

## Semiconductor

### \* Band structure in Semiconductor

Because of band overlapping, the valence as well as conduction bands of semiconductors consist of mixed s- and p states.

Eight highest S+p states of split into two separate (S+p) bands, each of which consists of one s and three p-states. The lower s-state can accommodate one electron per atom whereas the three lower p states can accommodate 3 electrons per atom. Because germanium and silicon possess four valence electrons per atom, the valence band is completely filled with electrons while conduction band remains empty.

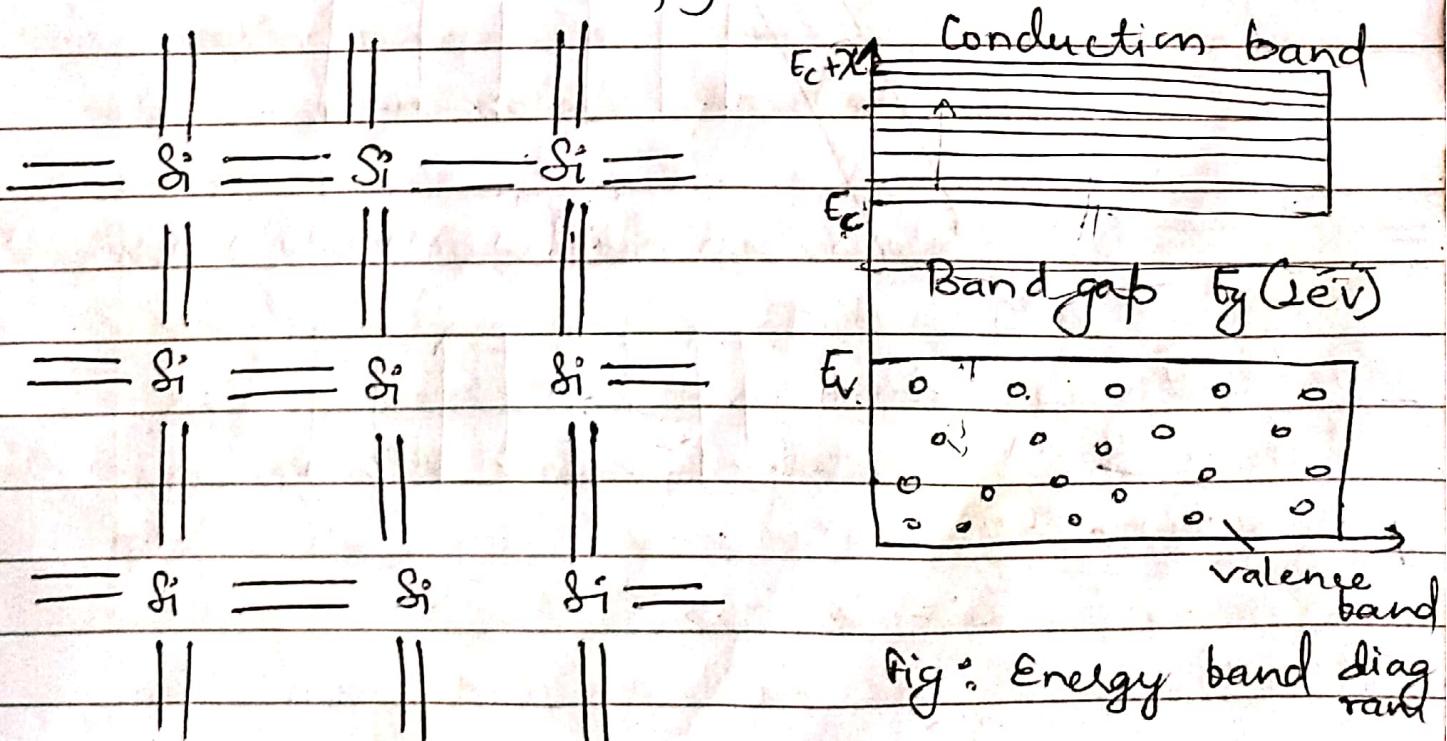


Fig: Energy band diagram

Fig: Two dimensional sketch of bonding in Semiconductor

The width of conduction band is denoted by  $\chi$  and is called electron affinity.

### \* Electron and hole.

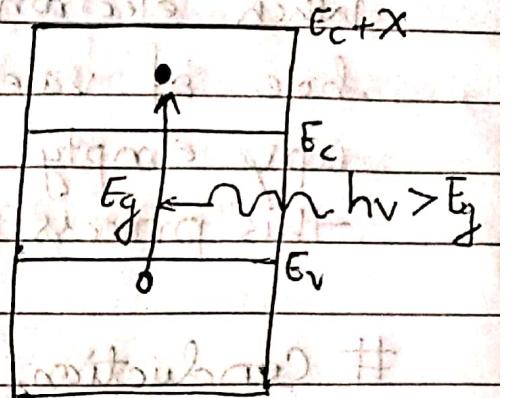
For a pure Silicon crystal covalent bond is saturated and there are no empty states available at valence band at absolute zero temperature.

The conduction band is empty, electrons from valence band cannot jump to conduction band unless it gets sufficient energy.

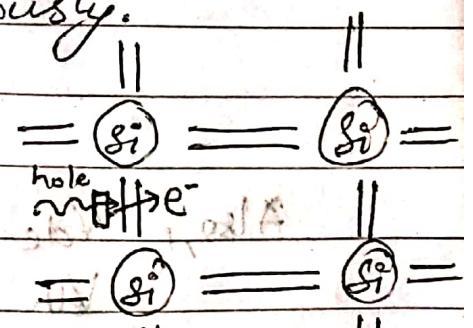
When a photon of energy greater than  $E_g$  is incident on electron, it moves to conduction band and space left behind in the valence band is called hole. Hence conduction electron and hole are generated simultaneously.

Also, as the temperature increases, thermal energy causes lattice vibration and bond may deform.

In, an electron hole pair get generated. Due to tunnelling, neighbouring electron at valence band may occupy the hole and the hole



i) photon excites electron to conduction band.



ii) Electron hole pair generation

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gets shifted in the direction opposite to the direction of electron in conduction band.

When electron in conduction band meets the hole of valence band, the electron will occupy empty state releasing some energy and this process is called recombination.

## # Conduction in Semiconductor

In order for semiconductor to become conducting, electrons have to be excited from valence band into conduction band where they are accelerated by external electric field, likewise electron holes left behind in valence band migrate in opposite direction to the electrons.

Current density ( $J$ ) =  $n e V_{de} + P e V_{dh}$

where,  $n$  = electron concentration.

$p$  = hole concentration

$V_{dh}$  = drift velocity of hole

$V_{de}$  = drift velocity of electron.

Also,  $V_{de} = m_e E_x$

$V_{dh} = m_h E_x$

where,  $m_e$  and  $m_h$  are electron and hole mobility.

Hence,  $J = n e m_e E_x + P e m_h E_x$

$\therefore J/E_x = n e m_e + P e m_h$

$\therefore \sigma = n e m_e + P e m_h$   $\sigma$  = electrical conductivity

## # Electron and hole Concentration

Let  $n$  be the number of conduction band electrons per unit volume,  $Z(E)$  be the density of states per unit volume, and  $F(E)$ , be the probability of occupation then number of electrons in the energy interval  $E$  and  $E + dE$  is

$$dn = Z(E) \cdot F(E) dE$$

$$n = \int_{E_c}^{\infty} Z(E) F(E) dE$$

Concentration of electron above  $E_c + \infty$  is zero, so upper limit can be considered upto  $\infty$ .

$$\therefore n = \int_{E_c}^{\infty} Z(E) F(E) dE$$

$$\text{Also, } F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

$$\approx \exp\left(-\frac{E - E_F}{kT}\right)$$

$$\text{and } Z(E) = c_1 (E - E_c)^{1/2}$$

$$= \frac{\pi}{4} K^{3/2} (E - E_c)^{1/2}$$

$$= \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} (E - E_c)^{1/2}$$

$$\frac{dn}{dE} = Z(E)$$

$$= \frac{\pi}{4} K^{3/2} E^{1/2}$$

$$\text{where, } K = \frac{8\pi m_e^*}{h^2}$$

$$\text{Since, } Z(E) = Z(c)$$

and concentration of electrons from eqn (i) is

$$\begin{aligned} n &= 2 \int_{E_c}^{\infty} \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} (E - E_c)^{1/2} \exp\left(-\frac{E - E_c}{kT}\right) dE \\ &= 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} \exp\left(-\frac{E - E_c}{kT}\right) dE \\ &= 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} \exp\left(-\frac{E - E_c + E_c - E_F}{kT}\right) dE \\ &= 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} \exp\left(-\frac{E_c - E_F}{kT}\right) \exp\left(-\frac{E - E_c}{kT}\right) dE \\ &= 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \exp\left(-\frac{E_c - E_F}{kT}\right) \int_{E_c}^{\infty} (E - E_c)^{1/2} \exp\left(-\frac{E - E_c}{kT}\right) dE \end{aligned}$$

Let,

$E - E_c = x$ , differentiating both sides w.r.t.  $x$ ,

$$\frac{d(E - E_c)}{dx} = \frac{dE}{dx} \approx -E + E_c - E_c - E_F$$

$$(i) \Rightarrow \frac{dE}{dx} = 1$$

$$\therefore dE = kT dx$$

when,  $E \rightarrow E_c$ ,  $x \rightarrow 0$

$E \rightarrow \infty$ ,  $x \rightarrow \infty$

(i)  $\Rightarrow$  (ii)

$$n = 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \exp\left(-E_c - E_F\right) \int_0^\infty (kT x)^{3/2} \exp(-x) kT dx$$

$$= 2 \times \frac{\pi}{4} \left( \frac{8m_e^*}{h^2} \right)^{3/2} (kT)^{3/2} \exp\left(-E_c - E_F\right) \int_0^\infty x^{3/2} e^{-x} dx$$

We know,

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

$$= 2 \times \frac{\pi}{4} (kT)^{3/2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \exp\left(-E_c - E_F\right) \times \frac{\sqrt{\pi}}{2}$$

$$= 2 \times \frac{\pi}{8} \left( \frac{8kT m_e^*}{h^2} \right)^{3/2} \exp\left(-\frac{E_c - E_F}{kT}\right)$$

$$= 2 \times \frac{1}{8} \left( \frac{8\pi k T m_e^*}{h^2} \right)^{3/2} \exp\left(-\frac{E_c - E_F}{kT}\right)$$

$$= 2 \times \frac{1}{8} \left( \frac{2^2 \cdot 2\pi k T m_e^*}{h^2} \right)^{3/2} \exp\left(-\frac{E_c - E_F}{kT}\right)$$

$$= 2 \times \left( \frac{2\pi k T m_e^*}{h^2} \right)^{3/2} \exp\left(-\frac{E_c - E_F}{kT}\right)$$

$$= N_c \exp\left(-\frac{E_c - E_F}{kT}\right)$$

where,  $N_c = 2 \left( \frac{2\pi k T m_e^*}{h^2} \right)^{3/2}$  = effective density of states at conduction band edge.

In the similar manner we can obtain the concentration of holes at valence band. The probability of occupation of holes can be found by

Subtracting the probability of occupation function from unity.

$$P_1 = \int_0^{E_F} Z_{VB}(E) (1 - F(E)) dE$$

$$\therefore P = N_V \exp\left(-\frac{E_F - E_V}{KT}\right)$$

$$\text{where, } N_V = 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2}$$

Also,

(no. of electrons)  $\times$  (no. of holes), i.e.  $n = P$

$$\therefore np = N_c N_V \exp\left(-\frac{E_c - E_F}{KT}\right) \exp\left(-\frac{E_F - E_V}{KT}\right)$$

$n = P = n_i$  (for intrinsic semiconductor)

(where,  $n_i$ ) called as intrinsic concentration.

$$n_i^2 = N_c N_V \exp\left(-\frac{E_c - E_V}{KT}\right)$$

$$n_i = \sqrt{N_c N_V} \exp\left(-\frac{E_g}{2KT}\right) \quad \left[ \because E_c - E_V = E_g \right]$$

We have known that,

$$\text{so, } N_V \exp\left[-\frac{E_F - E_V}{KT}\right] = (N_c N_V)^{1/2} \exp\left[-\frac{E_g}{2KT}\right]$$

Consider,  $E_F$  be denoted as Fermi Energy level for intrinsic semiconductor.

Up to now we want to write down the Fermi energy for intrinsic semiconductor to get

$$T \rightarrow \infty, \exp \left[ -\frac{E_F - E_V}{kT} \right] = \frac{1}{N_V} (N_c - N_V)^{1/2} \exp \left[ -\frac{E_g}{2kT} \right]$$

taking natural logarithm on both the sides, we will have

$$\exp \left[ -\frac{E_F - E_V}{kT} \right] = \frac{1}{N_V} (N_c - N_V)^{1/2}$$

$$\ln \left( \frac{E_F - E_V}{kT} \right) = \ln \left( \frac{N_c - N_V}{N_V} \right)^{1/2} + \left[ -\frac{E_g}{2kT} \right]$$

$$-E_F + E_V = kT \ln \left( \frac{N_c - N_V}{N_V} \right)^{1/2} + kT \left[ -\frac{E_g}{2kT} \right]$$

$$\text{or, } E_F = E_V - \frac{1}{2} kT \ln \left( \frac{N_c}{N_V} \right)^{1/2} + \frac{E_g}{2}$$

$$E_F = E_V - \frac{1}{2} kT \ln \left( \frac{8\pi m_e^* kT/h^2}{8\pi m_h^* kT/h^2} \right)^{1/2} + \frac{E_g}{2}$$

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

Thus, if effective masses of electron in conduction band and of hole in valence band are equal to each other, the intrinsic Fermi level in semiconductor lies in the middle of the energy gap.

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

$$\text{also, } E_F = E_C - \frac{E_g}{2}$$

Normally, effective masses of conduction electron and valence hole differ slightly, which means the intrinsic Fermi level does not lie precisely at the centre of the energy band gap, but is shifted a little bit. In Si the hole effective mass is slightly greater than that of the electron, so, the intrinsic Fermi level is slightly above the mid-gap.

### # Extrinsic Semiconductors:-

In order to modulate the electrical properties of Semiconductor atoms of foreign elements belonging to III A and IV A group are introduced intentionally in pure silicon crystal.

This process is called doping and resulting semiconductor is called extrinsic semiconductor.

#### \* N-type Semiconductor:

On adding pentavalent impurities into silicon such as arsenic, it is forced to bond with neighbouring silicon atom as in diamond crystal structure. only four ele-

electrons will participate in bonding and 5<sup>th</sup> electron continuously goes on orbiting to arsenic ( $As^+$ ) ion and core similar to electron in hydrogen atom. Hence ionization energy required to free the electron is : For hydrogen,

$$E_i = \frac{-m_e e^4}{8\epsilon_0^2 h^2} = -13.6 \text{ eV}$$

Since, the electron is orbiting in the silicon environment hence we have to use absolute permittivity of silicon and effective mass of electron in silicon.

$$E_{bi}^{(Si)} = \frac{-m_e^* e^4}{8\epsilon_0^2 \epsilon_r^2 h^2} = -0.032 \text{ eV}$$

where,  $m_e^* = m_e/3$ ,  $\epsilon_r = 11.9$  (for silicon)

Also, average thermal energy of atomic vibration is  $3kT$  & nearly equals 0.07 eV.

Thus, this 5<sup>th</sup> electron is normally found in conduction band.

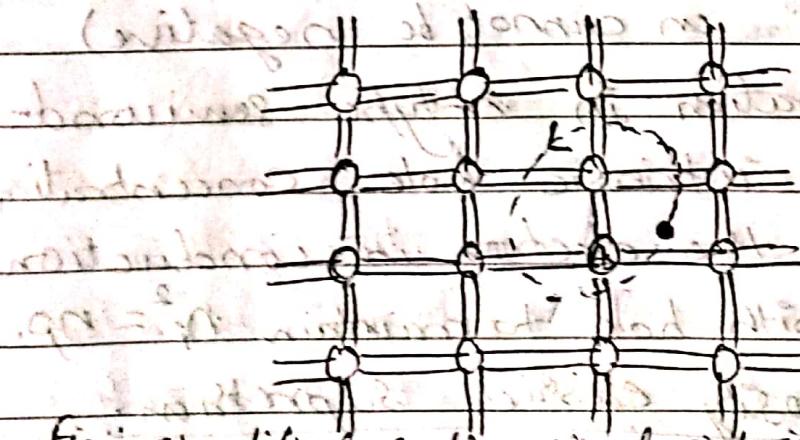


Fig: Simplified 2-dimensional pictorial view of As-doped Si crystal

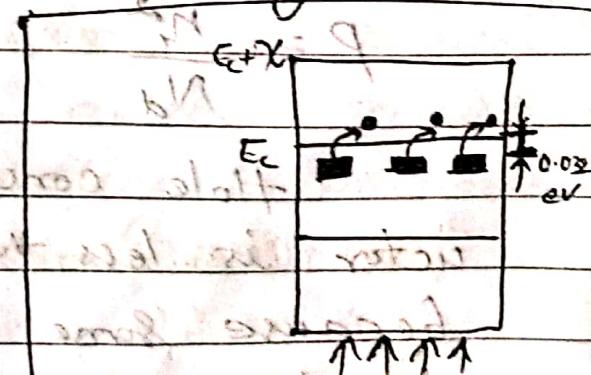


Fig: As atom sites every  $10^6$  silicon atoms Energy band diagram for n-type semiconductor with As

In n-type Semiconductor, the conduction electrons are majority charge carriers and holes are minority charge carriers. If  $n$  and  $p$  are electron and hole concentration and  $N_d$  is donor concentration, then  $n = N_d + p$

but also we have  $N_d = \text{donor concentration}$   
 $n_i^2 = np$

$$p = \frac{n_i^2}{n}$$

$$\therefore n = N_d + n_i^2$$

$$n^2 - N_d n - n_i^2 = 0$$

$$(n - N_d) = \frac{N_d}{2} \pm \sqrt{\frac{N_d^2}{4} + n_i^2}$$

But  $n_i^2 \ll \frac{N_d^2}{4}$  Then

$$n = \frac{N_d}{2} + \frac{N_d}{2} \quad \therefore n = N_d$$

$$p = \frac{n_i^2}{N_d}$$

(-ve value is not assumed because electron concentration cannot be negative)

Hole concentration in n-type semiconductor is less than intrinsic hole concentration because some of the electron in conduction band recombine with hole to maintain  $n_i^2 = np$ .

This is called minority carrier expression.

$$\sigma = \mu n_e + \mu n_h p = e N_d \mu e + e \mu h \frac{n^2}{N_d}$$

$$\therefore \sigma \propto e N_d \mu$$

So, conductivity is mainly due to mobility of electrons in  $n$ -type semiconductor.

### # P-type semiconductor

On adding trivalent impurities  $\text{B}$  to silicon such as Boron, it is forced to bond with neighbouring silicon atom. Only three electrons will participate in bonding and 4<sup>th</sup> is not present. That is why, hole formation takes place in the valence band.

The binding energy is very small  $\approx 0.05\text{eV}$ . So at room temp all the acceptor sites are ionized by thermal vibrations in the lattice. When the boron accepts electron from neighbouring Si-Si bond, the hole is shifted away from the boron to Si-Si bond in valence bond. The boron atom accepts an electron from Si-Si bond, and resulting in Semiconductor called as P-type Semiconductor.

If  $n$  and  $p$  be the electron and hole concentration in the semiconductor and  $N_a$  be the acceptor concentration.

Then, hole concentration is given by,

$$p = N_a + n$$

$$np \propto n_i^2$$

$$n = \frac{N_a}{2}$$

$$\text{Thus, } p = N_a + \frac{n_i^2}{2}$$

$$p = \frac{N_a}{2} \pm \left( \frac{N_a^2}{4} + n_i^2 \right)^{1/2}$$

Since,  $n_i^2 \ll N_a^2$  then

$$\text{thus, } p \approx \frac{N_a}{2}, N_a \approx N_d$$

The conductivity in p-type Semiconductor is mainly due to hole concentration which can

$$\sigma = e n \mu_e + e p \mu_h = e \mu_e \left( \frac{n^2}{N_a} \right) + e N_a \mu_h$$

$$\boxed{\sigma = e N_a \mu_h}$$

(Explain minority carrier suppression as above)

### # Compensation Doping

Adding trivalent impurities will increase hole concentration in the semiconductor while as by adding pentavalent impurities

to the same will compensate for the increase in hole concentration and decrease in electron concentration. Assuming all donor impurities and acceptor impurities ionized at room temp<sup>r</sup>, the effective hole concentration & electron concentration are calculated based on which of the impurity is greater in concentration.

If  $N_A$  &  $N_D$  are acceptor and donor concentration respectively &  $N_D > N_A$ , the holes due to acceptor doping will be combine with the electrons due to donor doping. So, the electron concentration is,

$$n = N_D - N_A$$

$$P = \frac{n_i^2}{n} = \left( \frac{n_i^2}{N_D - N_A} \right)$$

Similarly, when  $N_A > N_D$ , the electrons due to donor doping recombine with holes due to acceptor doping & the resultant hole concentration are

$$P = N_A - N_D$$

$$n = \frac{n_i^2}{P} = \frac{n_i^2}{N_A - N_D}$$

where,  $n_i$  is intrinsic concentration of semiconductor.

# Temperature dependence of carrier concentration

The intrinsic concentration of semiconductor is given by,

$$n_i = \sqrt{N_c N_v} \exp\left[-\frac{E_g}{2kT}\right]$$

The above relation shows that concentration of electrons and holes is a function of band gap and temperature. Also  $N_c$  and  $N_v$  have expression  $T^{3/2}$ , so they have also function of temp<sup>2</sup>. Both for exponential term and  $N_c$  and  $N_v$  it can be observed that increase in temp<sup>2</sup> causes increase in concentration. Since band gap is built in characteristics of a material so it cannot be altered. Temperature can be controlled to suit our purpose.

For Extrinsic

In extrinsic semiconductor, carrier concentration depends on different parameters of different temperatures. For n-type semiconductor at very low temperature, the

recombination

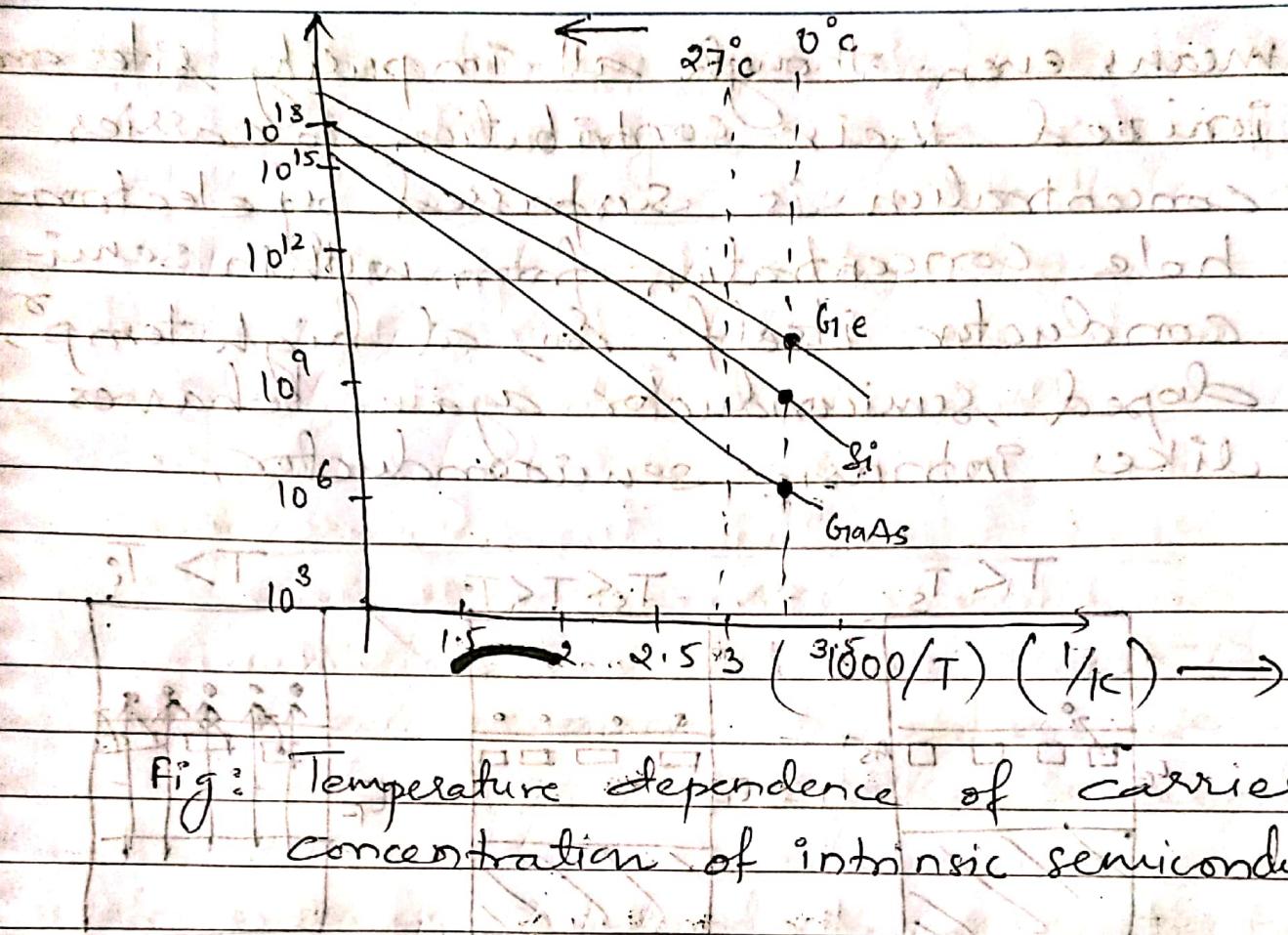
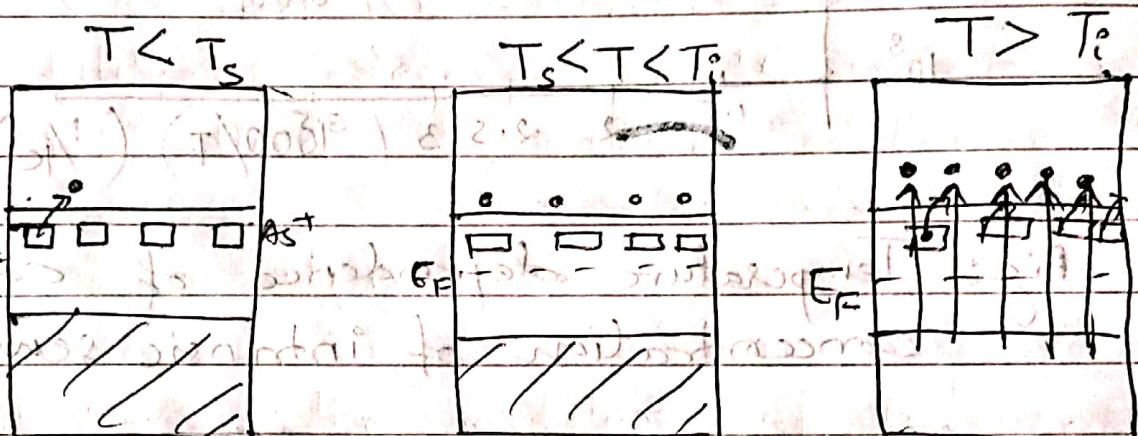


Fig: Temperature dependence of carrier concentration of intrinsic semiconductors

donor sites will not be ionized and carrier concentration will be very low and determined only by intrinsic concentration at these temperatures. As temperature increases, thermal energy of lattice vibrations become more and more, and most of donor sites are ionized thereby defining the carrier concentration. In the high temperature again, the generation of electron-hole pair in Semiconductor is more than Impurity concentration, which

means even though all impurity sites are ionized their contribution to carrier concentration is surpassed by electron-hole concentration from within semiconductor itself. So, at high temp<sup>o</sup>, doped semiconductor again behaves like intrinsic semiconductor.



Ques a)  $T = T_s$  b)  $T = T_i$  c)  $T = T_c$

fig: Energy band diagram showing ionized donors at diff. temperature.

$T_s \rightarrow$  Saturation temperature

$T_i \rightarrow$  Ionization temperature

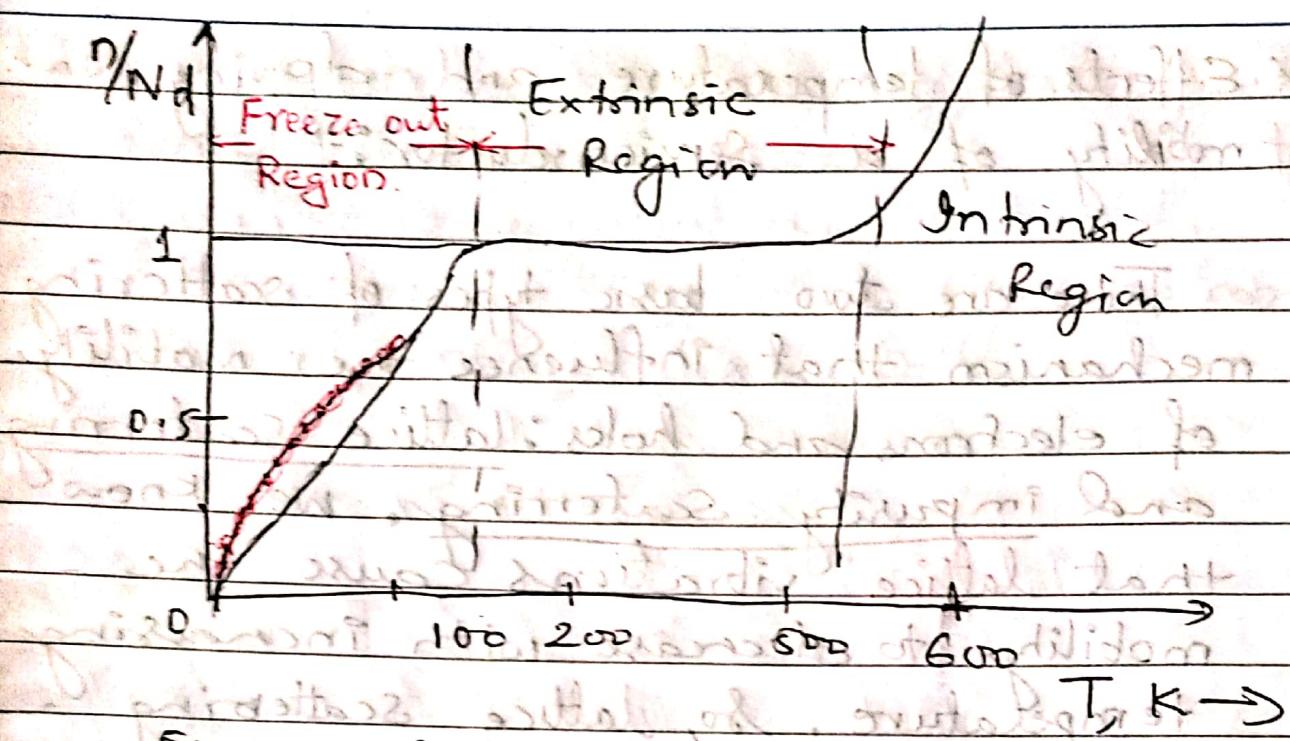


Fig: Temp<sup>r</sup> dependence of extrinsic semiconductor in n-type silicon semiconductor

In extrinsic semiconductor, the electron concentration at low temperature is when thermal vibrations are unable to ionize donor sites & excite the electrons from donor site Ed to conduction band Ec can be expressed as :

$$n = \sqrt{\frac{1}{2} N_c N_V} \exp \left[ -\frac{E_c - E_d}{kT} \right]$$

$$n = \sqrt{k N_c N_V} \exp \left[ -\frac{\Delta E}{kT} \right]$$

\* Effects of temperature and doping on drift mobility of a semiconductor:-

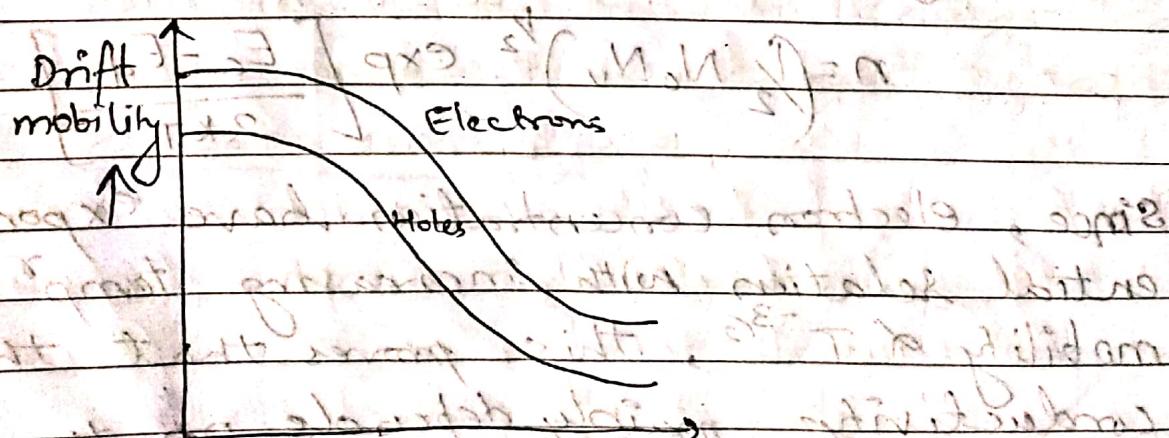
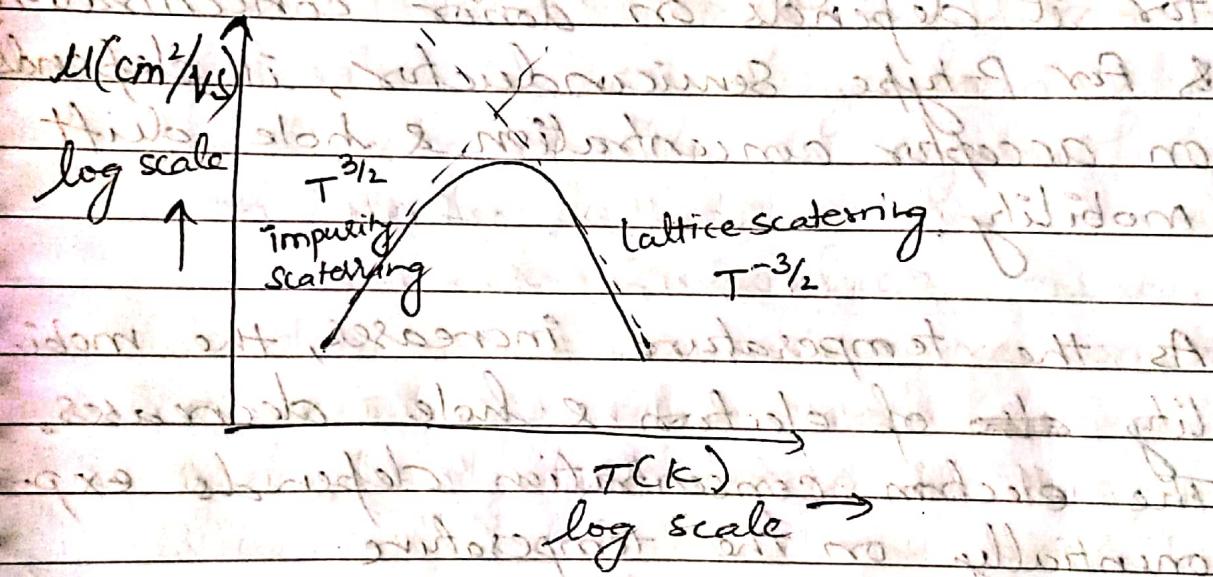
There are two basic types of scattering mechanism that influence the mobility of electrons and holes: lattice scattering and impurity scattering. We know that lattice vibrations cause the mobility to decrease with increasing temperature. So, lattice scattering gives mobility,  $\propto T^{-3/2}$ .

However, the mobility of the carriers in a semiconductor is also influenced by the presence of charged particles. Impurity scattering is caused by the presence of crystal defects such as ionized impurities. At lower temperature carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering & mobility decreases. This is just opposite of lattice scattering.

~~$M_I \rightarrow$  impurity mobility, scattering & ionization impact~~

Ionization scattering / Impurity scattering limited mobility will be

$\mu_I \propto T^{3/2}$  where,  $N_I \rightarrow$  Concentration of ionized impurities.



## # Conductivity Temperature dependence $\rightarrow$

We know, conductivity of Semiconductor is given by,

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

The expression shows that conductivity depends on carrier concentration and drift mobility. For n-type semiconductor it depends on donor concentration & for P-type semiconductor, it depends on acceptor concentration & hole drift mobility.

As the temperature increases, the mobility ~~of~~ of electron & hole decreases. The electron concentration depends exponentially on the temperature

$$n = \left( \frac{1}{2} N_c N_v \right)^{1/2} \exp \left[ \frac{E_c - E_d}{2kT} \right]$$

Since, electron concentration have exponential relation with increasing temp & mobility  $\propto T^{-3/2}$ , this proves that the conductivity mainly depends on the electron concentration. Thus, conductivity increases with the increase in temp.

But in extrinsic region,  $n = N_d$  and thus the conductivity follows temperature dependence of drift mobility.

### # Diffusion in Semiconductor :-

Diffusion is the process in which particle tends to spread out & distribute themselves as a result of their random thermal vibration migrating from region of high concentration to region of low concentration.

In n-type semiconductor, when doping is done then there is more concentration of one type of carriers so it gets diffused i.e. get distributed throughout the semiconductor. Since the particles are charged, diffusion of charge causes flow of electrical current called diffusion current.

$$\text{Diffusion current density } (J_{\text{diff}}) = e D_e \frac{dn}{dx}$$

$$\text{and } J_h/\text{diff} = -e D_h \frac{dp}{dx} \quad ①$$

where,  $D_e$  and  $D_h$  are electron & hole diffusion co-efficients respectively measured in  $\text{cm}^2/\text{sec}$ .

The diffusion currents are directly proportional to the carrier concentration gradients.

For diffusion to occur,

$$\frac{dn}{dx} \neq 0 \text{ and } \frac{dp}{dn} \neq 0 \quad (\text{for 1-dimensional})$$

For three dimensional

$$\nabla p \neq 0 \text{ & } \nabla n \neq 0.$$

To measure net current density from

eq<sup>n</sup> ① & ② is called Fick's first  
law of diffusion in one-dimension.

(-ve sign meaning: for +ve concentration gradient in x-direction ( $\frac{dn}{dx} > 0$  &  $\frac{dp}{dn} > 0$ ),

diffusion will take place in negative x-direction, for both holes & electrons)

Total Current density in semiconductor

Total current density due to drift + total current density due to diffusion

$$i.e. J = J_e/\text{drift} + J_h/\text{drift} + J_e/\text{diff} + J_h/\text{diff}$$

$N_c$  = effective density of states at conduction band edge  
 $N_v$  = " " " " " at valence " "

## # Degenerate and Non-Degenerate semiconductors

band: and carrier density which is proportional to

individual state and distribution function

We have concentration of electron in conduction band

$$n = N_c \exp\left(-\frac{E_c - E_F}{kT}\right) \quad \text{(i)}$$

which is derived by replacing Fermi-Dirac distribution with Boltzman's statistics which is valid if  $E_c \gg kT$  above  $E_F$ .

We assume no. of states is far greater than no. of electrons so we can assume no two electrons are found in the same state i.e. it neglects Pauli's exclusion principle.

Boltzman statistics is valid if no. of states is very very greater than no. of electrons in conduction band. Semiconductor with  $n \ll N_c$  and  $p \ll N_v$  are termed as non-degenerate semiconductor.

When the semiconductors are highly doped then concentration of electron gets nearly equal to the number of states  $N_c$  in conduction band. In such a case

Pauli's exclusion principle cannot be neglected and Fermi Dirac Distribution has to be used. Such semiconductor shows some properties similar to that of metal (for eg. R increase with increase in T) Semiconductor with  $n \gg N_c$  and  $p \gg N_V$  are degenerate semiconductors.

In N-type semiconductor, when donor orbitals overlap to form narrow energy band, it overlaps and becomes part of conduction band thereby slightly shifting  $E_F$  downward. Fermi level in n-type degenerate semiconductor is within the original conduction band. In p-type degenerate semiconductor, fermi energy lies below  $E_V$ .

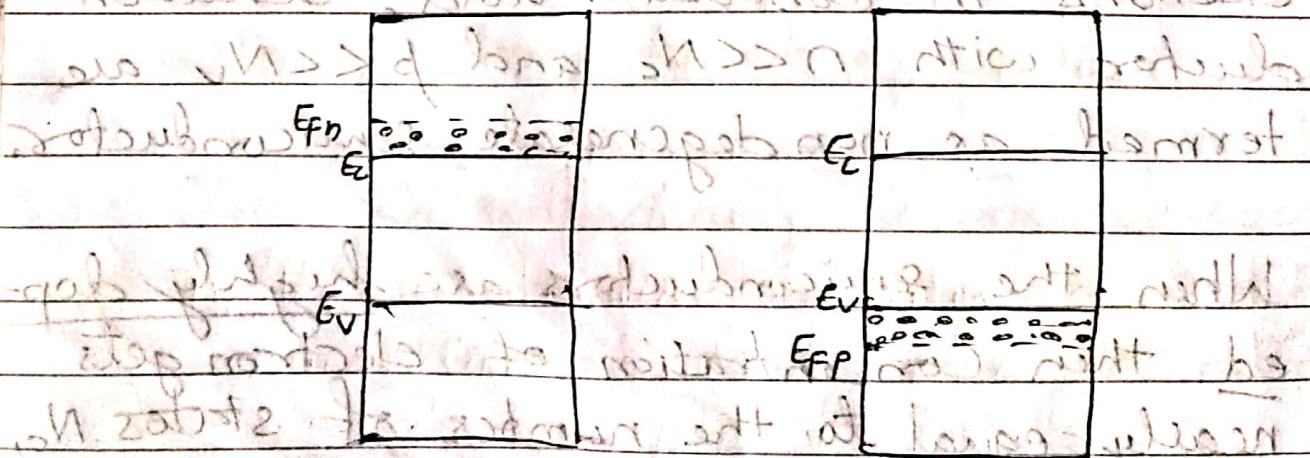


Fig: Degenerate n-type semiconductor & p-type semiconductor.

## # Einstein Relationship $\Rightarrow$

For a non-degenerate semiconductor, the doping profile along its length is given by fig below.

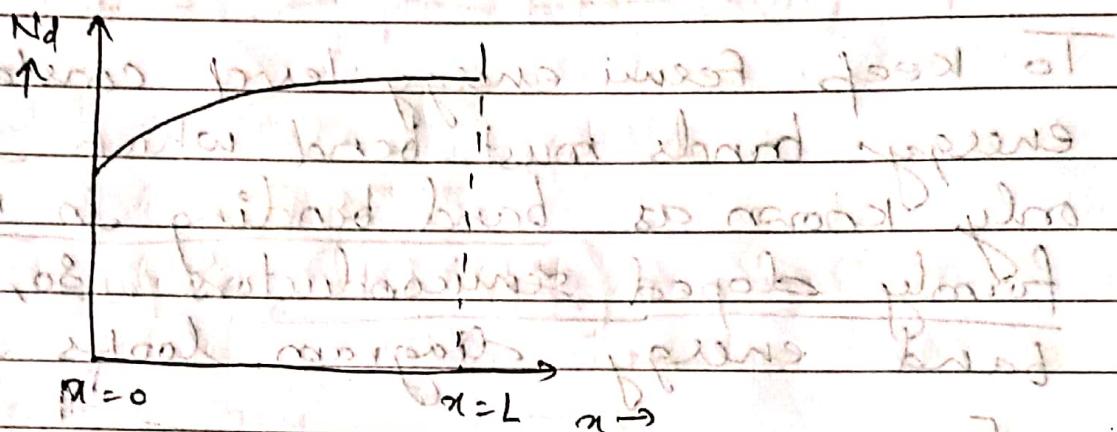


Fig: Doping profile of n-type, non-degenerate semiconductor.

So, we expect corresponding energy band diagram to be as shown in fig. below.

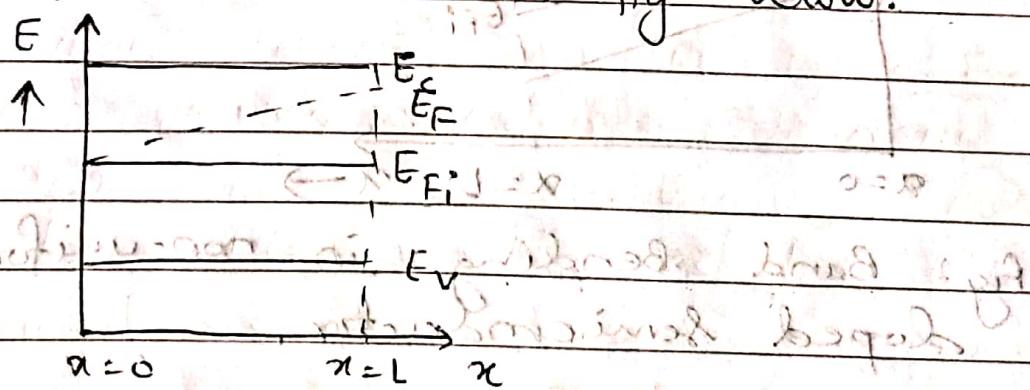


Fig: Energy band diagram (corresponding to doping profile).

The above diagram shows the variation in Fermi energy level along length. But in equilibrium Fermi energy level inside a

material cannot vary with respect to position.

Mathematically,

$$\frac{dE_F}{dx} = \frac{dE_F}{dy} = \frac{dE_F}{dz} = 0$$

To keep Fermi energy level constant, other energy bands must bend which is commonly known as band bending in non-uniformly doped semiconductors. So, the band energy diagram looks like

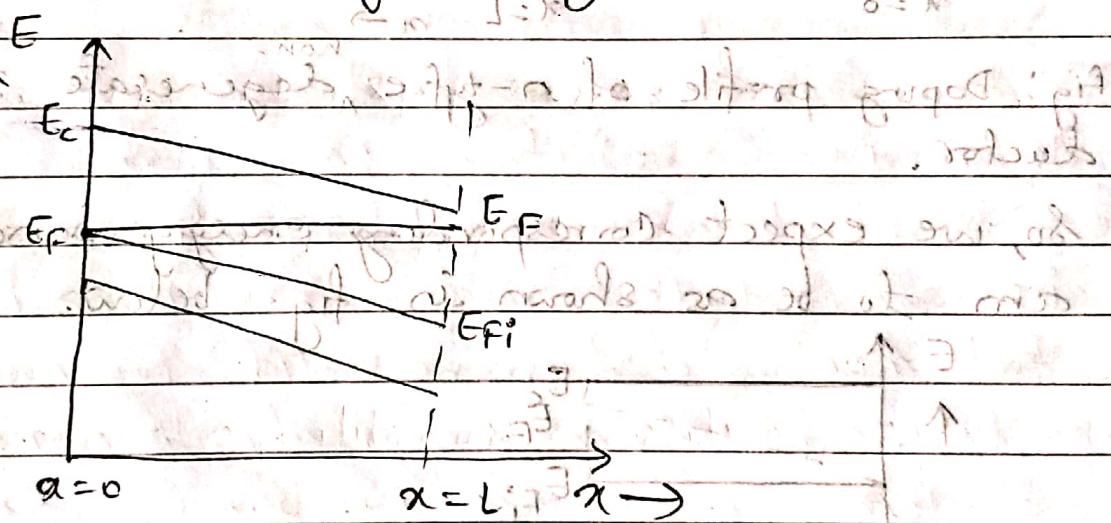


fig: Band Bending in non-uniformly doped semiconductor.

Under equilibrium condition, current in Semiconductor must be zero.

$$J_e = J_e/\text{drift} + J_e/\text{diff} = 0$$

$$en\frac{dE}{dx} + eD_e \frac{dn}{dx} = 0 \quad \text{(i)}$$

$$J = eE \quad J = n \cdot e N_d \vec{E} \quad N_d = \frac{eI}{me^*} \quad V_D = \frac{eE}{m^*} T \\ = N_d \cdot \vec{E}$$

Potential energy  $PE = -ev \rightarrow \text{ii}$   
 with respect to some reference  $E_{ref}$ , potential energy is given as,

$$P.E. = (E_c - E_{ref}) \rightarrow \text{iii}$$

From  $\text{ii}$  &  $\text{iii}$

$$-ev = E_c - E_{ref}$$

$$V = -\frac{1}{e}(E_c - E_{ref}) \rightarrow \text{iv}$$

$$\text{Electric field } \vec{E} = -\nabla V$$

$$\text{in one dimension, } \vec{E} = -\frac{\partial V}{\partial x}$$

$$\vec{E} = \frac{1}{e} \left\{ \frac{d E_c}{dx} - \frac{d E_{ref}}{dx} \right\}$$

$$a. \vec{E} = \frac{1}{e} \left( \frac{d E_c}{dx} - \frac{d E_{ref}}{dx} \right)$$

$$b. \vec{E} = \frac{1}{e} d E_c$$

$$\therefore \frac{d E_{ref}}{dx} = 0, \quad E_{ref} = \text{constant}$$

$$\therefore \vec{E} = \frac{d E_c}{dx} = \frac{d V}{dx} - \frac{d E_{ref}}{dx}$$

To find  $\frac{d V}{dx}$ , we have

$$n = N_c \exp\left(-\frac{E_c - E_F}{kT}\right) \quad (\text{For } n\text{-type semiconductor})$$

$$n_i = N_c \exp\left(-\frac{E_c - E_{F_i}}{kT}\right) \quad (\text{For intrinsic concentration})$$

$$\frac{n}{n_i} = \frac{N_c \exp\left(-\frac{E_c - E_F}{kT}\right)}{N_c \exp\left(-\frac{E_c - E_{F_i}}{kT}\right)}$$

$$\frac{n}{n_i} = \exp\left(-\frac{E_c - E_F}{kT}\right)$$

$$\frac{n}{n_i} = \exp\left(-\frac{E_c - E_{F_i}}{kT}\right) \times \exp\left(+\frac{E_c - E_{F_i}}{kT}\right)$$

$$\text{or, } n = n_i \exp\left(\frac{-E_c + E_F + E_c - E_{F_i}}{kT}\right)$$

$$\text{Under equilibrium condition, } \frac{dE_F}{dn} = 0$$

diff eq<sup>n</sup> (v) on both sides w.r.t. x,

$$\frac{dn}{dx} = n_i \frac{d}{dx} \exp\left(\frac{E_F - E_{F_i}}{kT}\right)$$

$$= n_i \exp\left(\frac{E_F - E_{F_i}}{kT}\right) \times \frac{d}{dx} \left(\frac{E_F - E_{F_i}}{kT}\right)$$

$$= n_i \exp\left(\frac{E_F - E_{F_i}}{kT}\right) \times \frac{1}{kT} \left(\frac{dE_F - dE_{F_i}}{dn}\right)$$

$$\frac{dn}{dn} = n_i \exp\left(\frac{E_F - E_{F_i}}{KT}\right) \times \frac{1}{KT} \left(0 - \frac{dE_{F_i}}{dn}\right)$$

$$\frac{dn}{dn} = \frac{n_i}{KT} \left(-\frac{dE_{F_i}}{dn}\right) \quad \text{[From eq^n vi]}$$

$$\therefore \frac{dn}{dn} = -\frac{n}{KT} \frac{dE_{F_i}}{dn} \quad \text{vii}$$

We have,  $\frac{dE_{F_i}}{dn} = e\vec{E}$  at large  $n$

Thus,

$$\frac{dn}{dn} = -\frac{n}{KT} e\vec{E} \quad \text{viii}$$

Using eq^n viii in eq^n (i) we get,

$$en\mu_e E + eD_e \left(-\frac{n}{KT} e\vec{E}\right) = 0$$

$$en \left(\mu_e - \frac{D_e}{KT} e\vec{E}\right) = 0$$

which implies,

$$\left(\mu_e - \frac{D_e}{KT} e\vec{E}\right) = 0$$

$$\mu_e = \frac{D_e \cdot e}{KT}$$

$$\mu_e KT = D_e \cdot e$$

$$\boxed{\frac{KT}{e} = \frac{D_e}{\mu_e}}$$

This is required Einstein relationship relating electron diffusion co-efficient to electron mobility.

At constant temp<sup>r</sup> ratio of diffusion co-efficient to electron mobility is constant and is equal to  $\frac{KT}{e}$

$$\sigma = \left( \frac{e^2 \mu_e}{T} \right) \cdot \left( g_f + g_{f'f''} \right)$$

$$\sigma = \sqrt{\left( \frac{e^2 \mu_e}{T} \right) \left( g_f + g_{f'f''} \right)}$$

$$\sigma = \left( \frac{e^2 \mu_e}{T} \right)^{1/2}$$

$$\sigma = D_e \cdot \mu_e$$

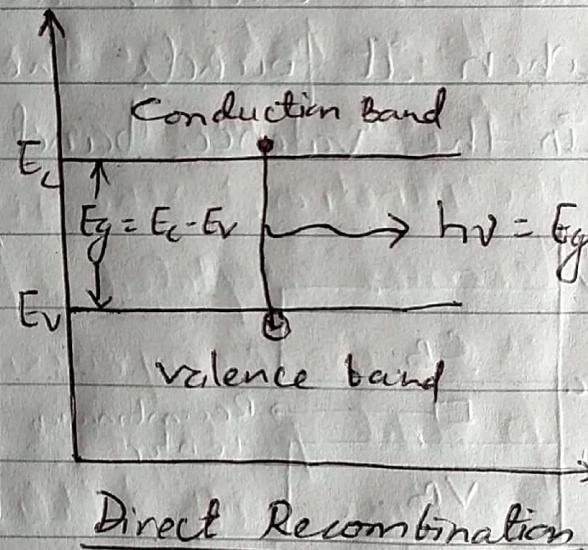
$$D_e \cdot \mu_e = D_e \cdot \frac{KT}{e}$$

## # Recombination and Generation

### (a) Direct Recombination and Generation :-

Above absolute zero temperature, the thermal electrons from the valence band to conduction band continuously generates electron-hole pairs. So, when a wandering free electron in conduction band falls down to low energy state and meets the hole by releasing the excess energy (as photon). This process is called recombination/direct recombination.

i.e electrons in conduction Band are annihilated or destroyed.

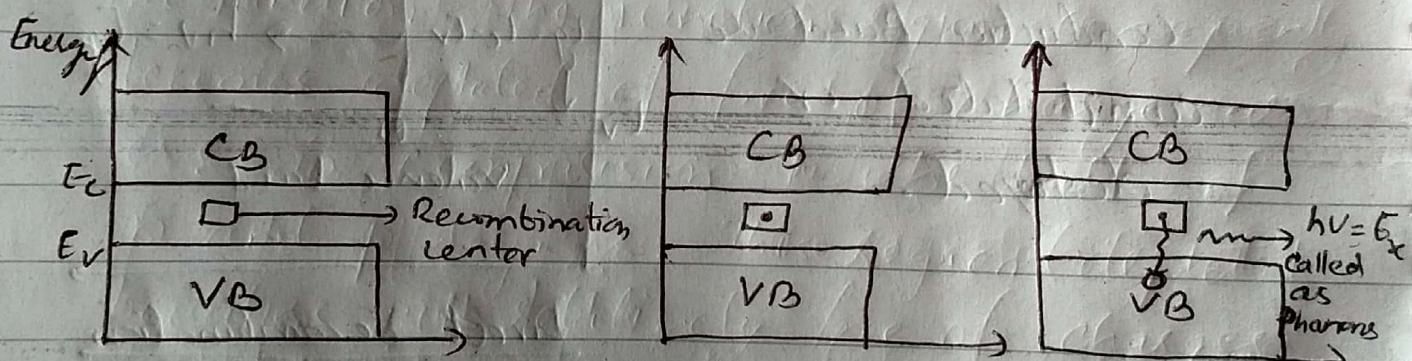


### (b) Indirect Recombination and Generation :

Indirect Recombination occurs through the recombination centers. A recombination center is formed due to the impurity or crystal defect which can take up any momentum

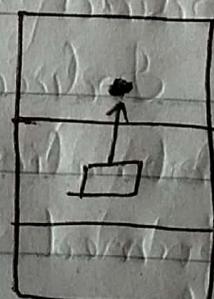
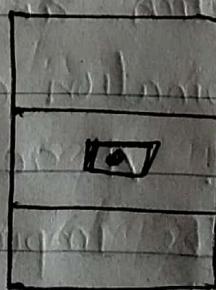
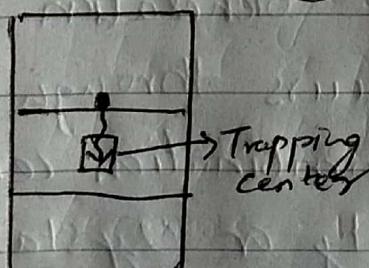
difference between a hole and electron. The electron is captured at the recombination center and are trapped until a hole arrives and recombines with it. Recombination center provides a localized electronic state below  $E_c$  in the band gap.

When an electron ( $e^-$ ) approaches the center, it is captured and is bound. The localized electron waits on the center and when it finds the hole, it recombines in the valence band.



(a)

Recombination



(b) Trapping

Fig: Indirect Recombination & Generation

It was the illustration of Indirect Recombination and trapping by Recombination centers and trapping centers.

## # PN Junction

- (i) What is metallurgical junction?
- (ii) what is space-charge region? How is it formed?
- (iii) Explain about diffusion and drift that flow takes place when P and N regions are brought in contact.
- (iv) Define PN Junction and explain with characteristics
- (v) Illustrate width of PN Junction and explain them by deriving built-in potential equation.
- (vi) Write short Notes on GaAs Semiconductor.

In n-type Semiconductor, electrons are majority charge carriers and in p-type Semiconductor holes are majority charge carriers. If these two semiconductors are brought together to form a junction electrons from n-type semiconductor starts diffusing to p-region and holes from p-region starts drifting to n-region due to concentration gradient. (Majority of one to minority of others)

These holes and electrons diffusing towards each other meet and recombine around the junction. The junction region consequently becomes depleted of free of charge carriers in comparison to the bulk of n and p regions. This region (depleted) because its relatively free of charges is called space charge region or depleted layer or transition layer.

N-region becomes +vely charged and P-region becomes -vely charged. So, the electric field

is developed between these two layers which try to drift holes in its direction and electrons in opposite direction. The strength of field will be determined by the equilibrium condition at which the number of carriers diffusing is compensated by no. of charge drifting in opposite direction.

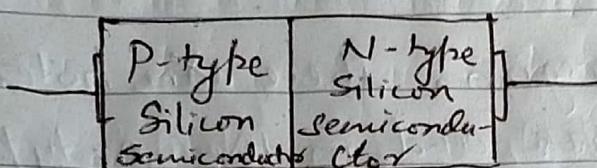
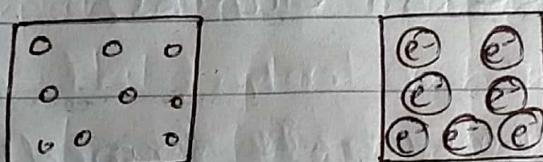


Figure a)

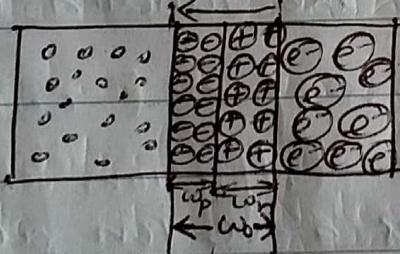


$e^{\oplus}$  electron  
○ holes

P N

figure b)

depletion region

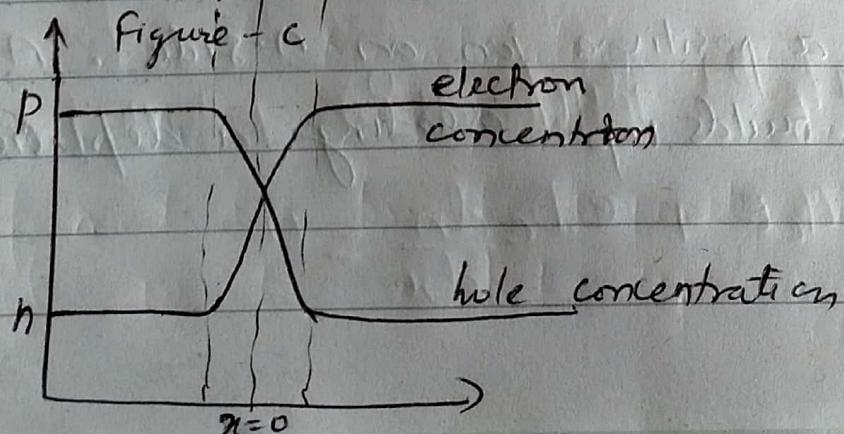


$\ominus$  -ve ion from filled hole

$\oplus$  +ve ion from removed electron

Figure - c

figure d)



## Summary

The combining of electrons and holes depletes the holes of the P-region and the electrons of the n-region near PN junction.

## Depletion Region Details

- In the p-type region, there are holes from acceptor impurities and in the n-type region, there are extra electrons.
- When a P-N junction is formed, some of the electrons from n-type region which have reached the conduction band are free to diffuse across the junction and combine with holes.
- Filling a hole makes a negative ion and leaves behind a positive ion on n-side. A space charge builds up, creating a depletion region.

Let us consider,

$W_p \rightarrow$  Width of depletion region in P-type

$W_N \rightarrow$  " " " " " " N-type

$W_0 \rightarrow$  Total width of depletion region.

$N_A \rightarrow$  acceptor concentration in P-region. /cm<sup>3</sup>

$N_D \rightarrow$  " " " " n-region

$n_{n_0} \rightarrow$  electron concentration in n-region

$p_{n_0} \rightarrow$  hole " " "

$n_{p_0} \rightarrow$  electron concentration in P-region

$p_{p_0} \rightarrow$  hole " " ",

Also, we know,

$$n_{n_0} = N_D$$

$$p_{n_0} = \frac{n_i^2}{n_{n_0}} = \frac{n_i^2}{N_D}$$

$$P_{p_0} = N_A$$

$$n_{p_0} = \frac{n_i^2}{P_{p_0}} = \frac{n_i^2}{N_A}$$

eq<sup>u</sup>

X

Figure (c) Shows PN junction formed when a p-type and n-type semiconductor are brought together.

The exposed charge in the left side of the junction must be equal to exposed charge in R.H.S. to maintain charge neutrality.

$$\frac{N_A}{N_D} = \frac{W_N}{W_P}$$

$$\therefore W_P N_A = W_N N_D$$

We have,

$$E = -\frac{eN_D W_N}{E} = -\frac{eN_A W_P}{E} \quad \text{--- (1)}$$

We know that potential at any point can also be calculated from electric field as,

$$E = -\frac{dv}{dx}$$

We know that sum of net current due to drift and diffusion is zero.

$$J_{drift/e} + J_{diff/e} = 0$$

$$\text{or, } eN_D E + eD_e \frac{dn}{dx} = 0$$

$$\text{or, } \phi n \parallel E = -\rho D_e \frac{dn}{dx}$$

$$\therefore E = -\frac{D_e}{\mu_e} \cdot \frac{dn}{n dx}$$

From Einstein Relationship

$$\left[ \frac{D_e}{\mu_e} = \frac{kT}{e} \right]$$

Substituting  $\left( \frac{D_e}{\mu_e} \right)$  in above expression we get,

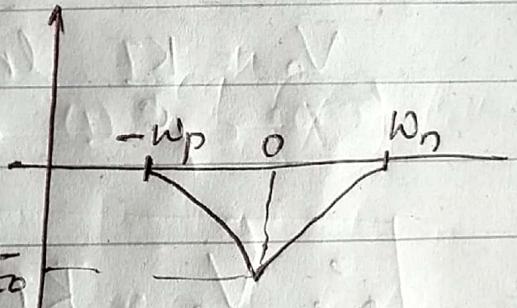
$$E = -\frac{kT}{en} \frac{dn}{dx} \quad \textcircled{2}$$

$$\text{Also, } E = -\frac{dv}{dx}$$

Thus,

$$\frac{dv}{dx} = -\frac{kT}{en} \frac{dn}{dx}$$

$$\text{or, } dv = \frac{kT}{e} \left( \frac{dn}{n} \right)$$



$E_0 \Rightarrow$  maximum electric field

Integrating from  $-w_p$  to  $w_p$ ,

$$\int_{-w_p}^{w_p} dv = \frac{kT}{e} \int_{-w_p}^{w_p} \left( \frac{dn}{n} \right)$$

$$\text{or, } V(w_n) - V(-w_p) = \frac{KT}{e} \left[ \ln n \right]_{-w_p}^{w_n}$$

↓  
Built in potential

$$\text{on } V_0 = \frac{KT}{e} \left[ \ln n(w_n) - \ln n(-w_p) \right]$$

where,

$n(w_n)$  = electron concentration at  $w_n$

AT  $w_n$ ,  $n = N_d$

AT  $-w_p$ ,  $n = \frac{n_i^2}{N_a}$

See in the consideration  
portion

$$V_0 = \frac{KT}{e} \left[ \ln N_d - \ln \left( \frac{n_i^2}{N_a} \right) \right]$$

$$V_0 = \frac{KT}{e} \ln \left( \frac{N_d}{\left( \frac{n_i^2}{N_a} \right)} \right)$$

$$\boxed{\therefore V_0 = \frac{KT}{e} \ln \left[ \frac{N_d N_a}{n_i^2} \right]}, \text{ this is the } \textcircled{3}$$

expression for the built in potential in p-n junction.

Using eq<sup>n</sup> (\*) we have,

$$V_0 = \frac{KT}{e} \ln \left( \frac{n_i^2}{n_{p_0}} \times \frac{n_{n_0}}{n_i^2} \right)$$

$$\therefore V_0 = \frac{KT}{e} \ln \left( \frac{n_{n_0}}{n_{p_0}} \right)$$

④

Similarly,

$$V_0 = \frac{KT}{e} \ln \left( \frac{P_{p_0}}{P_{n_0}} \right)$$

For the width of PN junction :

In the above expression,  $n_{n_0}$  and  $n_{p_0}$  represent electron concentration in bulk of n-region respectively. Similarly  $P_{p_0}$  and  $P_{n_0}$  represent hole concentration in bulk p and n regions respectively.

Also, the built in potential =  $-\frac{Ew_0}{2}$  ————— ⑤

$$\therefore E = -\frac{dv}{dx} \quad (dv = V_0 - 0, dx = w_0/2)$$

$$E = -\frac{V_0}{\frac{w_0}{2}}, \therefore V_0 = -\frac{Ew_0}{2}$$

where,  $w_0 = w_p + w_n$   
and  $w_p = w_0 - w_n$

Also we have,

$$w_n N_d = w_p N_a$$

$$w_n N_d = (w_0 - w_n) N_a$$

$$\text{or } w_n N_d = w_0 N_a - w_n N_a$$

$$\text{or } w_n N_d + w_n N_a = w_0 N_a$$

$$\boxed{\therefore w_n = \frac{w_0 N_a}{N_a + N_d}}$$

? — ⑥

$$\text{Similarly, } \boxed{w_p = \frac{w_0 N_d}{N_a + N_d}}$$

from eq<sup>n</sup> ① using eq<sup>n</sup> ⑥ in ①

$$E = -\underline{e N_a w_p}$$

$$= -\frac{e \cdot N_a w_0 N_d}{E(N_a + N_d)} \quad — ⑦$$

we have,

$$V_0 = -\frac{EW_0}{2}$$

[from (7) substituting  
the value of E]

$$\therefore V_0 = \frac{eN_a N_d W_0^2}{2\epsilon(N_a + N_d)}$$

$$\text{or } W_0^2 = \frac{2\epsilon(N_a + N_d) \cdot V_0}{e(N_a \cdot N_d)}$$

$$\text{or } W_0 = \sqrt{\frac{2\epsilon V_0}{e} \left( \frac{N_a + N_d}{N_a \cdot N_d} \right)}$$

$$\therefore W_0 = \sqrt{\frac{2\epsilon V_0}{e} \left( \frac{1}{N_a} + \frac{1}{N_d} \right)} \quad \text{--- (8)}$$

eq<sup>n</sup> (8) is the required expression for the width of the depletion layer.

- Q) How is forward and reverse biasing done in PN junction. Also draw the V-I characteristics  
[Read Yourself]