

Chapter 6

Semiconducting Materials

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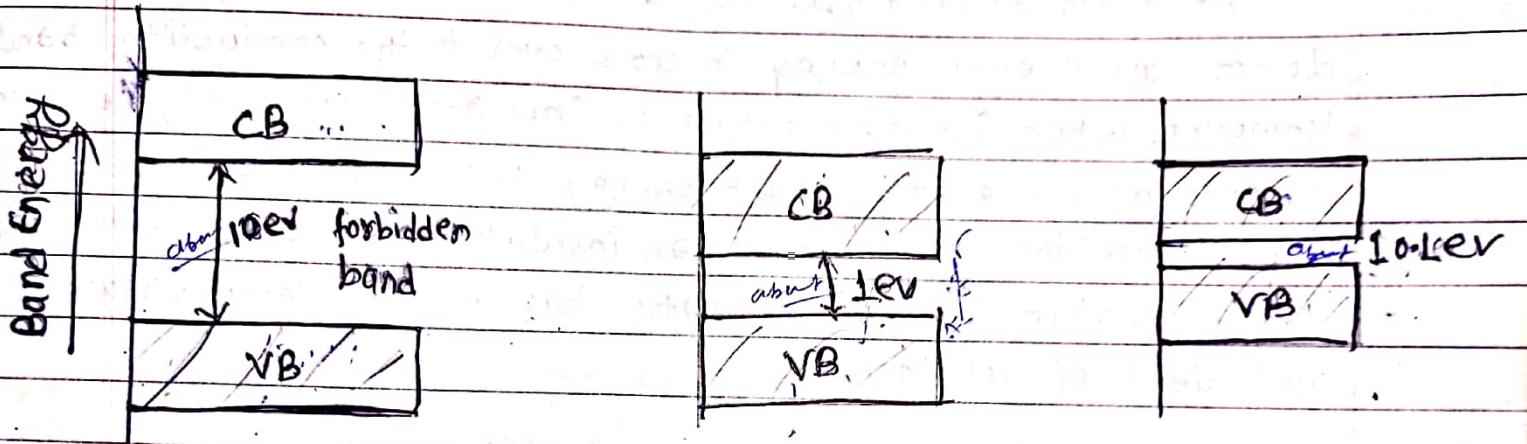
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Semiconducting Materials

Insulator

Semiconductor

Conductor



Eg: wood, plastic

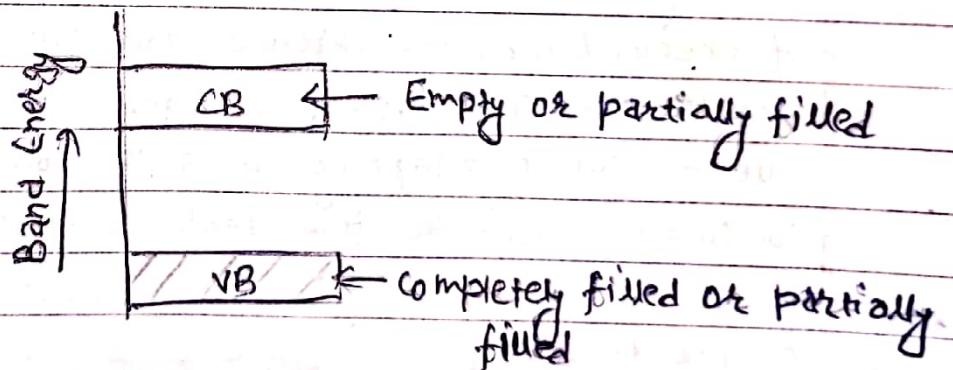
(>4 electrons)

Eg: silicon, Germanium

(4 electron)

Eg: Cu, Al, Zn, Ag

(< 4 electron)



Insulator

Insulators are those substances which do not allow the passage of electric current through them. In terms of energy band, the V.B is full while the conduction band is increased. Further the energy gap between V.B and C.B is very large (about 10eV). Therefore, a very high electric field is required to push the valence electron to the conduction band. For this reason, the electrical conductivity

2. Insulator (Rigid conductor) (Q. 92)

of such materials is extremely small and may be zero under ordinary condition.

At room temperature, the valence electrons of the insulators do not have enough energy to cross over to the conduction band. However, when the temperature is increased, some of the valence electrons may acquire enough energy to cross over to the conduction band. Hence the resistance of an insulator decreases with increase in temperature i.e. an insulator has negative temperature coefficient of resistance.

2. Conductors

Conductors are those substances which easily allow the passage of electric current through them. It is because there are a large number of free electrons present in a conductor. In terms of energy band, the valence and conduction band are ~~above~~ overlapped each other (the band gap energy is about 0.1 eV). Due to this overlapping, a slide potential difference across a conductor causes the free electrons to constitute electric current.

3. Semiconductors

Semi-conductors are those substances, whose electrical conductivity lies in between conductors and insulators. In terms of energy band, the valence band is almost filled and conduction band is almost empty. Further, the energy gap between valence band and conduction band is very small (about 1 eV). Therefore, smaller electric field is required to push the electrons from the valence band to the conduction band.

At low temperature, the valence band is completely filled & conduction band is completely empty. Therefore, the semi-conductor acts as insulator at low temperature. As the temperature is increase, more valence electron is cross over to the CB and the conductivity increases. This shows that the electrical conductivity of the semi-conductor increases with the rise in temperature. i.e the semi-conductor has positive temperature coefficient of conductor.

Valence band and conduction band

The outermost electrons of an atom i.e those in the shell farther most from the nucleus are called valence electron and have the highest energy. The band of energy occupied by the valence electrons is called valence band and is obviously the highest occupied band. It may be completely filled or partially filled with electrons but never empty.

The next higher permitted energy band is called conduction band and may be either be empty or partially filled with e⁻s. In fact it may be defined as the lowest unfilled energy band. In CB, electrons can move freely and hence are known as conduction electron. The gap between these two bands is known as the forbidden energy gap.

Semi-Conductors

Intrinsic

Extrinsic

N-type

p-type

(penta-valent)
atoms

(Tri-valent atoms)

→ Donor

→ Acceptor

Eg: Arsenic (As)

Eg: Gallium (Ga)

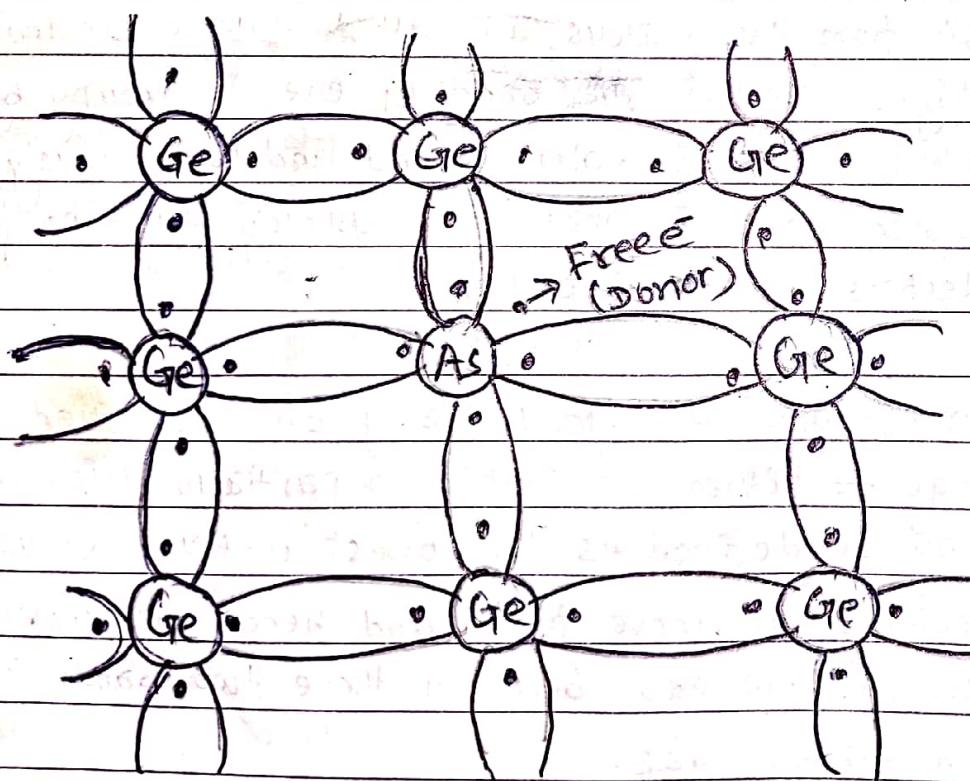


Fig: N-type semi-conductor

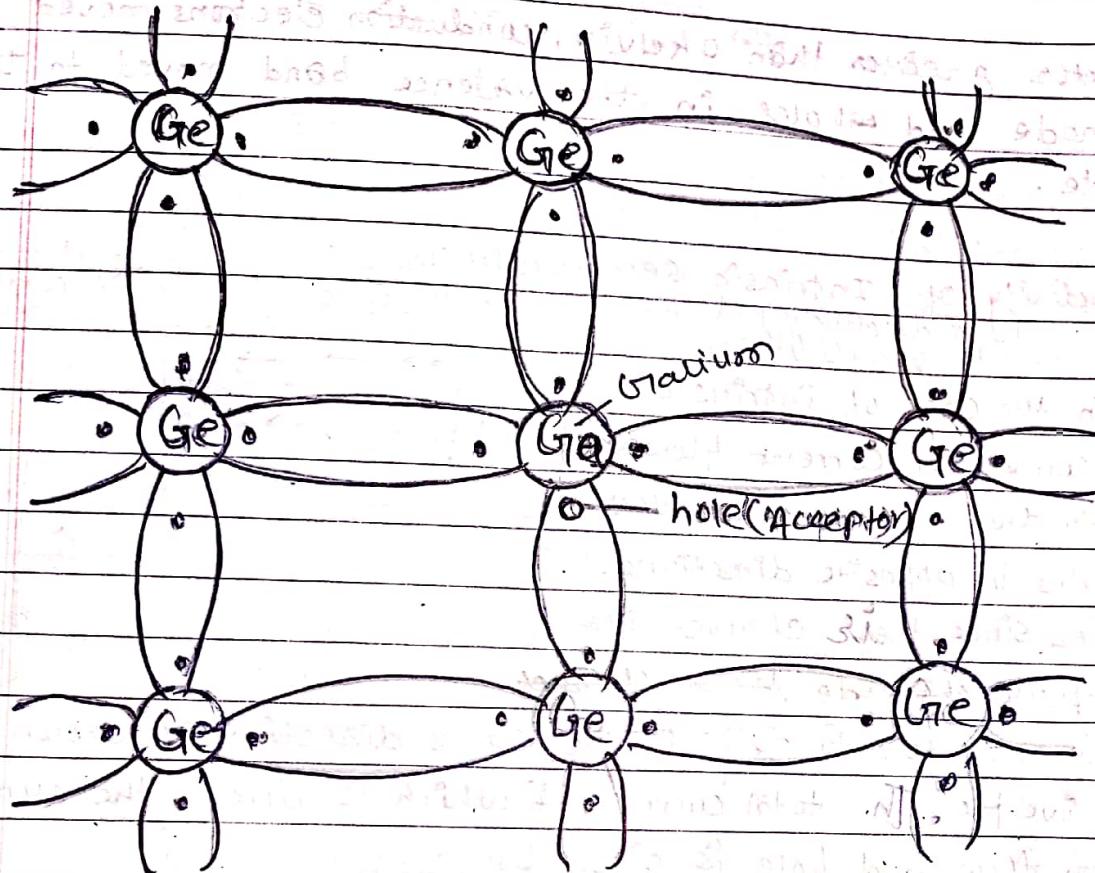


Fig: p-type Semiconductor.

Intrinsic Semiconductor

Pure semiconductors are known as intrinsic Semiconductors. The common examples of such conductors are pure silicon, pure Germanium, which has forbidden energy gaps are of 0.72 & 1.0 respectively. The energy gap is so small that even at ordinary temperature, there are many electrons which has sufficient energy jump across the small energy gap between valence band and conduction band.

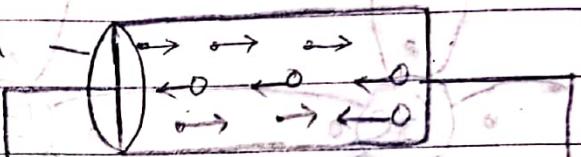
When an electric field is applied to an intrinsic semi-conductor it is go

conductor greater than 0 kelvin, conduction electrons move to the anode and holes in the valence band move to the cathode.

Conductivity of Intrinsic Semiconductor

Show that the conductivity within the metallic conductor is product of charge density & mobility.

In the case of intrinsic semiconductor, current flow is due to the movement of electrons and holes in opposite directions.



However, since their charges are of opposite sign, the current due to each in the same direction as shown in the above fig. The total current which is due to the sum of electron flow and hole is given by,

$$I = I_e + I_h$$

Let, v_e = Drift velocity of electrons (m/s)

v_h = Drift velocity of holes (m/s)

n_i = Density of free electrons in an intrinsic semiconductor (per m^3).

p_i = Density of holes in an intrinsic semiconductor (per m^3)

e = Charge of an electron.

A = Area of cross-section of the semiconductor.

Since, in an intrinsic semiconductor, $n_i = p_i$ — ①

$\therefore I = neVA$ (Reln of drift velocity of e^- in the conductor).

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potential gradient $E = \frac{V}{l}$

$$\therefore I = n_i e (V_d + V_h) A - \textcircled{II}$$

$$\text{or, } I = n_i e (V_d + V_h) E \cdot A - \textcircled{III}$$

where, Drift velocity $V_d = l \mu_e E$

$$\text{or, } I = n_i e (V_d + V_h) \cdot \frac{l}{A} \cdot A - \textcircled{IV}$$

$$\text{or, } \frac{V}{I} = \frac{l}{A} \left(\frac{1}{n_i e (V_d + V_h)} \right)$$

$$\text{or, } R = \frac{l}{A} \left[\frac{1}{n_i e (V_d + V_h)} \right]$$

Comparing with $R = \frac{\rho l}{A}$

$$\Rightarrow \rho = \frac{1}{n_i e (V_d + V_h)} - \textcircled{IV}$$

$$\therefore \text{conductivity } (\sigma) = n_i e (V_d + V_h) - \textcircled{V}$$

Also we have,

$$J = \frac{I}{A} - \textcircled{VI}$$

$$\therefore J = \frac{n_i e (V_d + V_h) E A}{A} \quad [\text{from eq } \textcircled{III}]$$

$$\text{or, } J = n_i e (V_d + V_h) E$$

$$\therefore J = \sigma E \quad - \text{VII}$$

For p-type semiconductors,

$$\sigma = n_A e \mu_h$$

$A \rightarrow \text{acceptor}$

where, n_A = concentration of acceptor

For N-type semiconductor,

$$\sigma = n_D e \mu_e$$

$D \rightarrow \text{Donor}$

Where, n_D = concentration of donor.

Numericals

The intrinsic resistivity of Germanium at 300K is $0.47 \Omega\text{-m}$. The electron mobility at 300K is $0.39 \text{ m}^2/\text{Vs}$. The hole mobility at the same temperature in Germanium is $0.19 \text{ m}^2/\text{Vs}$. Calculate the density of electrons in the intrinsic material. Also calculate the drift velocity of holes and electrons for an electric field $E = 10^4 \text{ V/m}$

$$\rho = \sigma A / I$$

Given,

$$\text{Resistivity } (\rho) = 0.47 \Omega\text{-m}$$

$$\text{mobility of electron } (\mu_e) = 0.39 \text{ m}^2/\text{Vs}$$

$$\text{mobility of hole } (\mu_h) = 0.19 \text{ m}^2/\text{Vs}$$

$$\text{Density of electron } (n_e) = ?$$

$$\text{Drift velocity of electrons & holes} = ?$$

$$\text{Electric field } (E) = 10^4 \text{ V/m.}$$

We know,

$$\text{conductivity } (\sigma) = \frac{1}{\rho} = \frac{1}{0.47} = 2.12 \Omega^{-1} m^{-1}$$

we also know,

$$\sigma = n_i e (v_{\text{e}} + v_{\text{h}})$$

$$\text{or, } n_i = \frac{\sigma}{e (v_{\text{e}} + v_{\text{h}})} = \frac{2.12}{1.6 \times 10^{-19} (0.39 + 0.19)}$$

$$\therefore n_i = 2.28 \times 10^{19} \text{ } \mu\text{m}^{-3}$$

Then,

$$\begin{aligned} v_{\text{e}} &= q_e E \\ &= 0.39 \times 10^4 \\ &= 3900 \text{ m/s} \end{aligned}$$

And,

$$\begin{aligned} v_{\text{h}} &= q_h E \\ &= 0.19 \times 10^4 \\ &= 1900 \text{ m/s} \end{aligned}$$

The intrinsic carrier concentration for silicon at room temperature (800K) is $1.5 \times 10^{10} \text{ cm}^{-3}$. If the mobilities of electrons and holes are $1300 \text{ cm}^2/\text{Vs}$ and $450 \text{ cm}^2/\text{Vs}$ respectively. What is the conductivity of silicon at that temperature? If silicon is doped with $10^{18} \text{ Boron atoms/cm}^3$ what is its conductivity?

Soln

Given,

$$\text{Carrier concentration } (n_i) = 1.5 \times 10^{10} \text{ cm}^{-3}$$

$$\text{mobility of electron } (\mu_e) = 1300 \text{ cm}^2/\text{Vs}$$

$$\text{mobility of hole } (\mu_h) = 450 \text{ cm}^2/\text{Vs}$$

Conductivity (σ) = ?

we know that,

$$n_A = 10^{18} \text{ cm}^{-3} \text{ (Boron} \rightarrow \text{Acceptor)}$$

$$\sigma = n_i e (\mu_n + \mu_e)$$

$$= 1.5 \times 10^{10} \times 1.6 \times 10^{-19} (450 + 1300)$$

$$= 4.2 \times 10^{-6} \Omega^{-1} \text{ cm}^{-1}$$

Also we have,

For 2nd part,

$$\sigma = n_A e \mu_h$$

$$= 10^{18} \times 1.6 \times 10^{-19} \times 450$$

$$= 72 \Omega^{-1} \text{ cm}^{-1}$$

Assignment

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- Q.3 Find the resistance of a 1 cm³ pure silicon crystal. What is the resistance when crystal is doped with arsenic if the doping is 1 in 10⁹?

Given data,

Atomic concentration of silicon is $5 \times 10^{22} \text{ cm}^{-3}$

$$n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$$

$$l_e = 1850 \text{ cm}^2/\text{Vs} \quad \& \quad l_h = 450 \text{ cm}^2/\text{Vs}$$

We know that,

$$\sigma = n_i e (l_h + l_e)$$

$$= 1.45 \times 10^{10} (450 + 1850) \times 1.6 \times 10^{-19}$$

$$= 4.176 \times 10^{-6}$$

$$P = \frac{1}{\sigma}$$

$$\therefore R = \rho \frac{l}{A}$$

$$= \frac{1}{\sigma} \times \frac{1}{l}$$

$$\Rightarrow R = \frac{1}{4.176 \times 10^{-6}}$$

$$\therefore R = 0.239 \times 10^6 \Omega$$

$$N_d = \frac{N_{Si}}{10^9}$$

temp ↑ - ve charge increase in $\text{Li}_{1-x} \text{FePO}_4$
there
How?
ne combined with opposite classmate
charge & discharge Date _____
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~~J. Imp S.B.~~

Mass Action law,

$$np = n_i^2$$

$\sigma_n = n_p = n_i$; where n_i is the intrinsic concentration and is a function of temperature.

Concentration of free electrons and holes is always equal in an intrinsic semiconductor. When N-type impurities is added to an intrinsic semiconductor, the concentration of free electrons is increased (or the concentration of holes is reduced below the intrinsic value). Similarly, addition of P-type impurity results in reduction of concentration of free electrons below the intrinsic value. Theoretically analysis proves that, under thermal equilibrium, the product of concentration of free electrons and concentration of holes is constant and is independent of the amount of doping by donor and acceptor impurities. This is known as mass action law. Therefore, we can write,

$$np = n_i^2$$

where, n_i = intrinsic concentration depends upon the temperature.

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Generation and recombination of charges

In pure semi-conductor (intrinsic) equal no. of free electrons and holes are created by thermal energy. The reason behind that a hole is created only by removing an electron from the co-valent bond. Thus, electrons and holes are created in pairs.

Since, the free electrons and holes move randomly within the crystal, there is possibility of an electron meeting a hole. When a free electron approaches the hole, it gets attracted and falls into the hole. This merging of a free electron and a hole is called re-combination. In this process of recombination, both the free electrons and holes are disappear and energy is released as a form of heat or light.

The recombination rate is proportional to the product of concentration or densities of free electrons and holes.

Thus, the process of breaking of covalent bond and ream.

- Creation of electrons and holes take place simultaneously. The amount of time between the creation and disappearance of free electrons and holes is called life time. It varies from a few nano-seconds to several microseconds. The rate of production of electrons and holes pairs increases with the rise in temperature.

Majority and Minority charge carriers

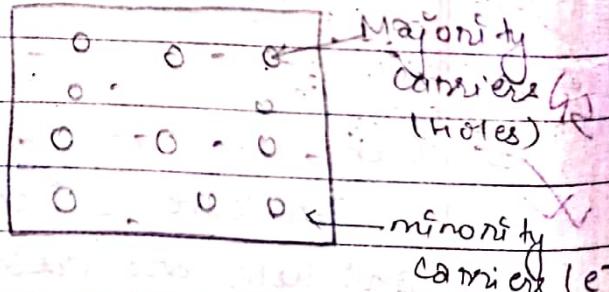
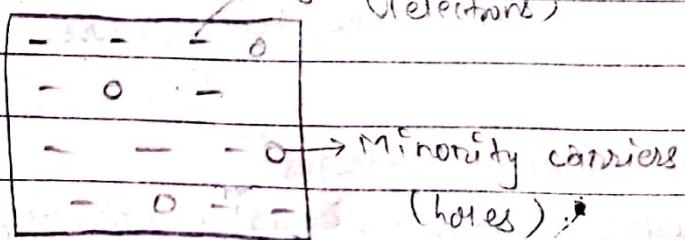


Fig. N-type semiconductor

In an N-type material, electrons are majority carriers and responsible for flow of current where the holes are minority carriers. In P-type material, holes are majority carriers and electrons are minority carrier.

Q. Find the concentration of holes and electrons in an N-type silicon at 300K if the conductivity is 0.1 S/cm^2 . Given that n_i at 300K for silicon is $1.5 \times 10^{10}/\text{cm}^3$ and μ_e at the same temperature is for silicon is $1800 \text{ cm}^2/\text{Vs}$

Soln

Given that

$$n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$$

$$\sigma = 0.1 \text{ S/cm}^2$$

$$\mu_e = 1800 \text{ cm}^2/\text{Vs}$$

We know,

$$\sigma = n_i e (\mu_e + \mu_h)$$

$$\text{or, } \mu_h = \left(\frac{0.1}{0.24 \times 10^{-9}} \right)^{-1/300}$$

$$\therefore \mu_h = 41.66 \times 10^6 \text{ cm}^2/\text{Vs}$$

And,

$$\sigma = n_A e \mu_h$$

$$\text{or, } n_A = \frac{0.1 \times 10^{13}}{1.6 \times 41.66}$$

$$\therefore n_A = 1.5 \times 10^{10}$$

Also,

$$\sigma = n_D e \mu_e$$

$$\Rightarrow n_D = \frac{0.1}{e \times 1800}$$

$$\therefore n_D = \frac{7.69 \times 10^{13}}{1.6 \times 10^{19}}$$

$$\therefore n_D = 4.806 \times 10^{14}$$

~~Assignment~~

$$P = (10^{17} - 10^{16}) \text{ Ans.,}$$

$$N = n^2 - Pn \text{ Ans.,}$$

- Q. An N-type semiconductor doped with $10^{16}/\text{cm}^3$ phosphorous atom has been doped with $10^{17}/\text{cm}^3$ boron atoms. Calculate the electron and hole concentration in the semiconductor.

Given that, the concentration of given pure semiconductor $n_i = 1.45 \times 10^{10}/\text{cm}^3$,

Given that,

$$n_i = 1.45 \times 10^{10}/\text{cm}^3$$

$$\therefore P = (10^{17} - 10^{16})$$

$$= 9 \times 10^{16}/\text{cm}^3$$

Then,

we have,

$$np = n^2$$

$$\Rightarrow n \times 9 \times 10^{16} = (1.45 \times 10^{10})^2$$

$$\therefore n = 2336.11/\text{cm}^3$$

Ans.,

Extrinsic high temp highly conductive
Intrinsic max temp low conductive

0K \rightarrow -273°C

273K \rightarrow -273°C + 273°C
= 0°C

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Effect of temperature on intrinsic semiconductor.

* At Absolute zero temperature. (0K or -273°C)

At absolute zero temperature (0K or -273°C), all the electrons of the intrinsic semi-conductors (Ge or Si) are held tightly by their atoms. The inner orbit electrons are bound to nucleus whereas the valence electrons are bounded by the forces of co-valent bond. Thus, at absolute zero temperature no free electrons are available in the intrinsic semi-conductor and so it behaves like a perfect insulator.

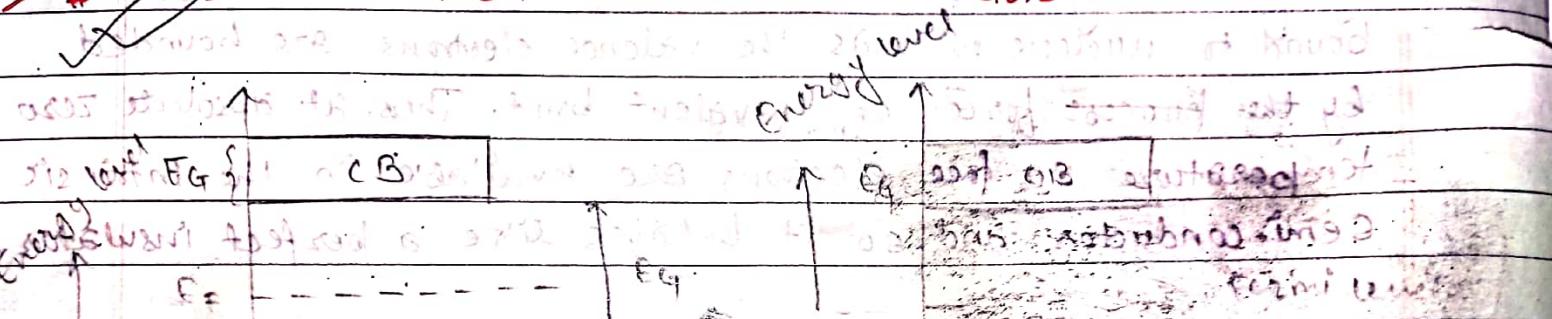
When the material is heated, electrons break away from their atoms and move from the valence band to the conduction band. This produces holes in the valence band and free electrons in the conduction band. Conduction can then occur by electron movement and by hole transfer. With the increase in temperature, the rate of generation of electron hole pairs is increased. This intern increases the rate of recombination.

Thus, with the increase in temperature, the concentration of charge carriers (electrons and holes) increases. As more charge carriers are available, the conductivity of a pure semiconductor increases with the increasing temperature. In other words, the resistivity of the pure semiconductor decreases with the increase in temperature i.e. semiconductors have negative temperature coefficient of resistance.

When the semiconductor is heated, its resistance decreases and conductivity increases till its limit crosses.

The forbidden energy gap, E_F also depends somewhat on temperature. It has been determined experimental that E_F for the semiconductors decreases with the increase in temperature.

VVI
Fermi level in an intrinsic semiconductor.



The Fermi-level is simply a reference energy level. It is the energy level at which the probability of finding an electron and energy emits above it in the conduction band is equal to that of finding a hole and energy units below it in the valence band. Simply it can be considered to be the average energy level of the electrons as shown in the above fig (a).

Let, at any temperature T ,

→ No. of electrons in the conduction band be n_c .

→ No. of electrons in the valence band be n_v .

\therefore Total no. of electrons in both bands, $n = n_c + n_v - \textcircled{1}$.

Now, for simplification let us assume that,

→ width of energy bands are small in comparison to
the forbidden energy gap between them.

→ All levels in a band have same energy.

→ Energies of all levels in V.B. are E_0 and energies of all levels in C.B. are E_F .

Let the zero energy level be taken at the top of valence band as shown in the above figure $\textcircled{6}$.

Now, the no. of electrons in conduction band, $n_c = n \cdot p(E_F) - \textcircled{2}$

where, $p(E_F)$ represents the probability of an electron having energy E_F .

The E_F value may be determined from Fermi-Dirac function;

∴ $n_c = n \cdot p(E_F) = n \cdot \frac{1}{1 + e^{(E_F - E_F)/kT}} - \textcircled{3}$

$$p(E) = \frac{1}{1 + e^{(E - E_F)/kT}} - \textcircled{3}$$

where, $p(E)$ is the probability of finding an electron having any particular value of energy, E .

$$p(E_F) = \frac{1}{1 + e^{(E_F - E_F)/kT}} - \textcircled{4}$$

Now, substituting the value of $P(E_F)$ from eq² ④ in eq² ②

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

NOW, no. of electrons in valence band, $n_v = n \cdot P(0)$

The probability $P(0)$ of an electron being found in the valence band with zero energy can be determined by substituting $E=0$ in eq² ③,

$$\text{i.e } P(0) = \frac{1}{1 + e^{-\left(\frac{E_F}{kT}\right)}}$$

Then,

$$n_v = n \cdot P(0) = \frac{n}{1 + e^{\left(-\frac{E_F}{kT}\right)}}$$

Now the total no. of electrons in both the bands,

$$n = n_c + n_v$$

$$\text{or, } n = \frac{n}{1 + e^{(E_F - E_F)/kT}} + \frac{n}{1 + e^{\left(-\frac{E_F}{kT}\right)}}$$

$$\text{or, } 1 = \frac{1}{1 + e^{(E_F - E_F)/kT}} + \frac{1}{1 + e^{\left(-\frac{E_F}{kT}\right)}}$$

$$\text{or}, \left(1 + e^{\frac{E_F - E_F}{kT}}\right) \cdot \left(1 + e^{\frac{E_F}{kT}}\right) = 1 + e^{-\frac{E_F}{kT}} + 1 + e^{\frac{E_F - E_F}{kT}}$$

$$\text{or}, 1 + e^{\frac{E_F - E_F}{kT}} + e^{-\frac{E_F}{kT}} + e^{\frac{E_F - E_F}{kT}} = 2 + e^{-\frac{E_F}{kT}} + e^{\frac{E_F - E_F}{kT}}$$

$$\text{or}, e^{\frac{E_F - 2E_F}{kT}} = 2 - 1$$

$$\text{or}, e^{\frac{E_F - 2E_F}{kT}} = e^0$$

$$\text{or}, \frac{E_F - 2E_F}{kT} = 0$$

$$\text{or}, E_F = 2E_F = 0$$

$$\therefore E_F = \frac{E_G}{2}$$

i.e In an intrinsic semiconductor fermi-level lies midway between valence band & conduction band.

- The energy band gap of Germanium is 0.72eV at 300K. Determine the fraction of the total number of electrons (conduction band as well as valence band). In the conduction band at 300K.
- Boltzmann constant is 8.61×10^{-5} ev/K.

Ans

Given,

$$E_G = 0.72 \text{ eV}$$

$$T = 300 \text{ K}$$

$$\text{Boltzmann constant (k)} = 8.61 \times 10^{-5} \text{ ev/K}$$

$$n_c/n = ?$$

Now,

We know that

$$n_c = n_p f(g)$$

$$\therefore \frac{n_c}{n} = P_E(g)$$

Again, we have,

$$E_F = \frac{E(g)}{2} = 0.72 = 0.36 \text{ eV}$$

Then,

$$P_E P_E(g) = \frac{1}{1 + e^{(E_g - E_F)/kT}}$$

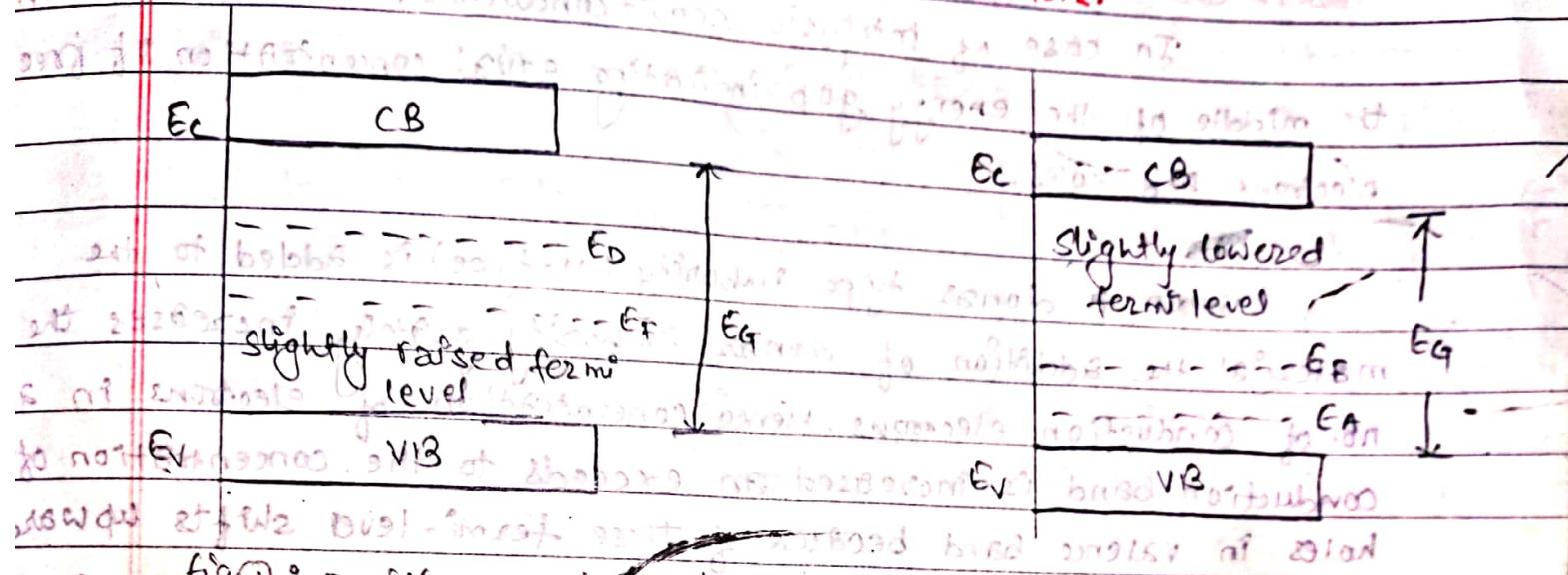
$$= \frac{1}{1 + e^{(0.72 - 0.36)/18.61 \times 10^3 \times 10^{-3}}}$$

$$= 8.82 \times 10^{-7}$$

Ans,

$$8.82 \times 10^{-7} = (8) \text{ electrons/cm}^2 \text{ at } T = 300 \text{ K}$$

* Fermi-level in a extrinsic semiconductor.



fig(1): Position of Fermi level

in a N-type semiconductor

fig(2): Position of Fermi level

in a P-type semiconductor

Concentration of free electrons and concentration of holes

are given as,

$$n = n_c e^{-(E_c - E_F)}$$

$$p = n_v e^{-\frac{(E_F - E_v)}{kT}}$$

where, n_c is the no. of electrons in the conduction band and n_v is the no. of electrons in the valence band.

E_c is the lowest energy in the conduction band and E_v is the maximum no. of valence band.

Fermi-level in N-type extrinsic semiconductor

In case of intrinsic semi-conductors, Fermi level lies in the middle of the energy gap indicating equal concentration of free electrons and holes.

When a donor type impurity (N-type) is added to the material the addition of donor impurity greatly increases the no. of conduction electrons. Hence concentration of electrons in a conduction band is increased and exceeds to the concentration of holes in valence band because of these fermi-level shifts upwards towards the bottom of the conduction band as shown in fig (1) and (2).

In P-type

The same kind of arguments leads to the conclusion that if most moved to the center of forbidden energy gap closer to the valence band for a p-type extrinsic semi-conductor. Since the change of concentration of holes in valence band is more than the concentration of electron in conduction band. Fermi-level shifts nearer to the valence band.

In N-type,

Now taking log on both sides we get,

$$\log_e N_D = \log_e (n_c e^{-(E_C - E_F)/kT})$$

$$\frac{n_c}{n} = P(E_V)$$

$$\text{or, } \log_e N_D = \log_e n_c + \log e^{-(E_C - E_F)/kT}$$

$$\frac{n_c}{n} = 1 + e^{\frac{E_C - E_F}{kT}}$$

$$\text{or, } \log_e N_D = \log_e n_c - \frac{(E_C - E_F)}{kT}$$

$$\text{or, } \frac{N_D}{n} = n_c + n_c e^{\frac{E_C - E_F}{kT}}$$

$$\text{or, } \frac{E_C - E_F}{kT} = \log_e \frac{n_c}{N_D}$$

$$\therefore \log_e \frac{N_D}{n} = \frac{E_C - E_F}{kT}$$

$$\therefore E_F = E_C - kT \log_e \frac{n_c}{N_D}$$

$$\text{Now, } \frac{n_V}{n} = P(E_V)$$

$$\frac{n_V}{N_A} = 1 + e^{\frac{E_V - E_F}{kT}}$$

$$E_F = E_V + kT \log_e \frac{n_V}{N_A}$$

$$\therefore \log_e \frac{N_A}{n} = \frac{E_F - E_V}{kT}$$

$$\therefore E_F = E_V + kT \log_e \frac{N_A}{n}$$

- Q. In an N-type semi-conductor, the fermi-level lies 0.3eV below the conduction band at 20°C. If the temperature is increased to 55°C. Find the new position of fermi-level.

Soln/

Given,

$$(E_C - E_F) = 0.3 \text{ eV}$$

We know that,

$$E_C - E_F = kT \log_e \frac{n_c}{N_D}$$

At 20°C, $kT = 0.025 \text{ eV}$

At 55°C, $kT = 0.034 \text{ eV}$

$$(n_e)^9 = \frac{300}{N_D}$$

$$T = 24 + 273k = 29300k$$

$$\therefore k \cdot \log \frac{n_e}{N_D} = \frac{0.3}{29300} \quad \text{--- (1)}$$

Second case,

$$T = 65 + 273 = 328k$$

Now,

$$(E_D - E_F) = ?$$

Then,

$$(n_e)^9 = E_D - E_F = kT \log \frac{n_e}{N_D}$$

$$\frac{1}{(n_e)^9} = \frac{N_D}{n_e}$$

$$E_D - E_F = 0.3 \times 328 = 98$$

$$\frac{1}{(n_e)^9} = \frac{N_D}{n_e}$$

$$\therefore E_D - E_F = 0.328 \text{ eV} \quad \text{Ans.}$$

Note :-

For barrier potential,

$$V_0 = kT \log \frac{N_D N_A}{n_i^2}$$

$$V_0 = (kT)$$

Where, kT = Intrinsic concentration

N_D = concentration of donor impurities.

N_A = " " " acceptor "

A. A Ge diode has each of the acceptor & donor impurities of concentration $9.5 \times 10^{14} \text{ /cm}^3$ assume $n_i = 2.5 \times 10^{13} \text{ /cm}^3$. At room temperature of 300K, calculate the value of potential energy barrier. Given that Boltzmann constant (k) = $8.6 \times 10^{-5} \text{ ev/K}$

Ans 21

$$N_A = 9.5 \times 10^{14} \text{ /cm}^3$$

$$n_i = 2.5 \times 10^{13} \text{ /cm}^3$$

$$T = 300\text{K}$$

$$V_0 = ?$$

$$k = 8.6 \times 10^{-5} \text{ ev/K}$$

We know that,

$$V_0 = kT \log_e \frac{N_D N_A}{n_i^2}$$

$$= 8.6 \times 10^{-5} \times 300 \log_e \frac{N_D + 9.5 \times 10^{14}}{(2.5 \times 10^{13})^2}$$

$$= 0.081 \text{ ev}$$

Ans.,

PN - Junction

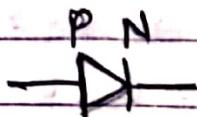


fig: symbol of diode

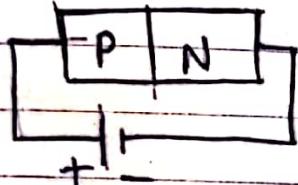


fig: P-N jxn
under F.B.

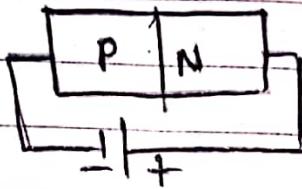


fig: P-N jxn
under R.B.

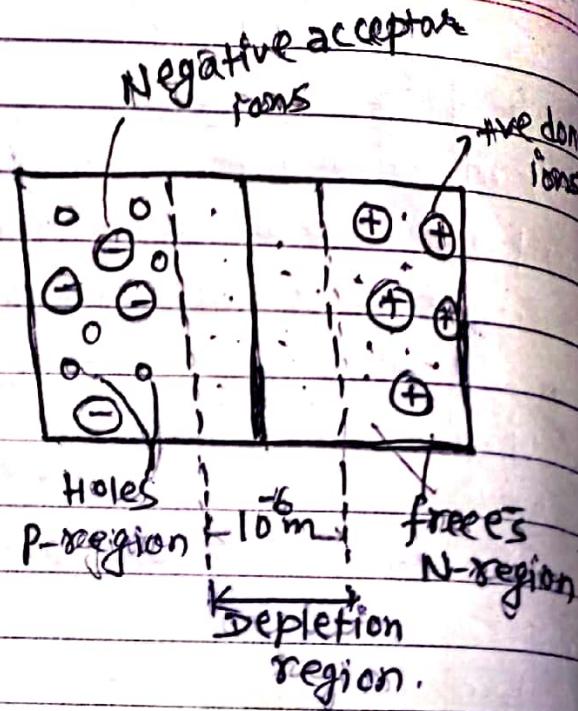


Fig: formation of PN junction

When a piece of P-type material is ~~slightly~~ joined to a piece of N-type material, P-N junction is formed. Such a P-N junction makes a very useful device and is called a semiconductor diode. The plane dividing the two zones is called a junction. A P-N junction cannot be made by simply pushing the two pieces together. Special fabrication (joining) techniques are needed to form a P-N jxn. The various methods of fabrication of P-N junctions are growing and alloying allowing techniques. The small region around the jxn where the charges diffuse is called depletion layer and the potential developed across the depletion layer is called barrier potential.

P-N junction with no external voltage. The P-region has holes and negatively charged impurity ions. The N-region has free electrons and positively charged impurity ions. Holes and electrons are mobile charges but ions are ~~mobile~~ immobile charges.

As soon as the P-N junction is formed, the following processes are initiated.

(1) Holes from the P-region diffuse into the N-region. They combine with free electrons in the N-region.

(2) Free electrons from N-region diffuse into the P-region.

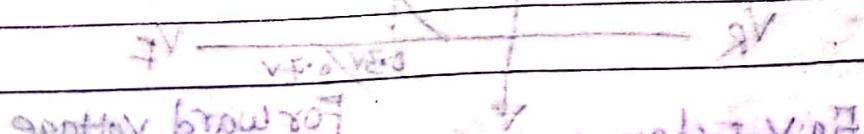
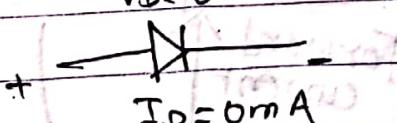
These electrons combined with the holes.

(3) The diffusion of holes (from P-to N-region) and electrons (from N-to P-region) takes place due to thermal energy with which they move randomly and also because of difference in their concentrations in the two regions.

Note:

In the absence of an applied voltage, the net flow of charge in any one direction for a semiconductor is zero.

$$\text{i.e. } V_D = 0$$



Forward Biasing

In this circuit arrangement, the holes on the p-side being +vely charged particles are repel from the biased terminal and driven towards the junction. Similarly, the electrons on the n-side are repelled from the -ve biased terminal and driven towards the jxn. The result is that the depletion layer is reduced in width & the barrier potential is also reduced.

If the applied biased voltage is increased from zero, the barrier potential gets progressively smaller and smaller until it effectively disappears and charge carriers can easily flow across the junction. Electrons from n-side are then attracted towards the positive biased terminal and holes from their p-side flow across the negative biased terminal on the n-side. Thus majority carrier current flows since the barrier potential energy is very small (0.3V for Ge, 0.7V for Si). Therefore, a small forward voltage is sufficient to eliminate the barrier completely. Once barrier is eliminated by the application of forward voltage, jxn resistance becomes almost zero, and the low resistance path is established in the entire circuit. The current called, the forward current flows in the circuit.

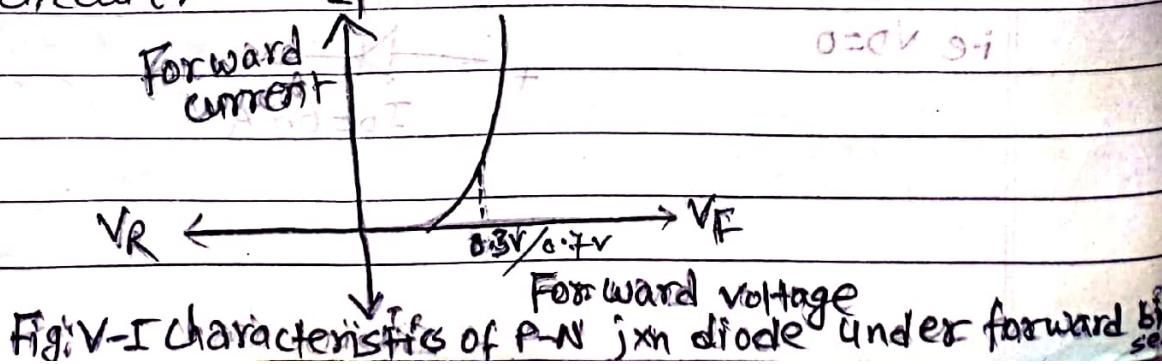
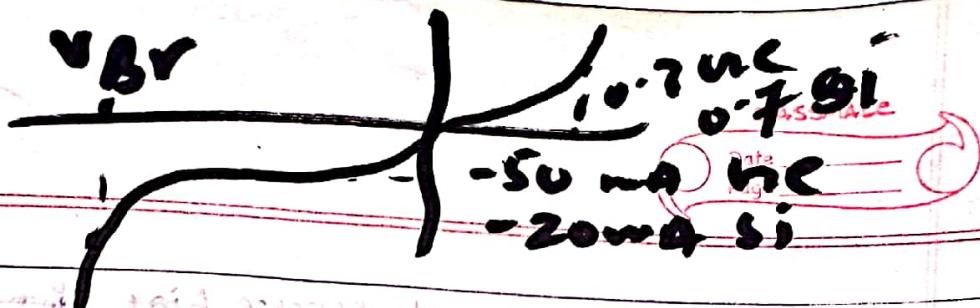


Fig: V-I characteristics of P-N jxn diode under forward bias



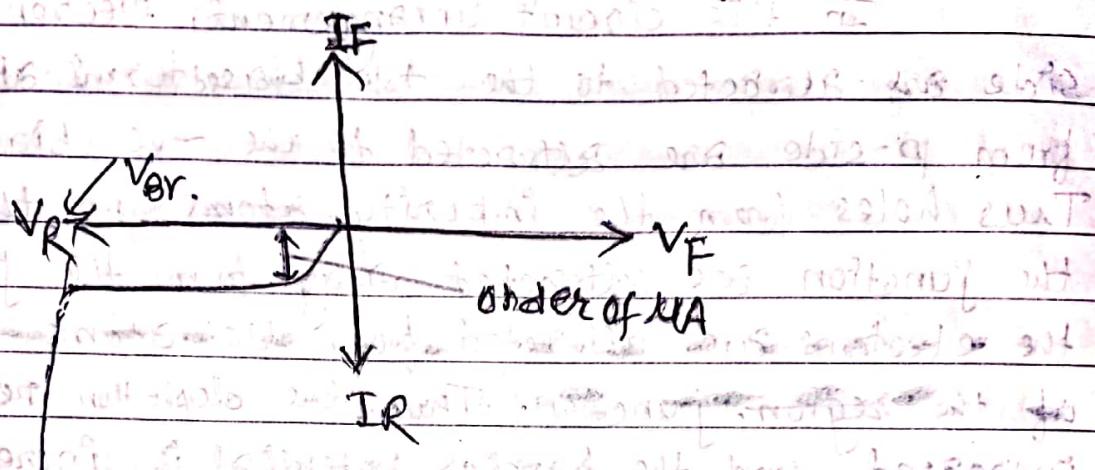
Reverse bias

In this circuit arrangement, electrons from the N-side are attracted to the +ve biased terminal and holes from P-side are attracted to the -ve biased terminal. Thus holes from the impurity atoms on the P-side of the junction are attracted away from the junction and the electrons are attracted from the atoms on the N-side of the junction. Thus, the depletion region layer is increased and the barrier potential is increased. With the increase in barrier potential, there is no possibility of majority carrier current flow across the junction. Thus, the PN-junction is in non-conductive state.

(a) In brief, it can be said that when the PN-junction is reversed biased;

1. barrier potential is increased and width of the depletion layer is also increased.
2. the junction offers high resistance caused the reverse resistance to the flow of current.
3. being of high resistance path, very small current caused the reverse leakage current flow through the circuit in the order of μA .

→ V-I characteristic of reverse bias junction diodes



→ Ideal Diode

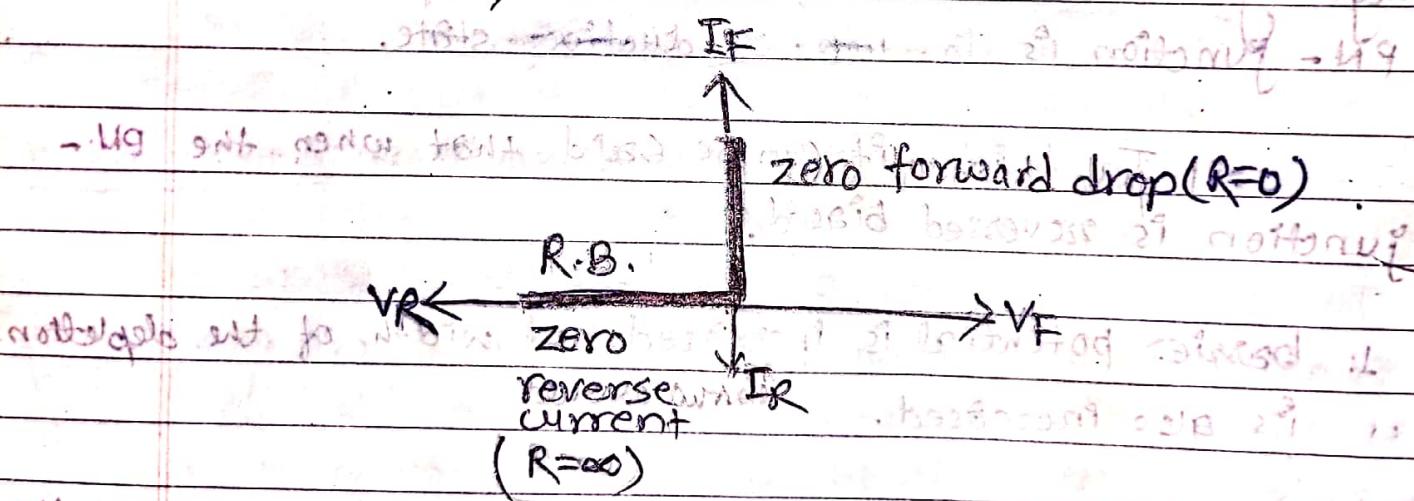
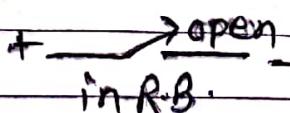
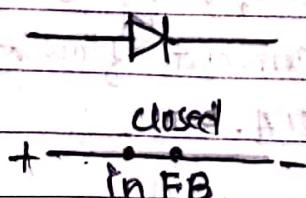


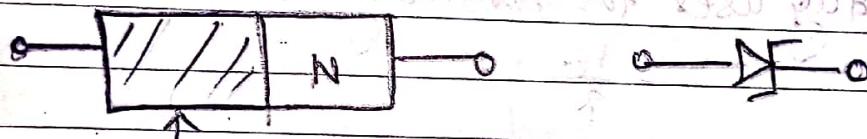
fig: Ideal diode characteristics



It is a two terminal devices and permits only unidirectional conduction. It conducts well in forward direction and poorly in the reverse direction. So an ideal diode is,

1) which behaves as a perfect conductor when forward bias

2) which behaves as a perfect insulator when reverse bias.



Metal

Symbol of Schottky diode

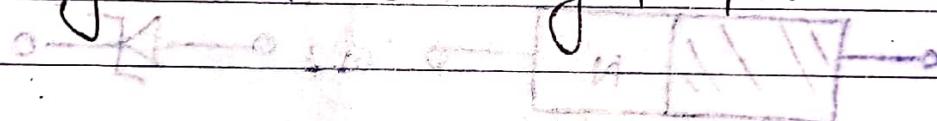
It is a metal-semiconductor junction diode with no depletion layer. It uses a metal (like, gold, platinum) on the side of the junction and usually an N-type doped silicon semiconductor on the other side. It is also called Schottky barrier diode or hot carrier diode.

When the diode is forward biased, conduction electrons on the N-side gain enough energy to cross the junction and enter into the metal. Since, these electrons plough into the metal with very large energy; they are commonly called hot carriers. i.e. why this type of diode is often referred as hot carrier diode.

Features of Schottky diode

It is unipolar device; it has electrons as majority carriers. An ordinary P-N junction diode is a bipolar device because it has both electrons and holes as majority carriers.

Since no holes are available in the metal, there is no depletion layer or stored charges. Hence, Schottky diode can switch off faster than a bipolar diode. Hence, it generally uses for switching purpose.



Practice Questions

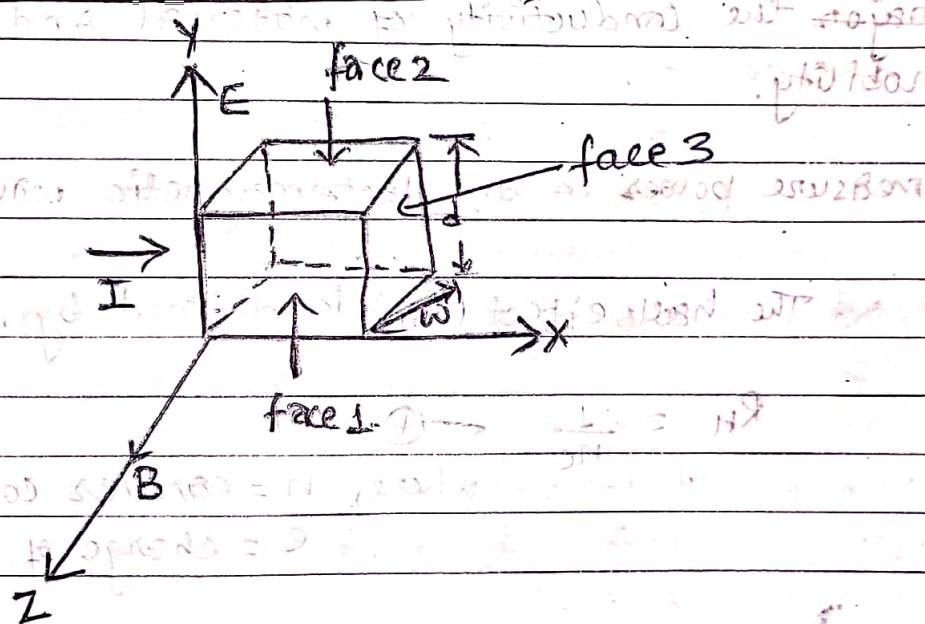
Q.1. For silicon the intrinsic concentration is approximately 10^{16} carriers/m³. If an impurity concentration of 10^{12} donor atoms/m³ is doped, determine the electron and hole concentration.

Q.2. A silicon (intrinsic carrier concentration is 1×10^{16} m⁻³) is doped with 8×10^{22} Aluminum atoms/m³ and 1.02×10^{22} Arsenic atoms/m³. Determine the minority carrier concentration.

Q.3. A sample of pure germanium atoms is 4.2×10^{28} atoms/m³. Determine the hole density.

Q.4 A sample of pure germanium at room temperature has a density of carrier at $2.5 \times 10^{19} \text{ m}^{-3}$. It is doped with donor impurity atoms at the rate of 1 impurity atom for 10^8 atoms of germanium. The density of germanium atom is $4.2 \times 10^{28} \text{ atoms/m}^3$. Determine the hole density.

Hall effect and its application



When a specimen (sample) (metal or semi-conductor) is placed in a transverse magnetic field and a direct current is passed through it then electric field is induced across its edges in the perpendicular direction of current as well as the magnetic field. The phenomenon is called the Hall effect.

Application of Hall effect

Hall effect may be used to:

- 1) determine whether the semi-conductor is of N-type or P-type.
- 2) determine the carrier (electron or hole) concentration.
- 3) measure the conductivity of material and then compute mobility.
- 4) measure power in an electromagnetic wave.

The Hall effect (R_H) is defined by,

$$R_H = \frac{1}{ne} \quad \text{--- (1)}$$

where, n = carrier concentration

e = charge of an electron.

Q. A single carrier holes in a silicon sample as $2.05 \times 10^{22} \text{ m}^{-3}$. Calculate its Hall coefficient (R_H).

Given, $n = 2.05 \times 10^{22} \text{ m}^{-3}$
 $e = 1.60 \times 10^{-19} \text{ C}$

We know that,

$$\therefore R_H = \frac{1}{ne} = \frac{1}{2.05 \times 10^{22} \times 1.60 \times 10^{-19}} = 4.60 \times 10^{-4} \text{ m}^3$$

The hall coefficient can also be defined by,

$$R_H = \frac{U}{S}; \text{ where, } U = \text{mobility} \text{ &} \\ S = \text{conductivity of the material}$$

from eqn ⑩ & ⑪,

$$\frac{1}{ne} = \frac{U}{S}$$

$$\therefore S = neU$$

Q. Resistivity of a sample semiconductor is 9 m.m.m. . Its holes have mobility of $0.03 \text{ m}^2/\text{Vs}$. Calculate the value of hall coefficient of the sample.

~~point~~

Given,

$$\therefore S = \frac{1}{\rho} = \frac{1}{9 \times 10^{-3}} \Omega^{-1} \text{ m}^{-1} = 0.11 \times 10^3 \Omega^{-1} \text{ m}^{-1}$$

0.27

$$U = 0.03 \text{ m}^2/\text{Vs}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

we know that,

$$R_H = \frac{0.03}{0.11 \times 10^3}$$

$$\therefore R_H = 2.72 \times 10^{14} \text{ m}^3/\text{C}$$

Q. A sample has the carrier concentration of $8.08 \times 10^{18} \text{ m}^{-3}$ & have the mobility of $0.023 \text{ m}^2/\text{Vs}$. Calculate the conductivity of the given sample.

Given,

$$n = 8.08 \times 10^{18} \text{ m}^{-3}$$

$$\mu = 0.023 \text{ m}^2/\text{Vs}$$

$$\sigma = ?$$

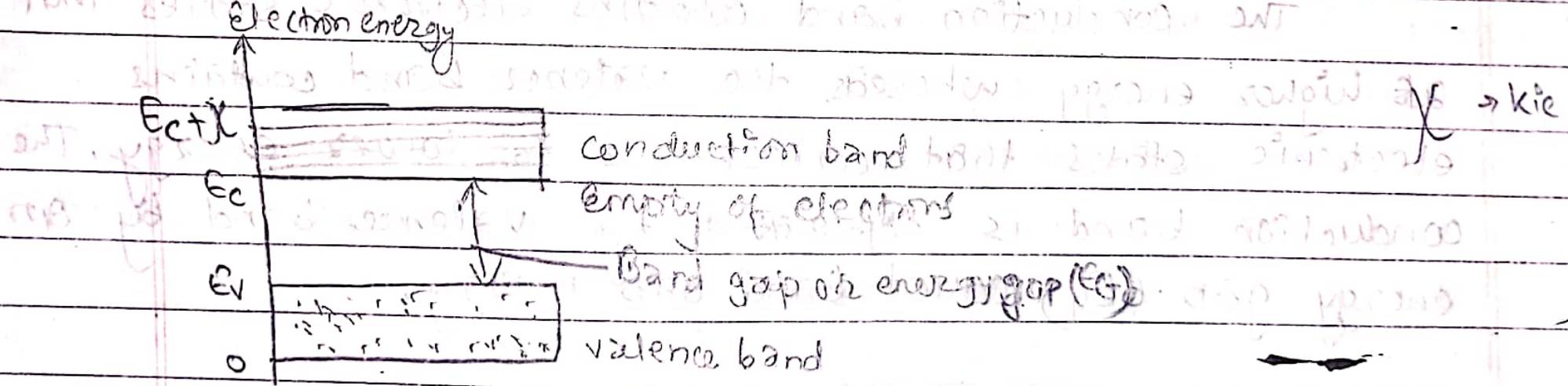
We know that,

$$\sigma = \mu e n$$

$$= 0.023 \times 1.6 \times 10^{19} \times 8.08 \times 10^{18}$$

$$\therefore \sigma = 0.01152 \text{ S/m}$$

Band structure of group IV materials.



Waves
→ high sound to
higher level

Date _____
Page _____

Semiconductors in the present day world are one of the most important materials due to their wide-spread-use. Almost all the modern engineering creations exhibit semiconductor devices for their effective functioning. 20th century has modern and phenomenal growth as well as advancement in semiconductor technology.

The group IV materials in Mendeleev's periodic table such as silicon, and germanium has four electron in the outermost orbit. These electrons are called valence electrons. To fulfill the outermost orbit, each atom shares an electron with other atom and the result is the covalent bond. Not all the group IV elements are semiconductors in the nature silicon and germanium in particular are semi-conductors by their own fault characteristics. They are commonly called intrinsic wave semiconductors.

The conduction band contains electronic states that at higher energy whereas the valence band contains electronic states that corresponds to lower energy. The conduction band is separated by valence band by an energy gap (E_g) caused band gap energy.

The width of the conduction band is caused the electron affinity and denoted by χ . The energy level, E_c represents the bottom of the conduction band

$$P = \frac{n_i^2}{N_A - N_D} \rightarrow N\text{-type}$$

$$n = n_i^2 \rightarrow P\text{-type}$$

classmate

Date _____
Page _____

and E_V represents the top of the valence band.

~~Tip~~ \rightarrow Compensation doping

As we have observed in the previous discussions, the properties of semiconductors are changed by doping with either trivalent or pentavalent impurities. The level of doping can be different so as to obtain different properties and operating characteristics of the resultant semiconductor device.

It is interesting to see what happens when both the trivalent & pentavalent impurities are added to silicon.

Adding trivalent impurities will increase the hole concentration in semiconductor, whereas by adding pentavalent impurities to the same will compensate further for the increase in hole concentration and decrease in electron concentration. Assuming all donor impurities and acceptor impurities are ionized at room temperature, the effective hole concentration and electron concentration are calculated on the basis on which occurs impurities concentration is greater and N_A and N_D are acceptor concentration and donor concentration respectively and N_D is greater than N_A , due to holes due to acceptor doping will be recombined with the electrons due to donor doping. So the electron concentration is,

$$n = N_D - N_A$$

$$\therefore P = \frac{n_i^2}{n} = \frac{n_i^2}{N_D - N_A} \quad \text{--- (1)}$$

Similarly, when $N_A > N_D$, the electrons due to donor doping recombined with holes due to acceptor doping and the resultant concentration are,

$$n = N_A - N_D$$

$$p = n^2 \quad \text{--- (ii)}$$

where, n^2 = intrinsic concentration of the semi-conductor

Boltzmann's classical statistics

Temperature is an example of a macroscopic property that describes the thermal energy of a system of particles. Not all the particles of the system will have the same energy. The total energy of the system (if isolated) most remains constant. This total energy must be distributed internally with some probability distribution among various microstates.

The appropriate probability distribution is the Maxwell-Boltzmann distribution function. It gives the probability that a single particle may have energy if it comes from a system of particles characterised by temperature.

$$\text{i.e. } P(E) = A e^{-E/kT}$$

where, $P(E)$ = probability for one atom to occupy the energy state.

E = particular energy

T = given temperature

A = constant variable

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

Interaction

In equilibrium condition,

$$P(E_1) \cdot P(E_2) = P(E_3) \cdot P(E_4) \quad \text{--- (I)}$$

Now, from the law of conservation of energy we have,

$$E_1 + E_2 = E_3 + E_4 \quad \text{--- (II)}$$

Thus, we required to find $P(E)$ which is satisfied for both the equation (I) & (II).

Using the distribution of energy among the gas molecules we can guess that, the solution of eqn (I) & (II) will be,

$$P(E) = Ae^{-\frac{E}{kT}}$$

22. Calculate the resistance of pure silicon cube crystal of 1 cm^3

at room temperature. What will be the resistance of the cube

when it is doped with 1 Arsenic in 10^9 silicon atoms and 1
boron atoms per billion silicon atoms. Given that the atomic
concentration of silicon is $5 \times 10^{22}/\text{cm}^3$, intrinsic concentration
 $1.45 \times 10^{10}/\text{cm}^3$ and the mobilities are $1350\text{ cm}^2/\text{Vs}$ and $450\text{ cm}^2/\text{Vs}$.

Soln

$N_D = e \Rightarrow N_D = N_i + n$ type

or $N_D = N_i + n$ and $N_A = N_D - n$ $\Rightarrow N_A = N_i - n$ p-type

We know that, $R = \rho \frac{l}{A}$

$$R = \rho \frac{l}{A}$$

$$\text{or } R = \rho \cdot \left(\frac{l}{A} \right)$$

$$\text{or, } R = \frac{l}{\rho A} = \frac{l}{n i e (\mu_e + \mu_h)}$$

$$\text{or, } R = \frac{l}{1.45 \times 10^{10} \times 1.6 \times 10^{-19} (1350 + 450)}$$

$$\text{Ans } 2.39 \times 10^5 \Omega$$

Now,

$$N_D = \frac{1}{10^9} \times \text{Atomic concentration of Si} (N_{Si})$$

$$= \frac{5 \times 10^{22}}{10^9} = 5 \times 10^{13} / \text{cm}^3$$

At room temperature, since all the donor concentrations are ionised so the concentration of electron is,

$$p = n_e^2 = (1.45 \times 10^{10})^2 = 2.025 \times 10^{20} / \text{cm}^3$$

Here, we can neglect the value of concentration of holes in comparison to the concentration of electron.

So,

$$R = \frac{\rho l}{A} = \frac{1}{\sigma} = \frac{1}{N_D e l}$$

$$= \frac{1}{5 \times 10^3 \times 1.6 \times 10^{-19} \times 1350}$$

$$= 92.6 \Omega$$

So, there is drastic fall in resistance of the cubic crystal when it is doped with 1 Arsenic atom in 10^9 silicon atoms.

Again,

$$N_A = N_D \times \frac{1}{10^9} = \frac{5 \times 10^{22}}{10^9} = 5 \times 10^{13} / \text{cm}^3$$

At room temperature,

$$n \propto N_A.$$

so,

$$R = \frac{1}{N_A e L h}$$

$$= \frac{1}{5 \times 10^{13} \times 1.6 \times 10^{-19} \times 4 \times 10^{-15}}$$

$$= 277.7 \Omega$$

From this example we can see the significance of donor doping and acceptor doping, as for the same doping concentration the resistance sample is different if the resulting sample is different and donor doping is more effective than acceptor doping.

(Q.) Calculate the barrier potential across the junction formed by joining silicon doped with 10^{17} donor atoms/ cm^3 and with 10^{16} acceptor atoms/ cm^3 at room temperature. The intrinsic concentration is given by $1.45 \times 10^{10} / \text{cm}^3$.

Ans

Given,

$$n_i = \sqrt{N_D - N_A} = \sqrt{10^{17} - 10^{16}} = 1.45 \times 10^{10} / \text{cm}^3$$

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

$$T = 800 \text{ K}$$

We know that,

$$V_0 = \frac{kT \log N_A N_D}{h^2}$$

$$= 1.38 \times 10^{-23} \times 200 \log \left(\frac{10^{17} \times 10^{16}}{(1.45 \times 10^{10})^2} \right)$$

$$= 2.177 \times 10^{-19} V$$

~~Step 1~~

Effective mass of an electron.

We know that the electron has

a well defined mass and the mass of electron changes with in the crystal and appears in general differential formed when the energy changes; referred to as

the effective mass and

generally called the effective mass of an electron (m^*)

For a free-particle,

$$E = \frac{1}{2} mv^2 = \frac{m^2 v^2}{2m} = \frac{p^2}{2m} \quad \text{--- (1)}$$

from De-Broglie equation,

$$\gamma = \frac{h}{mv}$$

$$\text{or, } \frac{2\pi}{\lambda} = \frac{h}{mv}$$

where, $k = \text{wave number} = \frac{2\pi}{\lambda}$

$$\text{or, } V = \frac{hk}{2\pi m}$$

$$\text{or, } V_m = \frac{hk}{2\pi} \quad \text{--- (1)}$$

Now, from eqⁿ ① & ⑦;

$$E = \frac{\left(\frac{hk}{2\pi}\right)^2}{2m}$$

$$\therefore E = \frac{h^2 k^2}{8\pi^2 m} \quad \text{--- (2)}$$

Then, differentiating eqⁿ (2), we get;

$$\frac{dE}{dk} = \frac{2h^2 k}{8\pi^2 m}$$

$$\text{or, } \frac{dE}{dk} = \frac{h^2 k}{m} \quad \left[\because 1 \text{ being small quantity can be neglected} \right]$$

$$\text{Or, } \frac{1}{h} \frac{dE}{dk} = \frac{hk}{m}$$

Since, the velocity of electron moving in a solid is proportional to the slope of E-k curve

$$\therefore \frac{1}{h} \frac{dE}{dk} = \frac{hk}{m} \propto V \quad \rightarrow \text{(iv)}$$

Now,

Acceleration (a) is given by,

$$a = \frac{dv}{dt}$$

Then, taking RHS of equation (iv), we get,

$$a = \frac{h}{m} \frac{dk}{dt} \quad \rightarrow \text{(v)}$$

Now, taking LHS of equation (iv),

$$a = \frac{d}{dt} \left(\frac{1}{h} \frac{dE}{dk} \right) = \frac{1}{h} \frac{d^2E}{dk^2} \cdot \frac{dk}{dt} \rightarrow \text{(vi)}$$

Now, from eqⁿ (v) & (vi), we get;

$$\frac{h}{m} \frac{dk}{dt} = \frac{1}{h} \frac{d^2E}{dk^2} \cdot \frac{dk}{dt}$$

$$\text{or, } \frac{h}{m} = \frac{1}{h} \cdot \frac{d^2 E}{dk^2}$$

$$\Rightarrow m = \frac{h^2}{\frac{d^2 E}{dk^2}}$$

$$\Rightarrow m^* = \frac{h^2}{d^2 E / dk^2}$$

which, m^* = effective mass of an electron.
which is the required expression.

(*) Metal - Metal Contact:

When two metals having different work functions are brought together, potential difference developed at the junction called Contact Potential.

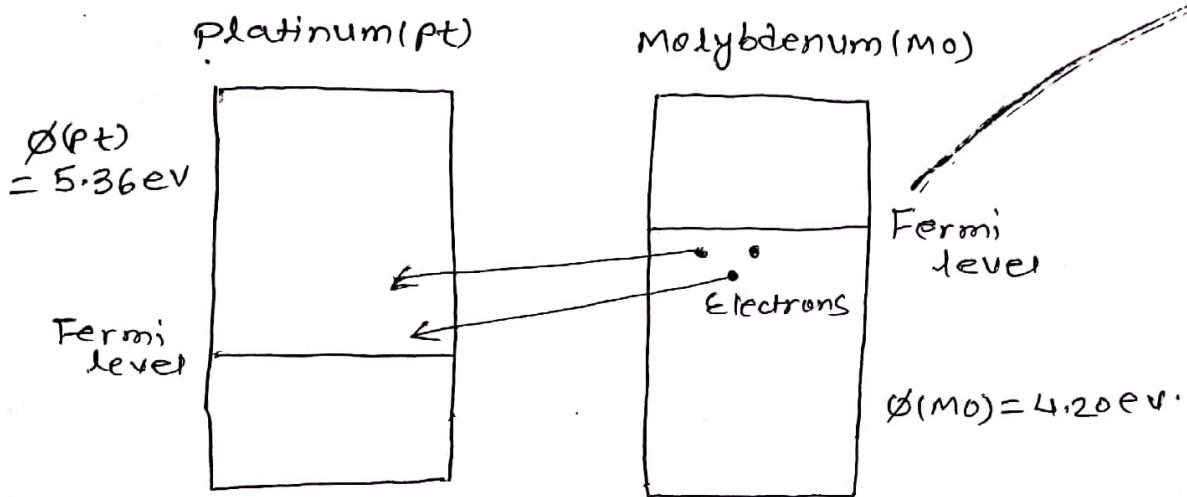


fig:- Exchange of electrons between two dissimilar metals when brought together.

Suppose that two metals, platinum(pt) with work function 5.36 eV. and molybdenum(mo) with the work function 4.20 eV. Since the fermi level is higher in mo (due to smaller ϕ) , the electrons in Mo are more energetic ; therefore they go over to the platinum surface where there are empty states at lower energies which they can occupy . A contact voltage develops at a junction between pt and Mo . The electron transfer from Mo to pt continues until the system which is equilibrium . The transfer of electrons from Mo to pt continues until the two fermi levels are lined up ;

//

L.

The Contact voltage (potential)

$$\begin{aligned} &= \phi(\text{Pt}) - \phi(\text{Mo}) \\ &= 5.36 \text{ eV} - 4.20 \text{ eV} \\ &= 1.16 \text{ eV} \end{aligned}$$

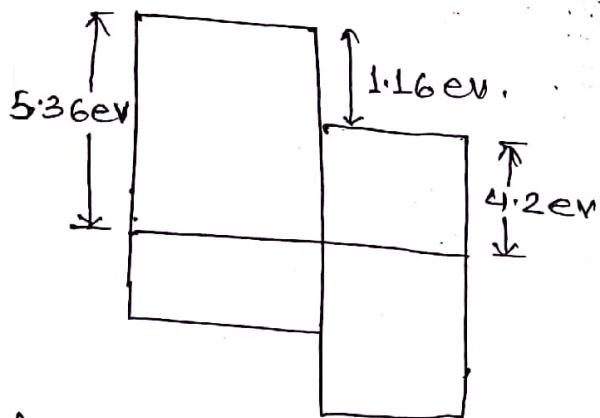


fig: Resulting condition of Pt & Mo after contacting.

(*) Work function (ϕ)

In solid state physics, the work function is the minimum thermodynamic work (i.e. energy) needed to remove an electron from a solid to a point in the vacuum immediately outside the solid surface. Here "immediately" means that the final electron position is far from the surface on the atomic scale, but still too close to the solid to be influenced by ambient electric fields in the vacuum. The work function is not a characteristic of a bulk material, but rather a property of the surface of the material (depending on crystal face and contamination).

Note:- Different materials have their different value of work function,

//.

(*) The Seebeck effect:-

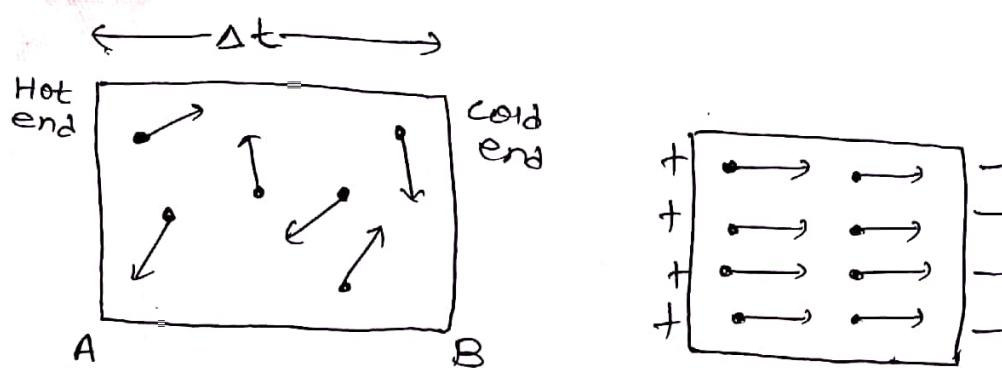


fig:- Seebeck effect within a Conductor.

When a conductor is heated at one end and cooled at the other end, the electrons in hot regions become more energetic and therefore have higher velocities than in the cold region. So there is net diffusion of electrons from the hot end to the cold end; which leaves behind exposed positive metal ions in the hot region and accumulates electrons in the cold region. A voltage develops between the hot and cold ends, with the hot end at positive (+ve) potential.

Hence, the potential difference developed across the rod of the conductor due to the temperature difference between the two ends is called the Seebeck effect.

Mathematically,

$$S = \frac{dV}{dT}$$

Where;

S = Seebeck coefficient

dV = Developed potential.

dT = Change in temperature.

//

3.

(*) Thermo couples:-

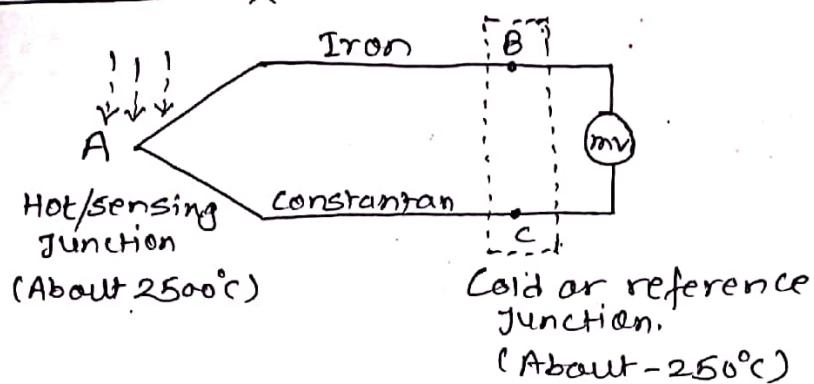


fig:- Thermocouple formed by Iron and Constantan

It consists of two dissimilar metal wires joined at one end as shown in the above figure. The end A is known as hot or sensing end. The other end is known as cold or reference end because it is kept at the lower but constant temperature (reference temp^r). When end A is heated then EMF in mv is produced between it and the cold ends B & C. The magnitude of this EMF depends on the temp^r difference between the hot and cold junctions. Since cold ends are kept constant temp^r, the mv output is indicative of the room temp^r of the hot junction of A which is kept in touch with the object whose temp^r is being measured.

(*) Applications of Thermocouple

- They are suitable for very low temp^r measurement i.e. in the industry, scientific researches, medical instruments etc.
- In industry, for measurement of temp^r of industrial furnaces.
- For monitoring the temp^r of liquids and gases for storage and while flowing in pipes.

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(*) Thermionic Emission \rightarrow Richardson Dushman

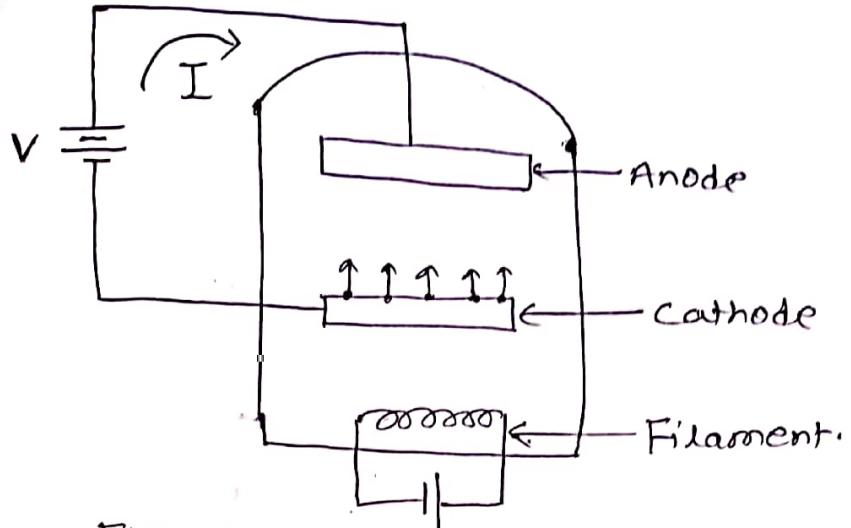


Fig:- Thermionic electron emission
in a vacuum tube.

The process of emission of electron due to heating of metal is called Thermionic emission. When a metal is heated, the electron becomes more energetic. Some of electrons gain sufficiently large energy to leave metal and becomes free. The cathode is heated by a filament or heater and it emits electrons. The battery connected with anode and the cathode to resupply electrons to cathode for emission purpose. The vacuum inside the tube ensures that the electrons do not collide with the air molecules to be dispersed.

When a +ve Voltage is applied to anode w.r.t. to cathode, the ~~electron~~ electric field at cathode helps the thermionic emission process by lowering the potential energy barrier. This field assisted emission is also called Schottky effect.

The current flow within the circuit due to thermionic emission effect is given by,

$$I = B_0 A T^2 \exp\left(-\frac{\phi}{kT}\right)$$

$$\text{or } I = B_0 A T^2 e^{-\frac{\phi}{kT}} \quad \text{--- (1)}$$

The above equation (1) is called the Richardson Dushman equation.

where

I = Generated current (A)

A = Surface area of ~~vacuum~~ tube. (m^2)

B_0 = Constant value. ($A m^{-2} K^{-2}$)

T = Given temperature (K)

ϕ = Boltzmann constant (eV/K)

ϕ = Work function (eV)

Numerical.

- (8) A certain vacuum tube has a cylindrical shape with tungsten as a cathode and which is 4 cm long and 2 mm in diameter. Estimate the current if the tube is operated at $1600^\circ C$. Given constant is $3 \times 10^4 \text{ A m}^{-2} \text{ K}^{-2}$ & $\phi = 2.6 \text{ eV}$.

Soln.

Here,

given,

$$A = 2\pi r h = 2\pi \times 2 \times 10^{-3} \times 4 \times 10^{-2} (\text{m}^2)$$

$$B_0 = 3 \times 10^4 \text{ A m}^{-2} \text{ K}^{-2}$$

$$T = 1600^\circ C = 1873 \text{ K}$$

$$\phi = 2.6 \text{ eV}$$

$$K = 1.38 \times 10^{-23} \text{ J/K} = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} \text{ eV/K}$$

$$I = ?$$

We know that;

From R-D equation,

$$I = B_0 A T^2 e^{-\frac{\phi}{kT}}$$

$$= \dots \text{ (A) (Solve yourself).}$$