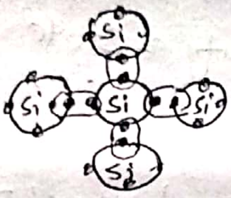
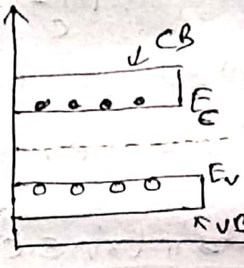
Unit-6 Semiconductor and semiconductor Devices :

Intrinsic semiconductor :

A semiconductor in its pure form is known as intrinsic semiconductor. e.g. Ge, Si etc., A pure semiconductor contains equal no. of electrons and holes. The Fermi level lies between the VB & CB as shown in fig. below.





$$E_{f0} = \frac{E_c + E_v}{2}$$

(1) Electron Concentration in intrinsic Semiconductor (n)

No. of electron per unit volume in CB is known as electron concentration (n) which is calculated as

$$n = \int_{E_c}^{\infty} D(E) f(E)\, dE \quad -(1)$$

where $D(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2} \quad -(2)$

is density of state at unit vol^m. $V=1m^3$

and

$f(E) = \frac{1}{1+e^{\frac{E-E_f}{K_BT}}}$ is Fermi-Dirac distribution function

For $(E-E_f) \gg K_BT$ in 'CB', $f(E) \approx \frac{1}{e^{(E-E_f)/K_BT}} = e^{-(E-E_f)/K_BT} \quad -(3)$

$\therefore$ Eq^n (1) becomes

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-(E-E_f)/K_BT}\, dE$$

or,
$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_f-E_c)/K_BT} \int_{E_c}^{E_\infty} (E-E_c)^{1/2} e^{-(E-E_c)/K_BT}\, dE \quad -(4)$$

put, $\frac{E-E_c}{K_BT} = x \Rightarrow E-E_c = K_BT x \Rightarrow \frac{dE}{dx} = K_BT \Rightarrow dE = K_BT dx$

when $E = E_c$ then $x = 0$

when $E = \infty$ then $x = \infty$

$\therefore$ Eq^n (4) becomes, $n = \frac{4\pi}{h^3}(2m_e^* k_B T)^{3/2} e^{(E_f - E_c)/k_B T} \int_0^{\infty} x^{1/2} e^{-x} dx$

$(k_B T)^{3/2} = k_B T (k_B T)^{1/2}$

$$\therefore n = \frac{4\pi}{h^3}(2m_e^* k_B T)^{3/2} e^{(E_f - E_c)/k_B T} \times \frac{\sqrt{\pi}}{2}$$

$$\text{or, } n = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} e^{(E_f - E_c)/k_B T}$$

$$\therefore \boxed{n = N_c e^{\frac{(E_f - E_c)}{k_B T}}} \quad -(5)$$

where $N_c = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$ $-(6)$ is called effective density of state in CB edge.

(2) Hole Concentration in intrinsic Semiconductor (P)

A hole is a state of energy in the valence band unoccupied by an electron. As $f(E)$ gives the probability of occupation by an electron for an energy state then the probability that it may be unoccupied by an electron is $(1 - f(E))$ ~~which is same thing as that it may occupied by~~ a hole. The Concentration of hole in VB is given by

$$P = \int_{-\infty}^{E_v} D(E)\{1 - f(E)\} dE \quad -(1)$$

$$1 - f(E) = 1 - \frac{1}{1 + e^{(E-E_f)/k_B T}} = \frac{e^{\frac{(E-E_f)}{k_B T}}}{1 + e^{(E-E_f)/k_B T}}$$

In VB, $E << E_f$

$$\therefore 1 - f(E) \approx e^{\frac{(E-E_f)}{k_B T}} \quad -(2)$$

Also, $D(E) = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)^{1/2}$ $-(3)$

$\therefore$ From eq^n (1), (2) & (3)

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{\frac{(E-E_f)}{k_B T}} dE$$

$$\text{or, } P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{\frac{(E_v - E_f)}{k_B T}} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{-\frac{(E_v - E)}{k_B T}} dE \quad -(4)$$

put $\frac{E_v - E}{K_B T} = x \Rightarrow E_v - E = K_B T \cdot x \Rightarrow -\frac{dE}{dx} = K_B T \Rightarrow dE = -K_B T\, dx$

when $E = -\infty$ then $x = \infty$

when $E = E_v$ then $x = 0$. Hence eqn. (4) becomes

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(E_v - E_f)/K_B T} \int_\infty^0 (K_B T x)^{1/2} e^{-x} (-K_B T\, dx)$$

$$\text{or, } P = \frac{4\pi}{h^3}(2m_h^* K_B T)^{3/2} e^{\frac{(E_v - E_f)}{K_B T}} \int_0^\infty x^{1/2} e^{-x} dx$$

$$\text{or, } P = \frac{4\pi}{h^3}(2m_h^* K_B T)^{3/2} e^{(E_v - E_f)/K_B T} \cdot \frac{\sqrt{\pi}}{2}$$

$\frac{\sqrt{\pi}}{2} = \Gamma^{1/2}$

$\Gamma + \Gamma^{1/2}$

$= \Gamma^{3/2}$

$$\text{or, } P = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2} e^{\frac{(E_v - E_f)}{K_B T}}$$

$$\Rightarrow \boxed{P = N_v e^{\frac{(E_v - E_f)}{K_B T}}} \quad \text{--(5)}$$ which is required expression

where $N_v = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2}$ is called effective density of states at the VB edge.

Fermilevel in Intrinsic semiconductor:

For an intrinsic semiconductor $n = P$

$$\text{or, } 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2} e^{\frac{(E_f - E_c)}{K_B T}} = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2} e^{\frac{(E_v - E_f)}{K_B T}}$$

$$\text{or, } e^{\frac{(E_f - E_c - E_v + E_f)}{K_B T}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \Rightarrow e^{\frac{2E_f - E_c - E_v}{K_B T}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

taking $\log_e$ on both side we get

$$\frac{2E_f - E_c - E_v}{K_B T} = \frac{3}{2}\ln\left(\frac{m_h^*}{m_e^*}\right) \longrightarrow E_f = \frac{E_c + E_v}{2} + \frac{3}{4}\ln\left(\frac{m_h^*}{m_e^*}\right)$$

put, $\text{or, } 2E_f - E_c - E_v = \frac{3}{2}\ln\left(\frac{m_h^*}{m_e^*}\right)$

$$\text{or, } 2E_f = (E_c + E_v) + \frac{3}{2}\ln\left(\frac{m_h^*}{m_e^*}\right)$$

at $T = 0$ kelvin, $\boxed{E_f = \frac{E_c + E_v}{2}}$ Hence at absolute zero temp^r, fermi level lies half way between top of VB & bottom of CB.

Extrinsic semiconductor: When trivalent or pentavalent impurity is dopped in a pure (intrinsic) semiconductor then extrinsic semiconductor is obtained. There are two types of extrinsic semiconductor

① n-type semiconductor: when pentavalent impurity like AS, P, Sb etc are added to pure semiconductor 'Si' or Ge then n-type semiconductor is obtained as shown in fig. aside

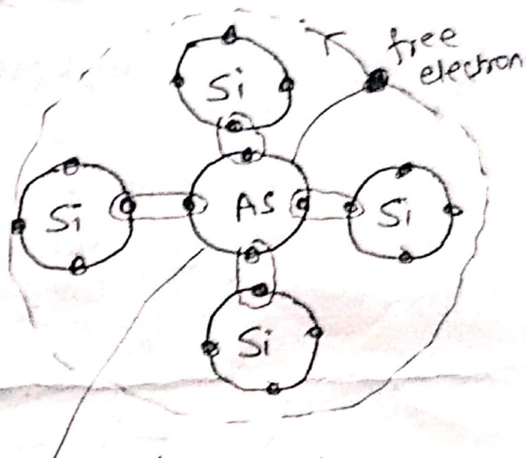


fig. n-type semiconductor

one free electron doneted ~~by every impurity atom is continuously~~ revolves around ion core, similar to H-atom. Hence, to free the extra electron from impurity atom, the energy required

$$E_i^{Si} = \frac{m_e^* e^4}{8(\epsilon_0 \epsilon_r)^2 h^2} \quad -①$$

Put $m_e^* = 0.31 m_e$, $\epsilon_r = 12$ for 'Si' in eqn. (1)

$$E_b = \frac{me^4}{8\epsilon_0^2 h^2}\frac{0.31}{(12)^2} = (13.6\,eV)\times\frac{0.31}{(12)^2} = 0.029\,eV$$

This is the energy necessary to free the excess electron from impurity atoms. Hence impurity or Doner energy level (E_d) lies 0.029 eV below bottom of CB as shown in fig. aside.

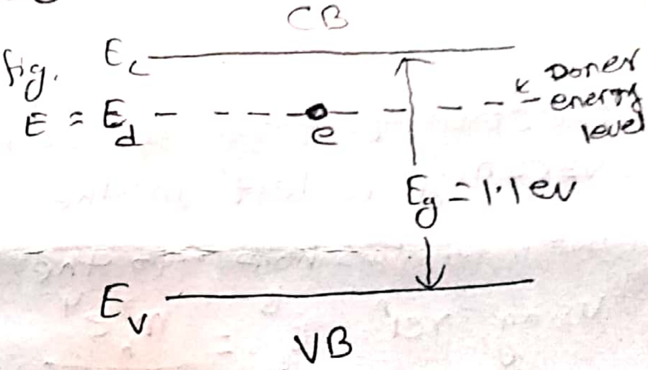


fig. energy level in n-type semiconductor

If N_d be the doner concentration then

$$n = p + N_d$$

$$n.p = n_i^2 \Rightarrow p = \frac{n_i^2}{n} \quad — (1)$$

$$\therefore n = \frac{n_i^2}{n} + N_d = \frac{n_i^2 + nN_d}{n}$$

or, $n^2 = n_i^2 + nN_d \Rightarrow n^2 - nN_d - n_i^2 = 0$

$$\Rightarrow n = \frac{-(-N_d) \pm \sqrt{(-N_d)^2 - 4\cdot 1(-n_i^2)}}{2}$$

$$\Rightarrow n = \frac{N_d}{2} \pm \sqrt{\frac{N_d^2}{4} + n_i^2}$$

taking +ve, $n = \frac{N_d}{2} + \frac{N_d}{2}$ where $\frac{N_d^2}{4} \gg n_i^2$

$\Rightarrow \boxed{n \approx N_d}$ hence eqn. (1) become $\boxed{p = \frac{n_i^2}{N_d}}$

Which is hole concentration in n-type semiconductor.

Increasing Doner atoms (N_d), minority carrier concentration 'p' decreases known as minority carrier suppression.

② P-type semiconductor

When trivalent impurity like B, Ga, In etc are added to pure ~~Stme~~ semiconductor Si or Ge then p-type semiconductor is obtained as shown in fig aside.

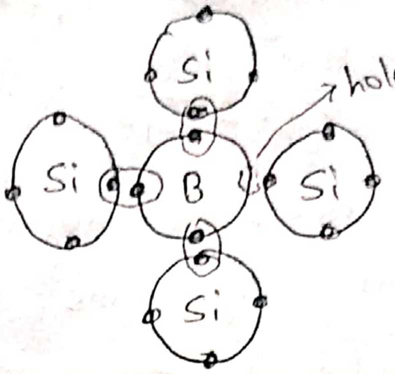


fig. P-type semiconductor

There is deficiency of one electron to form ~~for~~ fourth bond. This means electron vacancy is left in the fourth bond known as hole. The B.E. of this hole to the B^- (ion) can be calculated by using relⁿ. $E_b^B = \frac{m_h^* e^4}{8\epsilon_0^2 h^2} \simeq 0.05eV$.

Hence Acceptor energy level lies 0.05eV above top of 'VB' as shown in fig. aside

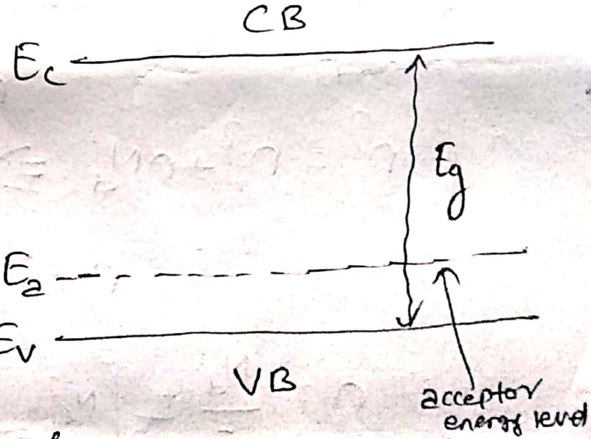


fig. energy level in P-type semiconductor

If 'N_a' be the acceptor concentration then

$$P = N_a + n$$

$$P = N_a + \frac{n_i^2}{P}$$

or $p^2 - N_a P - n_i^2 = 0$

$$P = \frac{-(-N_a) \pm \sqrt{(-N_a)^2 - 4.1.(-n_i^2)}}{2} = \frac{N_a}{2} \pm \sqrt{\frac{N_a^2}{4} + n_i^2}$$

taking +ve $P \simeq \frac{N_a}{2} + \frac{N_a}{2}$ where $\frac{N_a^2}{4} >> n_i^2$

$\therefore$ $\boxed{P \simeq N_a}$ $\therefore$ Eqⁿ. ① becomes $n.P = n_i^2$

$$\Rightarrow \boxed{n = \frac{n_i^2}{N_a}}$$

which is electron concentration in p-type semiconductor increasing acceptor atoms (N_a), minority carrier concentration 'n' decreases known as minority carrier suppression.

① Carrier Concentration and Fermi level in n-type Semiconductor :

Energy level of n-type semiconductor is shown in fig. below.

At equilibrium,

$$n = p + N_d^+ \quad \text{— ①}$$

(N_d^+ → concentration of ionized doner)

$$N_d^+ = N_d\left[1 - f(E_d)\right]$$

(N_d → total doner concentration)

$$= N_d\left[1 - \frac{1}{e^{(E_d - E_f)/k_BT} + 1}\right]$$

$$\therefore N_d^+ \simeq N_d\, e^{(E_d - E_f)/k_BT} \quad \text{— ②} \quad \text{where } (E_f - E_d) \gg k_BT$$

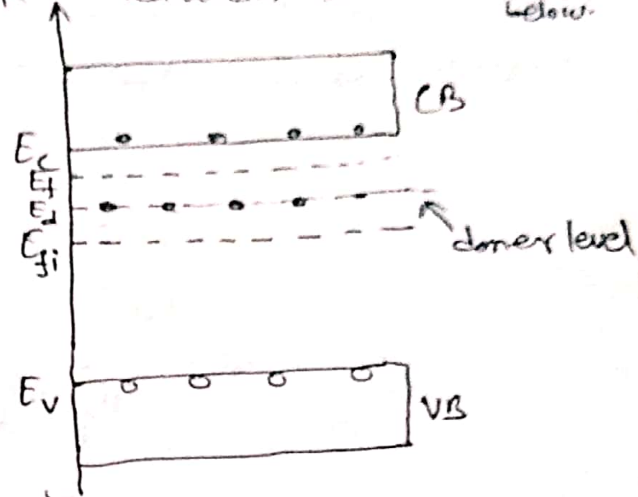


fig. energy level of n-type

Again

$$n = N_c\, e^{(E_f - E_c)/k_BT} \quad \text{— ③} \quad \& \quad p = N_v\, e^{(E_v - E_f)/k_BT} \quad \text{— ④}$$

where, $N_c = 2\left(\dfrac{2\pi m_e^* k_BT}{h^2}\right)^{3/2}$ & $N_v = 2\left(\dfrac{2\pi m_h^* k_BT}{h^2}\right)^{3/2}$

from ①, ②, ③ & ④ we get

$$N_c e^{(E_f - E_c)/k_BT} = N_v e^{(E_v - E_f)/k_BT} + N_d e^{(E_d - E_f)/k_BT} \quad \text{— ⑤}$$

For n-type semiconductor $N_v = 0$

$\therefore$ Eqn. ⑤ becomes, $N_c e^{(E_f - E_c)/k_BT} = N_d e^{(E_d - E_f)/k_BT}$

$$\text{or } e^{\frac{E_f - E_c - E_d + E_f}{k_BT}} = \frac{N_d}{N_c}$$

$$\text{or, } e^{\frac{2E_f - E_c - E_d}{k_BT}} = \frac{N_d}{N_c}$$

$$\text{or, } \frac{2E_f - E_c - E_d}{k_BT} = \ln\left(\frac{N_d}{N_c}\right)$$

$$2E_f - E_c - E_d = k_BT \ln\left(\frac{N_d}{N_c}\right)$$

$$2E_f = E_c + E_d + k_BT \ln\left(\frac{N_d}{N_c}\right)$$

$$\therefore \boxed{E_f = \frac{E_c + E_d}{2} + \frac{k_BT}{2} \ln\left(\frac{N_d}{N_c}\right)} \quad \text{— ⑥}$$

at low temp^n, $T \simeq 0$ kelvin

$E_f \simeq \dfrac{E_c + E_d}{2}$ i.e. Fermilevel lies half way between E_d & bottom of CB. Putting value of 'E_f' from eqn. ⑥ to eqn. ③ we get

$$n = N_c\, e^{\left[\frac{E_c + E_d}{2} + \frac{k_BT}{2} \ln\left(\frac{N_d}{N_c}\right) - E_c\right]/k_BT}$$

or, $\boxed{n = (N_c N_d)^{1/2} e^{-\frac{\Delta E}{2K_BT}}}$ —(7) which is required expression for carrier concentration of n-type semiconductor at low tempr.

where $\Delta E = E_c - E_d$.

From eqn. (6) the variation of 'E_f' with tempr. for different impurity concentration 1, 2, & 3 is shown in fig. below

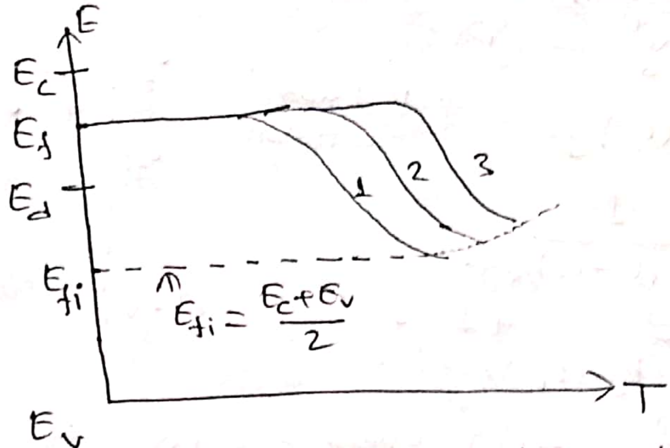


fig: Dependence of fermilevel with tempr. in n-type

(2) Carrier Concentration and Fermilevel in p-type semiconductor: The energy level diagram of p-type semiconductor is shown in fig. below

At equilibrium,

$P = n + N_a^-$ —(1) N_a^- → concentration of ionized acceptor

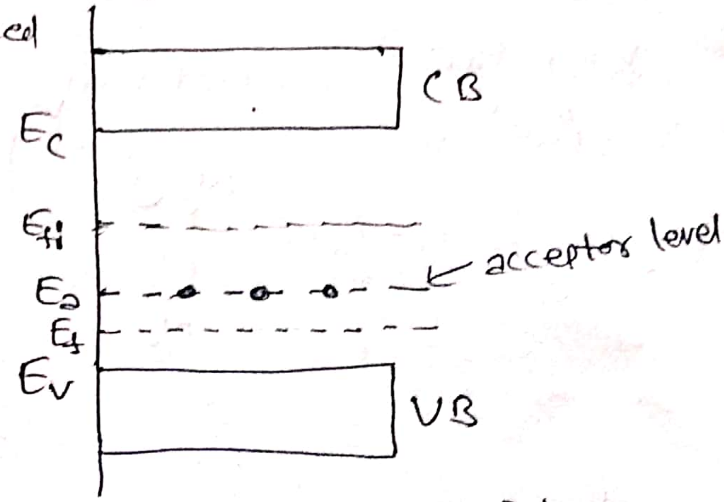


fig. Energy level of p-type

$N_a^- = N_a f(E_a)$

N_a → Total acceptor concentration

or, $N_a^- = N_a \dfrac{1}{e^{(E_a - E_f)/K_BT} + 1}$

as $(E_a - E_f) >> K_BT$ then

$N_a^- \simeq N_a e^{-(E_a - E_f)/K_BT}$ —(2)

Also $P = N_v e^{(E_v - E_f)/K_BT}$ —(3) & $n = N_c e^{(E_f - E_c)/K_BT}$ —(4)

From eqn. (1) (2) (3) & (4)

$$N_v e^{(E_v-E_f)/k_BT} = N_c e^{(E_f-E_c)/k_BT} + N_a e^{-(E_a-E_f)/k_BT} \quad -(5)$$

For p-type $N_c = 0$, ∴ eq^n (5) becomes,

$$N_v e^{(E_v-E_f)/k_BT} = N_a e^{-(E_a-E_f)/k_BT}$$

or, $$e^{(E_v-E_f+E_a-E_f)/k_BT} = \frac{N_a}{N_v}$$

or, $$\frac{(E_v+E_a)-2E_f}{k_BT} = \ln\left(\frac{N_a}{N_v}\right)$$

or, $$(E_v+E_a)-2E_f = k_BT\ln\left(\frac{N_a}{N_v}\right)$$

$$2E_f = E_v+E_a - k_BT\ln\left(\frac{N_a}{N_v}\right)$$

or $$\boxed{E_f = \frac{E_v+E_a}{2} - \frac{k_BT}{2}\ln\left(\frac{N_a}{N_v}\right)} \quad -(6)$$

at low temp^r. $T \approx 0$ kelvin

$$E_f \simeq \frac{E_v+E_a}{2}$$

i.e. fermilevel lies half way between acceptor level and top of VB.

Putting value of E_f from eq^n (6) to eq^n (3) we get

$$P = N_v e^{\left[E_v - \left\{\frac{E_v+E_a}{2} - \frac{k_BT}{2}\ln\left(\frac{N_a}{N_v}\right)\right\}\right]/k_BT}$$

or, $$\boxed{P = (N_vN_a)^{1/2} e^{-\frac{\Delta E}{2k_BT}}} \quad -(7)$$

where $\Delta E = E_a - E_v$

Which is required expression for carrier concentration of p-type semiconductor at low temp^r.

From eq^n (6) the variation of 'E_f' with temp^r. for different impurity concentration 1, 2, 3 is shown in fig. below

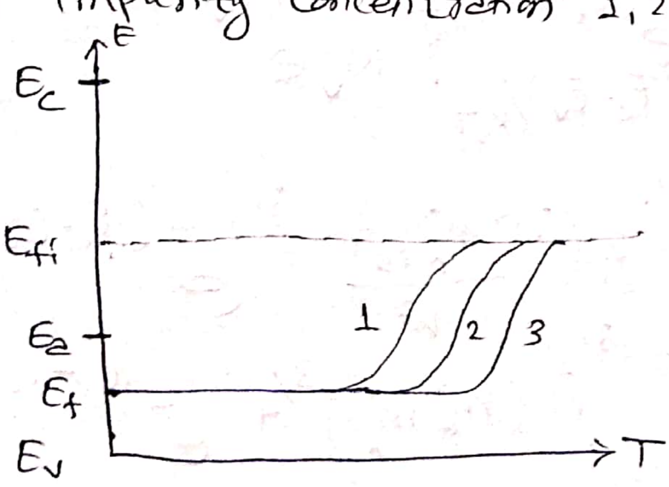


fig. dependence of fermilevel with temp^r. in p-type

Electrical Conductivity of semiconductor:

Total current density in semiconductor is

$J = J_e + J_h = nev_e + pev_h$ where 'v_e' is drift velocity electron & 'v_h' is drift velocity hole

Since, mobility $\mu = \frac{v}{E} \Rightarrow v = \mu E$ ← applied e.f.

then, $J = ne\mu_e E + pe\mu_h E = (ne\mu_e + pe\mu_h)E$ — ①

Comparing eqⁿ ① with $J = \sigma E$ → Conductivity of Semiconductor

$$\boxed{\sigma = ne\mu_e + pe\mu_h}$$

where, electron mobility $\mu_e = \frac{e\tau_e}{m_e^*}$

& hole " $\mu_h = \frac{e\tau_h}{m_h^*}$

① Electrical Conductivity of intrinsic semiconductor:

For intrinsic semiconductor, at eqⁿ state,

$n = p = n_i$ say, ∴ Eqⁿ ① becomes

$$\therefore \sigma = en_i(\mu_e + \mu_h) \quad - ②$$

Now, $n_i^2 = np = N_c e^{(E_f - E_c)/k_BT} \cdot N_v e^{(E_v - E_f)/k_BT}$

$$n_i^2 = N_c N_v e^{-(E_c - E_v)/k_BT}$$

$$= 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} \cdot 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} e^{-(E_c - E_v)/k_BT}$$

$$n_i = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-(E_c - E_v)/2k_BT}$$

∴ Eqⁿ ② becomes

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

where $E_c - E_v = E_g$

or, $\boxed{\ln\sigma = -\frac{E_g}{2K_B}\cdot\frac{1}{T} + \frac{3}{2}\ln T + C}$ —(2)

variation of 'σ' with temp^r. 'T' is shown in graph.,
graph of $\ln\sigma$ versus $\frac{1}{T}$ is straight line whose ~~so~~ slope gives value of band gap energy
$E_g = \text{slope} \times (2K_B)$

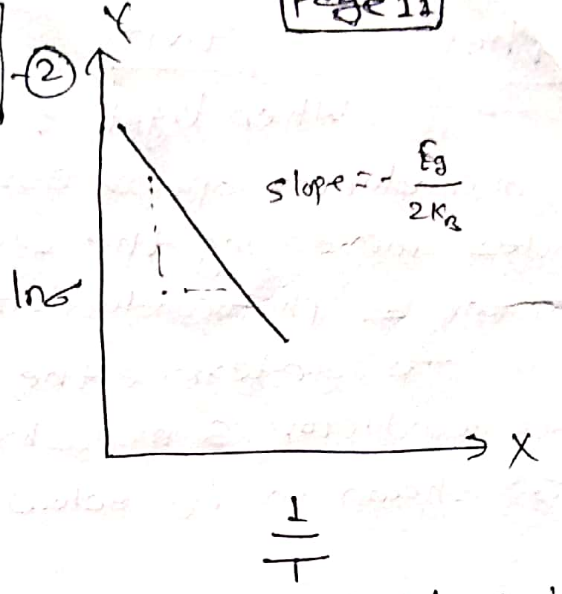


fig. variation of $\ln\sigma$ with $1/T$

(2) Electrical Conductivity of n-type semiconductor:

$\sigma = ne\mu_e$

or, $\sigma = e\mu_e \frac{N_d}{1 + e^{(E_f - E_d)/k_BT}}$ — doner concentration

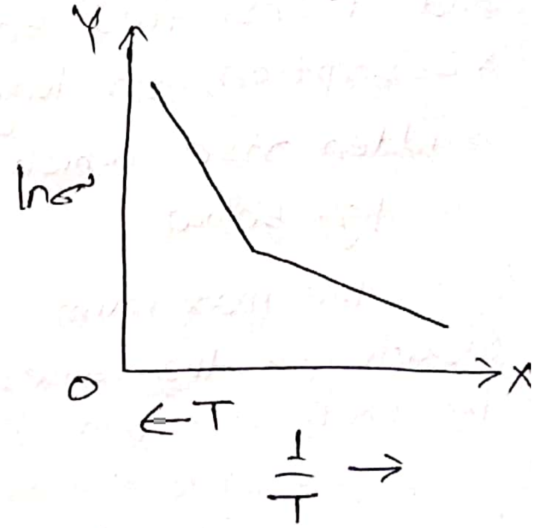
~~[illegible]~~

$\therefore \sigma = e\mu_e N_d \frac{1}{(e^{(E_f-E_d)/k_BT}+1)}$

$\ln\sigma = -\ln\left[e^{(E_f-E_d)/k_BT}+1\right] + C$ —(3)

where $C = \text{Const} = \ln(e\mu_e N_d)$

at low temp^n. $E_f > E_d$
So $\ln\sigma$ varies linearly with $\frac{1}{T}$ as shown in fig. below



(3) Electrical Conductivity of p-type semiconductor

$\sigma = pe\mu_h$

$\sigma = e\mu_h \frac{N_a}{e^{(E_a-E_f)/k_BT}+1}$

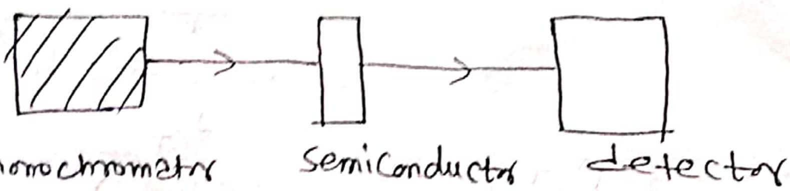
$\ln\sigma = -\ln\left[e^{(E_a-E_f)/k_BT}+1\right] + C$

graph is same above.

Photoconductivity

When light of suitable frequency is illuminated on the semiconductor optical absorption creats extra electrons and holes increasing the electrical conductivity of semiconductor known as photoconductivity.

To determine the absorption of em radiation by a semiconductor, a monochromator is used in a experiment as shown in fig. below



Here, light of different frequency from monochromator is allowed to strike on semiconductor and intensity of transmitted radiation is measured by detector. The absorbed radiation is calculated by taking difference of intensity of incident and transmitted beam. The semiconductor shows negligible absorption for long wavelengths (small frequency) and then sudden rise, which is called absorption edge as shown in fig. below

The maximum wavelength that causes the photoconduction is known as critical wavelength (λ_c) whose value is 1.13×10^{-6} m for Si

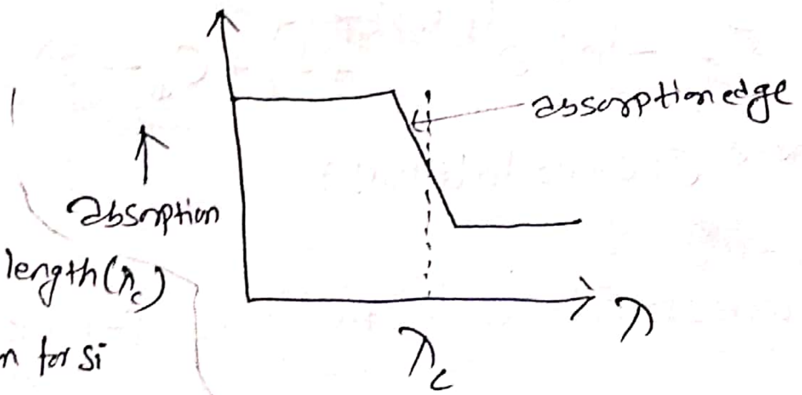


fig. absorption edge

If $\frac{hc}{\lambda_c} < E_g$ then electron will not able to excited from VB into CB and photon will not be absorbed by electrons. So that radiation will go through semiconductor.

If $\frac{hc}{\lambda_c} = E_g$ then electron absorbed photon or radiation

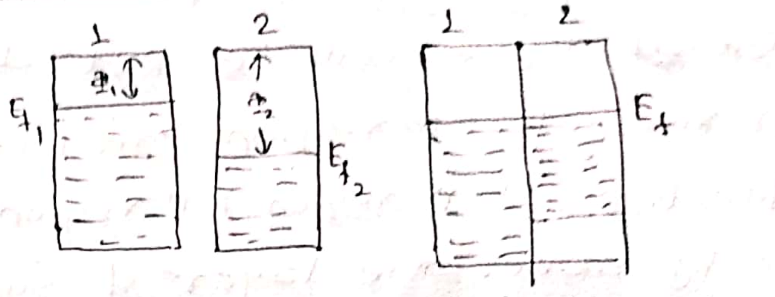
for Si $E_g = \frac{6.63\times10^{-34}\times3\times10^{8}}{1.13\times10^{-6}} \simeq 1.8\times10^{-19}\,J = \frac{1.8\times10^{-19}}{1.6\times10^{-19}}\,eV = 1.1\,eV$

Metal-metal Junction (Contact Potential)

When two metals of different fermilevel and workfunctions are brought in contact, electron from higher feremilevel flow into lower fermilevel ($E_{f_1} > E_{f_2}$). ~~metal~~ As a result pd. is developed at the junction called Contact potential which prevents the further flow of electron when becomes maximum value 'V_c' (equilibrium state). At equilibrium the Fermilevel of both metal is same (E_f) as shown in fig above.

If Φ_1 & Φ_2 be work function of metal '1' & metal '2' then

$$eV_c = \Phi_2 - \Phi_1$$



fig① before Contact   fig② after contact

The semiconductor Diode:

When p-type semiconductor is suitably joined to an n-type semiconductor, a junction is formed called p-n junction and device so formed is called p-n junction diode as shown in fig. below

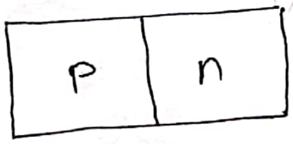


fig ① physical Composition of p-n Junction diode

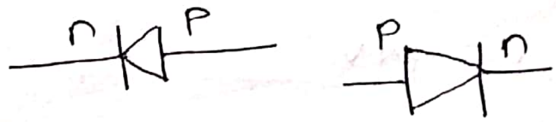
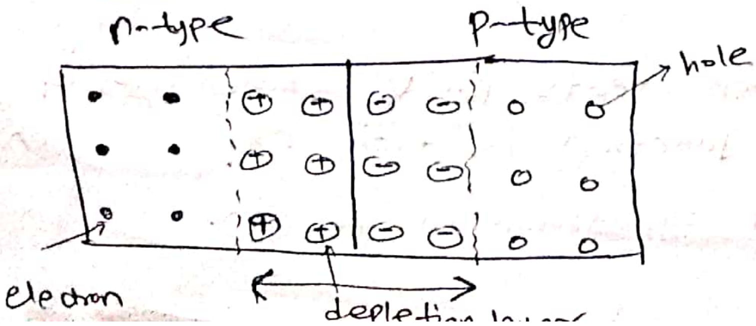
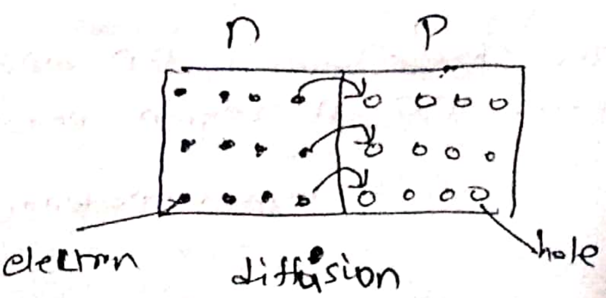


fig. ② electronic symbol of p-n junction diode.

Formation of Depletion layer and Barrier potential:

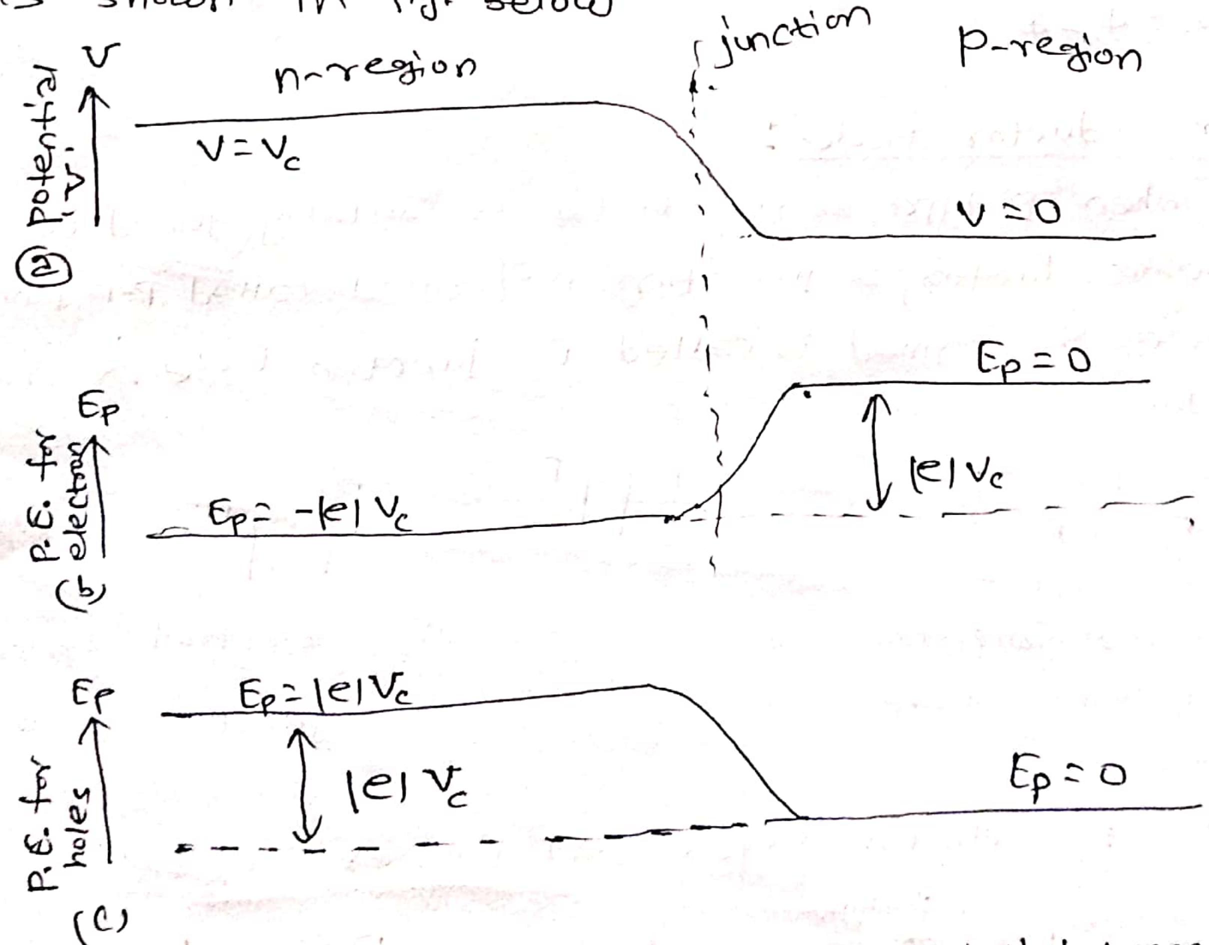




When two types of semiconductor are in contact then ~~et~~ there will be net diffusion of electron from n-region to p-region creating +ve & -ve ions near junctions at 'n'-region & p-region respectively as shown in fig. above. The layer of such ions is called depletion layer and corresponding p.d. is called Barrier potential which prevents further diffusion of electron. Barrier potential is denoted by "V_c" or 'V_b'.

Band scheme of a p-n junction

The variation of potential and P.E. barrier for electron & hole ~~is~~ in n-region & p-region of p-n junction is shown in fig. below



The charge layer in p-n junction creats p.d. 'V_c' between sides of junctions. Since n-region near junction is +vely charged then n-region is higher potential as shown in fig. (a).

~~When~~ P.E. of electron in n-region $= -|e|V_c = E_p$
" " " " p-region $= 0 = E_p$
So that P.E. of electron in p-region shifted upward by an amount $|e|V_c$.

P.E. of hole in n-region $(E_p) = 0$
While " " " " p-region $(E_p) = |e|V_c$ This P.E. barrier stops the further flow of majority carriers across junction.

~~The upward shift of~~

Due to contact potential (V_c), there is upward shift of electronic energy bands in p-side, relative to n-side by amount $|e|V_c$. The energy band of n-type and p-type semiconductor with fermilevel before and after contact is shown in fig. below.

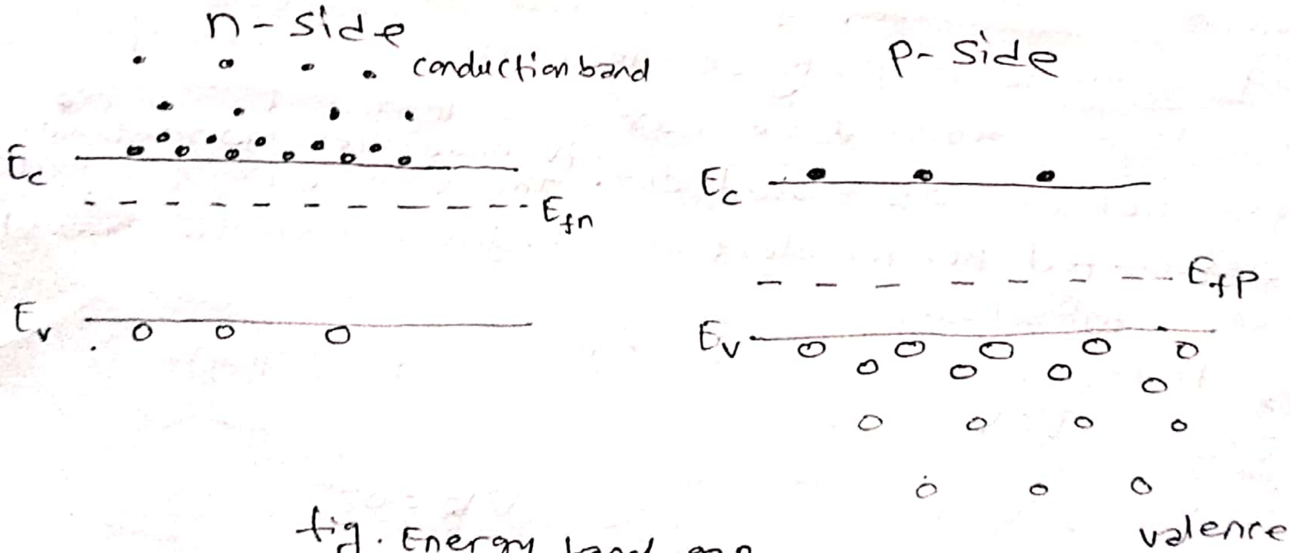


fig. Energy band gap before contact

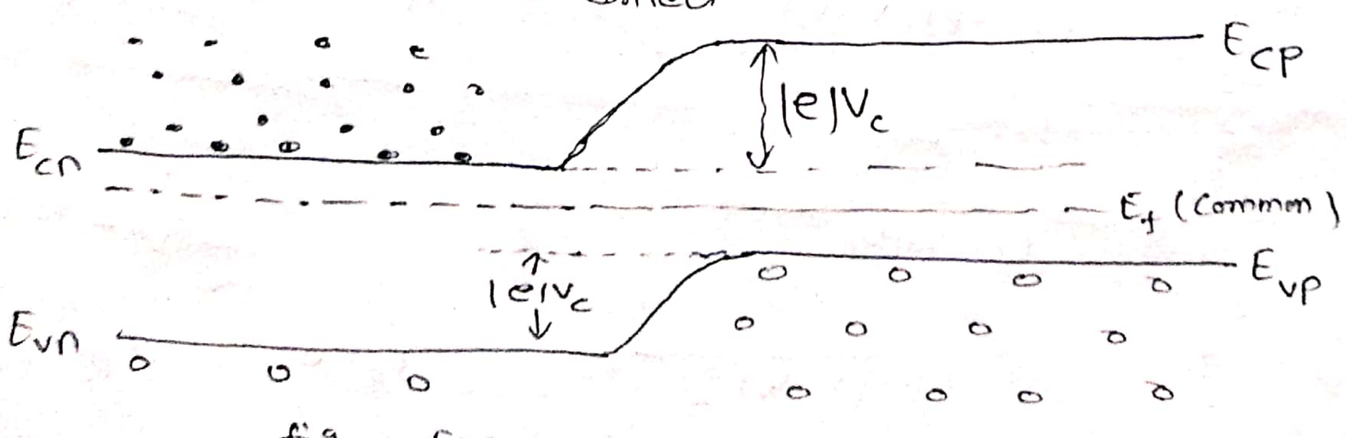


fig. Energy band after contact

~~When~~ P.E. of electron in n-region $= -|e|V_c = E_p$
" " " " p-region $= 0 = E_p$

So that P.E. of electron in p-region shifted upward by an amount $|e|V_c$.

P.E. of hole in n-region $(E_p) = 0$
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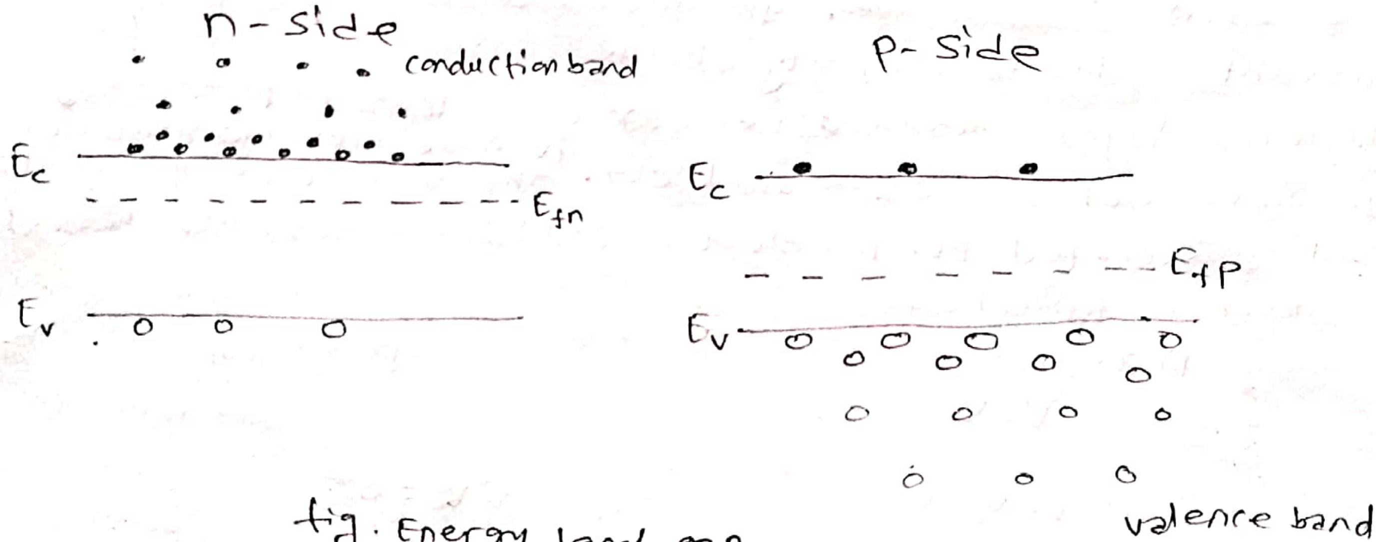


fig. Energy band gap before contact

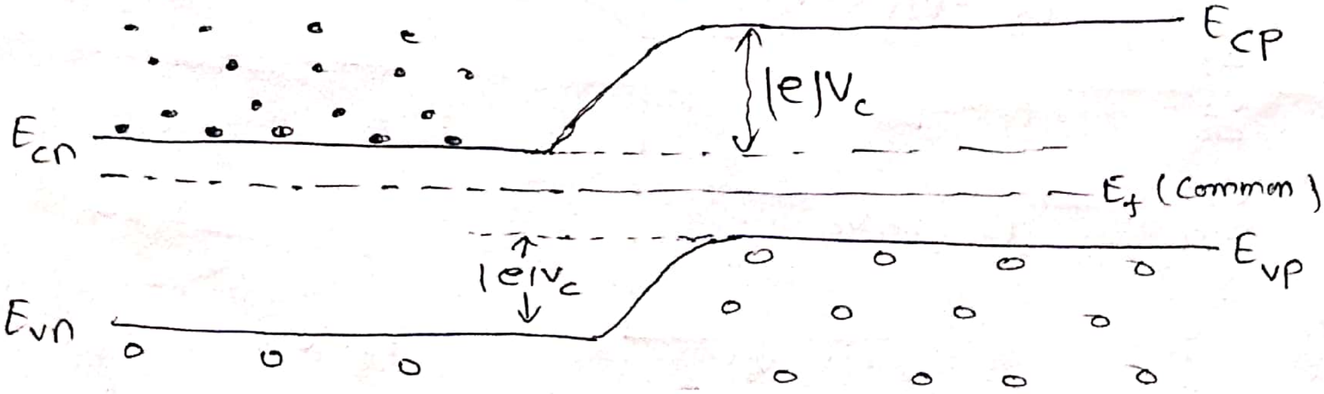


fig. Energy band after contact

As common fermi energy (E_f) fermilevel is same on both side after contact, the energy shift in bands $|e|V_c$ must be equal to the difference between the energies of the conduction band and the energies of VB.

i.e. $|e|V_c = E_{cp} - E_{cn} = E_{vp} - E_{vn}$

~~Forward~~

Forward and Reverse Biased p-n Junction diode

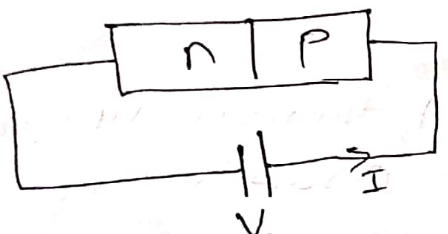


fig ① Forward Biased

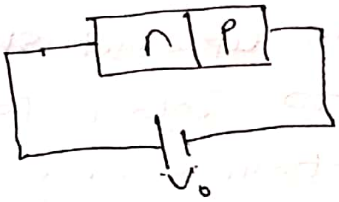


fig ② Reversed biased

Forward biased In forward biasing +ve terminal of Battery is connected to to n-side to p-side while -ve terminal is connected as shown in fig ① above. In forward biasing ① flow of current is due to majority charge carrier (ii) width of depletion layer decreaseds i.e. barrier potential decreased (iii) Diode behaves as closed ckt. (iv) Diode offers low resistance. The variation of potential and associated P.E. for electrons and holes in forward biased is shown in fig ③ below.

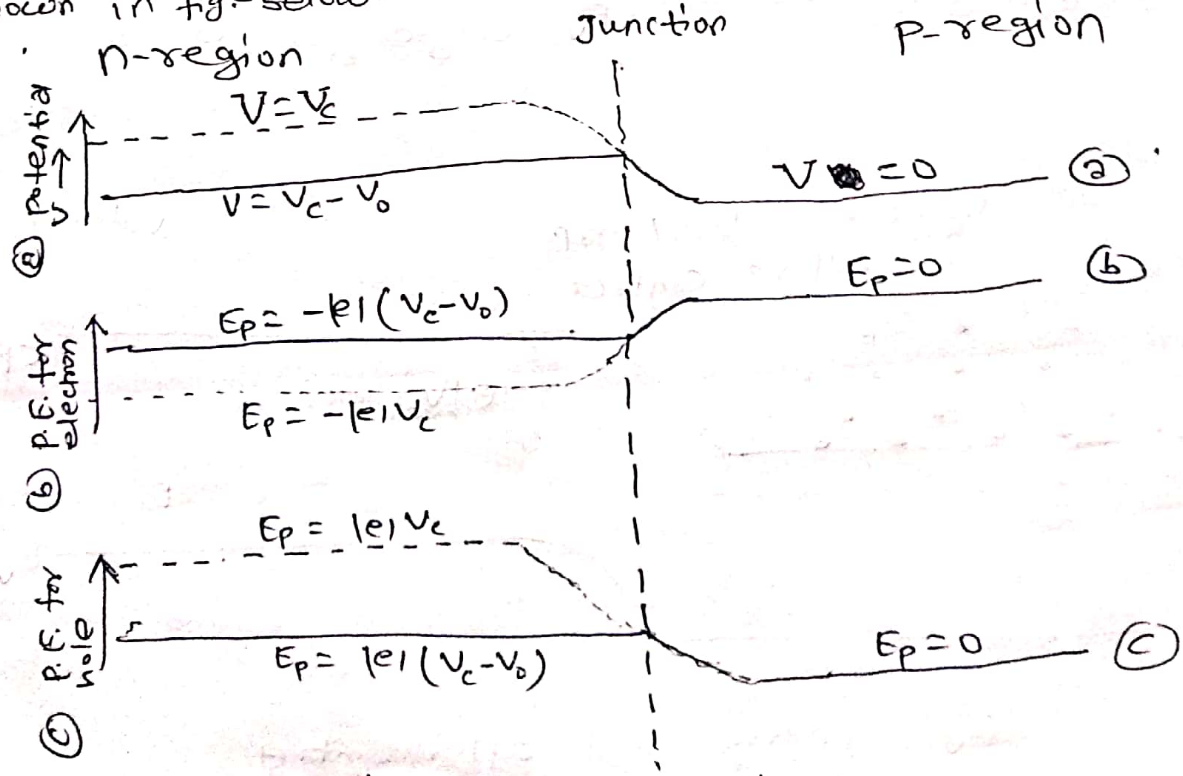


fig. ③ Forward biased.

Due to applied potential V_o, ~~potential~~ pd. between p-side and n-side reduced to $(V_c - V_o)$ as shown in fig. (3) a. So that The P.E. of electron in n-region $E_p = +|e|(V_c - V_o)$ where as in p-region $E_p = 0$ as shown in fig. (3) b (solid line)

The P.E. of hole in n-region $E_p = |e|(V_c - V_o)$ where as in p-region $E_p = 0$ as shown in fig. (3) c (solid line)

Here dashed line represents old energy barrier (unbiased condition)

Reversed biased:

In reversed biasing +ve terminal of battery is connected to n-region while -ve terminal is connected to p-region as shown in fig. (2) above. In ~~forward~~ reverse biasing (i) flow of current is due to minority carrier (ii) width of depletion layer increases i.e. barrier potential increases. (iii) Diode behaves as open ckt. (iv) Diode offers high resistance

The variation of potential and associated P.E. for electrons and holes in in reversed biased is shown in fig (4)

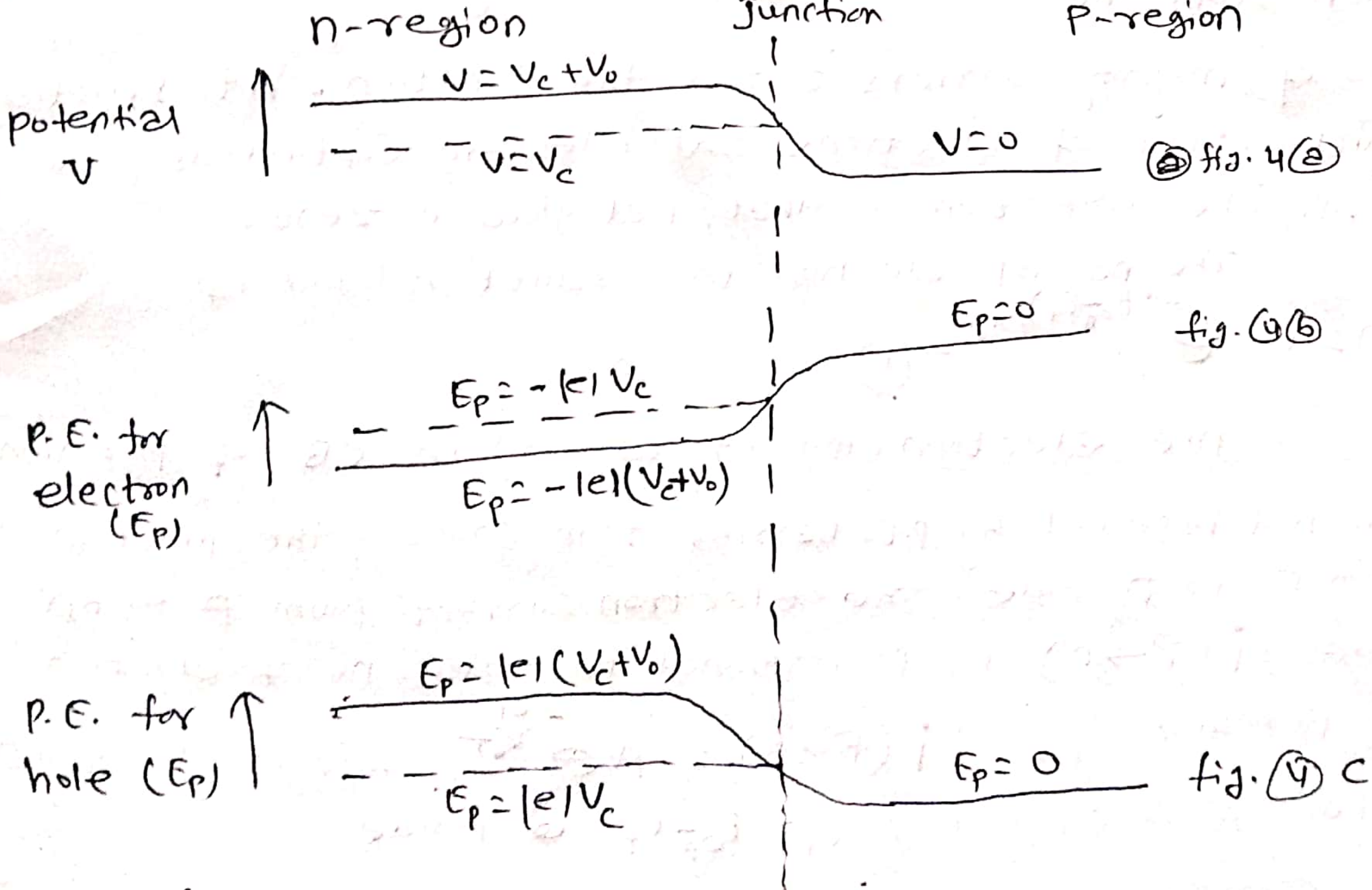


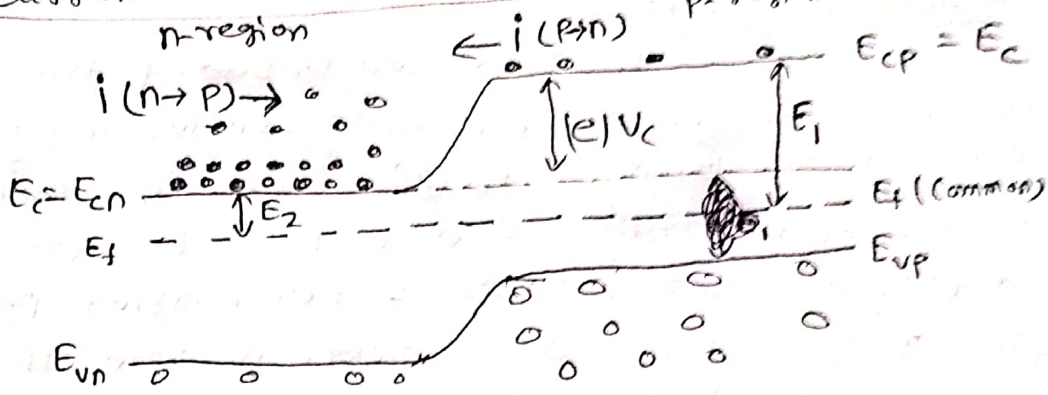
fig. (4) Reverse biased.

Due to applied potential V_o, pd. between p-side and n-side near junction increased to $(V_c + V_0)$ as shown in fig. (4) a. So that that P.E. of electron near n-region is $E_p = -|e|(V_c + V_0)$ where as p-region $E_p = 0$ as shown in fig. (4) b (solid line)

The P.E. of hole in n-region $E_p = |e|(V_c + V_0)$ where as p-region $E_p = 0$ (solid line). Dashed line represents energy barriers in unbiased condition.

Current Flow across P-n Junction Diode

(i) Equilibrium currents across P-n Junction:



When p-n junction is formed, P.E. barrier $|e|V_c$ is formed which stops the

fig. (1) Energy band at eq^n.

flow of majority carriers across the junction. At junction, equal amount of electrons and holes are continuously flowing in opposite direction so that, net flow is zero.

The no. of electron in conduction band is

$$n = N_c \, e^{-(E_{cn} - E_f)/K_B T} \quad -(1)$$

The electron (minority carrier) in CB of p-region are not impeded by P.E. barrier from crossing the junction from 'p' to 'n' side. The electron current from 'p' to 'n' side $i(P \to n)$ is proportional to total no. of electron in p-region i.e.

$$i(P \to n) = A \, e^{-\frac{E_1}{K_B T}} \quad -(2)$$

where 'A' is constant & $E_1 = E_{cp} - E_f$ of p-side

In n-region, there are large no. of electron (majority carrier) in CB. Only electrons having energy equal or greater than barrier energy $|e|V_c$ will able to

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cross the Junction, so that electron current

$i(n \to p)$ is proportional to no. of electrons with energy higher than or equal to $|e|V_c$.

i.e. $i(n\to p) = A\, n\, f(E \geq |e|V_c)$ — (3)

According to maxwell-Boltzman distribution of energies, the fraction of particle energies $f(E \geq |e|V_c) = e^{-|e|V_c/K_BT}$ — (4)

from (1), (3) & (4) $i(n\to p) = A\, e^{-(E_{cn} - E_f + |e|V_c)/K_BT}$

$E_{cn} - E_f = E_2$

$\therefore \quad i(n\to p) = A\, e^{-(E_2 + |e|V_c)/k_BT}$ — (5)

Put $E_2 + |e|V_c = E_1$ in eq^n (5), $\therefore \; i(n\to p) = A\, e^{-E_1/K_BT}$ — (6)

from eq^n (2) & (6) $i(n\to p) = i(p\to n)$

which is the condition for eq^m current across the junction

(ii) Net flow of charge carriers accross the junction (Diode Equation)

When potential $V_0 = V$ is applied across the junction under forward biased condition, the height of P.E. barrier at p-n junction is $|e|(V_c - V_0)$. The net electron current from 'n' to 'p' side is $i = i(n\to p) - i(p\to n)$.

$$i = A\, e^{-\{E_2 + |e|(V_c - V_0)\}/K_BT} - A\, e^{-E_1/K_BT}$$

$$i = A\, e^{-\{E_1 - |e|V_0\}/K_BT} - A\, e^{-E_1/K_BT} \quad \text{where } E_2 + |e|V_c = E_1$$

$$i = A\, e^{-E_1/K_BT}\left(e^{|e|V_0/K_BT} - 1\right)$$

$$\boxed{i = i_0\left(e^{\frac{|e|V_0}{K_BT}} - 1\right)} \text{ — (7)}$$

Eq^n (7) is called diode Eq^n.

where $i_0 = A\, e^{-E_1/K_BT}$