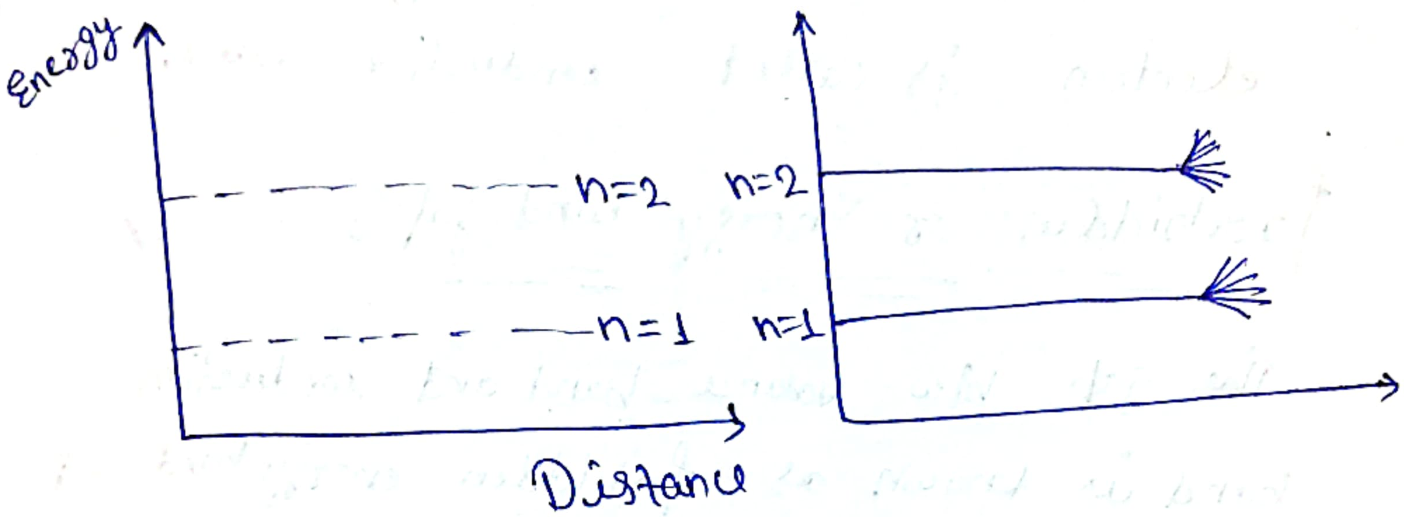
Unit : (2)

: Semi - Conductor Physics :

Band Theory in Solids :



In a Solid, atoms are very closed to each other, therefore the interaction b/w the electron of different atoms in the same orbit takes place. as a result, the energy of electron in the same orbit get modified and forms a band known as energy band.

⇒ Hence, the range of energies possessed by the electron in the same orbit in a solid known as energy band.

Valunce band :- The range of energies possessed by the valunce electrons or outermost shell electrons is called valunce band.

Conduction band :- The range of energies possessed by free electron is called conduction band.

forbidden or Energy band gap :-

The gap b/w valunce band and conduction band is known as forbidden energy band gap.

⇒ The unit of band is eV or Joule.

for ex :- Sillicon have 1.1eV band gap,
Germanium have 0.7eV band gap

Classification of Conductors, Insulators and Semiconductors on the basis of band theory :-

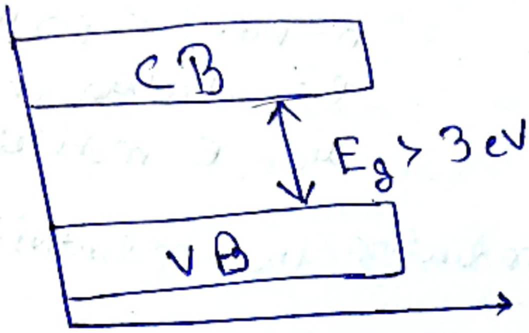
According to band theory :-

⇒ Solids are divided into three categories :-

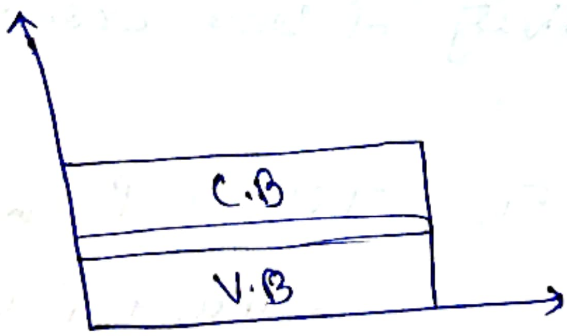
(i) Insulator
(ii) Conductor
(iii) Semi-conductor

Insulator :- In insulator, the valence band is completely full ~~or~~ while conduction band is empty.

they have large energy gap between valence band & conduction band (more than 3 eV)



Conductors :- Conductors are the material in which conduction band and valence band overlap with each other.



Semiconductor :- The valence band & conduction band are separated by a small distance (1.1 eV for sillicon and 0.7 eV for germanium).

⇒ Semiconductor behaves as insulator at temp. 0K. when temperature increases or small electric field is applied than e^- jump to the conduction band and conduct electricity.

Eg:- Sillicon, Germanium.

Conductivity in Semiconductors:-

according to free e^- theory, the conductivity of metals are given by:

$\sigma = n_e n e \mu_e$ $\quad$ n = no. of e^- per unit volume

e = electron charge

μ_e = e^- mobility.

in case of semiconductor the conductivity due to e^- is $\sigma_n = ne\mu_e$

similarly for holes $\sigma_h = Pe\mu_h$

where P is the no. of holes/volume. μ_h is holes mobility

∴ the total conductivity of semi-conductor is given by

$$\sigma = \sigma_n + \sigma_h \quad = ne\mu_e + Pe\mu_h$$

$$= e(n\mu_e + P\mu_h)$$

Intrinsic semiconductors are pure semiconductors.

Eg:- Sillicon, Germanium.

In intrinsic semiconductor,
no. of holes = no. of e^-

$$n = p$$

therefor the conductivity of intrinsic semiconductor is given by.

$$\sigma_i = e[n\mu_e + p\mu_h]$$

$$\sigma_i = ne[\mu_e + \mu_h]$$

Conductivity in Extrinsic Semiconductor :-

when a small amount of impurity atom is added to pure semiconductor than the semiconductor is called Extrinsic semiconductor.

they are of two types :-

(i) P-type extrinsic semiconductor
(ii) N-type extrinsic semiconductor

P-type Semiconductor :-

when trivalent impurity atom is added to pure semiconductor. than the semiconductor is called P-type semiconductor.

Conductivity in P-type Semiconductor :-

In P-type semiconductor, the no. of holes or concentration of holes is much greater than concentration of e^-.
In P-type semiconductor, the holes concentration is represented by by N_A (where N_A is the concentration of acceptor atom)

therefore the conductivity for P-type semiconductor is :-

$$\boxed{\begin{aligned} \sigma_h &= p\mu_h e \\ \sigma_h &= eN_A\mu_h \end{aligned}}$$

N-type Semiconductor :-

N-type semiconductors are those semiconductor which is produced when pentvalent impurity is added to intrinsic semiconductor

→ the majority charge carriers in of N-type semiconductor are e^-.

* The conc. of of e^- also represented by N_d (conc. of donor atom)

and $\sigma_p = n e \mu_e$

$$\boxed{\sigma = N_D e \mu_e}$$

Fermi Dirac Probability Distribution fn:

Fermi Dirac Probability Distribution fn, gives the probability of finding the electrons in particular energy level of energy E at particular temperature T.

The Fermi-Dirac Probability distribution fn is given by:

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

where $E \rightarrow$ energy of e^- of energy level having energy E

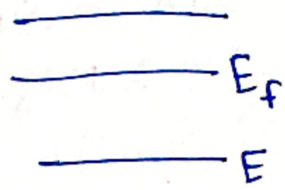
E_F = Fermi energy

$K \rightarrow$ Boltzman constant

$T \rightarrow$ absolute temperature (in K).

To study the Fermi - Dirac probability fn for the following cases:

(i) when $E < E_f$ and $T = 0K$



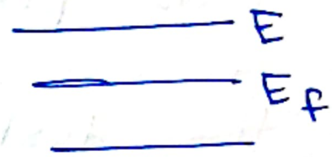
$\therefore E - E_f$ is $-ve$

$$\therefore \quad F(E) = \frac{1}{1+e^{-\infty}}$$

$$F(E) = \frac{1}{1+1/e^{\infty}} = \frac{1}{1+0} = 1$$

$$F(E) = 1$$

(ii) when $E > E_f$ and $T = 0K$



$\therefore \quad E - E_f > 0$

$$F(E) = \frac{1}{1+e^{\infty}} = 0$$

$$F(E) = 0$$

* Case (I) & case (II) concluded that all energy levels are occupied at 0K when e $E < E_f$ and empty when $E > E_f$.

Fermi - level :

It is the energy in a solid below which all energy levels are occupied and ~~empty~~ all energy levels above this are empty at 0K.

(*) In another words, fermi energy is maximum energy occupied by e^- at 0K.

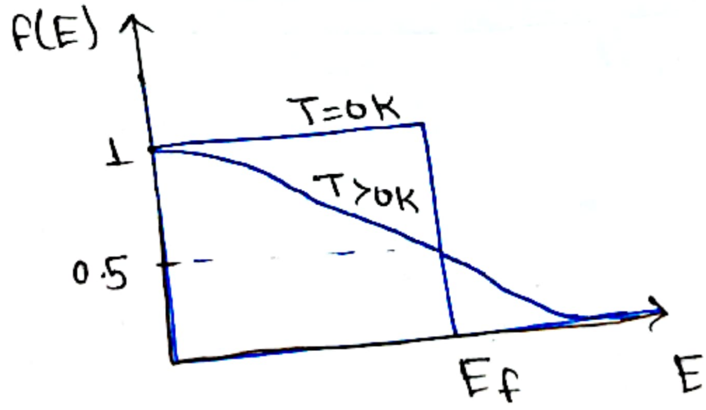
(iii) If $E = E_f$ and $T > 0K$

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

$$F(E) = \frac{1}{1+1} = \frac{1}{2}$$

(*) it concluded that, fermi level may also be defined for which, the probability of occupation finding of electron is half at $E = E_f$ at 0K.

⇒ The variation of $F(E)$ vs E at T=0K : and at $t > 0$



Ques: find the value of F(E) for $E - E_f = 0.01\ eV$ at 200K

~~Ans~~ **Sol:**

$$F(E) = \frac{1}{1 + e^{(E-E_f)/kT}}$$

$$F(E) = \frac{1}{1 + e^{\frac{0.01}{8.6 \times 10^{-5} \times 200}}}$$

$$F(E) = \frac{1}{1+e}$$

Ques: At what temp. can we expect a 10% probability that e^- in a metal will have an energy which is 1% above E_f. the fermi energy of metal is 5.5 eV.

Fermi-level :

Fermi level is the energy level that corresponds to the center of gravity of e^- and holes weighted according to their energies.

Fermi-level in intrinsic semiconductor :

In intrinsic semiconductor, no. of e^- & no. of holes are equal therefore, fermi level lie in the middle of conduction band and valence band.

Derivation :

⇒ In intrinsic semiconductor, no. of e^- is given by :-

$$\boxed{n = N_c e^{-(E_c - E_f)/KT}}$$

E_c = lowest energy of conduction band

E_f = fermi-level energy

K = boltzmann constant

N_c = Density of state function in conduction band / allowed energy states C.B.

T → absolute temp.

$K = 1.38 \times 10^{-23}\ m^2 kg\, s^{-2} K^{-1}$

$\boxed{1.38 \times 10^{-23}}$

⇒ No. of holes in valence band :

$$\boxed{p = N_v e^{-(E_f - E_v)/KT}}$$

N_v = density of state fn in V.B.

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

E_v = highest energy of V.B.

m_e^* = effective mass of e^-.

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

In intrinsic semiconductor,

no. of e^- = no. of holes

$$N_c e^{-(E_c - E_f)/KT} = N_v e^{-(E_f - E_v)/KT}$$

$$\frac{N_c}{N_v} = \frac{e^{-(E_f - E_v)/KT}}{e^{-(E_c - E_f)/KT}}$$

$$\frac{N_c}{N_v} = e^{(E_c + E_f - 2E_f)/KT}$$

$$\log\left(\frac{N_c}{N_v}\right) = \cancel{Ec + Ev + 2} \; \frac{E_c + E_v - 2E_f}{KT}$$

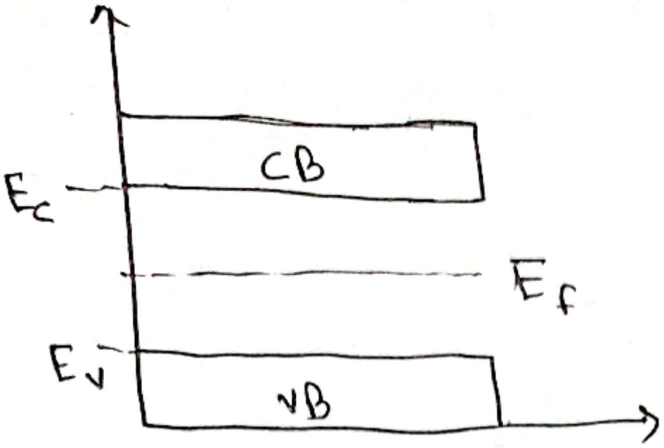
in intrinsic semiconductor, $N_c = N_v$

$$\log(1) = \frac{E_c + E_v - 2E_f}{KT}$$

$$E_c + E_v = 2E_v$$

$$\boxed{E_f = \frac{E_c + E_v}{2}}$$

⇒ which shows that fermi level lies between C.B. & V.B. in intrinsic semiconductor.



Fermi level in N-type semi-conductor :-

In N-type semiconductor, e^- are the majority charge carriers. Now fermi levels in upward direction and shifted towards the conduction band.

In N-type semiconductor.

No. of e^- = No. of donar atoms.

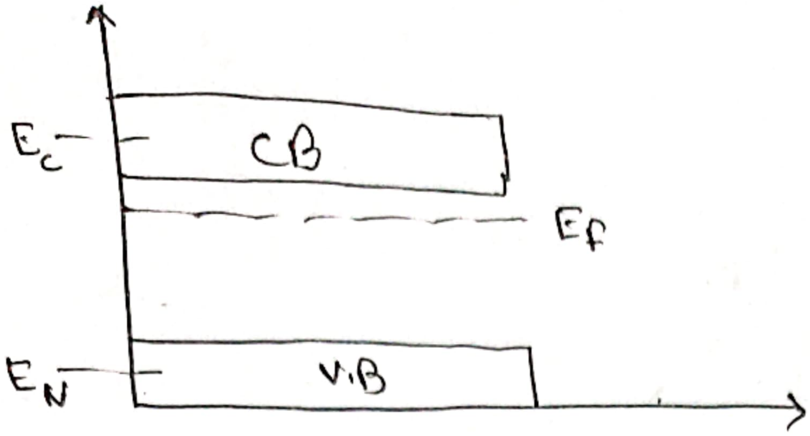
$$n = N_D$$

$$N_c\, e^{-(E_c - E_f)/KT} = N_D$$

$$\frac{N_c}{N_D} = e^{(E_c - E_f)/KT}$$

$$\log\left(\frac{N_c}{N_D}\right) = (E_c - E_f)/KT$$

$$\boxed{E_f = E_c - KT \log\left(\frac{N_c}{N_D}\right)}$$

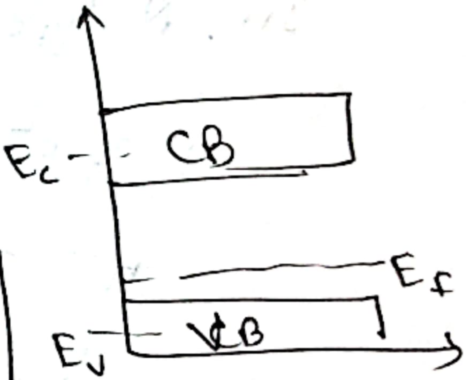


Fermi level of p type semiconductor :

$P = N_A \rightarrow$ no. of acceptor atom

$$N_v e^{-(E_f - E_v)/KT} = N_A$$

$$\frac{N_v}{N_A} = e^{(E_f - E_v)/KT}$$



$$\boxed{E_f = E_v + KT \log\left(\frac{N_v}{N_A}\right)}$$

Free charge carrier density in intrinsic semiconductor :

In intrinsic semiconductor, carrier density is represented by $\boxed{n_i^2 = n \times P}$

$$n_i^2 = n \times p$$

$$n_i^2 = N_c e^{-(E_c - E_F)/KT} \cdot N_v e^{-(E_F - E_v)/KT}$$

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

$$n_i^2 = \left(\frac{2\pi KT}{h^2}\right)^3 (m_e^* . m_h^*)^{3/2} e^{-E_g/KT}$$

$$n_i = \left(\frac{2\pi KT}{h^2}\right)^{3/2} (m_e^*)^{3/4} . (m_h)^{3/4} e^{-E_g/2KT}$$

Ques:- In a P-type semiconductor, the fermi-level is 0.3 eV above the valence band at temp. 300K, determine the new position of fermi level at temp. 400K.

Sol:- as

$$E_f = E_v + KT \log\left(\frac{N_V}{N_A}\right)$$

$$E_f = E_v + 0.3$$

$$E_f - E_v = 0.3 \quad \text{—— (1)} \longrightarrow \text{at temp 300K}$$

as $$E_f - E_v = KT \log\left(\frac{N_v}{N_A}\right)$$

$$0.3 = K(300) \log\left(N_v/N_A\right) \quad \text{—— (2)}$$

Similarly $E_f - E_v = K(400) \log\left(\frac{N_v}{N_A}\right)$ — (III)

on (II)/(III),

$$\frac{0.3}{E_f - E_v} = \frac{300}{400}$$

$$E_{f_0} - E_v = 0.4\,eV$$

Ques: In an N-type semiconductor is 0.3 eV below the conduction band at 300K. if the temperature is increased and become 330 K.

Sol:

$$E_f = E_c - KT \log\left(\frac{N_c}{N_D}\right)$$

$$E_f - E_c = 0.3\,eV$$

as at 300 K

$$E_f - E_c = K(300) \log\left(\frac{N_c}{N_D}\right)$$

~~and~~ $\Rightarrow$ $0.3\,eV = K(300) \log\left(\frac{N_c}{N_D}\right)$ — (I)

and at 330 K,

$$E_f - E_c = K(330) \log\left(\frac{N_c}{N_D}\right) \quad \text{— (II)}$$

on (I)/(II) $\frac{0.3}{E_f - E_c} = \frac{300}{330}$

$$\boxed{E_f - E_c = 0.33\,eV}$$

Bipolar Junction Transistor (BJT) :

Transistor is a three terminal semiconductor device which can be used as amplifier and switch in electronics.

In transistor, there are two P–N junction, one is emitter - base junction and another is base - collector junction.

There are three parts of transistor :

(i) **Emitter (E)** emitter is represented by E which is in medium size and supply e^- therefore, it is heavily dopped.

(ii) **Base (B) :** It is very thin and lightly dopped, control transistor action

(iii) **Collector (C) :** It is moderately dopped & collects e^-.

Types of Transistors:

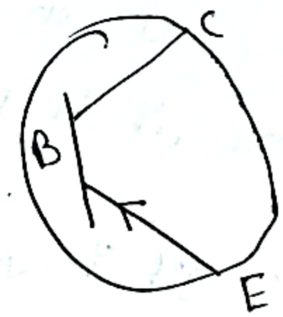
There are two type of bipolar junction transistor,

(i) PNP transistor
(ii) NPN transistor

PNP Transistor: when N-type semiconductor is sandwiched b/w two P-type semiconductor, than BJT is known as PNP transistor.

In PNP transistor, emitter is of P-type-semiconductor, base is N-type semiconductor, and collector is P-type semiconductor.

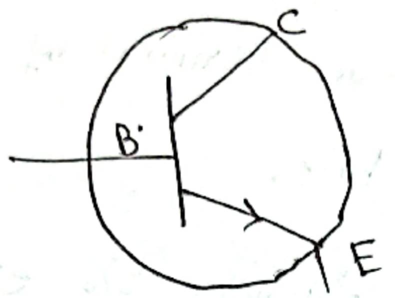
→ the notation of P-N-P transistor is shown in diagram:



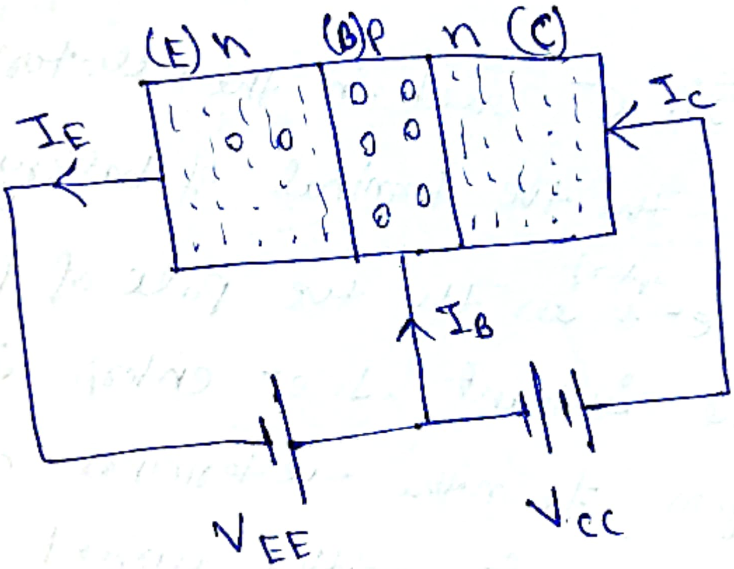
NPN Transistor: when a P-type semiconductor is sandwiched b/w two N-type semiconductor than BJT is called NPN transistor.

In NPN transistor, emitter is N-type semiconductor, base is P-type semiconductor and ~~N~~ collector is N-type semiconductor.

⇒ In NPN transistor, the notation shown below :



Working of NPN transistor :



$I_E - I_B - I_C = 0$

$I_E = I_B + I_C$

⇒ The working of a NPN transistor is shown in diagram.

⊛ In diagram, N-type emitter is connected to the -ve terminal of battery V_{EE}. therefore, emitter - base junction is forward bias.

* Similarly, N-type collector is connected by the +ve of the battery V_{CC}. therefore, collector-base junction is reverse bias.

* The majority charge carriers e^- in the emitter are repelled due to the -ve terminal of battery V_{EE} and move towards the base.

* Base is very thin, so only 5% e^- are recombine with the holes in the base region which constitutes the base current I_B.

* Rest of 95% e^- reach in the collector and attracted by the +ve terminal of battery V_{CC}.

* When an e^- enters in the +ve pole of battery V_{CC}. at the same instant, 1 e^- enters in the emitter region from the -ve terminal of battery V_{CC}. as a result emitter current I_E and collector current I_C also flow in the circuit which is shown in diagram.

The emitter current I_E is given by,

$$I_E = I_B + I_C$$

Working Principle of PNP Transistor:

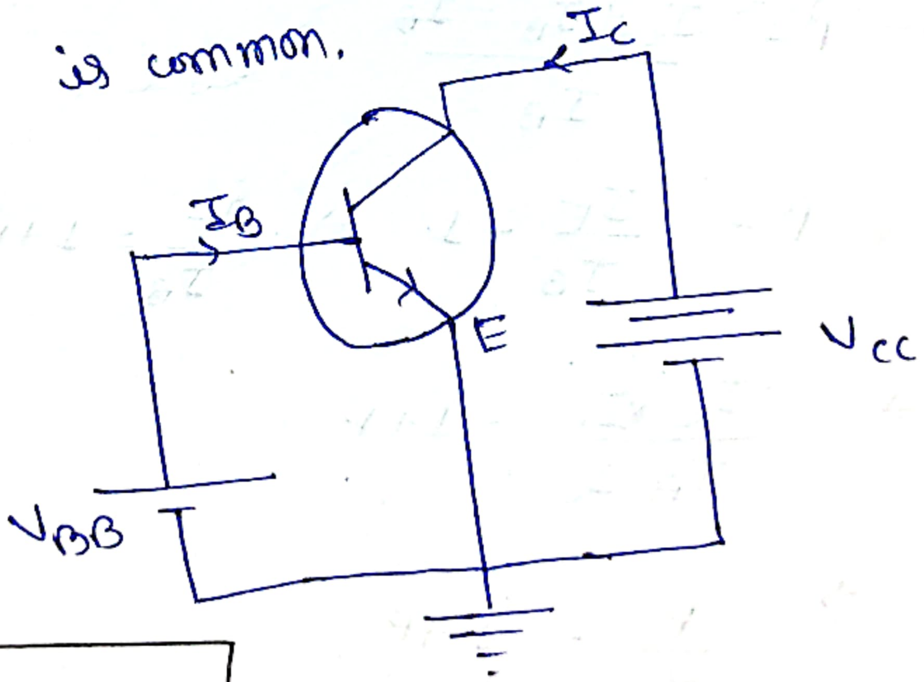
Configuration of N-P-N Transistor:

There are three type of configuration:

1. Common - emitter
2. Common - Base
3. Common - Collector

1. Common-Emitter configuration:

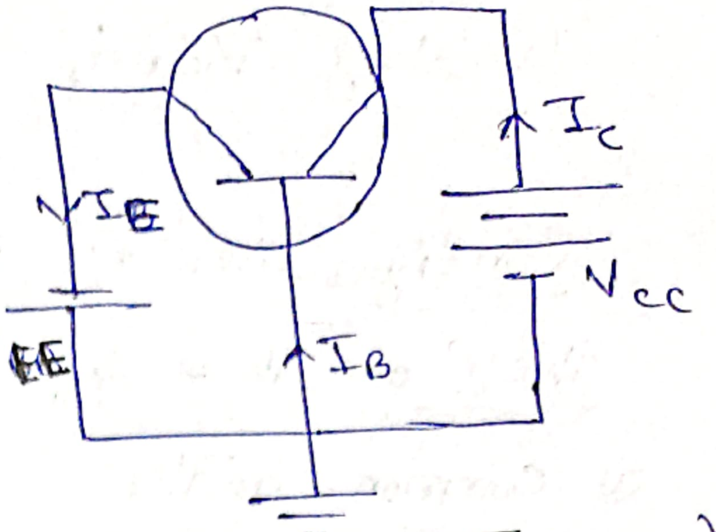
In common Emitter configuration, base is input terminal, collector is output terminal and emitter is common.



$$\boxed{\beta = \frac{I_C}{I_B} > 1}$$

(which is greater than 1)

Common - ~~Emitter~~ Base configuration



In common base configuration, emitter is input terminal collector is output terminal and base is common.

$$\boxed{\alpha = \frac{I_C}{I_E} < 1}$$ (less than one)

Relation b/w α & β :

$$\alpha = \frac{I_C}{I_E}, \quad \beta = \frac{I_C}{I_B} \quad \& \quad I_E = I_B + I_C$$

$$\beta = \frac{I_C + I_B - I_B}{I_B}$$

$$\beta = \frac{I_E}{I_B} - 1 \Rightarrow \frac{I_E}{I_B} = 1 + \beta$$

$$\Rightarrow \frac{I_C \times I_E}{I_B \, I_C} = 1 + \beta$$

$$\Rightarrow \frac{\beta}{\alpha} = 1 + \beta$$

$$\boxed{\cancel{\alpha = \frac{1+\beta}{\beta}}} \qquad \boxed{\alpha = \frac{\beta}{1+\beta}}$$

Common Collector Configuration:

$$\gamma = \frac{I_E}{I_B}$$

Ques: Calculate the I_E for $I_B = 2\mu A$ and $\beta = 100$

Sol: $I_B = 2\mu A$, $\beta = 100$

$$\beta = \frac{I_C}{I_B} \Rightarrow 100 = \frac{I_C}{2\mu A}$$

$$I_C = 200\mu A$$

$$\therefore \; I_E = I_B + I_C$$

$$I_E = (2 + 200)\mu A = 202\mu A$$

Ques: $I_B = 100\mu A$ and I_C is $3mA$.
calculate I_E, β, α.

Sol: $I_B = 100\mu A$, $I_C = 3mA$

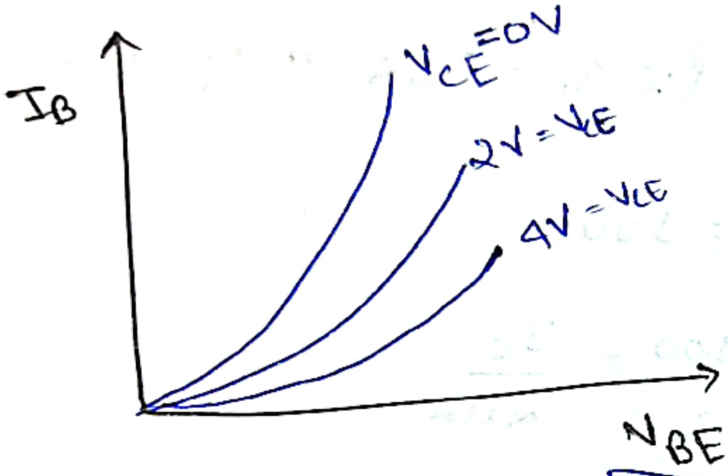
$$I_E = 100\mu A + 3000\mu A = 3100\mu A$$

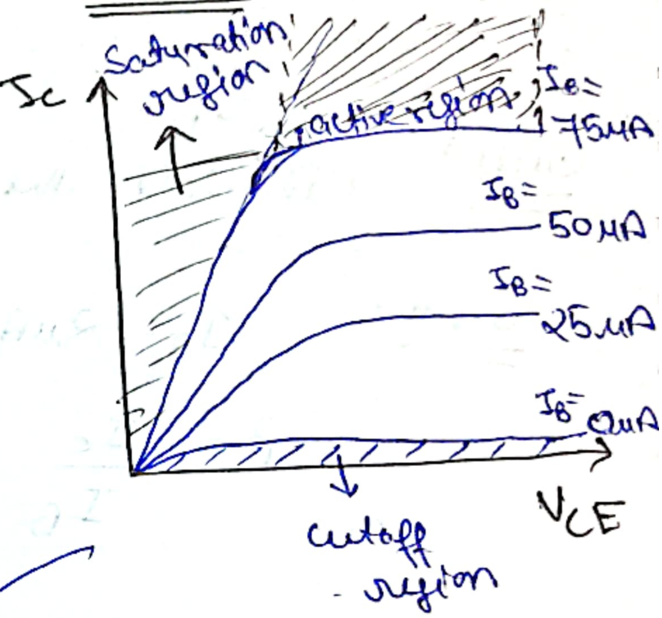
$$\beta = \frac{I_C}{I_B} = \frac{3000\mu A}{100\mu A} = 30$$

and $\alpha = \frac{I_C}{I_E} = \frac{3000\,\mu A}{3100\,\mu A} = 0.97$

Characteristics of N-P-N transistor in CE configuration :

(common emitter)





input characteristic :

(see variation & read)

(i) Input characteristics curve gives the relationship between I_B and V_{BE} at const V_{CE}

(ii) Beyond knee voltage base current increases in B-E voltage for silicon 0.7V and for Germanium 0.3V.

Output characteristics:

Output characteristics gives the relation between

I_C and