

ELE 226.2 Electrical Engineering Materials (2-2-0)

Evaluation:

	Theory	Practical	Total
Sessional	50	-	50
Final	50	-	50
Total	100	-	100

Course Objectives:

The purpose of the course is to provide a basic understanding of the electric and magnetic properties of materials used in electrical and electronics engineering.

Course Contents:

- 1. Theory of Metals** (3 hrs)
 - 1.1. Elementary quantum mechanical ideas
 - 1.2. Free electron theory, Energy well model of a metal and Density of states function
 - 1.3. The Fermi-Dirac distribution functions, Thermionic emission, Work function and The Fermi level at equilibrium, Contact Potential
- 2. Free Electron Theory of Conduction in Metals** (4 hrs)
 - 2.1. Thermal velocity of electrons at equilibrium, Lattice scattering, Mean free time between collisions and Drift velocity of electrons in an electric field
 - 2.2. Diffusion of electrons, Diffusion coefficient, Einstein's relationship between mobility and diffusion coefficients
 - 2.3. Chemical and physical properties of common conduction of materials such as As, Au, Ag, Cu, Al, Mn, N etc.
- 3. Conduction in Liquid and Gases** (2 hrs)
 - 3.1. Ionic conduction in electrolytes
 - 3.2. Electrical conduction in gas arc discharges in electric breakdown
- 4. Dielectric Materials** (4 hrs)
 - 4.1. Macroscopic effects, Polarization, Dielectric constant and Dielectric losses
 - 4.2. Frequency and temperature effects and Dielectric breakdown
 - 4.3. Ferro electricity and piezoelectricity
 - 4.4. Properties of common dielectrics such as glass, Porcelain, Polyethylene, PVC, Nylon, bakelite, rubber, mica, transformer oil etc.
- 5. Magnetic Materials** (5 hrs)

- 5.1. Ferromagnetism, Ferrimagnetisms, Para magnetism
- 5.2. Domain structure, Hysteresis loop, Eddy current losses, Soft magnetic materials
- 5.3. Fe-Si alloys, Ni-Fe alloys, ferrites for high frequency transformers
- 5.4. Square loop materials for magnetic memory, relaxation oscillators, hard magnetic materials such as carbon steels alnico and barium ferrites

6. Semiconducting Materials (8 hrs)

- 6.1. Band structure of group iv materials, Energy gap, density of states function
- 6.2. Fermi-Dirac distribution function
- 6.3. Hole and electron densities in an intrinsic crystal
- 6.4. Effective densities of states, intrinsic concentration, Fermi level of energy at equilibrium
- 6.5. Group iii and group iv impurities, acceptors and donors, p-and n-type materials
- 6.6. Energy band diagrams for uniformly-doped and graded p-and n-type materials
- 6.7. Generation PN, recombination of electrons and holes, concept of lifetime
- 6.8. Mobility and diffusion coefficients for electrons and holes in semiconductors
- 6.9. Transport and continuity equations for electrons and holes, concept of diffusion length, energy band diagram for a p-n junction
- 6.10. Contact potentials, metal-semiconductor contacts

7. Semiconductor Materials Procession (4 hrs)

- 7.1. Crystal growing, doping by solid state diffusion, ion implantation
- 7.2. Oxidation Photolithography, the planar process, metallization, contacts

Text Book:

R.A. Colcaseer And. Dichi-Nagle, *Materials and Devices for Electrical Engineers and Physicists*, McGraw-Hill, New York, 1985.

Reference:

R.C. Jaeger, *Introduction to Microelectronic Fabrication-Volume IV*, Addison-Wesley Publishing Company Inc., 1988.

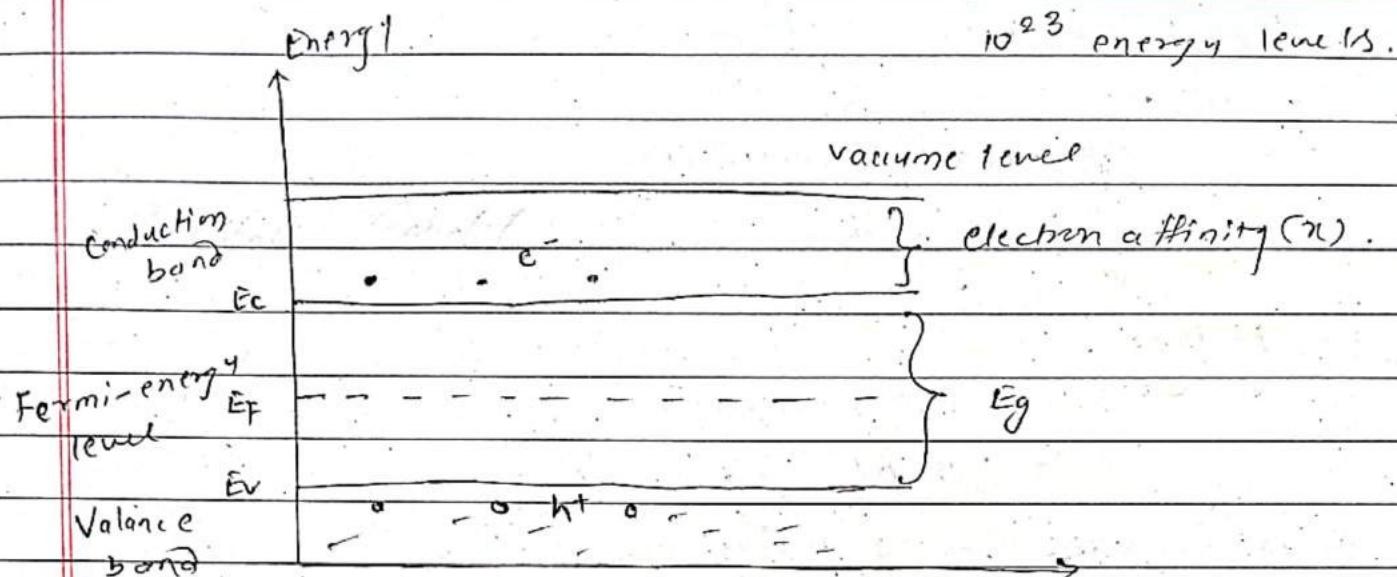
SEMICONDUCTOR MATERIALS

fig. Band Energy diagram.

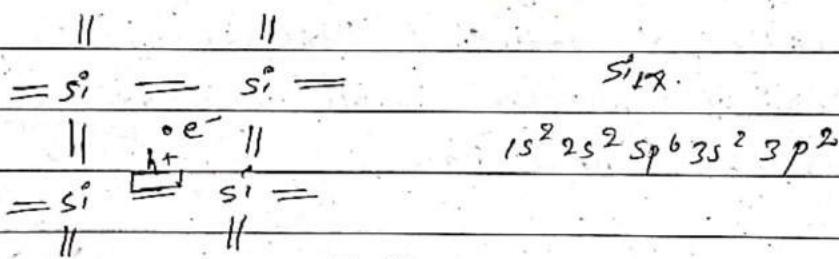


fig. Lattice structure

$n \rightarrow$ no of e^- s

$p \rightarrow$ no of h^+ s

pure / intrinsic semiconductor

$$n = p = n_i$$

$$n \cdot p = n_i^2 \quad \text{called mass law action.}$$

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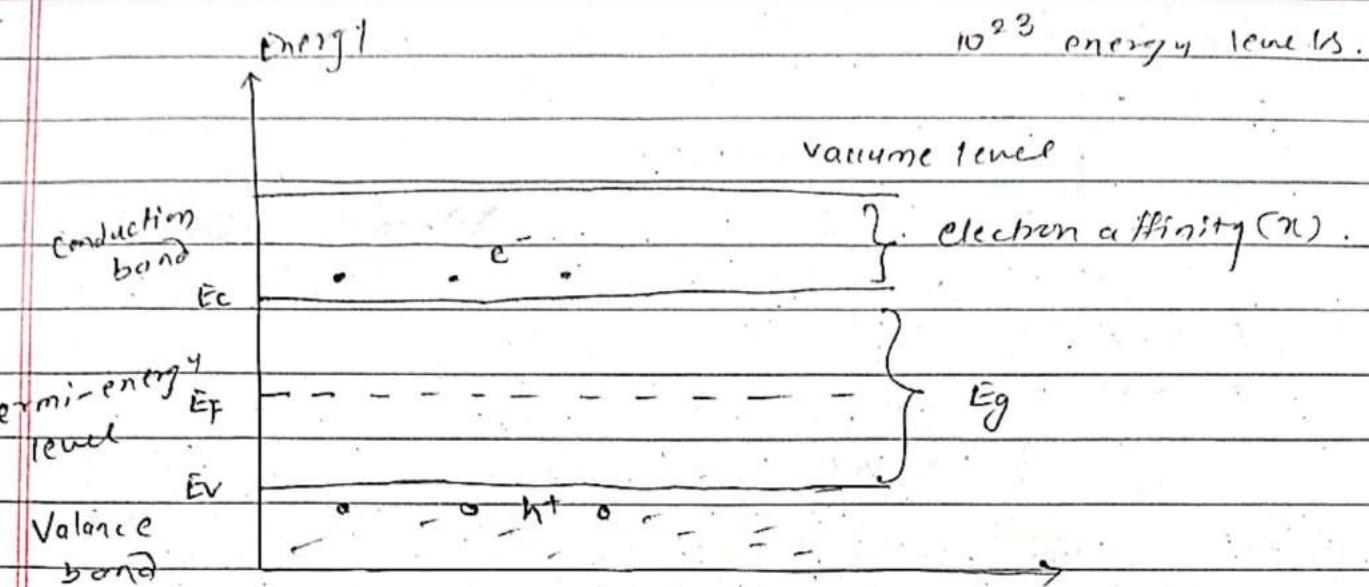


fig. Band Energy diagram.

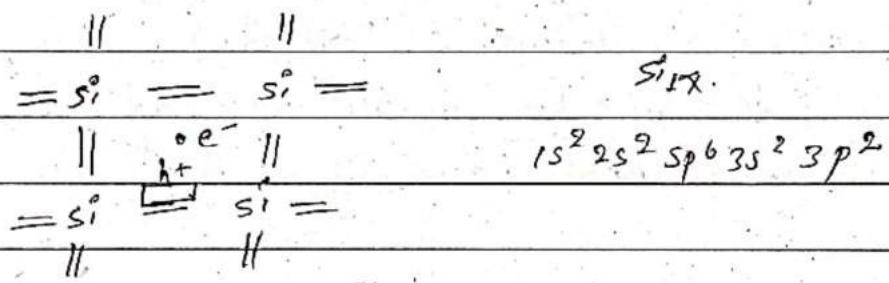


fig. Lattice structure

$n \rightarrow n_0$ of e^-s

$p \Rightarrow \text{no of } h^+$

pure / intrinsic semiconductor

$$n = p = n;$$

$$n \cdot p = n_i^2 \quad \text{called mass law action.}$$

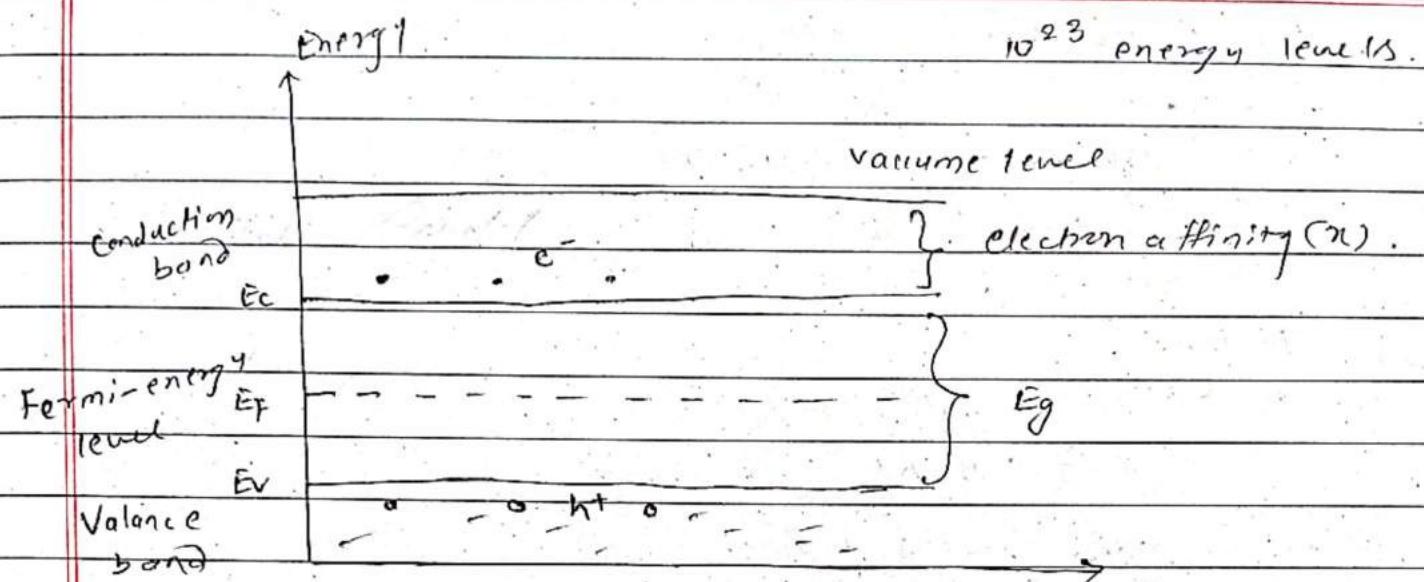
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fig. Band Energy diagram.

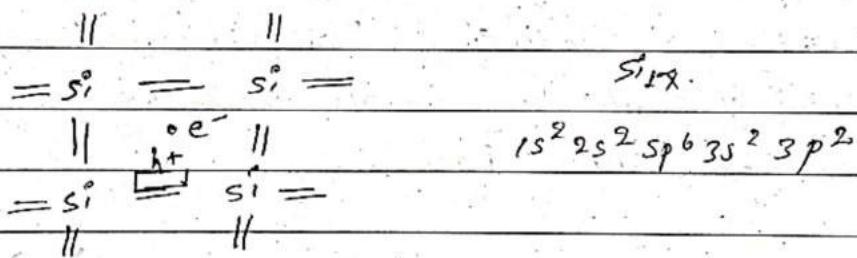


fig. Lattice structure

 $n \rightarrow$ no of e^- s $p \rightarrow$ no of h^+ s

pure / intrinsic semiconductor

$$n = p = n_i$$

$$n \cdot p = n_i^2 \quad \text{called mass law. action.}$$

Impure / Extrinsic SiC

(i) n-type

→ pentavalent impurities

e.g. As, Sb

(ii) p-type

→ trivalent impurities

e.g. B, Al

10^6 Si - atom = 1 doping.

Electron-hole pair generation

① Vibration of lattice / Thermal vibration

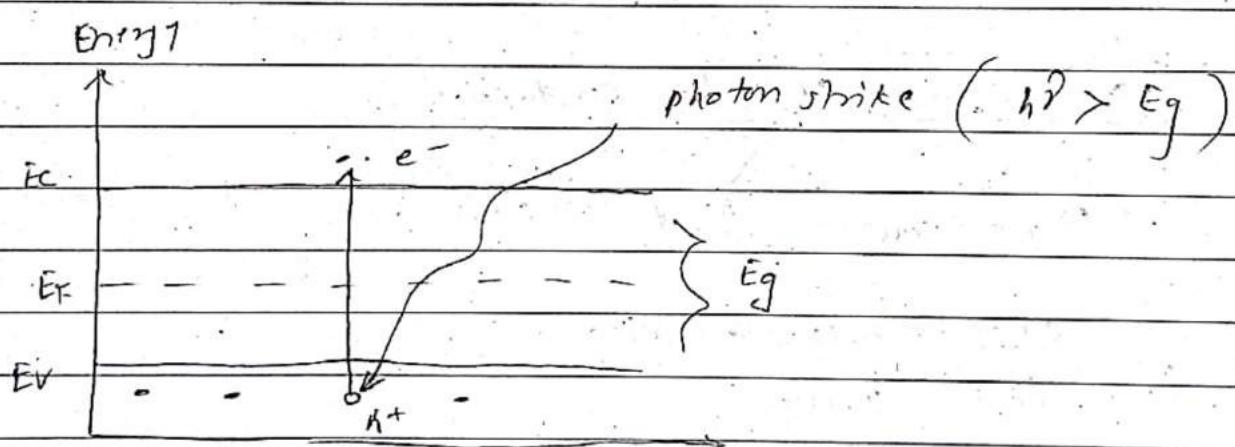
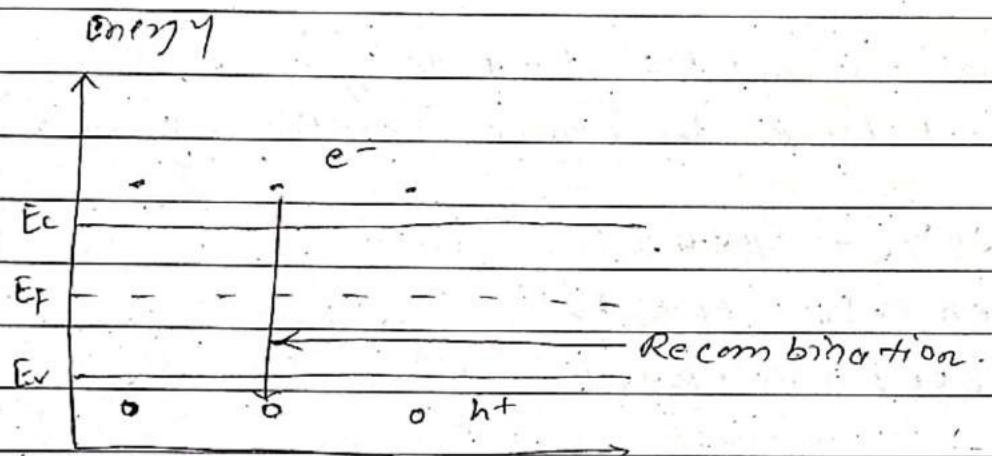
② Incident of photon in SiC material

such that $h\nu > E_g$

- Electron in conduction band can move around the crystal / lattice and contribute to electrical conduction when an electric field is applied such electrons are called free electrons.

- A hole is effectively an empty electronic state in valence bond that behaves as if it were a negative charge particle free to respond to an applied electric field.

- When a free electron in conduction band meets a hole in valence band, this implies that e^- has found an empty state of lower energy and occupies the hole, this is called recombination.



- When an external electric field is applied on a semiconductor, there will be the drifting of electron in the conduction band opposite to the applied field direction.

The drifting velocity of e^- is given by $V_{de} = \mu_e E_x$
 μ_e = mobility of electrons.

Similarly, There is drift of holes and is given by

$$v_{dh} = \mu_h E_x$$

where, μ_h = mobility of holes.

The drifting of e^- s and h^+ s lead to give electrical conduction and hence the current density is given by,

$$\begin{aligned} J &= e n v_{de} + e p v_{dh} \\ &= e n \mu_e E_x + e p \mu_h E_x \\ &= e E_x (n \mu_e + p \mu_h) \end{aligned}$$

$$\frac{J}{E_x} = e n \mu_e + e p \mu_h$$

$$\boxed{\sigma = e n \mu_e + e p \mu_h} - \text{conductivity}$$

no. of e^- s conc. no. of h^+ s conc.

$$\mu = \frac{e t}{m_e} \quad \begin{matrix} \leftarrow \text{Relaxation time} \\ \leftarrow \text{mass of } e^- \end{matrix}$$

- Q. Find the resistance of a cubic pure silicon crystal.
- (i) If this Si crystal is doped with Arsonic ($1 A\text{s}^{-1}$ in 10^9 Si). what will be the change in its resistance?
- (iii) If Si crystal is doped with Boron ($1 B\text{s}^{-1}$ in 10^9 Si). what will be the new conc. resistance?

Take,

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

$$\text{Intrinsic concentration } (n_i) = 1 \times 10^{10} \text{ cm}^{-3}$$

$$\text{mobility of } e^- (m_e) = 1350 \text{ cm}^2 V^{-1} s^{-1}$$

$$\text{mobility of } h^+ (m_h) = 450 \text{ cm}^2 V^{-1} s^{-1}$$

$$G = \frac{1}{g}$$

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

$$g = \frac{RA}{l}$$

$$\sigma = \frac{l}{RA}$$

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

solution

For pure Si ,

$$\text{let } l = 1 \text{ cm}, A = 1 \text{ cm}^2$$

$$R = \frac{l}{\sigma A} \quad \textcircled{1}$$

$$(n = p)$$

$$\sigma = en m_e + ep m_h$$

$$= 1.6 \times 10^{-19} \times 1 \times 10^{10} (1350 + 950)$$

$$= 2.88 \times 10^{-6} \text{ A}^{-1} \text{ cm}^{-1}$$

$$\text{from } \textcircled{1}, R = 347.2 \text{ A}.$$

(ii) 1 As atom in 10^9 Si atoms

$$1 e^- \rightarrow 10^9 Si$$

$$\frac{5 \times 10^{22}}{10^9} e^- \rightarrow 5 \times 10^{22} Si$$

$$\Rightarrow 5 \times 10^{13} \text{ cm}^{-3}$$

$$n = N_d = 5 \times 10^{13} \text{ cm}^{-3}$$

$$\Rightarrow P = \frac{n_i^2}{n}$$

$$= \frac{(10^{10})^2}{5 \times 10^{13}}$$

$$= 2 \times 10^6 \text{ cm}^{-3}$$

$$\text{we have, } np = n_i^2$$

Now,

$$\sigma = en\mu_e + ep\mu_h$$

$$= 1.6 \times 10^{-19} (5 \times 10^{13} \times 1350 + 2 \times 10^6 \times 950)$$

$$= 1.08 \times 10^{-2} \text{ } \Omega^{-1} \text{ cm}^{-1}$$

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

$$= 92.6 \text{ } \Omega.$$

Change in resistance after doping

$$= 397.2 \times 10^3 \text{ } \Omega - 92.6 \text{ } \Omega$$

$$= 397.107 \times 10^3 \text{ } \Omega$$

(iii)

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

$$np = n_i^2$$

$$n = \frac{(10^{10})^2}{5 \times 10^{13}} = 2 \times 10^6 \text{ cm}^{-3}$$

$$\sigma = en\mu_e + ep\mu_h$$

$$= 1.6 \times 10^{-19} (2 \times 10^6 \times 1350 + 5 \times 10^{13} \times 950)$$

$$= 3.6 \times 10^{-3} \text{ } \Omega^{-1} \text{ cm}^{-1}$$

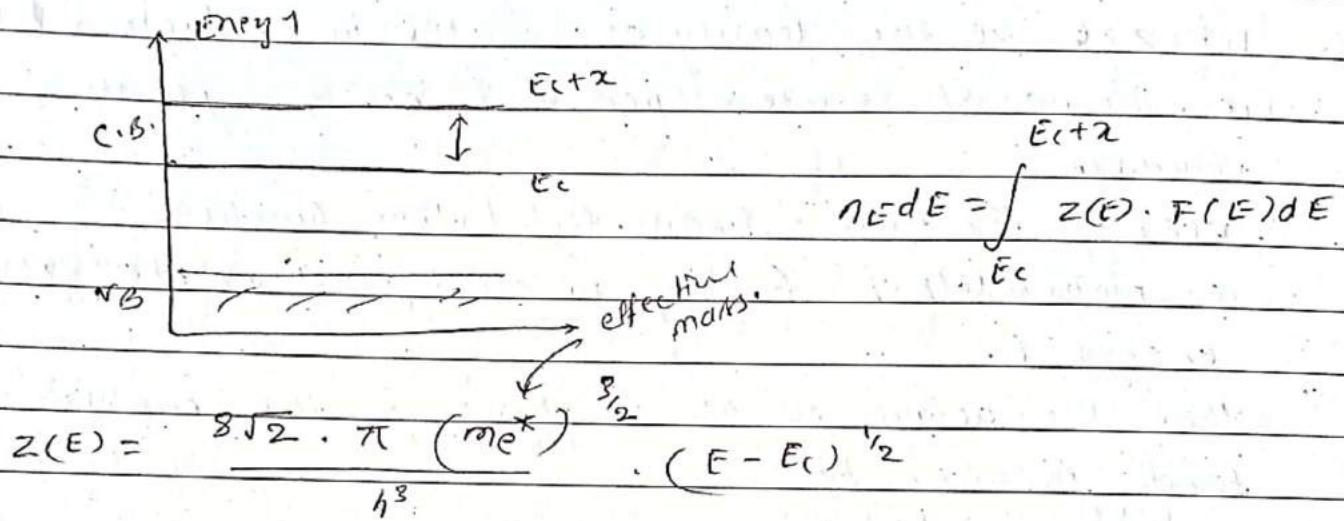
$$\text{then } R = \frac{l}{\sigma A}$$

$$= 277.77 \text{ } \Omega$$

Sb.

① Density of states, $Z(E)$

② Fermi - Dirac Distribution Function, $F(E)$



$$F(E) \approx \exp \left[-\frac{E(E - E_F)}{kT} \right] \quad \text{for, } (E - E_F \gg kT)$$

\uparrow
Boltzmann's constant $1.38 \times 10^{-23} \text{ J/K}$

\uparrow
h = Planck's constant $6.627 \times 10^{-34} \text{ Js}$
T → Temp. in Kelvin.

E_C = conduction band energy

E_F = Fermi energy.

* Electron & hole concentration in intrinsic SiC.

Let $z(E)$ be the density of state in conduction band i.e. no. of states per unit energy per unit volume.

$F(E)$ is the Fermi-Dirac distribution function:

i.e. probability of finding an electron in a state with energy E .

Then the actual no. of electrons in the conduction band is given by:

$$n = \int_{E_C}^{E_C + \Delta E} n_E dE = \int_{E_C}^{E_C + \Delta E} z(E) \cdot F(E) dE$$

$$n_E = z(E) \cdot F(E)$$

$$= \frac{8\sqrt{2} \pi (m e^*)^{3/2}}{h^3} \int_{E_C}^{\infty} (E - E_C)^{1/2} \exp \left[-\frac{(E - E_F)}{kT} \right] dE$$

Since $(E_C + \Delta E) \rightarrow \infty$

$z(E) \cdot F(E) \rightarrow 0$ at top level.

On solving this we get.

$$n = N_C \exp \left[-\frac{(E_C - E_F)}{kT} \right].$$

i.e. electron concentration in conduction band,
 N_C is effective density of states at CB edge.

where,

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

similarly. no of holes,

~~$$p = N_V \exp \left[\frac{-(E_F - E_V)}{kT} \right]$$~~

when

 N_V is one effective density of states at VB edge.

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

since, $(n_i)^2 = np$

$$n_i^2 = N_C \cdot N_V \exp \left[\frac{-(E_C + E_F - E_F + E_V)}{kT} \right]$$

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

$$\Rightarrow n_i = (N_C N_V)^{1/2} \exp \left(-\frac{E_g}{2kT} \right)$$

Q. Compute the intrinsic concentration and resistivity of silicon at 27°C. If

$$m_e^* = 1.08 m_e$$

$$m_h^* = 0.6 m_e$$

$$m_e = 1350 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$$

$$m_h = 450 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$$

$$\text{Take band gap } \Rightarrow E_g = 1.1 \text{ eV}$$

$$= 1.1 \times 1.6 \times 10^{-19} \text{ J}$$

$$n_i = ? , \beta = ?$$

$$N_c = \frac{2 \left(2\pi m_e^* kT \right)^{3/2}}{h^2}$$

$$= \frac{2 \left(2\pi \times 1.08 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300 \right)^{3/2}}{(6.627 \times 10^{-34})^2}$$

$$= 2.81 \times 10^{25} \text{ m}^{-3}$$

$$= 2.81 \times 10^{19} \text{ cm}^{-3}$$

$$N_v = \frac{2 \left(2\pi m_h^* kT \right)^{3/2}}{h^2}$$

$$= \frac{2 \left(2\pi \times 0.6 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300 \right)^{3/2}}{(6.627 \times 10^{-34})^2}$$

$$= 1.16 \times 10^{25} \text{ m}^{-3}$$

$$= 1.16 \times 10^{19} \text{ cm}^{-3}$$

$$n_i = (N_c N_v)^{1/2} \exp\left(\frac{-E_g}{2kT}\right)$$

$$= (2.81 \times 10^{25} \times 1.16 \times 10^{25})^{1/2} \exp\left[\frac{-1.1 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300}\right]$$

$$= 1 \times 10^{16} \text{ m}^{-3}$$

$$= 1 \times 10^{10} \text{ cm}^{-3}$$

$$\therefore n = p = n_i$$

$$\begin{aligned} G &= e n_i u_e + e p_i u_h \\ &= e n_i^0 (u_e + u_h) \\ &= 1.6 \times 10^{-19} \times 1 \times 10^{10} \times (1350 + 450) \\ &= 2.88 \times 10^{-26} \text{ Urn} \text{ cm}^{-1} \end{aligned}$$

$$S = \frac{1}{6}$$

$$= 3.472 \times 10^{25} \text{ J cm}^{-2}$$

$$\begin{array}{l} P = \frac{dF}{dA} \\ P = \frac{SF}{A} \end{array}$$

* Fermi-level Energy at Equilibrium

Fermi-level is important in determining both carrier concentrations for any intrinsic semiconductor.

$$n = p = n_i$$

Taking $p = n_i$ we can write

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

$$\text{or, } \exp\left[\frac{-E_{F_i}}{kT} + \frac{E_V}{kT} + \frac{E_g}{2kT}\right] = \left(\frac{x_i c N_V}{N_V^2}\right)^{1/2}$$

$$= \left(\frac{x_i c}{N_V}\right)^{1/2}$$

Taking ln on both sides,

$$-\frac{E_{F_i}}{kT} + \frac{E_V}{kT} + \frac{E_g}{2kT} = \ln\left(\frac{x_i c}{N_V}\right)^{1/2}$$

$$\text{or } -\frac{E_{F_i}}{kT} = -\frac{E_V}{kT} + \ln\left(\frac{x_i c}{N_V}\right)^{1/2} - \frac{E_g}{2kT}$$

$$\Rightarrow E_{F_i} = E_V + \frac{E_g}{2} - \frac{1}{2} kT \ln\left(\frac{x_i c}{N_V}\right) \quad (1)$$

we have,

$$\frac{x_i c}{N_V} = \frac{\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}{2}$$

$$2 \left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}$$

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

From ① and ② we get

$$E_F = E_V + E_g - \frac{1}{2} kT \ln\left(\frac{m_e^*}{m_h^*}\right)^{\frac{3}{2}}$$

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

- If $N_c = N_v$ or $m_e^* = m_h^*$, then $E_F = E_V + \frac{E_g}{2}$.

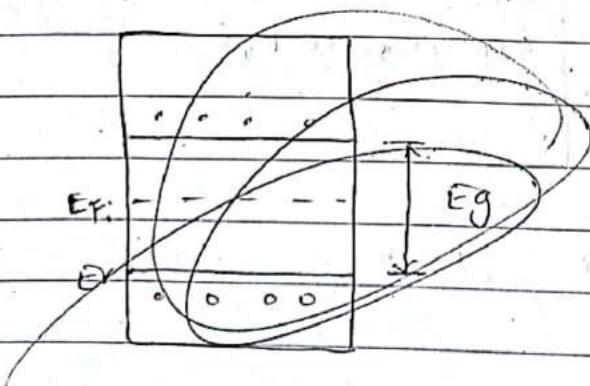
i.e. The intrinsic Fermi-level would lie exactly at the middle of the band gap if the above condition is satisfied.

Note: For Silicon and Germanium, $m_e^* > m_h^*$.

Hence E_F lies slightly ~~slightly~~ below the middle of the band gap.

→ for n-type semiconductor i.e. $n > p$

E_F is closer to E_C and for p-type semiconductor i.e. $p > n$, E_F is closer to E_V



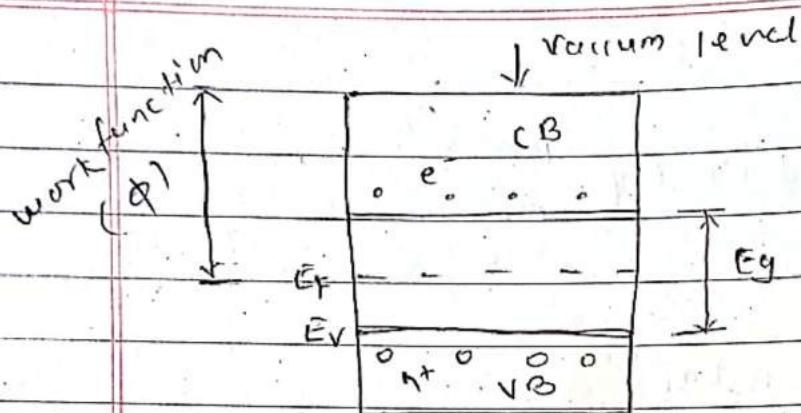


fig. (a) $p = n = n_i$ (intrinsic SiC)

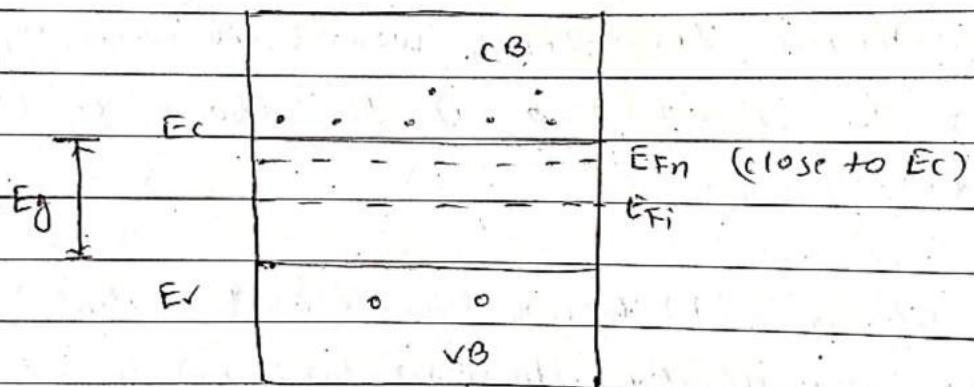


fig (b) n-type SiC ($n > p$)

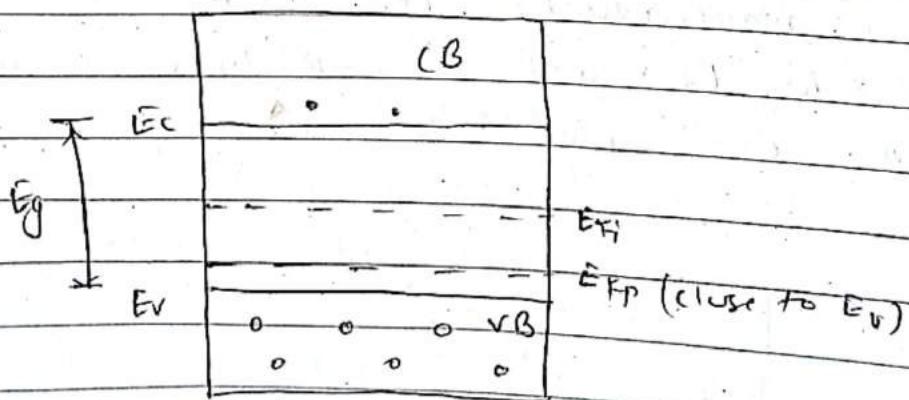


fig (c) P-type SiC ($p > n$)

→ Thus if we know Fermi energy level we can effectively determine both electron and hole concentration also. It helps to determine the energy required to remove an electron from the n.c. i.e. work function (ϕ) where ϕ is one ($E_{\text{vacuum}} - E_F^{\circ}$)

$$\phi = (E_{\text{vacuum}} - E_F^{\circ}) \\ = E_C + z - E_F^{\circ}$$

Q. An n-type Si wafer has been doped uniformly with 10^{16} antimony atoms per cm^{-3} . Calculate the position of Fermi energy with respect to the intrinsic Si Fermi energy. Take.

$$T = 300 \text{ K}, \quad kT = 0.0259 \text{ eV}, \quad n_i = 10^{10} \text{ cm}^{-3}$$

$$(E_{Fn} - E_{Fi}^{\circ} = ?)$$

$$\text{S.D.H.P.H. } N_d + \text{no. of donors} = 10^{16} \text{ cm}^{-3}$$

$$\text{no. of e's} = \text{no. of donors}$$

$$\text{i.e. } n = N_d$$

$$n = n_i \exp \left[\frac{-(E_C - E_{Fn})}{kT} \right] \quad \text{--- (1)}$$

for intrinsic S.I.C.

$$n_i = n = P$$

$$n_i = n = n_i \exp \left[\frac{-(E_C - E_{Fi}^{\circ})}{kT} \right] \quad \text{--- (2)}$$

Dividing (1) by (2)

$$\frac{N_d}{N_i} = \exp \left(\frac{-E_c + \bar{E}_{F_n} + E_c - \bar{E}_{F_i}}{kT} \right)$$

$$kT \ln\left(\frac{N_d}{N_i}\right) = \bar{E}_{F_n} - \bar{E}_{F_i}$$

$$\Rightarrow \bar{E}_{F_n} - \bar{E}_{F_i} = 0.0259 \ln\left(\frac{10^{16}}{10^{10}}\right)$$

$$= 0.36 \text{ eV.}$$

Q.1

In an n-type SiC the Fermi level lies 0.3 eV below the conduction band at 300 K. If the temperature is increased to 330 K, find the new position of the Fermi level.

(Ans. $\rightarrow 0.33 \text{ eV}$)

$$\left\{ -k \times 300 \ln\left(\frac{n}{n_i}\right) = 0.3 \text{ eV} \right\}$$

Q.2

In an n-type SiC the Fermi level lies 0.2 eV below the C.B. If the concentration of donor atoms is doubled. Find the new position of the Fermi level.

Take $kT = 0.03 \text{ eV}$

(Ans. $\rightarrow E_c - \bar{E}_{F_n} = 0.37 \text{ eV}$)

1. So?

Here, $E_{F_1} = 0.3 \text{ eV}$ below the conduction band

$$\therefore E_C - E_{F_1} = 0.3 \text{ eV}$$

$$\text{Temp. } (T) = 300 \text{ K}$$

$T' = 330 \text{ K}$ now, new position of fermi level?

We have:

$$n = N_c \exp \left[-\frac{(E_C - E_{F_1})}{kT} \right]$$

$$\text{or } \ln \left(\frac{n}{N_c} \right) = -\frac{(E_C - E_{F_1})}{kT}$$

$$\text{or } kT \ln \left(\frac{N_c}{n} \right) = E_C - E_{F_1} \quad \text{--- (1)}$$

$$300 \text{ K} \ln \left(\frac{N_c}{n} \right) = 0.3 \quad \text{--- (2)}$$

for second case,

$$330 \text{ K} \ln \left(\frac{N_c}{n} \right) = (E_C - E_{F_1})_{\text{new}} \quad \text{--- (3)}$$

Dividing (1) by (2) we get,

$$\frac{300}{330} = \frac{0.3}{(E_C - E_{F_1})_{\text{new}}}$$

$$\Rightarrow (E_C - E_{F_1})_{\text{new}} = 0.33 \text{ eV}$$

Hence, fermi level lies 0.33 eV below conduction band.

2. soln

$$\text{Hence, } E_C - E_{F_n} = 0.4 \text{ eV}$$

If concentration of donor atom is double.

$$(E_C - E_{F_n})_{\text{new}} = ?$$

$$\text{i.e. } n_D' = 2n_D$$

$$kT = 0.03 \text{ eV}$$

$$\text{we have, } n_D = n = N_C \exp \left[\frac{-(E_C - E_{F_n})}{kT} \right]$$

first case,

$$n = N_C \exp \left[\frac{-0.4}{0.03} \right] \quad \textcircled{1}$$

second case,

$$2n = N_C \exp \left[\frac{-(E_C - E_{F_n})_{\text{new}}}{0.03} \right] \quad \textcircled{2}$$

Dividing \textcircled{1} by \textcircled{2} we get,

$$\frac{1}{2} = \exp \left(\frac{-0.4}{0.03} + \frac{(E_C - E_{F_n})_{\text{new}}}{0.03} \right)$$

$$\ln \left(\frac{1}{2} \right) = \frac{-0.4 + (E_C - E_{F_n})_{\text{new}}}{0.03}$$

$$\Rightarrow (E_C - E_{F_n})_{\text{new}} = 0.3792 \text{ eV}$$

Ans.

Importance of fermi-energy.

- ① To determine $n \& p$, $p = N_c \exp \left[-\frac{(E_F - E_v)}{kT} \right]$
- ② To determine work function. $\rightarrow E_C + n - E_F$
- ③ To determine fermi-dirac distribution function & minimum amount of energy required to eject an electron from the surface of metal.

$$+ \quad -$$

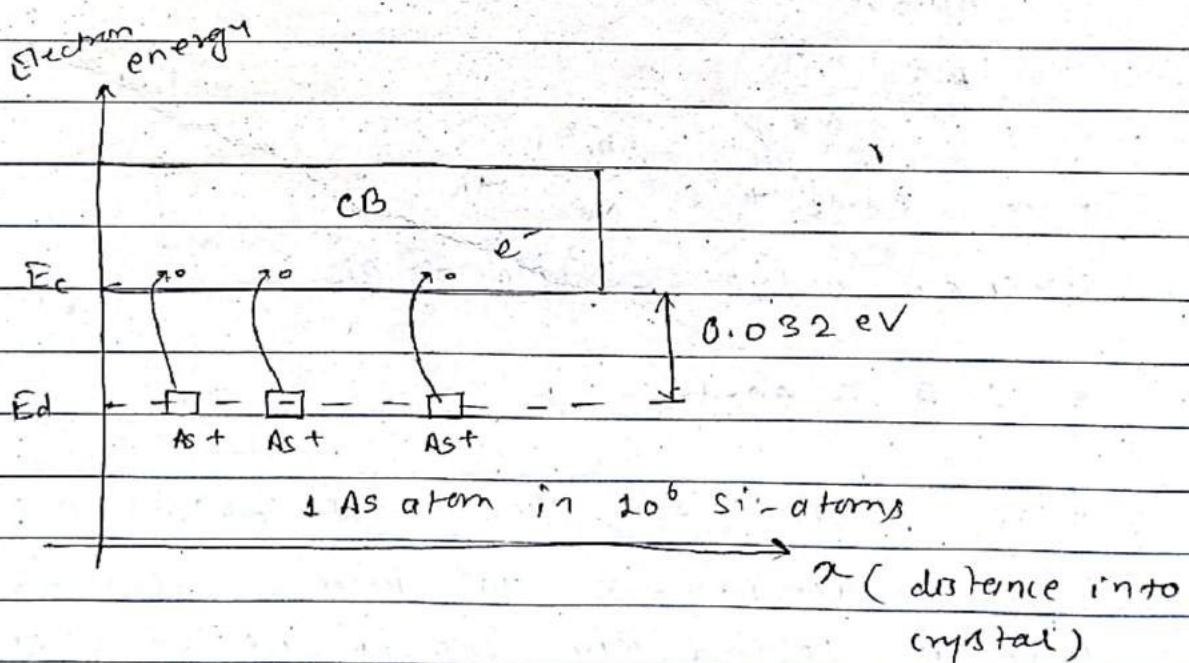
$$F(E) = \frac{1}{1 + \exp \left[\frac{(E - E_F)}{kT} \right]}$$

* n-type SiC

\rightarrow pentavalent impurities (Group V \rightarrow As, P, Sb)

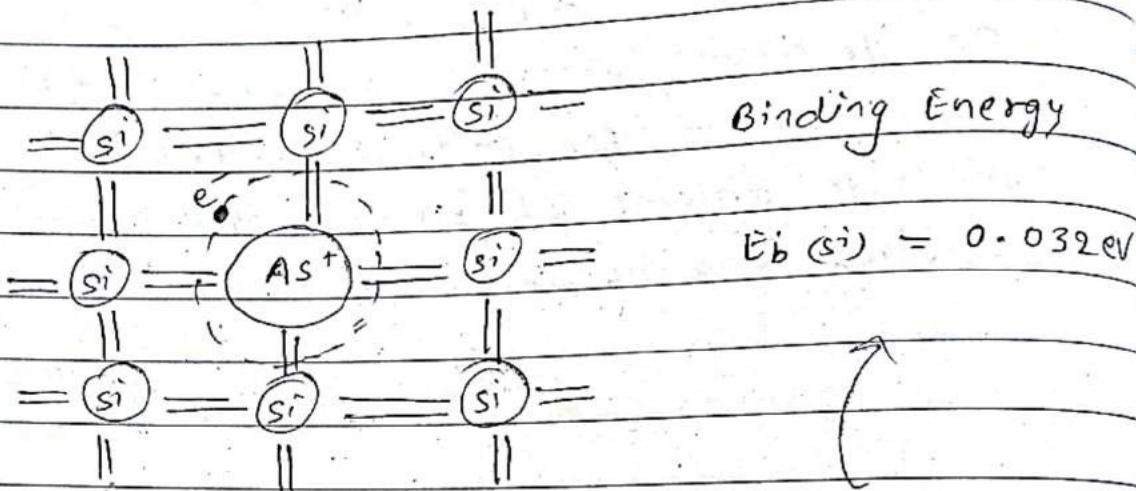
donors \rightarrow It donates ~~one~~ one extra e^-

No. of donors $\rightarrow N_d$.



As \rightarrow un-ionized.

As⁺ \rightarrow ionized (donates e^-)



In a SiC.

$$\sigma = enme + epnh$$

$$\text{for } n\text{-type SiC} \quad n = N_d$$

thermal energy \approx
sufficient to release e^-
from Atom
or to overcome E_b

$$np = n_i^2$$

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

$$\Rightarrow \sigma = enme + e \left(\frac{n_i^2}{N_d} \right) nh$$

since for n -type SiC $N_d \gg n_i$

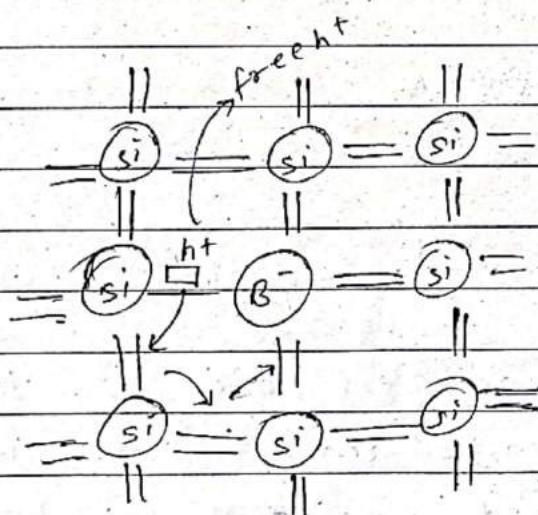
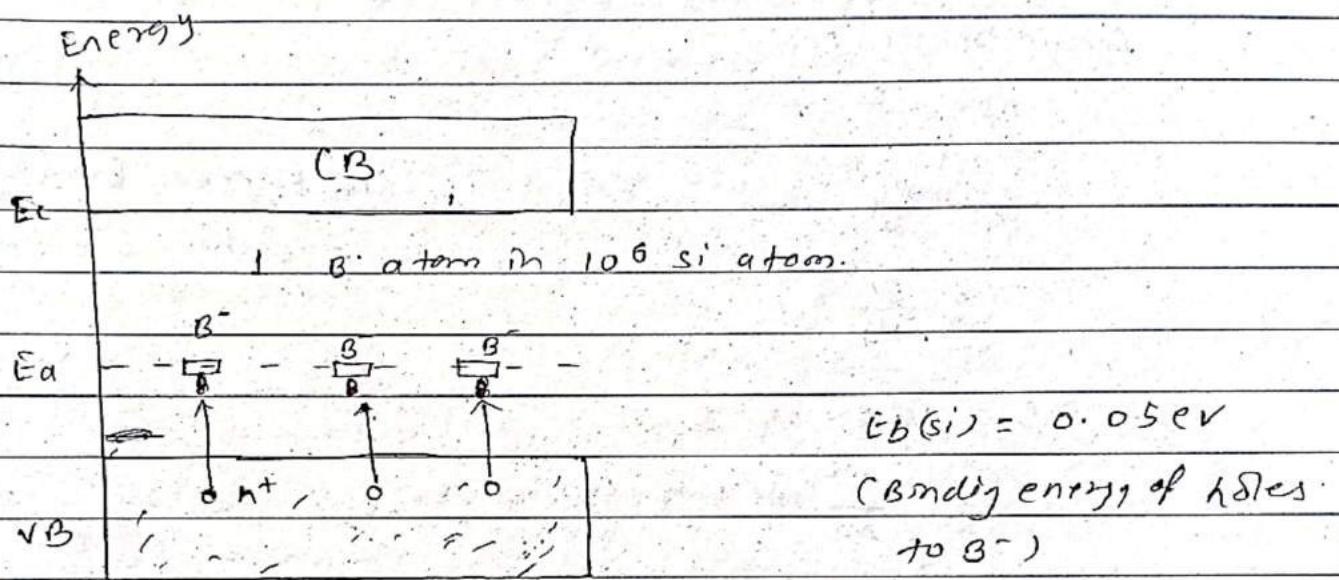
$$\therefore \sigma \approx enme$$

In an n -type SiC, the no. of donors are very large in comparison to intrinsic concentration. Hence the second term can be neglected or we can say that; the concentration of holes are suppressed. Therefore, the conductivity in n -type SiC is mainly because of electron concentration (n).

* P-type SiC

→ Trivalent impurities → B, Al, Ga, In.

→ Accept an e⁻ so called acceptors (x_{M}) \nearrow No of acceptor



B-doped in Si-crystal.

In n-type SiC, $p = N_a$

$$\text{since, } \sigma = e\epsilon n_m e + e p \mu_h \quad \textcircled{1}$$

for n-dense SiC

$$np = n_i^2$$

$$\begin{aligned} \Rightarrow n &= \frac{n_i^2}{p} \\ &= \frac{n_i^2}{N_a} \end{aligned}$$

(to be free binding energy must have overcome)

$$\text{since, } N_a \gg n_i$$

$$\therefore \frac{n_i^2}{N_a} \text{ is very less}$$

From ①

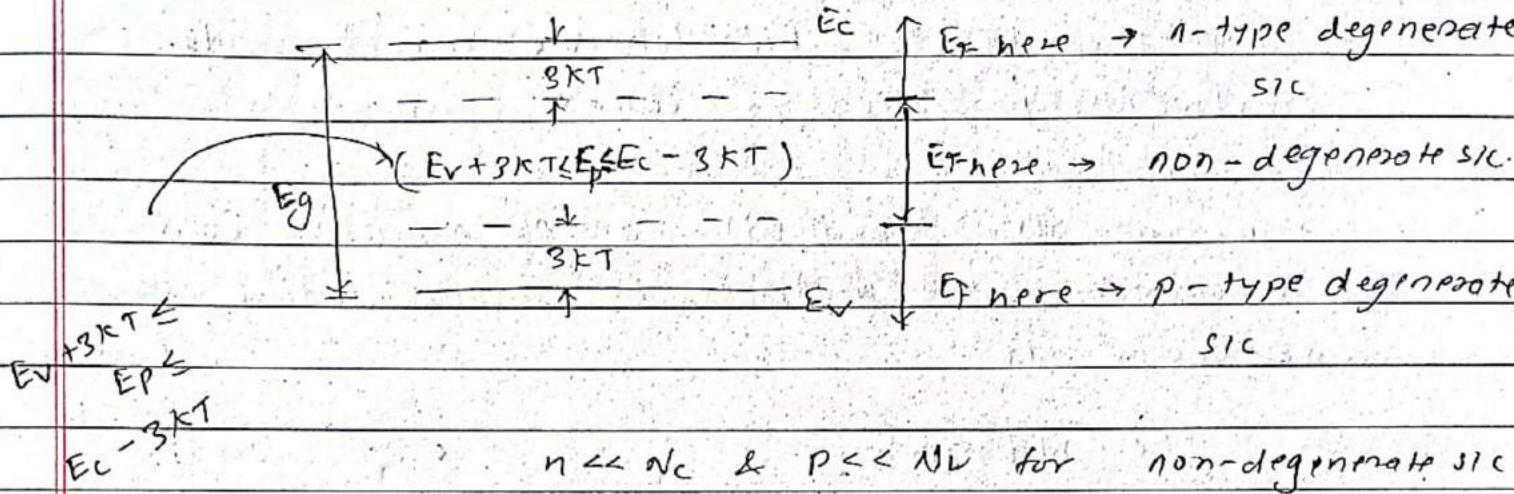
$$\sigma = e \left(\frac{n_i^2}{N_a} \right) n_m e + e p \mu_h$$

$$\therefore \sigma \approx e p \mu_h$$

IN p-type SiC, no. of acceptors are very large in comparison to intrinsic concentration.. Hence n_i^2/N_a is very small and first term can be neglected. So the concentration of e's are suppressed.

Therefore, The conductivity in p-type SiC is mainly due to holes concentration (p).

* Degenerate and non-degenerate SiC



SiCs for which Fermi-energy (E_F) is at least $3kT$ away from either of the band edges inside the band gap (E_g) are called non-degenerate SiCs. They are lightly doped and hence have less e⁻ and h⁺ concentration such that $n \ll N_c$ and $p \ll N_V$.

Semiconductors for which Fermi energy (E_F) lies in the band gap closer than $3kT$ to either band edge or goes beyond one of the bands E_C or E_V are called degenerate SiCs. They are heavily doped and hence have very high concn. of e⁻s and h⁺s such that $n \gg N_c$ and $p \gg N_V$.

Note: Degenerate SiC are used in
laser diodes, zener diodes and as
metal gates in MOS devices.

} laser diode
} zener diode
MOS \rightarrow metal oxide SiC

* Compensation doping

- Doping of a sic with donors & acceptors to control its properties is called compensation doping.
For example,

A p-type sic doped with ~~No~~ acceptors can be converted to n-type by simply adding ~~No~~ excess Na

i.e. $N_d \gg N_a$

For a sic with more donors (N_d) than Na:

$$n = N_d - N_a$$

$$P = \frac{n_i^2}{n} \quad (N_d \gg N_a)$$

$$= \frac{n_i^2}{(N_d - N_a)}$$

For a sic with more acceptors than donors

$$P = N_a - N_d \quad (N_a \gg N_d)$$

$$n = \frac{n_i^2}{(N_a - N_d)}$$

Q: A Si sample has been doped with 10^{17} As atoms ~~per~~ cm^{-3} . Calculate the conductivity of sample at 27°C . If the above sample is further doped with 9×10^{16} B-atoms cm^{-3} , calculate the new conductivity at 27°C . Take

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

$$\text{mobility of } e^- \text{ at } 27^\circ\text{C}, m_e = 800 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

$$\text{mobility of } h^+ \text{ at } 27^\circ\text{C}, m_h = 850 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

Sol ^A case I:

$$\text{no. of donors } N_d = 10^{17} \text{ cm}^{-3} = n$$

$$\text{temp } T = 27^\circ\text{C} = 300 \text{ K}$$

$$\sigma = ?$$

$$S = \frac{R}{A}$$

since,

$$\sigma = e n_i m_e + e p_i m_h$$

we have

$$n_p = n_i^2$$

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

then,

$$\sigma = e n_i m_e + e \left(\frac{n_i^2}{n} \right) m_h$$

$$= 1.6 \times 10^{-19} \left\{ 10^{17} \times 800 + \frac{(10^{10})^2}{10^{17}} \times 850 \right\}$$

$$= 12.8 \text{ S}^{-1} \text{ cm}^{-1}$$

Case II

Now above sample is further doped with B.

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

$$\begin{aligned} n = N_d - N_A &= 10^{17} - 9 \times 10^{16} \\ &= 10^{16} \text{ cm}^{-3} \end{aligned}$$

$$P = \frac{n_i^2}{(N_d - N_A)}$$

and

$$\begin{aligned} \sigma &= e \{ n_i \mu_e + p \mu_h \} \\ &= 1.6 \times 10^{-19} \{ 10^{16} \times 800 + \frac{(10^{10})^2}{10^{16}} \times 950 \} \\ &= 1.28 \text{ } \Omega^{-1} \text{ cm}^{-1}. \end{aligned}$$

* Recombination & Trapping

sound postscript

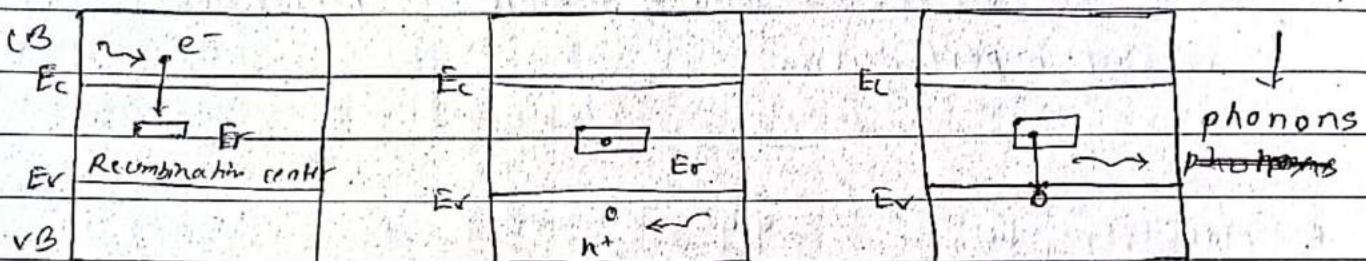


fig. # Recombination.

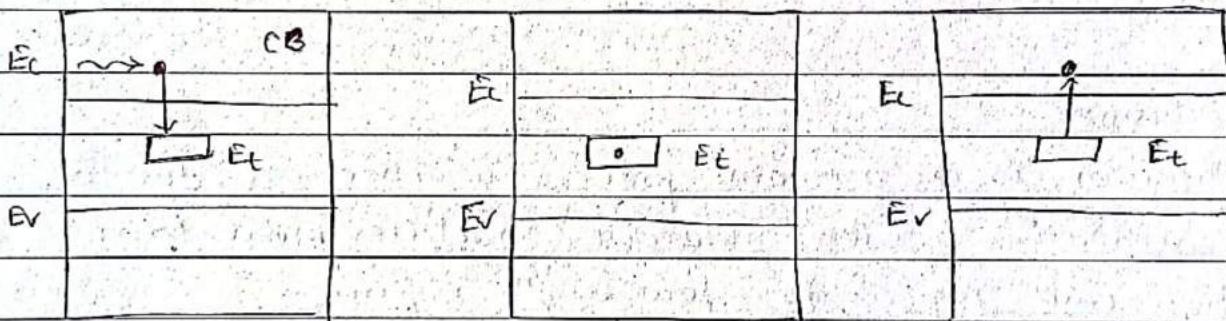


fig. # Trapping

~~Ans~~

- Recombination is the process of combination of e^- s in the C.B. to the holes of V.B. with the release of excess energy as phonons.
- In this process, there will be the permanent removal of e^- from the C.B.
- The recombination centers can be donor or acceptor impurities, metallic impurities or crystal defects.

metals
ions

→ Trapping is the temporary removal of e^- from the conduction band.

- The trap centers are usually because of impurities or crystal imperfection.

$$\ast \text{ Mobility } (\mu) = \frac{e\tau}{m_e}$$

- Mobility is hindered by ionized impurities.
- movement of charge carriers. (μ).

* Diffusion

- Diffusion is the random process which occurs due to concentration gradient whereby particles move from high concn region to low concn region.

- Diffusion occurs till a uniform distribution of particles throughout the material is obtained.

- since the particle are charged their diffusion will give rise to diffusion current called diffusion current in SIC.

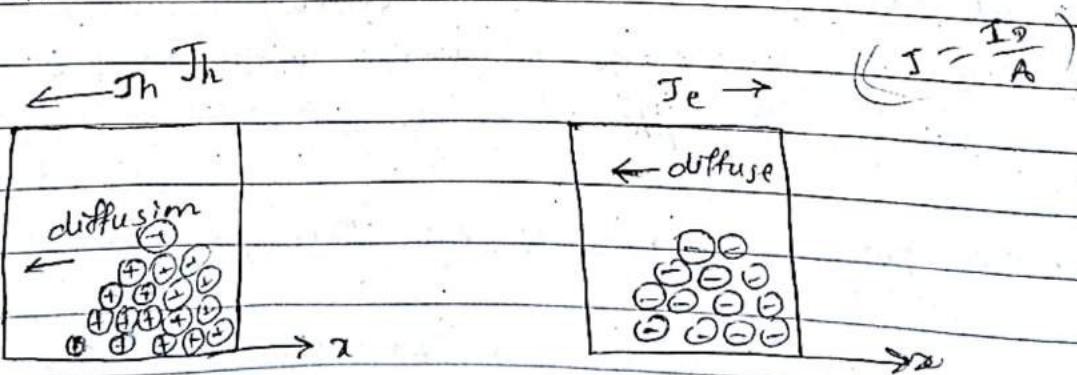


Fig. Diffusion of charge carriers giving diffusion current in SIC.

Q. A silicon wafer has been doped uniformly with 10^{12} phosphorous atoms cm^{-3} . If it is further doped with 10^{18} Al atoms cm^{-3} . What will be the change in fermi energy level with respect to one intrinsic Si fermi energy?

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

$T = 300 \text{ K}$

~~so~~ $N_d = 10^{12} \text{ cm}^{-3}$

$N_a = 10^{18} \text{ cm}^{-3}$

$$p = N_a - N_d = 10^{18} - 10^{12} = 9.9 \times 10^{13} \text{ cm}^{-3}$$

$$p = nV \exp \left[-\frac{(E_{Fp} - E_F)}{kT} \right] \quad \text{--- (1)}$$

similarly for intrinsic Si.c.

$n_i = p = n$

$$\text{so, } n_i = nV \exp \left[-\frac{(E_{Fi} - E_F)}{kT} \right] \quad \text{--- (2)}$$

Dividing eqn (1) by (2)

$$\frac{n_i}{p} = \exp \left[-\frac{E_{Fi}}{kT} + \frac{E_F}{kT} + \frac{E_{Fp}}{kT} - \frac{E_F}{kT} \right]$$

$$\text{or, } \frac{n_i}{(N_a - N_d)} = \exp \left[-\frac{(E_{Fi} - E_{Fp})}{kT} \right]$$

Taking \ln on both sides,

$$KT \ln\left(\frac{n_i}{N_{d+}N_{a-}}\right) = - (E_{F_i} - E_{F_p})$$

$$-(E_{F_i} - E_{F_p}) = 1.38 \times 10^{-23} \times 300 \times 17 \left(\frac{10^{10}}{9.9 \times 10^{13}} \right)$$

$$\Rightarrow E_{F_i} - E_{F_p} = 3.81 \times 10^{-20} \text{ J.}$$

$$\Rightarrow 0.2381 \text{ eV.}$$

Solved Numerical Examples:

1. The density of states related effective masses of electrons and holes in silicon are approximately 1.08 me and 0.56 me respectively. The electron and hole drift mobilities at room temperature are 1350 and $450 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ respectively. calculate intrinsic concentration and intrinsic resistivity of silicon. The energy band gap for silicon is 1.1 eV .

$$n_i = (\pi \mu_{\text{eff}})^{1/2} \cdot \exp\left(\frac{-E_g}{2kT}\right) = 1$$

$$g = \mu_e = ?$$

Effective densities of states at conduction and valence band edge are given by,

$$N_c = 2 \cdot \left(\frac{2\pi m_e^{*} k T}{h^2} \right)^{3/2}$$

$$= 2 \left(\frac{2\pi \times 1.08 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.624 \times 10^{-34})^2} \right)^{3/2}$$

$$= 9.267 \times 10^{23} \text{ m}^{-3} \quad 2.54 \times 10^{25} \text{ m}^{-3}$$

$$= 2.54 \times 10^{19} \text{ cm}^{-3}$$

$$\mu_{\text{eff}} = 2 \left(\frac{2\pi m_h^{*} k T}{h^2} \right)^{3/2}$$

$$= 2 \left(\frac{2\pi \times 0.56 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.624 \times 10^{-34})^2} \right)^{3/2}$$

$$= 1.05 \times 10^{25} \text{ m}^{-3}$$

$$= 1.05 \times 10^{19} \text{ cm}^{-3}$$

Now intrinsic carrier density

$$n_i = (N_c N_v)^{1/2} \exp\left(\frac{-E_g}{2kT}\right)$$

$$= \left(2.59 \times 10^{95} \times 1.09 \times 10^{25}\right)^{1/2} \times \exp \left[\frac{-1.1 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300} \right]$$

$$\approx 9.58 \times 10^{15} \text{ m}^{-3}$$

Resistivity,

$$\rho = \frac{1}{e n_i} \quad \begin{pmatrix} \text{for intrinsic} \\ n = p = n_i \end{pmatrix}$$

$\mu_{\text{electron}} + \mu_{\text{hole}}$

$$= \frac{1}{e n_i (\mu_e + \mu_h)}$$

$$= \frac{1}{1.6 \times 10^{-31} \times 9.58 \times 10^9 \times (1350 + 450)}$$

$$= 3.62 \times 10^5 \text{ ohm.cm.}$$

J

9. calculate the resistance of pure silicon cubic crystal of 1cm^3 at room temperature. What will be the resistance of the cube when it is doped with 1 arsenic atom in 10^9 silicon atoms and 1 boron atom per billion silicon atom?

Atomic concentration of silicon is $5 \times 10^{22} \text{ cm}^{-3}$, $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$

Assume the mobilities as in the previous example.

$$n_e = 1350 \text{ cm}^2 \text{V}^{-1}\text{s}^{-1} \quad n_h = 450 \text{ cm}^2 \text{V}^{-1}\text{s}^{-1}$$

$\stackrel{\text{SDT}}{=}$ Resistance of the cube.

$$R = \frac{sl}{A} = \frac{l}{\sigma A} = \frac{l}{e n_i (\mu_e + \mu_h)}$$

$$= \frac{l}{1.6 \times 10^{19} \times 1.45 \times 10^{10} (1350 + 450)}$$

$$= 2.39 \times 10^5 \text{ ohm}$$

When Si is doped with 1 arsenic atom per 10^9 silicon atoms.

then donor concentration

$$N_d = \frac{n_{Si}}{10^9} = \frac{5 \times 10^{22}}{10^9} = 5 \times 10^{13} \text{ cm}^{-3}$$

At room temp. all the donors are ionized so electron concentration is

$$n \approx N_d = 5 \times 10^{13} \text{ cm}^{-3}$$

then holes concentration,

$$p = \frac{n_i^2}{N_d} = \frac{(1.45 \times 10^{10})^2}{5 \times 10^{13}}$$

$$= 4.2 \times 10^6 \text{ cm}^{-3}$$

Now resistance.

$$R = \frac{1}{\sigma A} = \frac{1}{e \mu n e + e p n h}$$

$$= \frac{1}{1.6 \times 10^{19} (5 \times 10^{13} \times 1350 + 4.2 \times 10^6 \times 450)}$$

$$= 92.6 \Omega.$$

Again.

Si is doped with 1 boron atoms per billion Si atoms.

then

$$p = N_A = 5 \times 10^{19} \text{ cm}^{-3}$$

$$n = \cancel{4.2 \times 10^6} \text{ cm}^{-3}$$

and

$$R = \frac{1}{1.6 \times 10^{19} (4.2 \times 10^6 \times 1350 + 5 \times 10^{13} \times 950)}$$

$$= 277.7 \Omega.$$

8. An n-type SiC is doped with 10^{16} cm^{-3} phosphorous atoms have been doped with 10^{17} cm^{-3} boron atoms. calculate the electron and holes concentrations in the semiconductor.

^{SN} First n-type SiC is doped with pentavalent phosphorus so, $N_d = 10^{16} \text{ cm}^{-3}$

If it is further doped with Boron
 $N_A = 10^{17} \text{ cm}^{-3}$

$$\text{So no. of acceptor concentration } n_s = N_A - N_D \\ = 10^{17} - 10^{16} \\ = 9 \times 10^{16} \text{ cm}^{-3}$$

$$\therefore p = N_A = 9 \times 10^{16} \text{ cm}^{-3}$$

and electron concentration

$$n_i^2 = \frac{n_i^2}{p} \\ = \frac{(1.45 \times 10^{10})^2}{9 \times 10^{16}} \\ = 2.34 \times 10^3 \text{ cm}^{-3}$$

4. An n-type silicon wafer is uniformly doped with 10^{16} antimony atoms per cm^3 . Where will be the Fermi level compared to its intrinsic Fermi level? Where will the Fermilevel be shifted if the sample is further doped with 2×10^{17} boron atoms per cm^3 ?

^{So} since, Si is doped with 10^{16} antimony so,

$$n \times N_D = 10^{16} \text{ cm}^{-3}$$

intrinsic concentration

$$n_i = N_c \exp \left[\frac{-(E_c - E_{F_i})}{kT} \right] \quad \textcircled{1}$$

doped concentration

$$n = N_D = N_c \exp \left[\frac{-(E_c - E_{F_D})}{kT} \right] \quad \textcircled{2}$$

Dividing ② by ①

$$\frac{N_d}{n_i} = \exp \left[-\frac{E_F + EF_n + EC - EF_i}{kT} \right]$$

$$\frac{EF_n - EF_i}{kT} = \ln \left(\frac{N_d}{n_i} \right)$$

$$EF_n - EF_i = \ln \left(\frac{10^{16}}{1.95 \times 10^{10}} \right) \times 1.38 \times 10^{-23} \times 300 \\ = 5.56 \times 10^{-20} \text{ J.} = 0.3775 \text{ eV}$$

Now the sample is further doped with 2×10^{17} O_2 -atoms

$$\text{So, } N_a = 2 \times 10^{17} \text{ cm}^{-3}$$

Total no. of acceptor greater than

$$P = N_a - N_d = 2 \times 10^{17} - 10^{16} \\ = 19 \times 10^{16} \text{ cm}^{-3}$$

$$\text{Since } P = N_a \exp \left[\frac{(EF_p - EC)}{kT} \right] \quad \textcircled{3}$$

$$n_i = N_a \exp \left[-\frac{(EF_p - EC)}{kT} \right] \quad \textcircled{4}$$

Dividing ③ by ④

$$\frac{P}{n_i} = \exp \left[-\frac{EF_p + EF_i + EC - EC}{kT} \right]$$

$$\ln \left(\frac{P}{n_i} \right) = \cancel{\text{exp}} \left[-\frac{(EF_p - EF_i)}{kT} \right]$$

$$E_{Fp} - E_{Fi} = -kT \ln\left(\frac{P}{n_i}\right)$$

$$\approx -300 \times 1.38 \times 10^{-23} \ln\left(\frac{1.9 \times 10^{16}}{1.45 \times 10^{10}}\right)$$

$$= -6.78 \times 10^{-20} \text{ J}$$

$$= -0.429 \text{ eV}$$

$$E_{Fi} - E_{Fp} = 0.429 \text{ eV.}$$

P

* Diffusion

$$J_{e, \text{diff}} = e D_e \frac{dn}{dx}$$

$$J_{h, \text{diff}} = -e D_h \frac{dp}{dx}$$

where dn are concentration
gradient for e^- and h^+ respectively.
 D_e & D_h are diffusion coefficients
for e^- & h^+ resp.

This is called Fick's first law of diffusion for e^- & h^+ .

Diffusion coefficient is a measure of how rapidly the particle diffuses in the medium. For most materials diffusion coefficient is found to vary with temp. in an activated manner given by $D = D_0 \exp(-\frac{\phi}{kT})$

where, ϕ = activation energy

D_0 = pre-factor.

* Einstein Relationship

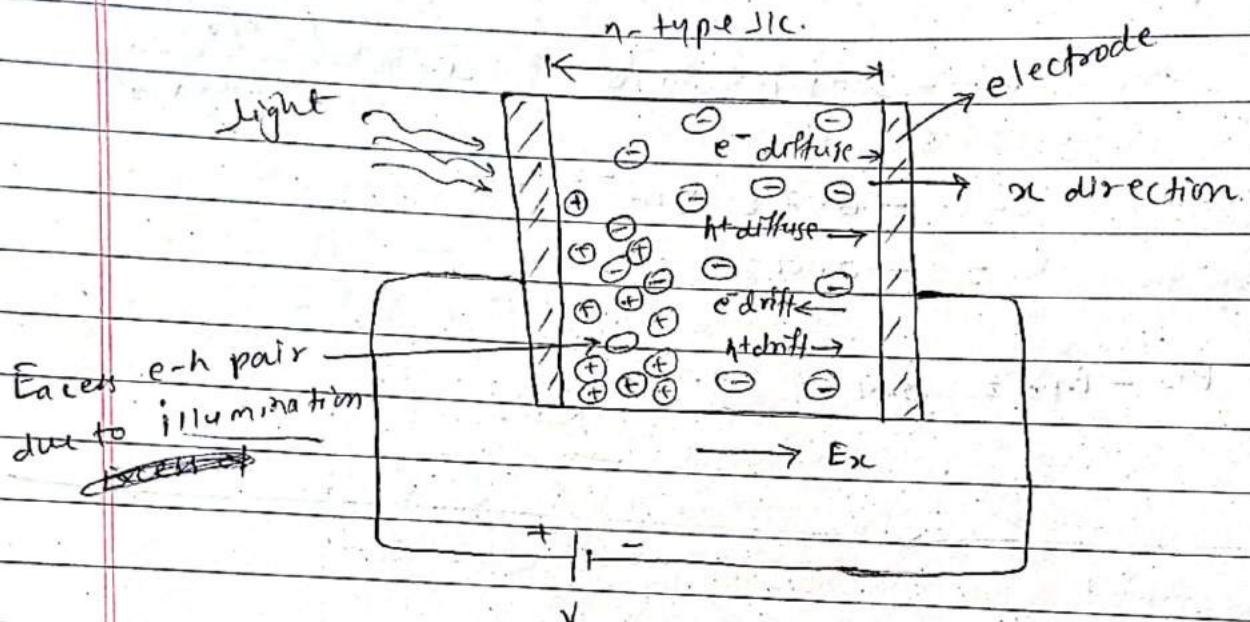


fig. presence of both electric field & concentration gradient in an n-type SiC.

Here due to concentration gradient left \rightarrow right, there is continuous diffusion of both charge carriers and also due to externally applied electric field E_x , there occurs drift of the charge carriers. Thus the total current density due to e's is given by

$$J_e = J_{edrift} + J_{ediff}$$

$$= \sigma E_x + e D_e \frac{dn}{dx}$$

$$\therefore J_e = e n u_e E_x + e D_e \frac{dn}{dx} \quad (1)$$

similarly, current density due to h's.

$$J_h = e p u_h E_x - e D_h \frac{dp}{dx} \quad (2)$$

Under equilibrium condition the net current density due to both e's and h's must be zero.

Thus at equilibrium from eqn ① we get, $J_e = 0$

$$en \mu_e E_x + e D_e \frac{dn}{dx} = 0$$

$$\Rightarrow en \mu_e E_x = - e D_e \frac{dn}{dx}$$

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

Integrating,

$$\ln(n) = - \frac{\mu_e E_x \cdot x}{D_e}$$

$$n = \exp \left[- \frac{\mu_e E_x \cdot x}{D_e} \right] \quad \text{--- (3)}$$

From Boltzmann's statistics, For external applied field,

$$n = \exp \left[- \frac{e E_x z}{kT} \right] \quad \text{--- (4)}$$

From (3) and (4) we can write,

$$\frac{-\mu_e E_x \cdot z}{D_e} = - \frac{e E_x \cdot z}{kT}$$

$$\Rightarrow \frac{D_e}{\mu_e} = \frac{kT}{e} ; \text{ This is called Einstein Relationship for n-type SIC.}$$

Similarly for p-type SIC.

$$\Rightarrow \frac{D_h}{\mu_h} = \frac{kT}{P} \quad \begin{matrix} \text{(rel. betw diff. coefficient, mobility \& temp.)} \\ \text{Temp.} \end{matrix}$$

* Carrier lifetime

In the process of recombination of e^- s and h^+ s there is a certain time lag or it takes certain time as e^- s and h^+ s have to find each other.

Thus the carrier lifetime (for holes (or mean recombination time)) (τ_h) is defined as average time during which a hole is free before it recombines with electron.

Carrier lifetime for e^- s (τ_e) is defined as average time during which an e^- is free before it recombines with a hole.

* Continuity eqn for charge carriers.

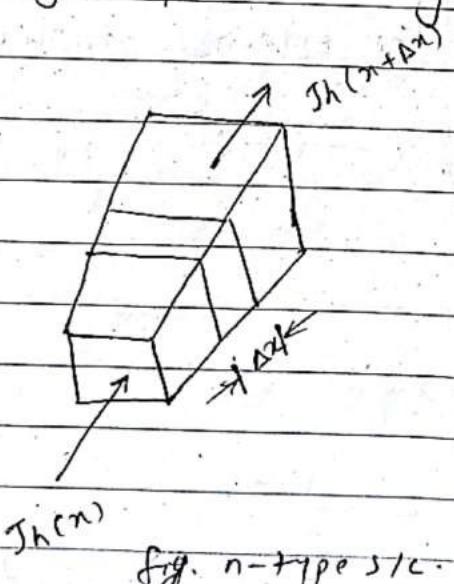


fig. n-type s/c.

Here the current density of h^+ entering the sample can be smaller or larger than the current density of holes leaving the sample.

Depending on the generation or recombination taking place within the sample. The net increase in h^+ conc per unit time is the difference bett the h^+ flow per unit volume entering and leaving - rate of combination given by

$$\frac{d \Delta P}{dt} = g_{ph} - \frac{\Delta P}{T_h} \quad \text{--- (1)}$$

↑ ↑ ↑
 Rate of increase in rate of rate of
 excess h^+ conc. photogeneration recombination

This can be written as,

$$\frac{d \Delta P}{dt} = \frac{1}{e} \left[\frac{J_h(n) - J_h(n+\Delta x)}{\Delta x} \right] - \frac{\Delta P}{T_h} \quad \text{--- (2)}$$

g_{ph} is defined as increase in hole concn per unit volume ($A \cdot \Delta x$) per unit time.

$$\text{i.e. } \frac{p}{t} = \frac{P \cdot A}{t \cdot n} = \frac{e P n}{e t x} = \frac{e P n}{e n} = \frac{J}{e x} \quad | \quad J = e P v$$

Using Taylor series,

$$J_h(n+\Delta x) = J_h(n) + \frac{d J_h(n)}{dx} \cdot \Delta x$$

Now, Excess hole concn.

$$\Delta P = (P - P_0)$$

$$\frac{d \Delta P}{dt} = \frac{\partial P}{\partial t}$$

From eqn ② we can write

$$\frac{\partial \Delta p}{\partial t} = \frac{1}{e} \left[J_h(m) - J_h(m) - \frac{\partial J_h(m)}{\partial x} \Delta x \right] - \frac{\Delta p}{T_h}$$

$$\Rightarrow \frac{\partial \Delta p}{\partial t} = - \frac{1}{e} \frac{\partial J_h(m)}{\partial x} \frac{\Delta p}{T_h} \quad \text{--- (3)}$$

This eqn is called continuity eqn for holes.

The total current density is due to diffusion and drifting

i.e. $J_h = e \mu_{th} E_x - e D_h \frac{dp}{dx}$

↑ drift ↑ diffuse

From eqn ③

$$\frac{\partial \Delta p}{\partial t} = - \frac{\Delta p}{T_h} - \frac{1}{e} \frac{\partial}{\partial x} \left[e \mu_{th} E_x - e D_h \frac{dp}{dx} \right]$$

For small volume and uniformly doped, electric field is small and can be neglected.

$$\Rightarrow \frac{\partial \Delta p}{\partial t} = - \frac{\Delta p}{T_h} + D_h \frac{\partial^2 p}{\partial x^2} \quad \text{--- (4)}$$

This is called Fick's second law of diffusion for holes.

Under steady state condition.

$\frac{\partial A P}{\partial z} = 0$ i.e. Rate of photogeneration is equal to recombination.

$$D_h \frac{\partial^2 P}{\partial z^2} - \frac{\Delta P}{T_h} = 0$$

$$\alpha \frac{\partial^2 P}{\partial z^2} - \frac{\Delta P}{D_h T_h} = 0$$

$$\frac{\partial^2 P}{\partial z^2} - \frac{\Delta P}{L^2} = 0$$

where,

$L = \sqrt{D_h \cdot T_h}$ is called diffusion length for holes. Diffusion length is defined as the length, a hole diffuse in average before it recombine with an e^- . In a n-type SiC, it is also called minority carrier diffusion length.

similarly the continuity eqn for e^- is given by

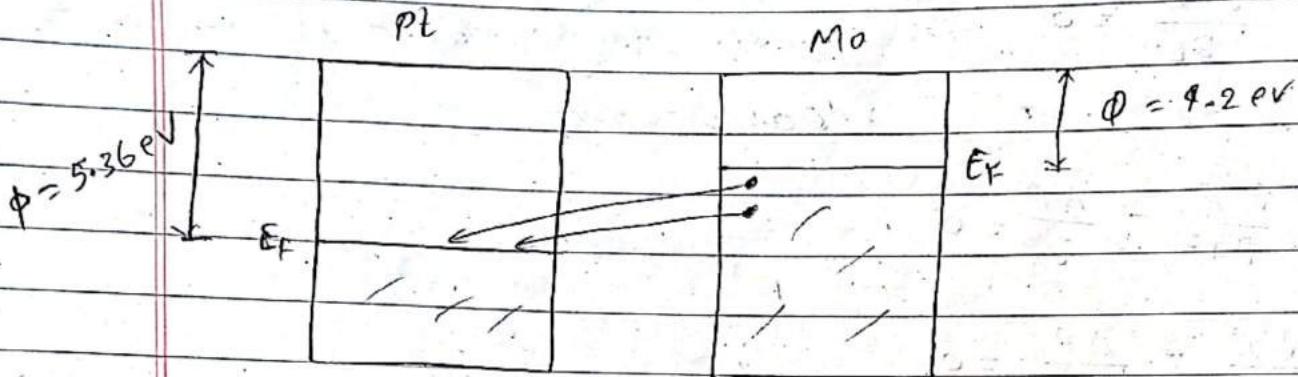
$$\frac{\partial \Delta n}{\partial z} = \frac{1}{e} \frac{\partial I(n)}{\partial z} - \frac{\Delta n}{T_e}$$

and diffusion eqn for Fick's 2nd law is

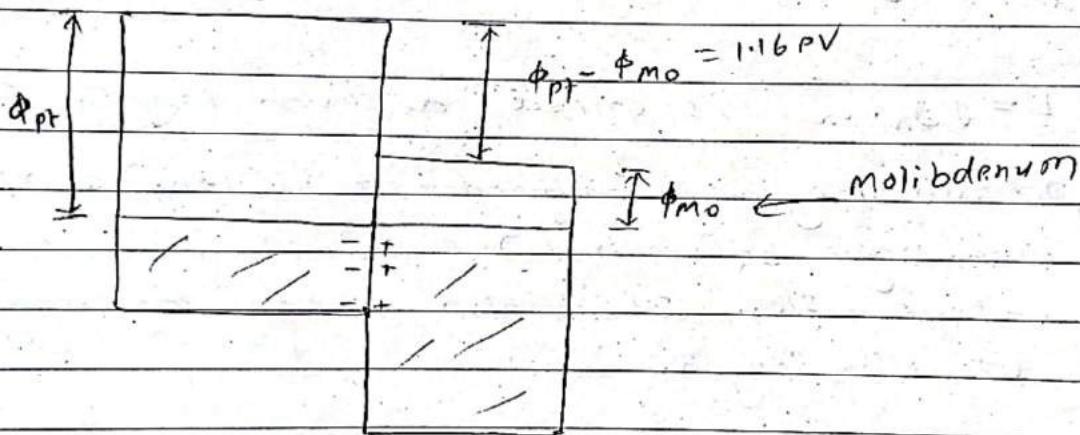
$$\frac{\partial \Delta n}{\partial z} = - \frac{\Delta n}{T_e} + \frac{2e}{D_e} \frac{\partial^2 n}{\partial z^2}$$

(Transport and diffuse eqn)

* Contact potential



Before contact



Equilibrium after contact

When two metals of diff. work functions are rubbed together, here Pt and Mo in our case. Due to smaller work function of Mo, its Fermi energy will be at higher level in comparison to Pt with higher work function. The electrons of Mo are also at high energy state in comparison to the e's of Pt. Hence these more energetic e's of Mo will immediately transferred to Pt surface by tunneling to

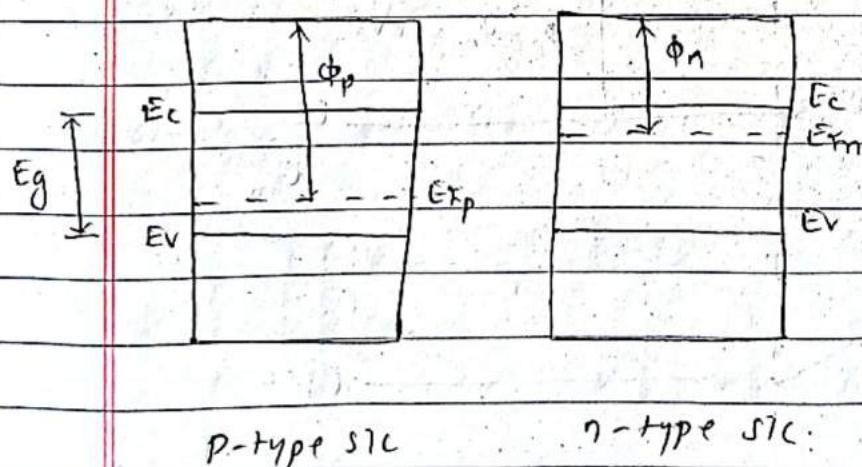
occupy the lower empty state.

Hence, Pt becomes negatively charged with respect to Mo and consequently a contact voltage also called potential difference will be developed at the junction between Pt and Mo. The transfer of e^- will occur from Mo to Pt until both the Fermi level balance each other or at same energy level. Therefore contact potential or voltage is given by

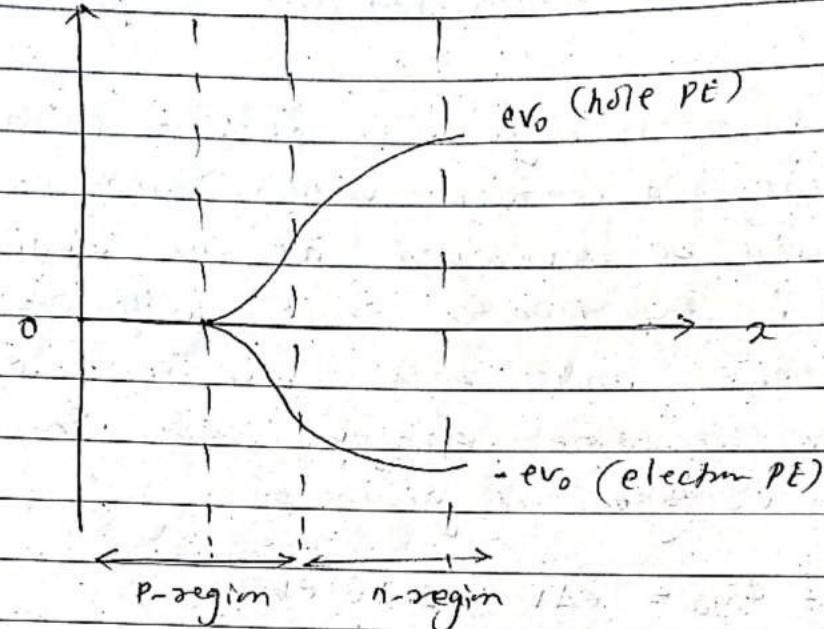
$$\phi_{Pt} - \phi_{Mo} = e\Delta V \approx 1.16 \text{ eV}$$

$$\Delta V = \left(\frac{\phi_{Pt} - \phi_{Mo}}{e} \right)$$

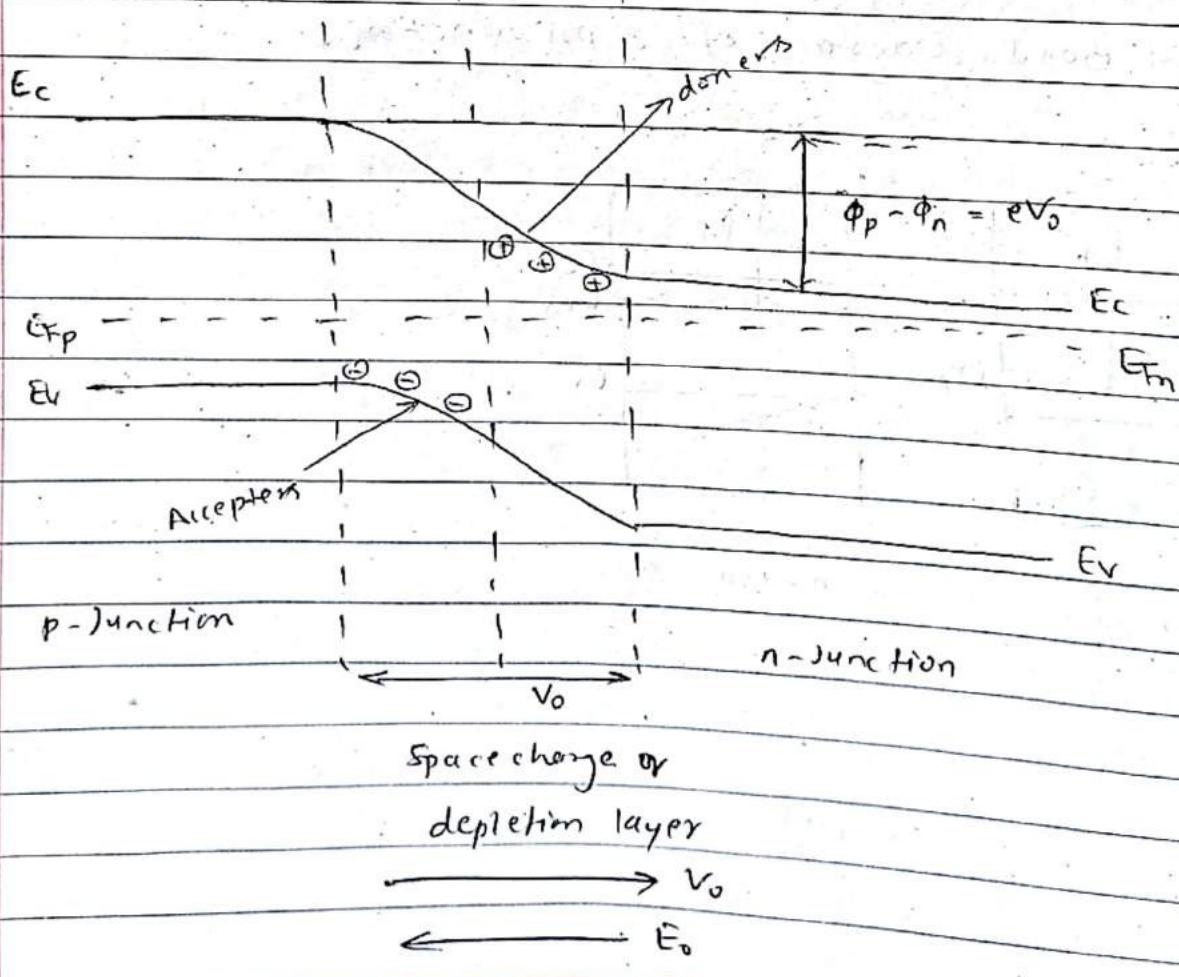
* Energy Band diagram of a pn junction.



Electrostatic
potential energy
 $P_E(x)$



(metallurgical junction)



As shown as the two Si's are brought together to form the pn junction. e^- diffused from $n \rightarrow p$ side and the region near the junction becomes depleted. Thus E_c must move away from E_{F_n} towards M. Similarly h^+ diffused from $p \rightarrow n$ side such that E_v must move away from E_{F_p} towards M.

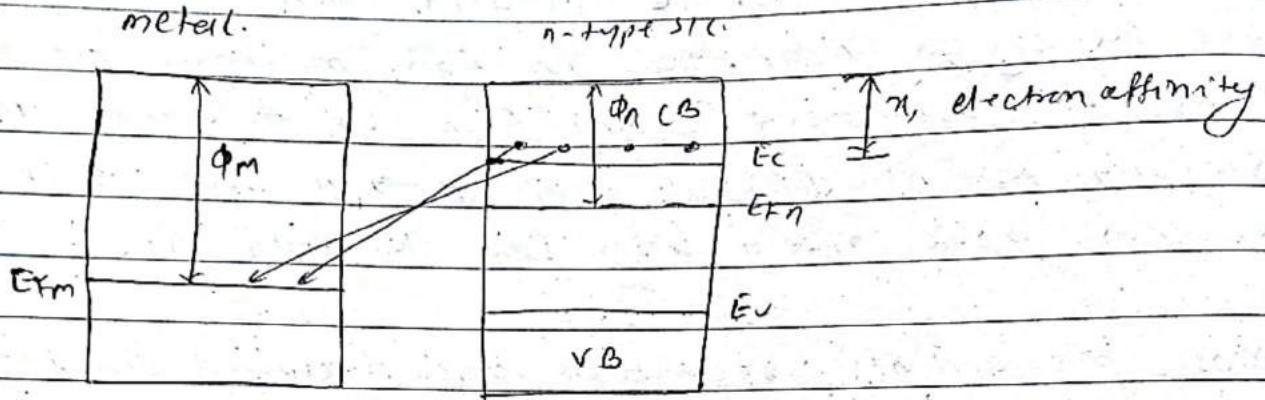
Most e^- s and h^+ s recombine and decipated disappear around M and that reach to the formation of depletion layer.

The electrostatic potential energy of e^- decrease from 0 inside p-region to $-eV_0$ inside n-region. In other words the e^- in n-type must overcome the potential barrier of eV_0 to reach our E_c in the p-side. Here V_0 is the built in potential and there will be band bending phenomenon around M due to this built in potential.

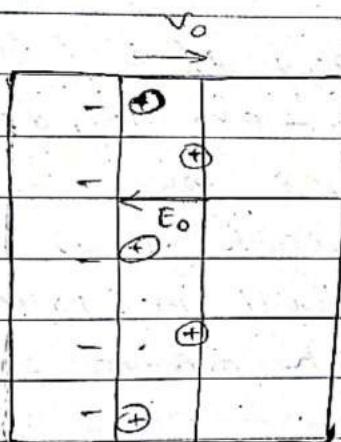
It also signifies the variation of e^- & h^+ conc' in this region. Here donors & acceptors around M are the exposed charged ionized impurities which are immobile.

* Metal - semiconductor contacts

metal.

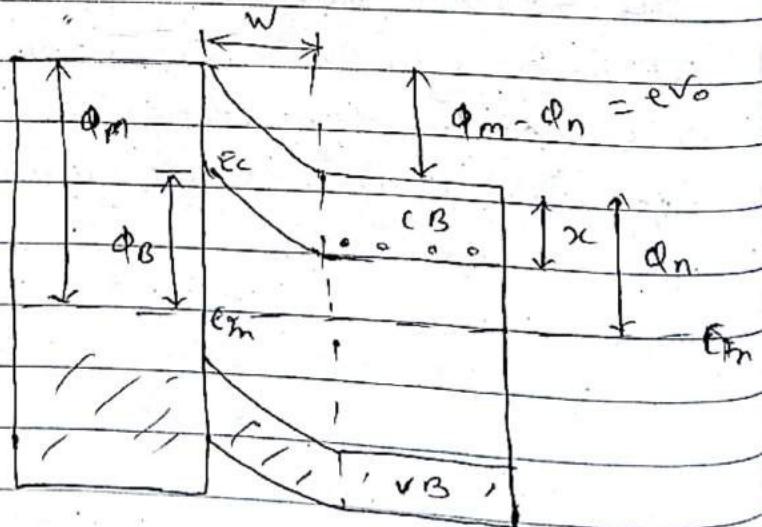


Before contact.



metal
depletion layer
n-type
semiconductor
 \rightarrow
n-type semiconductor

$E_{Fm} =$



$\phi_B = \phi_m - \chi$
Schottky barrier
height

After contact

$$\begin{aligned}\phi_B &= \phi_{m-x} \\ &= \phi_0 + \phi_n - \phi_n + (E_c - E_{F_n}) \\ \Rightarrow \phi_B &= \phi_0 + (E_c - E_{F_n})\end{aligned}$$

Here in metal-SiC junction, more energetic e⁻s in the C.B of SiC can easily tunnel into the metal to find any lower E⁻s leaving behind exposed truely charge region with immobile ions and the region will be depleted of free charge carriers.

This depletion region extends upto the n-region only. Consequently the charge difference between depleted n-region and metal surface will develop a built in potential between the metal and SiC contact.

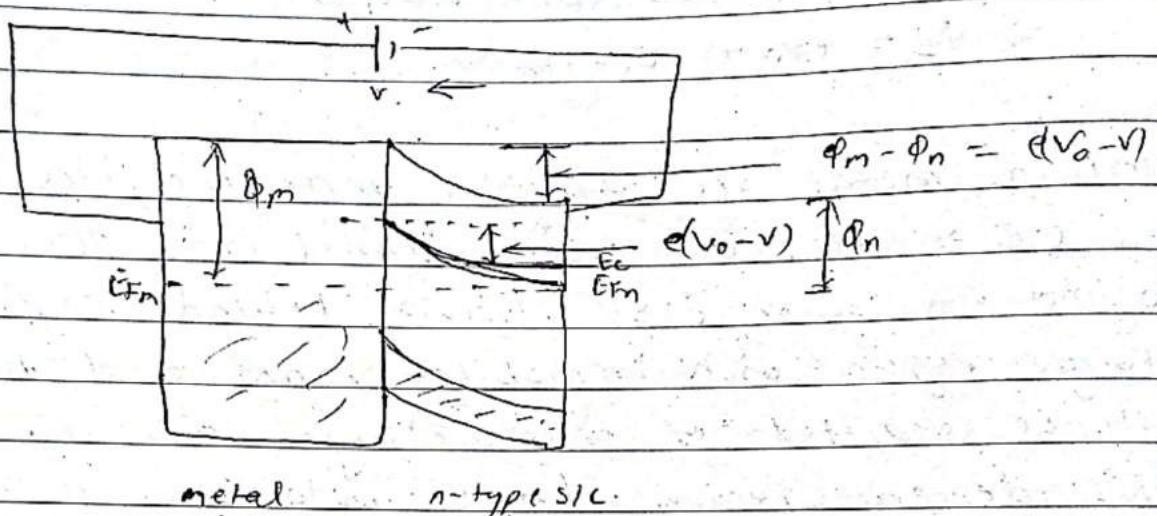
The transfer of e⁻s will occur until the Fermi level ~~at~~ is at the same level and $E_c - E_{F_n}$ must increase as the electron conc? decreases. At the so the band must bend near the junction to increase $E_c - E_{F_n}$.

The potential energy barrier for e⁻s moving from the metal to the SiC is called as Schottky barrier height given by

$$\phi_B = \phi_{m-x}$$

$$\phi_B = \phi_0 + (E_c - E_{F_n}), \quad \phi_m = \phi_0 + \phi_n, \quad E_n = \phi_n - (E_c - E_{F_n})$$

* Forward bias condition



metal - SiC junction at forward biased cond?

When the metal - SiC junction is forward biased, the external biased voltage is in opposite to the built in voltage (V_0). This reduces the potential (V_0) to ($V_0 - V$). However the barrier Schottky barrier height (Φ_B) as seen from the metal to the SiC side remains the same.

The barrier potential energy for thermal emission of e-s from the SiC to the metal will be given by $e(V_0 - V) = \Phi_m - \Phi_n$

This reduce barrier potential will be easily overcome by the e-s moving from n-type SiC to the metal. So the new value of current density is given by

$$J_{\text{sic to metal}}^{\text{forward}} = A_2 \exp \left(\frac{-e(V_0 - V)}{kT} \right)$$

So the net increase in the current density from metal to Ni Sic will be given by

$$J_{\text{net increase}} = J_2^{\text{forward}} - J_2^{\text{reverse}}$$

$$= A_2 \exp\left(\frac{-e(V_0 - V)}{kT}\right) - A_2 \exp\left(\frac{-eV_0}{kT}\right)$$

$$= A_2 \exp\left(\frac{-eV_0}{kT}\right) \cdot \exp\left(\frac{eV}{kT}\right) - A_2 \exp\left(\frac{-eV_0}{kT}\right)$$

$$= A_2 \exp\left(\frac{-eV_0}{kT}\right) \left[\exp\left(\frac{eV}{kT}\right) - 1 \right]$$

$$J_{\text{net increase}} = J_2 \left\{ \exp\left(\frac{eV}{kT}\right) - 1 \right\}$$

$$\text{since, } J_2 = J_1 = J_{oc} = J_0$$

$$J = 1$$

$$\therefore J_{\text{net}} = J_0 \left[\exp\left(\frac{eV}{kT}\right) - 1 \right]$$

Where J_0 is called reverse saturation current that depends upon material and surface properties of the two solids.

pico $\rightarrow 10^{-12}$

Date _____
Page _____

Q. Find the resistance of pn junction gr diode. If the temp is 27°C and reverse saturation current is 1 nA for an applied forward bias voltage of 0.2 V .

$$T = 300\text{ K}, I_0 = 10^{-6}\text{ A}, V = 0.2\text{ V}$$

now,

$$I_{\text{new}} = I_0 \left[\exp \left(\frac{eV}{kT} \right) - 1 \right]$$

$$= 10^{-6} \left[\exp \left(\frac{1.6 \times 10^{-19} \times 0.2}{1.38 \times 10^{-23} \times 300} \right) - 1 \right]$$

$$= 2.27 \times 10^{-3} \text{ Amp.}$$

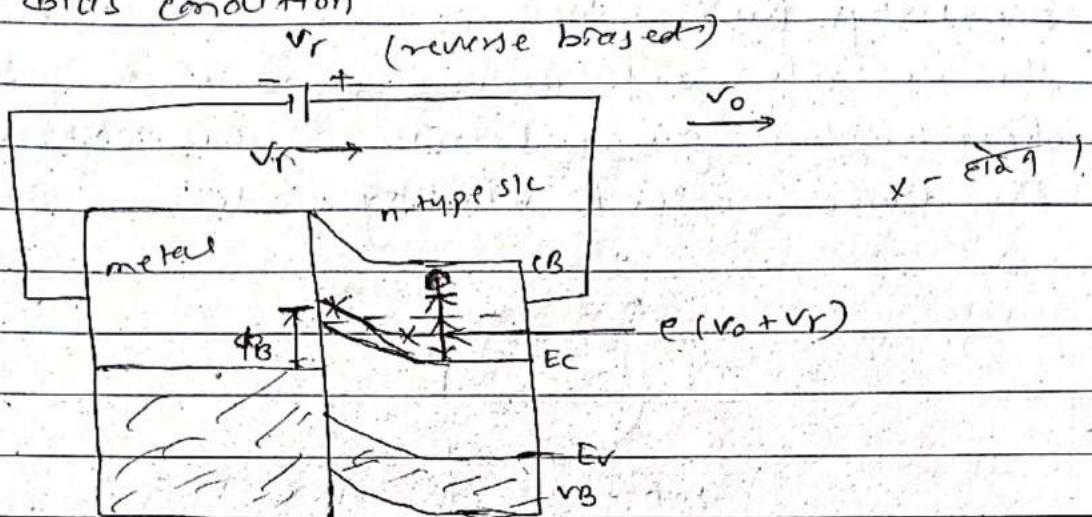
now,

$$R = \frac{V}{I_{\text{new}}}$$

$$= \frac{0.2}{2.27 \times 10^{-3}}$$

$$= 88.105 \text{ }\Omega.$$

* Reverse Bias condition



When the schottky junction is reverse biased the +ve terminal of the battery is connected to n-type and -ve terminal connected to the metal. The built-in potential now will be increase from V_0 to $V_0 + V_r$ as the direction of V_0 and V_r are same.

The potential energy barrier for thermal emission of e-s from CB of SiC to metal increases from eV_0 to $e(V_0 + V_r)$ and the corresponding current will be

J_2

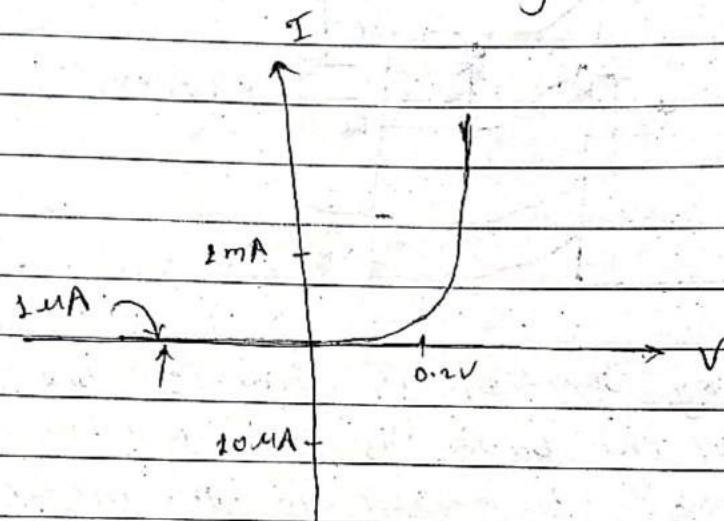
$$\text{reverse} \quad J_2 = A_2 \exp \left(-\frac{e(V_0 + V_r)}{kT} \right)$$

This will be less than the current due to emission of e-s from metal to SiC over potential barrier of η_B which is still the same as O.C. condition.

$$J_2^{\text{reverse}} \ll (J_1 \approx J_2) \text{ at O.C.}$$

Since built-in voltage (V_0) is very small and reverse bias voltage V_r is few volts. The reverse current is

essentially limited by current from metal to the sic side and is very small. The I-V characteristics given below is the property of my device called schottky diode.



Note :

$$\text{Built-in potential, } (V_0) = \frac{kT}{e} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

$$\text{Total depletion width, } (w_0) = \sqrt{\frac{2eV_0}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)}$$

$$\text{Depletion layer in n-side } (w_n) = \left(\frac{w_0 N_A}{N_A + N_D} \right)$$

$$\text{Depletion layer in p-side } (w_p) = w_0 - w_n$$

$$\epsilon = \epsilon_0 \epsilon_r$$

$$\uparrow \\ 8.859 \times 10^{-12} \text{ F/m.}$$