

Unit 3

Semiconductor Pysics



Electron and hole concentrations in semiconductor

With an increase in temperature covalent bonds are broken in an intrinsic semiconductor and electron-hole pairs are generated. We expect that a large number of electrons can be found in the conduction band and similarly, a large number of holes in the valence band. Carrier concentration is the number of electrons in the conduction band per unit volume (n) and the number of holes in the valence band per unit volume (p) of the material. Carrier concentration is also known as the density of charge carriers.

The expression for the electron concentration in the conduction band of an intrinsic semiconductor is given by

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

Where

$$N_C = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$$

Electron and hole concentrations in semiconductor

The expression for the holes concentration in the valance band of an intrinsic semiconductor is given by

$$p = N_V e^{-(E_F - E_V) / kT}$$

Where

$$N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$

Intrinsic Density

A single event of bond breaking in a pure semiconductor leads to generation of an electron hole pair. At any temperature T , the number of electrons generated will be equal to the number of holes generated.

$$n = p = n_i \text{ -----(1)}$$

$$n_i^2 = np$$

$$n_i^2 = (N_C e^{-(E_C - E_F)/kT}) (N_V e^{-(E_F - E_V)/kT})$$

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

We know that $(E_C - E_V) = E_g$

$$n_i^2 = (N_C N_V) e^{-E_g/kT}$$

$$n_i = (N_C N_V)^{1/2} e^{-E_g/2kT} \text{ -----(2)}$$

Where

$$N_C = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$$

$$N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$

Intrinsic Density

Substituting the values of N_C and N_V in eqn (2) equation

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

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

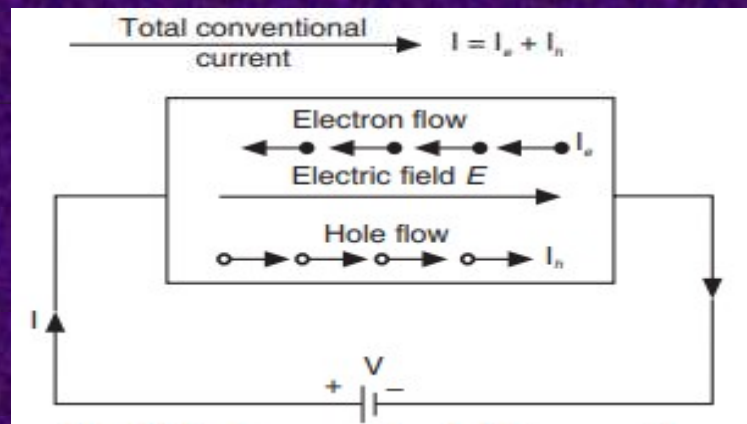
From eqn (3)

- The intrinsic concentration is independent of Fermi level.
- The intrinsic concentration has an exponential dependence on the band gap value E_g .
- It strongly depends on the temperature.
- The factor 2 in the exponent indicates that two charge carriers are produced for one covalent bond broken.

The experimental value of n_i in silicon at room temperature is 1.5×10^{16} carriers/m³ and in germanium 2.5×10^{19} carriers/m³

INTRINSIC CONDUCTIVITY

Let us consider a sample of semiconductor across which a DC voltage is connected. The electric field E due to potential difference V causes a current I due to the electrons moving towards the positive terminal and holes moving towards the negative terminal. Current is composed of two currents one consisting of electrons drifting in the conduction band and other consist of holes drifting in the valence band



The total current through the semiconductor is

$$I = I_e + I_h \text{ -----(1)}$$

$$I = neV_d A + peV_d A$$

Current density $J = (I_e/A) + (I_h/A)$ where A is cross-sectional area of the crystal

INTRINSIC CONDUCTIVITY

$$J = J_e + J_h \quad \mu = V_d/E \quad \text{there fore } V_d = \mu E$$

$$J = (n e \mu_e + p e \mu_h) E \text{ -----(2)}$$

But $\sigma = J/E$ There fore conductivity is given by

$$\sigma = n e \mu_e + p e \mu_h$$

As $n_i = n = p$

$$\sigma = e n_i (\mu_e + \mu_h) \text{ -----(3)}$$

Substitute the value of n_i in eqn (3)

$$\sigma = 2 \left[\frac{2\pi k}{h^2} \right]^{3/2} (m_e^* m_h^*)^{3/4} T^{3/2} e (\mu_e + \mu_h) e^{-E_g/2kT} \text{ -----(4)}$$

$$\sigma = \sigma_0 e^{-E_g/2kT} \text{ -----(5)}$$

INTRINSIC CONDUCTIVITY

Where

$$\sigma_0 = 2 \left[\frac{2\pi k}{h^2} \right]^{3/2} (m_e^* m_h^*) T^{3/2} \exp(-\mu_e - \mu_h) \quad \text{-----(6)}$$

Taking log on both sides of Eqn (5)

$$\ln \sigma = \ln \sigma_0 - E_g / 2kT \quad \text{-----(7)}$$

A plot of $\ln \sigma$ versus $1/T$ gives straight line , the slope gives $E_g/2K$

Slope = $E_g/2K$ or $E_g = 2K$ Slope



Extrinsic Conductivity

Conductivity for n-type Semiconductor is

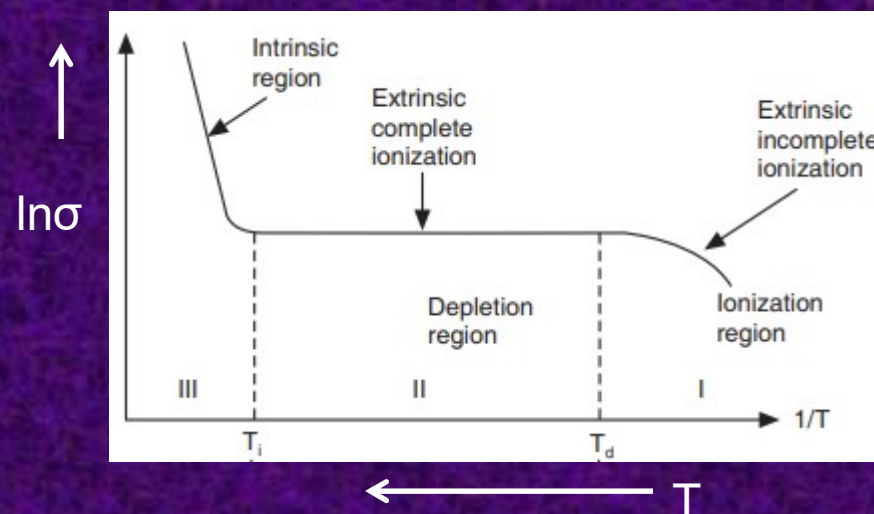
$$\sigma_n = n_n e \mu_e$$

OR $\sigma_n = N_D e \mu_e$ Depletion region (where N_D donor concentration)

Conductivity for p-type Semiconductor is

$$\sigma_p = p_p e \mu_h$$

OR $\sigma_p = N_A e \mu_h$ Depletion region (Where N_A acceptor concentration)



Position of fermilevel in intrinsic semiconductor

In an intrinsic semiconductor, the electrons and holes concentrations are equal.

Thus, $n = p$

The electron concentration in the conduction band is given by

$$n = N_C e^{-(E_C - E_F)/kT} \text{-----} (1)$$

The hole concentration in the valence band is given by

$$p = N_V e^{-(E_F - E_V)/kT} \text{-----} (2)$$

From eqn (1) and (2)

$$N_C e^{-(E_C - E_F)/kT} = N_V e^{-(E_F - E_V)/kT}$$

Taking logarithm on both sides, we get

$$-\frac{(E_C - E_F)}{kT} = \ln \frac{N_V}{N_C} - \frac{(E_F - E_V)}{kT}$$

$$-E_C + E_F = kT \ln \frac{N_V}{N_C} - E_F + E_V$$

$$2E_F = (E_C + E_V) + kT \ln \frac{N_V}{N_C}$$

$$E_F = \frac{E_C + E_V}{2} + \frac{1}{2} kT \ln \frac{N_V}{N_C} \text{-----} (3)$$

Position of fermilevel in intrinsic semiconductor

$$\text{But } N_C = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2} \text{ and } N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$

$$\therefore \frac{N_V}{N_C} = \left(\frac{m_h^*}{m_e^*} \right)^{3/2}$$

$$\therefore \ln \left(\frac{N_V}{N_C} \right) = \frac{3}{2} \ln \left(\frac{m_h^*}{m_e^*} \right)$$

Substitute the value of $\ln \left(\frac{N_V}{N_C} \right)$ in eqn (3)

$$E_F = \frac{E_C + E_V}{2} + \frac{3}{4} kT \ln \left(\frac{m_h^*}{m_e^*} \right)$$

Above equation can also be written as

$$E_F = \frac{E_C + E_V}{2} - \frac{3}{4} kT \ln \left(\frac{m_e^*}{m_h^*} \right)$$

If the effective mass of a free electron is assumed to be equal to the effective mass of a hole, then

$$m_h^* = m_e^* \\ \ln \left(\frac{m_h^*}{m_e^*} \right) = 0$$

Position of fermilevel in intrinsic semiconductor

$$\therefore E_F = \frac{E_C + E_V}{2}$$

To make the meaning of the above equation more explicit, we write

$$E_F = \frac{E_C - E_V}{2} + E_V$$

$$E_F = \frac{E_g}{2} + E_V$$

If we denote the top of the valence band E_V as zero level, $E_V = 0$.

Adding and subtracting E_V to the equation

There fore

$$E_F = \frac{E_g}{2}$$

In an intrinsic semiconductor the Fermi level lies in the middle of the forbidden gap

Law of mass Action

the electrons and holes concentrations in an intrinsic semiconductor is

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

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

As $n = p = n_i$

$$np = n_i^2 = N_C N_V e^{-E_g/kT} \quad \text{-----} \quad (3)$$

The electron and hole concentrations in extrinsic semiconductor is given by the Same equation (1) and (2)

For n-type semiconductor

$$\begin{aligned} n_n &= N_C e^{-(E_C - E_F)/kT} \\ p_n &= N_V e^{-(E_F - E_V)/kT} \\ n_n p_n &= N_C N_V e^{-E_g/kT} \\ n_n p_n &= n_i^2 \end{aligned} \quad \text{-----} \quad (4)$$

Law of mass Action

Similarly, if we denote the hole concentration in a p-type semiconductor by p_p and electron concentration by n_p , we can express

$$\begin{aligned} p_p &= N_V e^{-(E_F - E_V)/kT} \\ n_p &= N_C e^{-(E_C - E_F)/kT} \\ p_p n_p &= N_C N_V e^{-E_g/kT} \\ p_p n_p &= n_i^2 \end{aligned} \quad \text{----- (5)}$$

Equations (4) and (5) imply that the product of majority and minority carrier concentrations in an extrinsic semiconductors at a particular temperature is equal to the square of the intrinsic carrier concentration at that temperature

Charge Neutrality Condition

In n-type semiconductor, the total number of electrons in the conduction band is equal to sum of the electrons originated from the donor atoms(donor level) and electrons excited from the valence band. Electrons originated from donor levels leave behind positive ions while electrons from valence band leave behind holes in valence band. So that the total negative charge of mobile electrons is equal to the total positive charge created in the crystal.

For n-Type $n_n = N_D + P_n$ -----(1)

For p-Type $p_p = N_A + n_p$ -----(2)

Since in n-type semiconductor $n_n \gg p_n$ there fore $n_n \approx N_D$ (Depletion region)

From law of mass action we get

$$P_n = n_i^2 / N_D \quad (\text{holes concentration in n-type})$$

For p-type semiconductor

$$P_p \gg n_p \quad \text{there fore } p_p = N_A \quad (\text{Depletion region})$$

$$n_p = n_i^2 / N_A \quad (\text{Electrons concentration in p-type})$$

Position of fermilevel in extrinsic semiconductor

$$n = N_c e^{-(E_c - E_f)/KT}$$

For n-type

$$N_D = N_c e^{-(E_c - E_f)/KT} \quad (n = N_D = n_n)$$

$$N_c/N_D = e^{+(E_c - E_f)/KT}$$

Take ln on both the sides

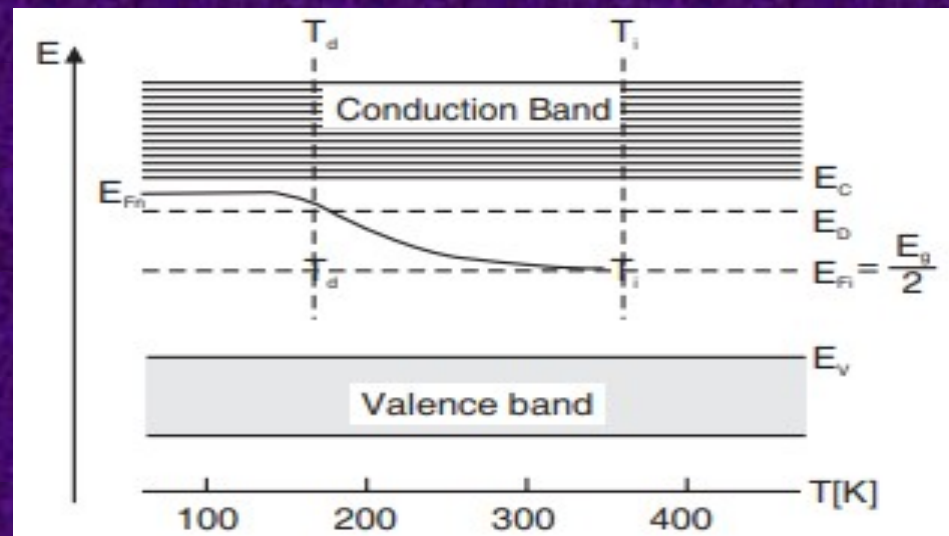
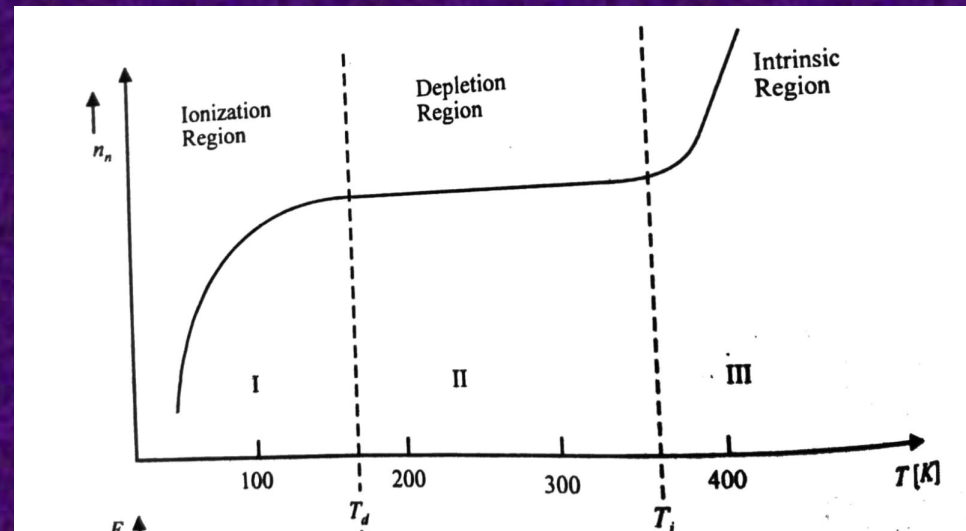
$$(E_c - E_f)/KT = \ln (N_c/N_D)$$

$$E_{fn} = E_c - KT \ln(N_c/N_D)$$

$$E_{fn} = E_D + E_c/2 \quad (T < T_D)$$

$$E_{fn} = E_D \quad (T = T_D)$$

$$E_{fn} = E_{fi} = E_g/2 \quad (T > T_i)$$



Position of fermilevel in extrinsic semiconductor

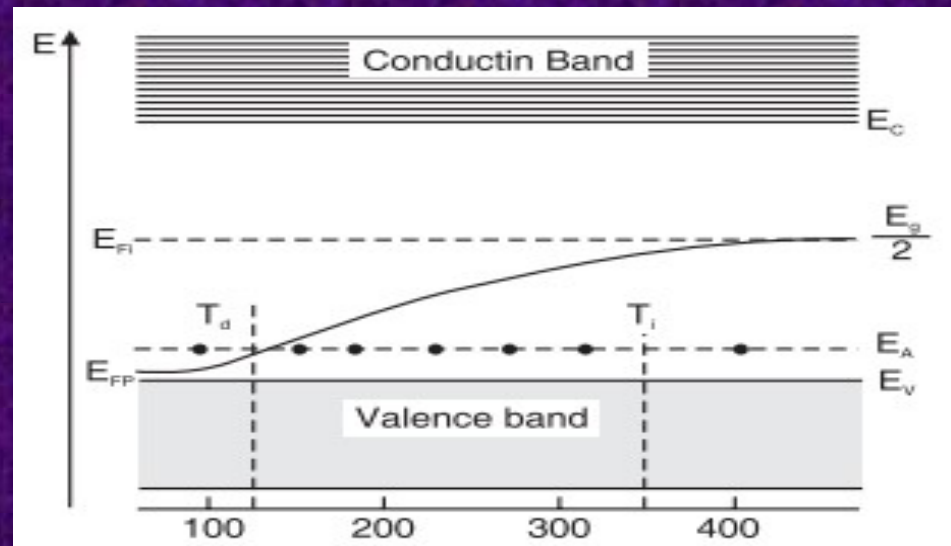
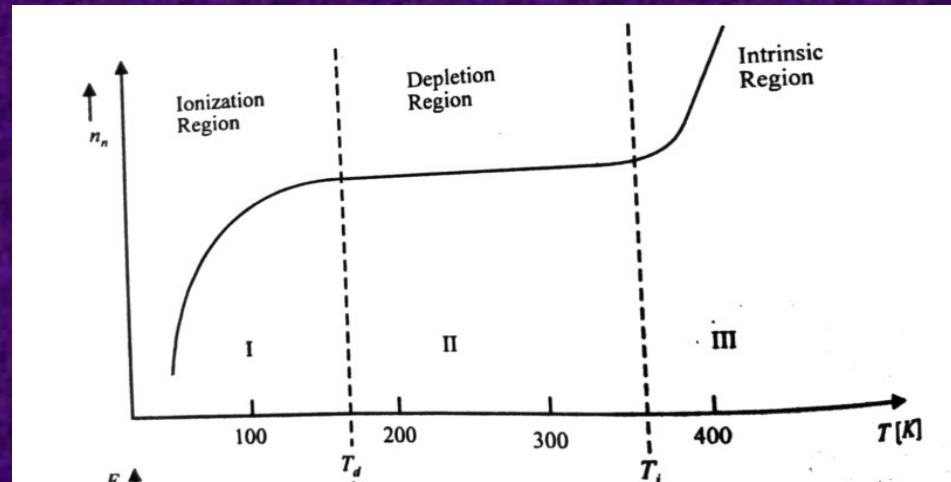
For p-type

$$E_{fp} = E_v + KT \ln (N_v/N_A)$$

$$E_{fp} = E_A + E_g/2 \quad (T < T_D)$$

$$E_{fp} = E_A \quad (T = T_D)$$

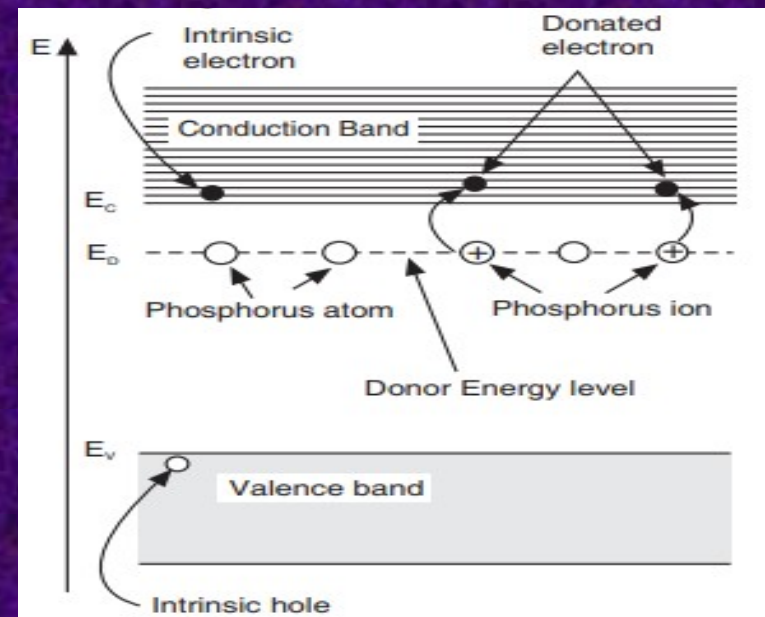
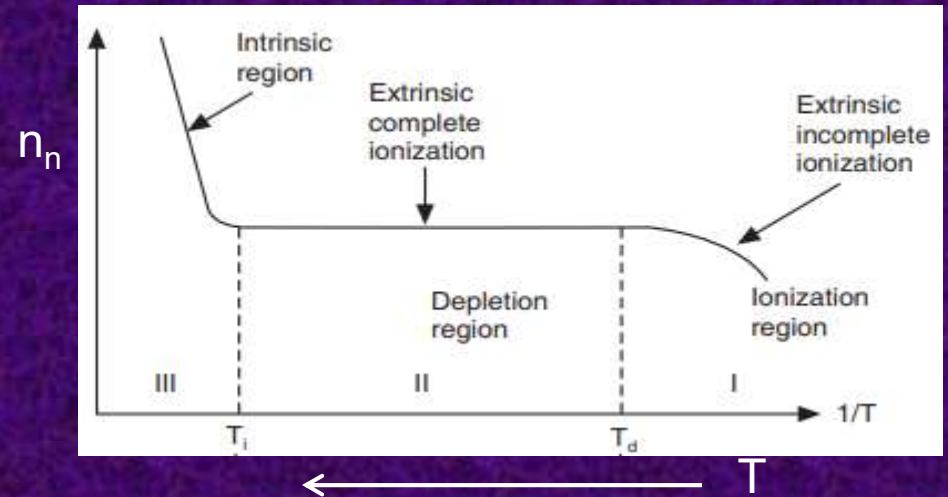
$$E_{fp} = E_{fi} = E_g/2 \quad (T > T_i)$$



Temperature Variation of Carrier Concentration in extrinsic semiconductor

N-type Semiconductor:

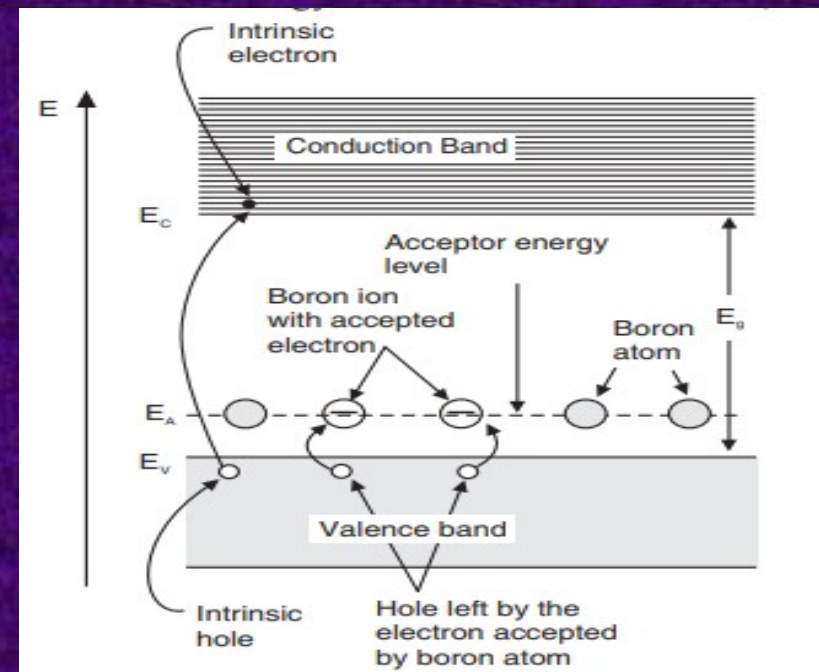
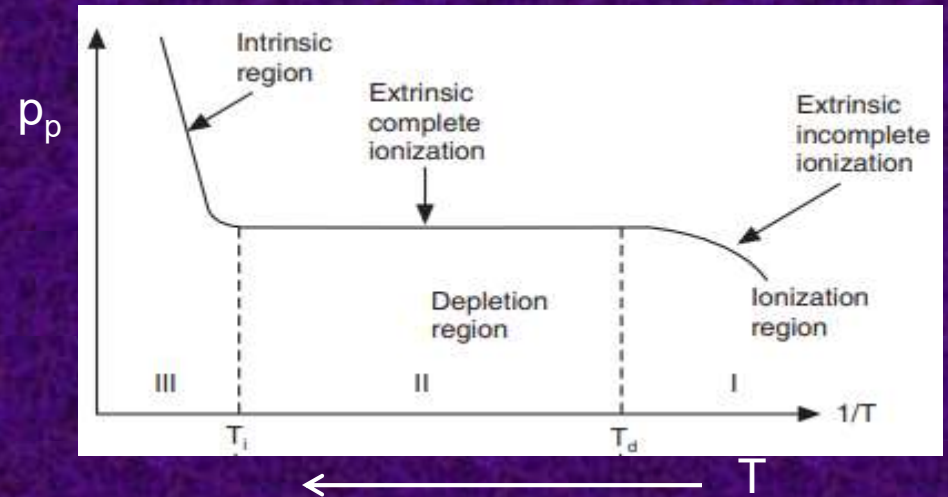
The general dependence of electron concentration on temperature is shown in Fig. At 0 K, the donor atoms are not ionized which means that all the donor electrons are bound to the donor atoms. The conduction band is empty. At slightly elevated temperatures, the donor atoms are ionized and the donor electrons go into the conduction band. In this process holes are not produced in the valence band. At about 100K, the donor levels are all ionized. Once all the donor atoms are ionized, further increase in temperature does not produce electrons and the curve levels off. As temperature increases further, some electrons from the valence band are also excited into the conduction band. The conduction band, contains electrons that have come through two different processes-namely (i) donor atom ionization and (ii) intrinsic process. The intrinsic process produces holes in the valence band



Temperature Variation of Carrier Concentration in extrinsic semiconductor

P-type Semiconductor:

At slightly elevated temperature, electrons from the valence band jump into the acceptor levels and holes are generated in the valence band. At about 100K, the acceptor atoms are all ionized. Once all the acceptor atoms are ionized, further increase in temperature does not produce holes and we say the acceptor levels are saturated. The region is called the saturation region. In the saturation region, the hole concentration in the valence band is nearly identical to the concentration of the acceptor atoms. As temperature is increased further, some electrons from the valence band are excited into the conduction band. The valence band now contains holes that have been generated by two different processes-namely, (i) acceptor atom ionization and (ii) intrinsic process. The intrinsic process causes electrons to appear in the conduction band.



Electrical conduction in extrinsic semiconductor

Under the condition of thermal equilibrium, the electrons and holes are uniformly distributed in the crystal and their average velocity is zero and no current flows through the crystal. This is equally true for an intrinsic or an extrinsic semiconductor.

The thermal equilibrium may be disturbed by an external agent and the chaotic motion of charge carriers acquire a directional movement leading to a flow of current in the material. Electric field and concentration gradients are examples of such disturbing agents.

Drift Current:

Under the action of electric field, two drift currents will generate

The electrons drift in the conduction band and produce J_e

$$J_{e \text{ (drift)}} = n e \mu_e E \text{ ----- (1)}$$

The holes drift in the valence band and produces

$$J_{h \text{ (drift)}} = p e \mu_h E \text{ -----(2)}$$

The total drift current density is

$$J_{\text{(drift)}} = J_{e \text{ (drift)}} + J_{h \text{ (drift)}}$$

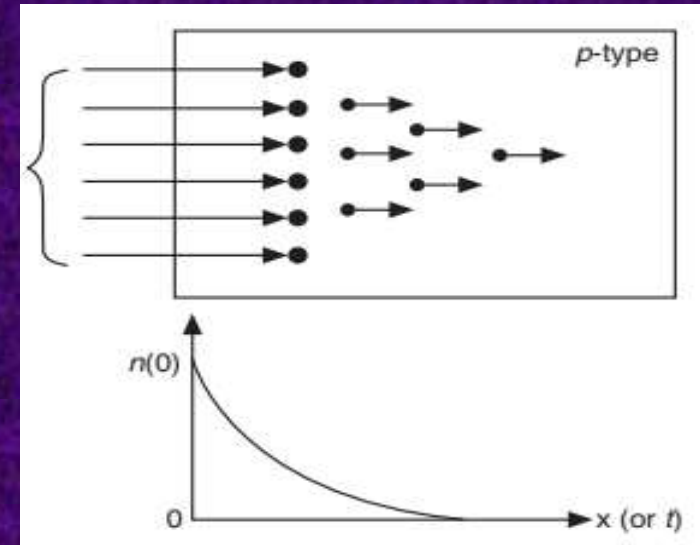
$$J_{\text{(drift)}} = e (n \mu_e + p \mu_h) E \text{ ----- (3)}$$

eqn (3) is applicable to intrinsic as well as extrinsic semiconductor

Electrical conduction in extrinsic semiconductor

Diffusion Current:

Concentration gradient may be produced in an extrinsic semiconductor by applying heat or light locally at one region. Suppose an external agent such as light or heat acts momentarily at one end of a p-type semiconductor, as shown in Fig. The external agent generates additional electron-hole pairs leading to a sudden increase in the concentration of charge carriers at that end. In the rest of the volume, the concentration of carriers is at equilibrium value. The difference in the concentration of charge carriers initiates the carriers to diffuse from the region of higher concentration to the region of lower concentration in order to restore the equilibrium condition. As the carriers are charged particles, their migration produces a current flow, which is the diffusion current. Diffusion current is proportional to the concentration gradient. In case of electrons moving left to right see Fig. current flows from right to left in the negative x-direction. I.e $(-dn/dx)$ as x-increases, n-decreases. In the diffusion current minority current plays the major role.



The current component due to electron diffusion in p-type is given by

$$J_e (\text{diff}) = eD_e \frac{dn}{dx} \quad \text{-----} \quad (3)$$

Electrical conduction in extrinsic semiconductor

The current component due to hole diffusion in n-type is given by

$$J_h (\text{diff}) = -eD_h \frac{dp}{dx} \quad \text{-----} \quad (4)$$

D_e and D_h are diffusion coefficients for electrons and holes respectively

Drift and diffusion currents coexist in semiconductors. The total current density due to drift and diffusion of electrons may be written as

$$J_e = J_e (\text{drift}) + J_h (\text{diffusion})$$

$$J_e = e \left(n\mu_e E + D_e \frac{dn}{dx} \right)$$

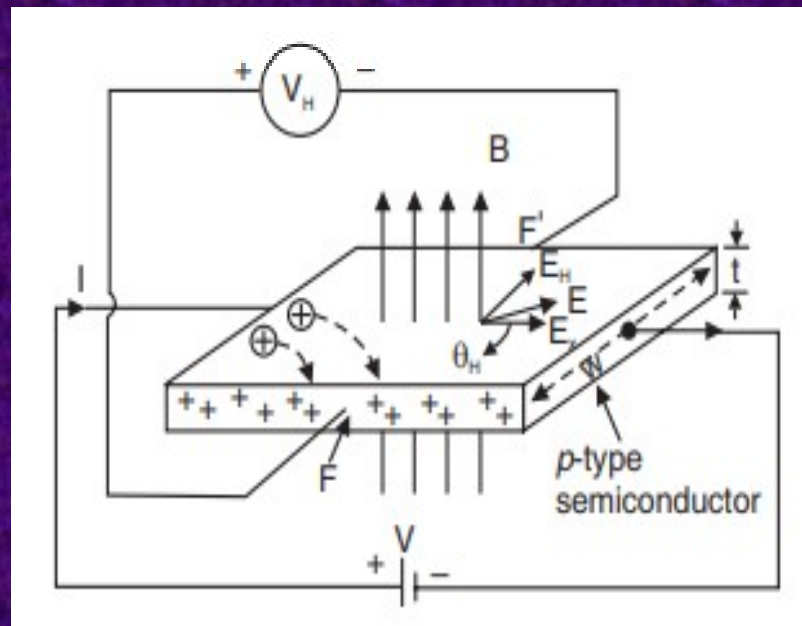
The total current density due to drift and diffusion of holes may be written as

$$J_h = e \left(p\mu_h E - D_h \frac{dp}{dx} \right)$$

Hall Effect

If a metal or a semiconductor carrying a current I is placed in a transverse magnetic field B , a potential difference V_H is produced in a direction normal to both the magnetic field and current directions. This is known as Hall effect.

The importance of Hall effect in the field of semiconductors is that it helps to determine (i) the type of semiconductor, (ii) the sign of majority charge carriers, (iii) the majority charge carrier concentration, (iv) the mobility of majority charge carriers



Let us assume that the semiconductor is a p-type semiconductor. Let a potential difference V be applied across its ends. A current of strength I flows through it along the x-direction Fig. Holes are the majority charge carriers in the p-type semiconductor. The current through the wafer is given by

$$I = peAV_d \quad \text{----- (1)}$$

where p is the hole concentration, A is the area of cross-section of the end face of semiconductor wafer, V_d drift velocity of holes

Hall Effect

The current density $J = I/A = pe V_d$ ----- (2)

if a magnetic field B is applied normal to the wafer surface and hence to the direction of current flow in it, then a transverse potential difference is produced between faces F and F' . It is known as Hall Voltage V_H

Before the application of magnetic field, holes move parallel to faces F and F' . On application of magnetic field B , the holes experience a sideways deflection due to the magnetic force F_L , which is given by

$$F_L = eBV_d \text{ ----- (3)}$$

Holes are deflected toward the front face F and pile up there. Due to this, a corresponding equivalent negative charge is left on the rear face F' . These opposite charges produce a transverse electric field, E_H . Due to the E_H , electric force F_E will develop in addition to the Lorentz force. When electric force F_E balances the magnetic force F_L , equilibrium condition is attained

In the equilibrium condition $F_E = F_L$ ----- (4)

$$eE_H = eV_d B \text{ ----- (5)}$$

Hall Effect

If 'w' is the width of the semiconductor wafer, $E_H = V_H/w$ ----- (6)

From eqn (5) $V_H/w = V_d B$ ----- (7)

From eqn (2) $V_d = J/pe$

There fore eqn (7) can be written as

$$V_H/w = BJ/pe \text{ ----- (8)}$$

$$V_H = wBJ/pe = wBI/peA \text{ ----- (9)}$$

If 't' is the thickness of the semiconductor plate, $A = w t$.

$$V_H = BI/pet \text{ ----- (10)}$$

Hall coefficient R_H is defined as Hall field per unit current density per unit magnetic induction. Thus, $R_H = E_H/ J B = (V_H/w)/J B$ ----- (11)

From eqn (8) $R_H = BJ/ peJ B$

$$R_H = 1/pe \text{ ----- (12)}$$

Hall Effect

Hall voltage, V can now be written as $V_H = R_H BI/t$ -----(13) (from eqn 10)

$$R_H = V_H t / BI$$

According to the equilibrium condition, namely $F_E = F_L$, we have

$$e \left(\frac{V_H}{w} \right) = e B v_d$$
$$v_d = \frac{V_H}{B w}$$

from (eqn 12) $p = 1/R_H e$

Similarly electron concentration $n = -1/R_H e$

problems

A sample of intrinsic Ge at room temperature has a carrier concentration $2.4 \times 10^{19} / \text{m}^3$. It is doped with antimony at a rate of one atom per million Ge atoms. If concentration of Ge atoms is $4 \times 10^{28} / \text{m}^3$. find hole concentration.

Given : $n_i = 2.4 \times 10^{19}$

Solution:

$$N_D = \text{Conc. of Ge atoms} / 1 \text{ million} = 4 \times 10^{28} / 10^6 = 4 \times 10^{22}$$

$$n_i^2 = n_n p_n = N_D P_n$$

$$p_n = n_i^2 / N_D = (2.4 \times 10^{19})^2 / 4 \times 10^{22} = 1.44 \times 10^{16} \text{ holes/m}^3$$