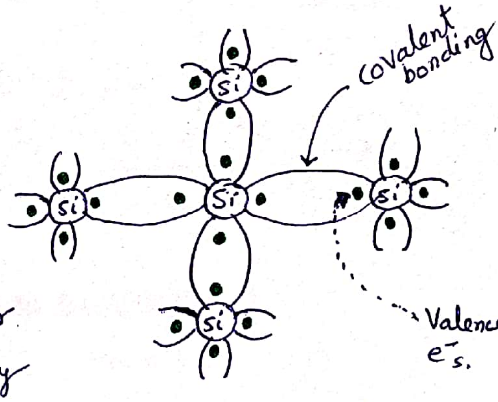
Examples :- Silicon, Germanium.

Effect of Temperature on Intrinsic Semiconductors :-

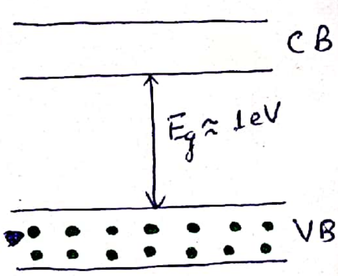
- At O K Temp :-

The V.B. is completely filled with electrons and C.B. is completely empty.

At oK temp, e^-_s in the V.B. do not gain sufficient energy to jump in the C.B. i.e. the Valence Band e_s never cross even this small energy band gap at OK temp. The Covalent bond is enough strong to hold the e^-_s.



Crystal lattice diagram



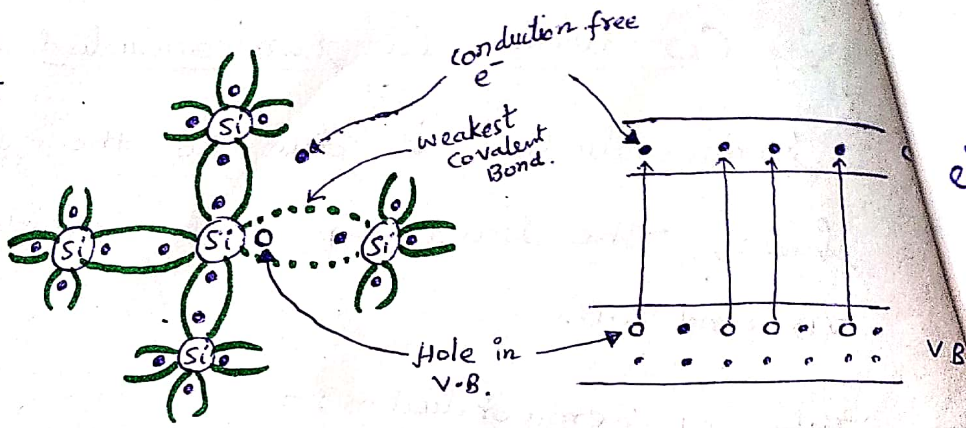
Energy Band Diagram.

So we can say that the semiconductor behaves as an insulator at 0 kelvin temp.

At room Temperature :→

The electrons gain sufficient amount of thermal energy to jump in the C.B.

A vacancy of $\bar{e}_s$ is created in the V.B., this vacancy is known as hole.



At this temp, covalent bonds get break and $\bar{e}_s$ becomes free as shown in fig.

So at room temp, $\bar{e}$ - hole pair is generated. The semiconductor behaves as a conductor because conduction takes place due to the free electrons present in the C.B.

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Carrier concentration in Intrinsic Semiconductors :→

The Charge carriers in intrinsic semiconductors are electrons and holes, therefore we will calculate the followings :

1) Number of electrons in the conduction Band
2) Number of holes in the Valence Band
3) Fermi Level in intrinsic semiconductor
4) Intrinsic concentration of charge carriers.

* **Number of electrons in the conduction Band :→**

In the conduction band $\bar{e}s$ are free to move with an effective mass m^*.

The density of $\bar{e}s$ in C.B. is given by

$$n_e = \int_{E_c}^{\infty} D(E)\, f(E)\, dE \quad \text{------} \quad (1)$$

where E_c = energy at the bottom of C.B

$D(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2}$, known as density of States in C.B.

$f(E) = \frac{1}{1+e^{(E-E_F)/KT}}$, known as Fermi Function

E_F = Fermi energy
K = Boltzman constt
T = Absolute Temp

Now put $D(E)$ & $f(E)$ in eqn (1)

$$n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^{\infty}\frac{(E-E_c)^{1/2}}{1+e^{(E-E_F)/KT}}\,dE$$

As $e^{(E-E_F)/KT} >>> 1$, therefore 1 is neglected

$$\therefore n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^{\infty}\frac{(E-E_c)^{1/2}}{e^{(E-E_F)/KT}}\,dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^{\infty}(E-E_c)^{1/2}e^{-(E-E_F)/KT}\,dE$$

$$n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^{\infty}(E-E_c)^{1/2}e^{(E_F-E)/KT}\,dE$$

Now put $E_F - E = (E_F - E_c) + (E_c - E)$

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

$$n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F-E_c)/KT} \int_{E_c}^{\infty} (E-E_c)^{\frac{1}{2}} e^{(E_c-E)/KT} dE \quad \text{------ (2)}$$

Now put $\frac{E-E_c}{KT} = x$, $E-E_c = xKT$

or $dE = KT\,dx$

and $(E-E_c) = xKT$

or $(E-E_c)^{\frac{1}{2}} = x^{\frac{1}{2}}(KT)^{\frac{1}{2}}$

For limits when $E = E_c$, $x = 0$

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

put these values in eqn (2)

$$n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F-E_c)/KT} \int_0^{\infty} x^{\frac{1}{2}}(KT)^{\frac{1}{2}} \cdot e^{-x}\, KT\,dx$$

$$n_e = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F-E_c)/KT} \cdot (KT)^{3/2} \int_0^{\infty} x^{\frac{1}{2}} e^{-x} dx$$

But $\int_0^{\infty} x^{\frac{1}{2}} e^{-x} dx = \frac{\sqrt{\pi}}{2}$, Gamma Function

$$\therefore \quad n_e = \frac{\cancel{4}^{2}\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F-E_c)/KT} \cdot (KT)^{3/2} \times \frac{\sqrt{\pi}}{\cancel{2}}$$

$$\boxed{n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \cdot e^{(E_F-E_c)/KT}}$$

— This is an expression for the concentration of electrons in the C.B. of an intrinsic Semiconductor.

Density of holes in Valence Band :→

Here, we shall use $[1 - f(E)]$ instead of $f(E)$ as this represents the probability for a state of energy E to be unoccupied.

occupied states = $f(E)$
unoccupied states = $1 - f(E)$

The hole density in the valence band is given by

$$n_h = \int_{-\infty}^{E_v} D(E)\,[1 - f(E)]\,dE \quad \text{-------} (1)$$

where $D(E) = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)^{1/2}$, density of states in V.B.

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

$$= 1 - [1 + e^{(E-E_F)/kT}]^{-1}$$

$$= 1 - [1 - e^{(E-E_F)/kT}]$$

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

Now eq^n (1) becomes,

$$n_h = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\int_{-\infty}^{E_v}(E_v - E)^{\frac{1}{2}}\, e^{(E-E_F)/kT}\,dE$$

put

$$E - E_F = E - E_F + E_v - E_v$$

$$E - E_F = (E_v - E_F) + (E - E_v)$$

$$\therefore \quad n_h = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\int_{-\infty}^{E_v}(E_v - E)^{\frac{1}{2}}\, e^{(E_v - E_F)/kT} \times e^{(E-E_v)/kT}\,dE$$

$$= \frac{4\pi}{h^3}(2m_h^*)^{3/2}\, e^{(E_v - E_F)/kT}\int_{-\infty}^{E_v}(E_v - E)^{\frac{1}{2}}\cdot e^{(E-E_v)/kT}\,dE \quad \text{-----} (2)$$

Now put $\frac{E_v - E}{kT} = x$

or $E_v - E = xkT$

$$-dE = KT\,dx$$

or $dE = -KT\,dx$

Also $(E_v - E) = x\,KT$

$$(E_v - E)^{\frac{1}{2}} = (KT)^{\frac{1}{2}} x^{\frac{1}{2}}.$$

For limits, if $E = -\infty$, $x = +\infty$

if $E = E_V$, $x = 0$

So eq^n (2) now becomes.

$$n_h = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(E_v - E_F)/KT} \int_{-\infty}^{0} (KT)^{\frac{1}{2}} x^{\frac{1}{2}} . e^{(E-E_v)/KT} \times (-KT\,dx)$$

$$n_h = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(E_v - E_F)/KT} . (KT)^{3/2} \int_0^{\infty} x^{\frac{1}{2}} e^{-x}\,dx$$

But $\int_0^{\infty} x^{\frac{1}{2}} e^{-x}\,dx = \frac{\sqrt{\pi}}{2}$, Gamma Function

$$\therefore \quad n_h = \frac{4\pi}{h^3}(2m_h^*)^{3/2} (KT)^{3/2} e^{(E_v - E_F)/KT} \times \frac{\sqrt{\pi}}{2}$$

$$n_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \exp\left\{\frac{E_v - E_F}{KT}\right\}$$

This is the expression for hole concentration in Valence band.

Combined carrier concentration in case of intrinsic Semiconductor :→

As the e^- density in CB is

$$n_e = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} e^{(E_F-E_c)/kT}$$

The hole density in VB is

$$n_h = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{(E_v-E_F)/kT}$$

Now let n_i be the charge carrier concentration

So

$$n_i^2 = n_i \times n_i$$

$$= (n_e) \times (n_h)$$

$$n_i^2 = \left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \times e^{(E_F-E_c)/kT}\right] \times \left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \times e^{(E_v-E_F)/kT}\right]$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/2} e^{\frac{E_F-E_c+E_v-E_F}{kT}}$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/2} e^{(E_v-E_c)/kT}$$

or

$$n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{(E_v-E_c)/2kT}$$

or

$$\boxed{n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2kT}}$$

$\because E_c - E_v = E_g$

Fermi Level in intrinsic Semiconductor :-

In an intrinsic semiconductor the electrons and holes are generated in pairs when temperature is raised.

Hence

$$n_e = n_h$$

$$\cancel{2}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} e^{(E_F - E_c)/kT} = \cancel{2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{(E_v - E_F)/kT}$$

$$(m_e^*)^{3/2} e^{(E_F - E_c)/kT} = (m_h^*)^{3/2} e^{(E_v - E_F)/kT}$$

$$\frac{e^{(E_F - E_c)/kT}}{e^{(E_v - E_F)/kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$e^{(E_F - E_c)/kT} \times e^{(E_F - E_v)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$e^{(E_F - E_c + E_F - E_v)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$e^{(2E_F - E_c - E_v)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

Taking log both Sides,

$$\frac{2E_F - E_c - E_v}{kT} = \frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right)$$

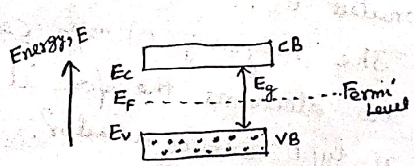
or $$2E_F - E_c - E_v = \frac{3}{2} kT \log\left(\frac{m_h^*}{m_e^*}\right)$$

$$2E_F = E_c + E_v + \frac{3}{2} kT \log\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} kT \log\left(\frac{m_h^*}{m_e^*}\right)$$

when $m_h^* = m_e^*$, then $\log\left(\frac{m_h^*}{m_e^*}\right) = \log 1 = 0$

Hence $\boxed{E_F = \frac{E_c + E_v}{2}}$



Fermi Level lies exactly half way b/w top of VC and bottom of C.B. when $m_e^* = m_h^*$

Extrinsic Semiconductor :→

(2)

The conductivity of intrinsic Semiconductor (pure Semiconductor) is found to be very poor.

So the properties of intrinsic semiconductors are modified by addition of certain impurities.

~~So extrinsic Semiconductor are impure semiconductors in which Suitable impurities (pentavalent or trivalent) are added.~~

When suitable impurities (Pentavalent or Trivalent) are added to pure Semiconductors in controlled amount then extrinsic Semiconductors are formed.

The process by which impurities are added is called doping.

Types of extrinsic semiconductors :→

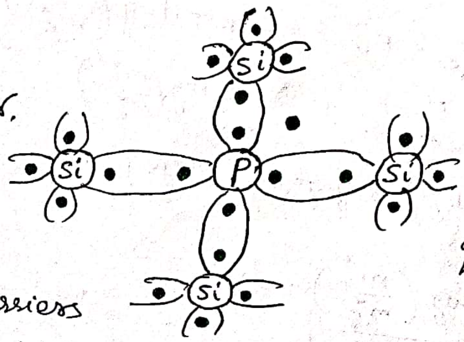
① n-type Semiconductor :→

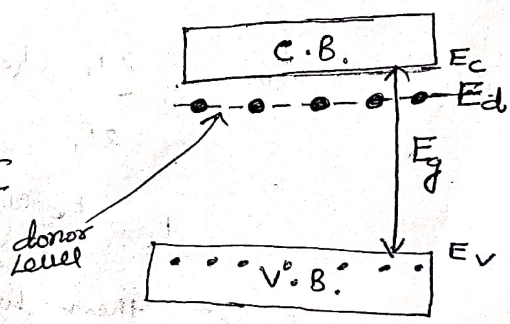
When pentavalent impurities (antimony, arsenic, Phosphorus, bismuth etc) are added to pure semiconductor then n-type semiconductor is formed. Pentavalent impurity has 5 electrons in their outermost shell and pure semiconductor (Si or Ge) has 4 electrons.

Out of 5 electrons of impurity atom, 4 electrons will form Covalent bond with 4 electrons of pure semiconductor. The 5th electron is free to move.

The impurity is known as donor impurity because it donates e^- to the semiconductor.
There is a donor level just below the C.B. which contains donated e^-s.

The majority charge carriers are electrons therefore it is n-type semiconductor.

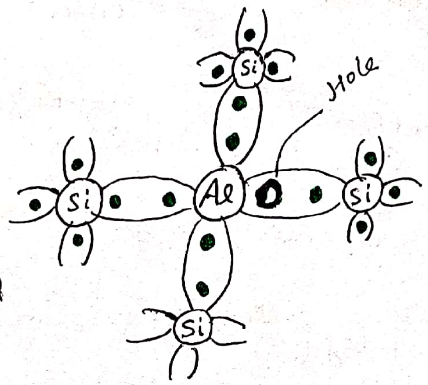


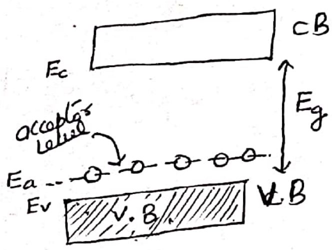


(2) **p-type Semiconductor :-** When trivalent impurity (Boron, Al, indium, gallium etc) are added to pure semiconductor (Si or Ge) then p-type semiconductor is formed. 3 electrons of added impurity are bonded covalently with 3 electrons of pure semiconductor. one vacant electron site or hole is generated.

The impurity is known as acceptor impurity because it accept electrons.

There is aceptor level just above the V.B. which are occupied with holes.





The majority charge carriers are holes (+ve charge sheet) therefore known as p-type semiconductors.

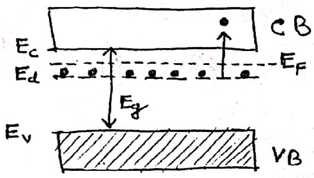
Charge Carrier Concentration in extrinsic Semiconductor :→

Charge carrier concentration in n-type Semiconductor :→

The electron density in C.B. is given by

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{(E_F - E_c)/KT} \quad \text{------- (1)}$$

The no. of vacancies per unit volume in the donor level is



$$n_d\left[1 - f(E)\right] = n_d\left[1 - \frac{1}{e^{(E_d - E_F)/KT} + 1}\right]$$

$$= n_d\left[\frac{e^{(E_d - E_F)/KT} + \cancel{1} - \cancel{1}}{e^{(E_d - E_F)/KT} + 1}\right] = n_d\left[\frac{e^{(E_d - E_F)/KT}}{1 + e^{(E_d - E_F)/KT}}\right]$$

Let $e^{(E_d - E_F)/KT} = x$

$$\therefore \quad n_d\left[1 - f(E)\right] = n_d\left[\frac{e^x}{1 + e^x}\right]$$

$$= n_d\left[\frac{1}{e^{-x}(1 + e^x)}\right] = n_d\left[\frac{1}{e^{-x} + e^{-x} \cdot e^x}\right] = n_d\left[\frac{1}{e^{-x} + e^0}\right]$$

$$= n_d\left[\frac{1}{1 + e^{-x}}\right] = n_d\left[\frac{1}{1 + e^{(E_F - E_d)/KT}}\right] \quad \text{------ (2)} \quad \text{By putting } x.$$

Since the density of $\bar{e}_s$ in C.B. = density of empty donors,

equating (1) and (2)

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{(E_F-E_c)/KT} = \frac{n_d}{1+e^{(E_F-E_d)/KT}}$$

As $E_F >> KT$, neglecting 1 from RHS

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{(E_F-E_c)/KT} = \frac{n_d}{e^{(E_F-E_d)/KT}}$$

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{(E_F-E_c)/KT} = n_d\left[e^{(E_d-E_F)/KT}\right]$$

Taking log on both sides, we get

$$\log 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} + \log\left(e^{(E_F-E_c)/KT}\right) = \log n_d + \log e^{(E_d-E_F)/KT}$$ $\left[\log ab = \log a + \log b\right.$

$$\log 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} + \frac{E_F-E_c}{KT} = \log n_d + \frac{E_d-E_F}{KT}$$

$$\frac{E_F-E_c-E_d+E_F}{KT} = \log n_d - \log 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}$$

$$\frac{2E_F-E_d-E_c}{KT} = \log\frac{n_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}$$

$$2E_F = E_d + E_c + KT\log\frac{n_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}$$

or
$$E_F = \frac{E_d+E_c}{2} + \frac{KT}{2}\log\frac{n_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}} \quad \text{-------- (3)}$$

put E_F in eq^n (1)

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \exp\left\{\frac{E_d+E_c}{2KT} + \frac{1}{2}\log\frac{n_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}} - \frac{E_c}{KT}\right\}$$

Let put $Z = \left(\frac{2\pi m_e^* KT}{h^2}\right)$

$$n_e = 2Z^{3/2}\cdot\exp\left[\frac{E_d-E_c}{2KT} + \frac{1}{2}\log\frac{n_d}{2Z^{3/2}}\right]$$

$$= 2Z^{3/2}\exp\left[\frac{E_d-E_c}{2KT} + \log\left(\frac{n_d}{2Z^{3/2}}\right)^{\frac{1}{2}}\right]$$

$$= 2Z^{3/2}\times\exp\left[\frac{E_d-E_c}{2KT}\right]\times\frac{(n_d)^{\frac{1}{2}}}{(2)^{\frac{1}{2}}Z^{3/4}}$$

$$= (2n_d)^{\frac{1}{2}} Z^{3/4} e^{(E_d-E_c)/2KT}$$

$$n_e = (2n_d)^{\frac{1}{2}}\cdot\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} e^{-\frac{\Delta E}{2KT}}$$

where $\Delta E = E_c - E_d$, ionization energy of donor

At $T = 0K$, then from eq^n (3)

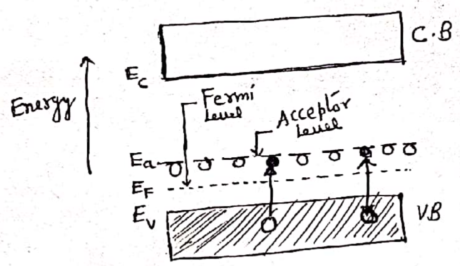
$$E_F = \frac{E_d + E_c}{2}$$

It means fermi level lies exactly half way between donor levels and the bottom of C.B.

When temperature increases, the Fermi level shifts below the donor level & at high temperature, E_F approach the centre of forbidden gap which means the substance is an intrinsic semiconductor.

Charge carrier concentration in P type Semiconductor :→

The hole density in the V.B.



$$n_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} e^{(E_v - E_F)/KT} \quad \text{------- (1)}$$

The number of e^-s per unit volume in the acceptor level is

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

Since $E_a - E_F >> KT$, Hence 1 is neglected.

Now

$$n_a f(E) = \frac{n_a}{e^{(E_a - E_F)/KT}} = n_a e^{(E_F - E_a)/KT} \quad \text{------ (2)}$$

Since the no. of e^-s in the acceptor level = No. of holes in V.B.,

equating eq^n (1) & (2)

$$2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} e^{(E_v - E_F)/KT} = n_a e^{(E_F - E_a)/KT}$$

Taking log on both sides, we get

$$\log 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} + \log e^{(E_v - E_F)/KT} = \log n_a + \log e^{(E_F - E_a)/KT}$$

use
$\log ab = \log a + \log b$
$\log e = 1$

$$\log 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} + \frac{E_v - E_F}{KT} = \log n_a + \frac{E_F - E_a}{KT}$$

or

$$\frac{E_v - E_F - E_F + E_a}{KT} = \log n_a - \log 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}$$

$$\frac{E_v + E_a - 2E_F}{KT} = \log \frac{n_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$$

$$-2E_F = -E_v - E_a + KT \log \frac{n_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$$

$$E_F = \frac{E_a + E_v}{2} - \frac{KT}{2} \log \frac{n_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$$

put value of E_F in eq^n (1)

$$n_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \exp\left[\frac{E_v}{KT} - \frac{(E_a + E_v)}{2KT} + \frac{1}{2} \log \frac{N_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}\right]$$

$$n_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \exp\left[\frac{E_v - E_a}{2KT} + \log \frac{(N_a)^{1/2}}{\left[2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}\right]^{1/2}}\right]$$

$$= 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_v - E_a}{2KT}\right) \cdot \frac{(N_a)^{1/2}}{(2)^{\frac{1}{2}} \left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4}}$$

$$n_h = (2N_a)^{1/2} \left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4} \exp.\left(\frac{E_v - E_a}{2KT}\right)$$

$$n_h = (2N_a)^{\frac{1}{2}} \left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4} e^{-\Delta E/KT} \qquad \left[\because E_a - E_v = \Delta E\right.$$

hole concentration in V.B. is proportional to the square root of the acceptor concentration at the temp near absolute zero.

At $T = 0\,K$, then

$$E_F = \frac{E_a + E_v}{2}$$

— 4 (a) End —

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