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Analog Electronics

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Chapter 1

Semiconductor Physics

1.1 Conductor, Semiconductor and Insulator

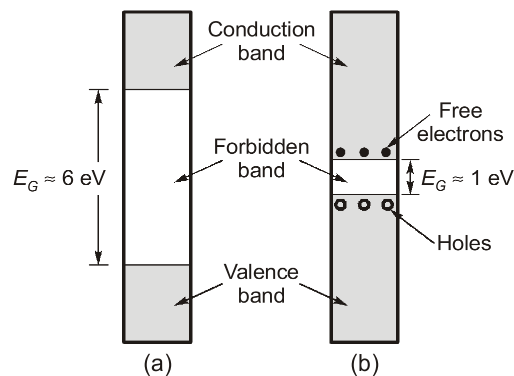


Fig. 1.1 : *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

1.1.1 Insulators

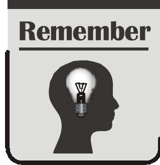
- An insulating material has an energy band diagram as shown in Fig. 1.1 (a).
- It has a very wide forbidden-energy gap ($\simeq$ 6 eV) separating the filled valence band from the vacant conduction band. Because of this, it is practically impossible for an electron in the valence band to jump the gap, reach the conduction band.
- At room temperature, an insulator does not conduct. However it may conduct if its temperature is very high or if a high voltage is applied across it. This is termed as the **breakdown of the insulator.**
- **Example:** diamond.

1.1.2 Semiconductors

- A semiconductor has an energy-band gap as shown in Fig. 1.1 (b).
- At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.
- The relatively small band gap of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy.
- The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.
- **Example:** Ge and Si.

1.1.3 Metals

- There is no forbidden energy gap between the valence and conduction bands. The two bands actually overlap as shown in Fig. 1.1 (c).
- Without supplying any additional energy such as heat or light, a metal already contains a large number of free electrons and that is why it works as a good conductor.
- **Example:** Al, Cu etc.



Conduction band electrons can move along sea of atoms present in the specimen under consideration while the valence band electrons (restrained electrons) are bound to parent atom. These conduction band electrons are known as ***free electrons***.

Relation of energy gap with temperature

Since the band-gap energy of a crystal is a function of interatomic spacing, it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G for silicon decrease with temperature at the rate of 3.60×10^{-4} eV/°K.

Hence, for silicon, $E_G(T) = 1.21 - 3.60 \times 10^{-4}\, T$

and at room temperature (300°K), $E_G = 1.1$ eV

Similarly, for germanium, $E_G(T) = 0.785 - 2.23 \times 10^{-4}\, T$

and at room temperature, $E_G = 0.72$ eV

In general $E_g(T) = E_{g0} - \beta T$

Where, $E_{g0} = E_g(T = 0\text{ K})$

$\therefore$ β : depends upon material, i.e. material constant.

1.1.4 Classification of semiconductor materials

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

Single crystal and compound crystal semiconductor are two classifications of semiconductor depending upon number of constitutional elements. Examples of single crystal semiconductors are germanium (Ge) and silicon (Si) whereas compound semiconductors are gallium arsenide (GaAs), cadmium sulphide (CdS), gallium nitride (GaN) and gallium arsenide phosphide (GaAsP) etc.

Intrinsic Materials and Covalent Bonding

Semiconductor in its purest form (without any impurity) is known as **intrinsic semiconductor**.

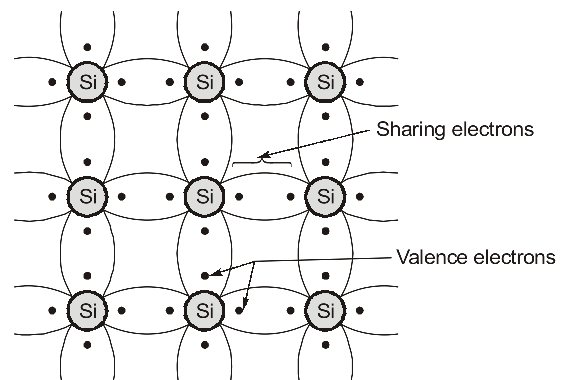


Fig. 1.2 : *Covalent bonding of the silicon atom*

An intrinsic semiconductor (such as pure Ge or Si), has only four electrons in the outermost orbit of its atoms. When atoms bond together to form molecules of matter, each atom attempts to acquire eight electrons in its outermost shell. This is done by sharing one electron from each of the four neighbouring atoms. This sharing of electrons in semiconductors is known as **covalent bonding.** Fig. 1.2 shows covalent bonding of the silicon atom.

A covalent bond consists of two electrons, one from each adjacent atom. Both the electrons are shared by the two atoms. At absolute zero, all the valence electrons are tightly bound to the parent atoms. No free electrons are available for electrical conduction. **The semiconductor therefore behaves as a perfect insulator at absolute zero.**

Charge Carriers in Intrinsic Semiconductor

At room temperature (say 300°K) sufficient thermal energy is supplied to make a valence electron of a semiconductor atom to move away from the influence of its nucleus. Thus, a covalent bond is broken. When this happens, the electron becomes free to move in the crystal. This is shown in Fig. 1.3 (a).

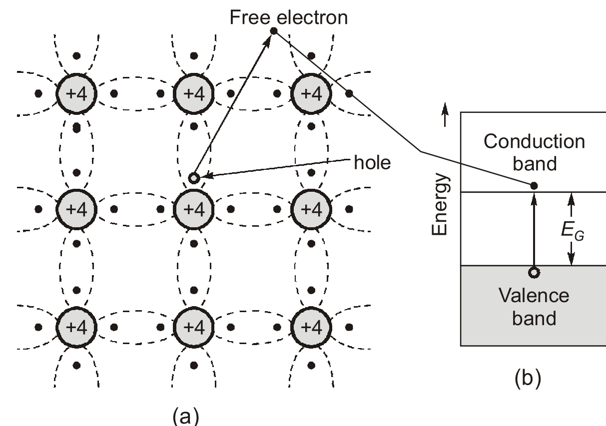


***Fig. 1.3 :** (a) Crystal structure (b) Energy band diagram*

When an electron breaks a covalent bond and moves away, a vacancy is created in the broken covalent bond. This vacancy is called a **hole.** Free electrons and holes are always generated in pairs. Therefore, the concentration of free electrons and holes will always be equal in an intrinsic semiconductor

$$\boxed{n = p = n_i}$$

where n_i is called the intrinsic concentration.

Although, strictly speaking, a hole is not a particle; for all practical purposes we can view it as a positively charged particle capable of conducting current. This concept of a hole as a positively charged particle merely helps in simplifying the explanation of current flow in semiconductors.

Effect of Temperature on Conductivity of Intrinsic Semiconductor

A semiconductor (Ge or Si) at absolute zero, behaves as a perfect insulator. At room temperature, some electron-hole pairs are generated. Now, if we raise the temperature further, more electron hole pairs are generated. The higher the temperature, the higher is the concentration of charge carriers. As more charge carriers are made available, the conductivity of intrinsic semiconductor increases with temperature. In other words, the resistivity (inverse of conductivity) decreases as the temperature increases. That is; **semiconductor have negative temperature coefficient of resistance.**

Intrinsic concentration, $$\boxed{n_i^2 = A_0 T^3 e^{-\left(\frac{E_{G0}}{kT}\right)}}$$

E_{G0} : Energy gap at 0°K in eV

k : Boltzman's constant in eV/°K

A_0 : Material constant independent of temperature

Extrinsic Materials

In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by purposely introducing impurities into the crystal. This process, called **doping**, is the most common technique for varying the conductivity of semiconductors. By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus there are two types of doped semiconductors, n-type (majority carriers electrons) and p-type (majority carries holes). When a crystal is doped such that the equilibrium carrier concentrations n_0 and p_0 are different from the intrinsic carrier concentration n_i the material is said to be **extrinsic.**

n-type semiconductor

An n-type semiconductor is created by introducing impurity elements that have five valence electrons (pentavalent), such as antimony, arsenic and phosphorus. The effect of such impurity elements is indicated in figure (1.4). Note that the four covalent bonds are still present. There is, however an additional fifth electron due to the impurity atom, which is unassociated with any particular covalent bond. This remaining electron loosely bound to its parent atom (antimony) atom, is relatively free to move within the newly formed n-type material. Since the inserted impurity atom has donated a relatively "free" electron to the structure.

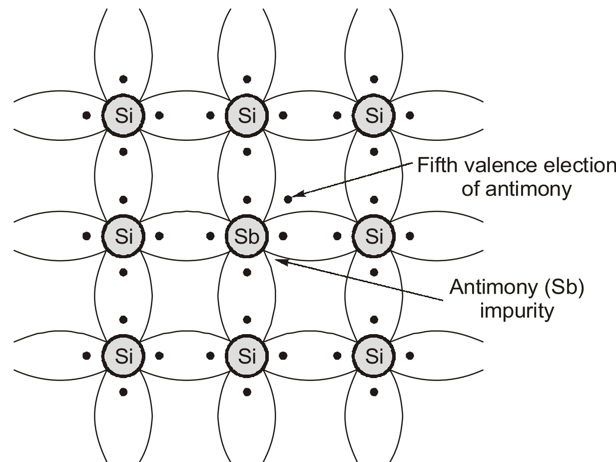


***Fig. 1.4 :** Antimony impurity in n-type material*

Diffused impurities with five valence electrons are called donor atoms.

When impurities or lattice defects are introduced into an otherwise perfect crystal, additional levels are created in the energy band structure, usually within the band gap. For example, an impurity from column V of the periodic table (P, As and Sb) introduces an energy level very near the conduction band in Ge or Si. Such an impurity level is called a donor level as shown in Fig. 1.5.

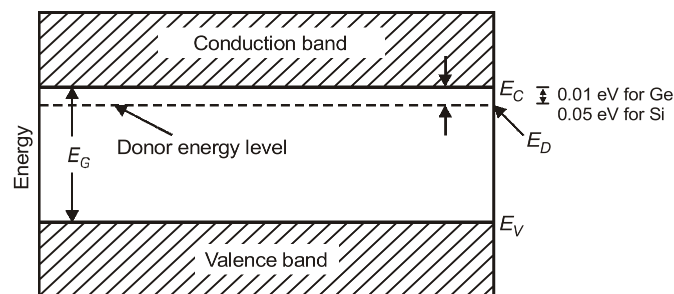


***Fig. 1.5 :** Energy-band diagram of n-type semiconductor*

n-type material is as a whole electrically neutral since ideally the number of positively charged protons in the nuclei is still equal to the number of free and orbiting negatively charged electrons in the structure.

p-type semiconductor

The p-type semiconductor is formed by doping a pure germanium or silicon crystal with impurity atoms having three valence electrons. The elements most frequently used for this purpose are boron, gallium and indium.

Note that, there is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called a hole and is represented by a small circle or a plus sign, indicating the absence of a negative charge. Since the resulting vacancy will readily accept a free electron;

The diffused impurities with three valence electrons are called acceptor atoms.

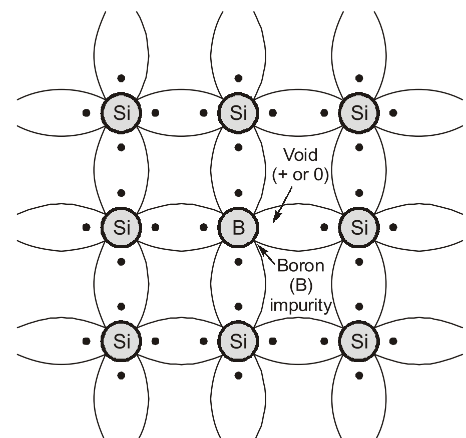


***Fig. 1.6 :** Boron impurity in p-type material*

The resulting p-type material is electrically neutral for the same reasons described for the n-type material.

Atoms from Column-III (B, Al, Ga and In) introduce impurity levels in Ge or Si near the valence band. These levels are empty of electrons at 0 K. At low temperatures, enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band. Since this type of impurity level **"accepts"** electrons from the valence band, it is called an acceptor level as shown in Fig. 1.7.

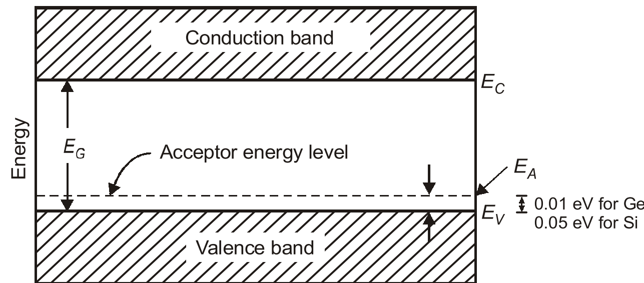


***Fig. 1.7 :** Energy-band diagram of p-type semiconductor*

Standard Doping Levels

1. Moderate doping : 1 in ($10^6 - 10^8$) : P, N
2. Lightly doped : 1 in 10^{11} : P^-, N^-
3. Highly (heavily) doped : 1 in 10^3 : P^+, N^+

$\Rightarrow$ 1 : 10^6 or 1 in 10^6 or $1/10^6$ is read as "1 impurity atom in 10^6 atoms".

1.2 The Mass-action Law

In a semiconductor under thermal equilibrium (constant temperature) the product of electrons and holes concentrations is always a constant and is equal to the square of intrinsic carrier concentration.

$$\boxed{np = n_i^2}$$

The intrinsic concentration n_i is a function of temperature.

The law is mainly used to calculate the concentration of minority carriers. In n-type semiconductor, the electrons are called the majority carriers, and the holes are called the minority carriers. In a p-type material, the holes are the majority carriers, and the electrons are the minority carriers.

$$\text{Minority carrier concentration} = \frac{n_i^2}{\text{Majority carrier concentration}}$$

But, Majority carrier concentration $\propto$ Doping concentration

So, $$\text{Minority carrier concentration} \propto \frac{1}{\text{Doping concentration}}$$

or, $$\boxed{\text{Minority carrier concentration} \times \text{Doping concentration} = n_i^2}$$

In a semiconductor, if majority carrier concentration increases the minority carrier concentration decreases this is due to the recombinations.

NOTE: Drawback of *Si* is less conductivity due to more energy gap.

1.3 Charge Neutrality Equation

Any part of a semiconductor bar is always electrically neutral.

or

Total positive charge densities = Total negative charge densities.

$$\boxed{p + N_D = n + N_A}$$

n-type:

$$p + N_D = n + N_A$$

$$n > p \ ; \ N_A \approx 0 \ (n\text{-type})$$

$$\Rightarrow \quad \frac{n_i^2}{n} + N_D = n = 0 \Rightarrow n^2 - N_D n - n_i^2 = 0$$

$$\Rightarrow \quad n = \frac{N_D}{2} \pm \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2} = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2} \qquad (n > 0, \text{ so only +ve sign})$$

$$n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

$$N_D >> n_i$$

So, $\boxed{n \approx N_D}$

Similarly, for *p*-type:

$$p = \frac{N_A}{2} + \sqrt{\left(\frac{N_A}{2}\right)^2 + n_i^2}$$

$$n_A >> n_i$$

$$\boxed{p \approx N_A}$$

1.4 Drift Velocity

It occurs in metals and semiconductor.

$v \propto E$ $\qquad v \rightarrow$ drift velocity

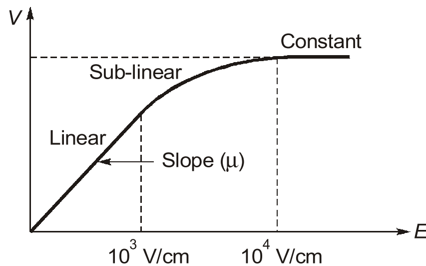
$v = \mu E$ $\qquad E \rightarrow$ Electric field

$\mu \rightarrow$ proportionality constant (mobility)

Mobility (μ)

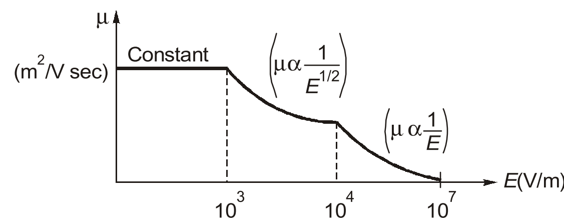
$$\mu = \frac{v}{E} = \frac{\text{Drift velocity}}{\text{electric field}} \frac{\text{m}^2}{\text{V sec.}}$$

Drift Velocity Vs Electric Field

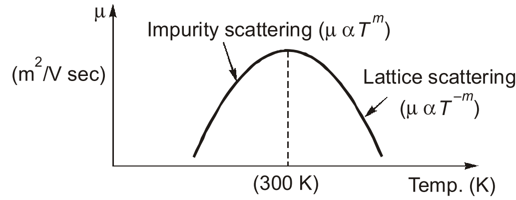


μ = constant	$E < 10^3$ V/cm
$\mu \propto \frac{1}{\sqrt{E}}$	$10^3 < E < 10^4$ V/cm
$\mu \propto \frac{1}{E}$	$E > 10^4$ V/cm

Mobility (μ) vs Electric Field (E)



Mobility vs Temperature



1.5 Current Density (J)

Let differential volume $dv = Adl$

Where, A : C.S.A of conductor

dl : differential length

$\therefore \quad d\phi = (ne)(Adl)$ ...(i)

Where, n : no. of e^-/m^3

e : charge of e^-

$d\phi$: differential charge passing through differential volume (dV)

Now, Drift velocity, $v = \dfrac{dl}{dt}$ ...(ii)

$\therefore \quad d\phi = (ne)(Avdt)$

$$\Rightarrow \quad \frac{d\phi}{dt} = ne\,Av = I$$

$$J = \frac{I}{A} = ne\,v$$

$$\boxed{J = \rho V}$$

$\rho = ne$ = charge density

= charge per unit volume

For metal: $J = ne\,v$

$v = \mu E$

$J = n\,e\,\mu\,E$

$J = \rho\mu\,E \qquad (\rho = ne)$

$$\boxed{\sigma = \rho\mu} \Rightarrow \boxed{J = \sigma E} \qquad (\sigma = \text{conductivity})$$

Semi-conductor: $J_{sc} = J_n + J_P$

$J_n = n \times q \times \mu_n \times E$

$J_p = n \times q \times \mu_p \times E$

$J_{sc} = (n\mu_n + p\mu_p)\,qE$

and we know, $J = \sigma E$

So, $\boxed{\sigma = (n\mu_n + p\mu_p)q}$

Case-I: Intrinsic semiconductor,

$$n = p = n_i$$

$$\sigma_{\text{intrinsic}} = n_i(\mu_n + \mu_p)q$$

Case-II: extrinsic semiconductor,

$$n >> P \text{ (for } n\text{-type)}$$

$$\sigma_{n\text{-type}} \simeq n\,\mu_n q$$

or, $\boxed{\sigma_{n\text{-type}} \simeq N_D\,\mu_n\,q}$

and for p-type, $\sigma_{p\text{-type}} \simeq p\,\mu_p q$

$$\boxed{\sigma_{p\text{-type}} \simeq N_A\,\mu_p q}$$

Minimum value of conductivity in a semi-conductor:

The conductivity of semiconductor is given as,

$$\sigma = nq\mu_n + pq\mu_p$$

Using mass-action law, $p = \dfrac{n_i^2}{n}$

Therefore, $\sigma = nq\mu_n + \dfrac{n_i^2}{n}\cdot q\mu_p$

Differentiating w.r.t. n, we get

$$\frac{d\sigma}{dn} = q\mu_n + \left(\frac{-1}{n^2}\right)n_i^2 q\mu_p$$

For minimum conductivity,

$$\frac{d\sigma}{dn} = 0 = q\mu_n + \left(\frac{-1}{n^2}\right)n_i^2 q\mu_p$$

$$n = n_i\sqrt{\frac{\mu_p}{\mu_n}}$$

The equation denotes the concentration of electrons in semiconductor when conductivity is minimum.

Similarly, we can find, $p = n_i\sqrt{\dfrac{\mu_n}{\mu_p}}$

The minimum conductivity in a semiconductor is given as,

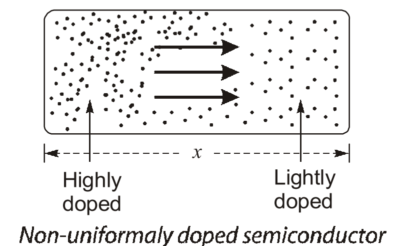
$$\sigma_{\min} = n_i\sqrt{\frac{\mu_p}{\mu_n}}\cdot q\mu_n + n_i\sqrt{\frac{\mu_n}{\mu_p}}\cdot q\mu_p = 2qn_i\sqrt{\mu_n\mu_p}$$

1.6 Diffusion Current

It occurs in a non-uniformly doped semiconductor,

- Rate of change of concentration with respect to distance x is called as concentration gradient dn/dx. The diffusion current depends on the concentration gradient.
- Without electric field, there is movement of charge from high density to low density side, and this movement is called diffusion current.

  i.e. $I_{\text{diff}} \neq 0$
- Best examples of non-uniformly doped *SC* will be P-N junction.



Non-uniformaly doped semiconductor

NOTE

- Drift current mechanism can also be called as potential gradient $\left(\dfrac{dv}{dx}\right)$.
- Diffusion current mechanism can also be called as concentration gradient $\left(\dfrac{dn}{dx}\right)$.

So, $(I_{\text{Total}})_{\text{Current in SC}} = I_{\text{drift}}$ (due to external battery) + $I_{\text{diffusion}}$(due to irregular concentration)

Derivation of $I_{diffusion}$:

Case-I : For electron

$$J_n \propto q\frac{dn}{dx} \propto \text{rate of change of concentration}$$

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

$$D_n = \textit{proportionality constant} = \text{diffusion constant for electron.}$$

$$J_n = qD_n\frac{dn}{dx}$$

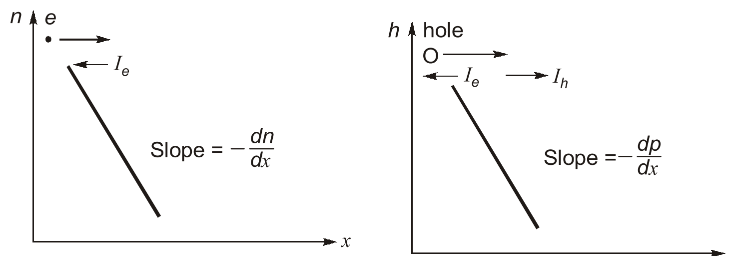
$$\boxed{I_n = qD_n\frac{dn}{dx}A}$$

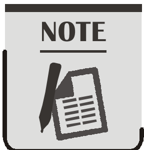
Case-II : For holes

$$J_p = -qD_p\frac{dp}{dx}$$

$$\boxed{I_p = -qD_p\frac{dp}{dx}\cdot A}$$

As from figure above mentioned, carriers moves from one side to another side then concentration decreases due to recombination.





- In case of hole current (–)ve sign is very - very important.
- In case of electron current also (–) ve sign is present but direction of electrons and current are different.

$$I_{\text{Total(SC)}} = I_{\text{drift}} + I_{\text{diffusion}} = (I_n + I_p)_{\text{drift}} + (I_n + I_p)_{\text{diffusion}}$$

$$\boxed{I_{SC} = \left\{(nq\mu_n EA) + (pq\mu_p EA) + q.D_n\frac{dn}{dx}.A - qD_P\frac{dP}{dx}A\right\}}$$

1.7 Einstein Relation

Relation between Diffusion constant (D) and mobility (μ)

$$D \propto \mu \qquad \text{(from kinetic gas theory)}$$

$$D = V_T\,\mu$$

$$\boxed{V_T = \frac{kT}{q} = \frac{T}{11600}}$$

V_T = volt equivalent temperature or thermal voltage

$$K = 1.38 \times 10^{-23} \text{ J/k} = \text{Boltzman constant}$$
$$q = 1.6 \times 10^{-19} \text{ C}$$
D = Proportionality constant for diffusion current
μ = Proportionality constant for drift current

At 27°C, $$V_T = \frac{T}{11600} = \frac{300}{11600} = 0.026 \text{ V or } 26 \text{ mV}$$

or, $$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T}$$ ...Einstein relation

1.8 Potential Variation in a Open Circuit Semiconductor Bar

Consider a p-type continuously graded semiconductor bar (i.e. non-uniformly doped).

No external voltage is applied to the bar. The bar is open-circuited, therefore, the net current through the bar is zero. But due to the non-uniform doping, there exists a diffusion current as holes move from high concentration to low concentration.

Therefore, $$J_{p\,\text{diffusion}} = -qD_p \frac{dp}{dx}$$

But as bar is open-circuited, net current through it is zero. This means there exists one more internal current which is equal to diffusion current but in opposite direction to it. This is a drift current flowing in the bar in opposite direction to that of diffusion current.

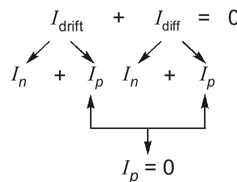
Given as, $$J_{p\text{drift}} = pq\mu_p E$$

But drift current cannot exist without a potential difference and applied voltage to the bar is zero. So externally E is zero. This indicates that the non-uniform doping of bar results in the induced voltage.

As, $J = 0$

or, $$J_{P\text{drift}} + J_{P\,\text{diffusion}} = 0$$

$$pq\mu_p E - qD_p \frac{dp}{dx} = 0$$



$$E = \left(\frac{D_p}{\mu_p}\right) \cdot \frac{1}{p} \cdot \frac{dp}{dx} = -\frac{dv}{dx} = V_T \cdot \frac{1}{p} \cdot \frac{dp}{dx}$$

$$-\int_{V_1}^{V_2} dv = V_T \int_{P_1}^{P_2} \frac{1}{p} \cdot dp$$

$$V_2 - V_1 = V_T(-ln\,p)_{P_1}^{P_2}$$

$$\boxed{V_{21} = V_T ln\left(\frac{P_1}{P_2}\right)}; \quad \boxed{P_1 = P_2 e^{\frac{V_{21}}{V_T}}} \quad \text{or} \quad \boxed{P_2 = P_1 e^{-\frac{V_{21}}{V_T}}}$$

Similarly for n-type semiconductor bar which is non-uniformly doped,

$$n_1 = n_2 e^{-V_{21}/V_T}$$

1.9 Fermi Energy

Electrons in solids obey Fermi Dirac distribution which is given as

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

Where, $f(E)$ = Fermi dirac distribution function at any energy level 'E'.

E_F = Fermi energy level

Function $f(E)$ gives the probability of finding an e^- at any energy level 'E' at temperature 'T'

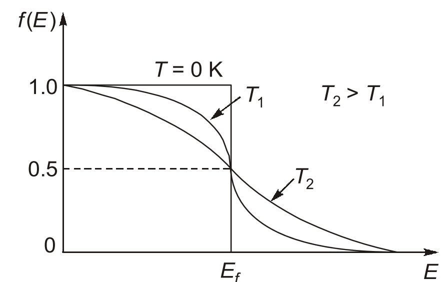
Thus, $1 - F(E)$ gives the probability of finding a hole at energy level 'E' at temperature 'T'.

At, $E = E_F$

$$f(E) = \frac{1}{1+e^0} = \frac{1}{2} = 50\%$$

Thus Fermi energy level (E_f) is an energy level at which probability of finding e^- is 50%.

From graph $f(E)$ is more gradual at higher temperature.



Now, $$n_0 = \int_{E_c}^{\infty} f(E)\,n(E)\,dE$$

Where, $n(E)$ represents effective density of states in energy range dE.

Also, $$n_0 = N_c e^{-(E_C-E_F)/KT} \quad \text{...(i)}$$

Where, N_C : Effective density of states in conduction band

Similarly, $$p_0 : N_v e^{-(E_F-E_V)/KT} \quad \text{...(ii)}$$

Where, N_V : Effective density of states in valence band

For intrinsic S.C., $$n_i = N_C e^{-(E_C-E_i)/KT} \quad \text{...(iii)}$$

$$p_i = N_v e^{-(E_i-E_V)/KT} \quad \text{...(iv)}$$

Fermi-Level in Intrinsic semiconductor:

For intrinsic semiconductor, $n_i = p_i$

$$N_C\, e^{-(E_c-E_i)/kT} = N_V\, e^{-(E_i-E_v)/kT}$$

$$In\left(\frac{N_C}{N_V}\right) = \frac{E_C + E_V - 2E_i}{kT}$$

$$E_i = \frac{E_C + E_V}{2} - \frac{kT}{2}\, In\left(\frac{N_C}{N_V}\right)$$

The intrinsic Fermi-level depends only on the temperature.

At $T = 0$ K°, the Fermi-level exist at the center of energy gap.

Fermi-level in *n*-type semiconductor:

$$n_0 = N_c e^{-(E_c-E_{Fn})/KT}$$

$$\Rightarrow \quad \frac{n_0}{N_C} = e^{-(E_c-E_{Fn})/KT}$$

$$\Rightarrow \quad E_{Fn} = E_c - KT\, In\left(\frac{N_C}{N_D}\right) \qquad (\because n_0 \simeq N_D)$$

In *n*-type semiconductor, Fermi-level depends on temperature and doping concentration.

As temperature increases, Fermi-level moves towards the center of energy gap. Hence, conductivity decreases with increase in temperature. As doping increases, Fermi-level moves upwards towards the conduction band and hence, the conductivity increases with increase in doping concentration. In a highly doped *n*-type semiconductor or highly degenerated *n*-type semiconductor, the Fermi-level exists on the conduction band.

Shift in the position of E_F w.r.t. center of Energy gap:

$$\text{Shift} = KT\ ln\left(\frac{N_D}{n_i}\right)$$

Fermi-level in *p*-type semiconductor:

$$p_0 = N_v e^{-(E_{Fp}-E_V)/KT}$$

$$ln\left(\frac{p_0}{N_v}\right) = \frac{-E_{FP}+E_V}{KT}$$

$$E_{FP} = E_V - KT\ ln\left(\frac{p_0}{N_V}\right)$$

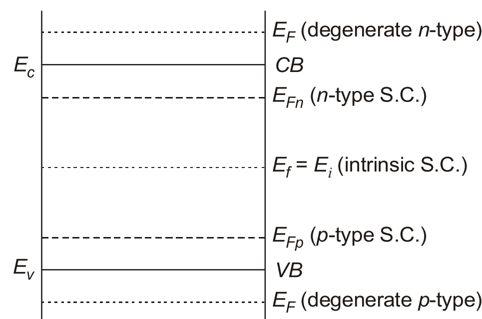
$$\therefore \quad E_{FP} = E_V + KT\ ln\left(\frac{N_V}{N_A}\right) \qquad (\because p_0 \simeq N_A)$$

In *p*-type semiconductor, Fermi-level depends on temperature and doping concentration. As temperature increases, the Fermi-level moves towards the center of energy gap. Hence, conductivity decreases with increase in temperature.

Fermi-level moves downwards towards the valence band and hence, the conductivity increases with increase in doping concentration. In a highly doped *p*-type semiconductor or highly degenerated *p*-type semiconductor, the Fermi-level will exist in the valence band.

Shift in the position E_F w.r.t. to center of Energy gap:

$$\text{Shift} = KT\ ln\left(\frac{N_A}{n_i}\right)$$



Example - 1.1 Differentiate between direct and indirect band gap materials with suitable E-K diagram?

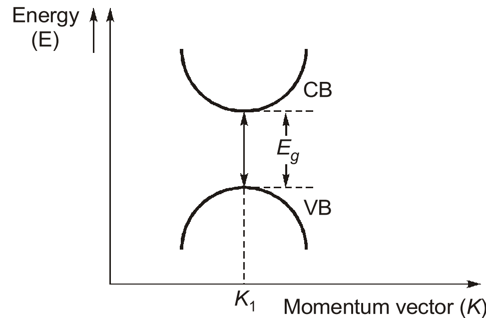
Solution:

(i) **Direct Band gap material:** These are the materials for which lowest energy state of conduction band and highest energy state of valence band occurs for "same value of momentum".

OR

These are the materials in which an e^- in the conduction band can fall to an empty state in the valence band, giving off the energy difference E_g as a photon of light.

E-K diagram:



Recombination occurs without the help of any external agent.

No 2nd particle is emitted.

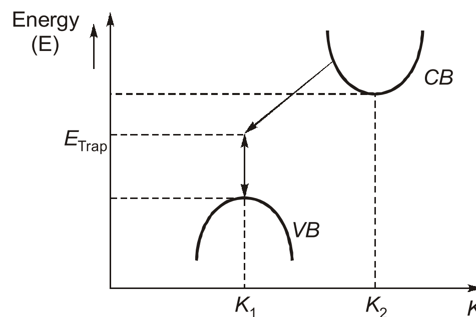
Application: In designing devices which require light as the output. e.g. LED

(ii) **Indirect Band gap material:** These are materials in which highest energy state of valence band and lowest energy state of conduction band occurs for different values of momentum.

OR

The materials in which an e^- in lowest energy conduction band cannot fall directly to valence band of maximum energy but also "undergoes a momentum change" as well as changing its energy.

E-K diagram:



- Recombination occurs with the help of external agent. Ex. Au
- A second particle phonon is emitted.
- Energy is released in the form of heat.

Process of Recombination:

1. 'Au' creates trap levels (energy state with momentum value K_1)
2. As soon as e^- jumps from CB to E_{trap}, its momentum becomes K_1.
3. Now it falls and recombines with hole having same value of momentum K_1 in opposite direction.

Example - 1.2 Describe the variation of Fermi energy due to doping concentration and temperature?

Solution:

(i) **Fermi Energy vs Doping Concentration:**

By increasing doping concentration, Fermi energy level moves away from intrinsic Fermi level.