VIVEKANANDA COLLEGE
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NAAC ACCREDITED ‘A’ GRADE

Topic: Introduction to Bipolar Junction Transistor.

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Introduction to BJT.

Transistor:-

Transistor is a semiconductor device consists of two pn junctions connected end to end. Here one type of semiconductor is common to two pn junctions. Thus we have either pop or npn structure. For the first case n is common and p is common for the second one as if n layer is sandwiched between two p layers or vice versa (fig1).

Figure 1: Basic structure of transistor

From the discussion about pn junction we get that this junction offers low resistive path for forward bias and its resistance becomes high enough for reverse bias condition. So the pn junction can be considered as a switch which is closed under forward bias and open in the reverse bias.

Under forward biased condition current voltage relationship is non-linear and it follows exponential variation under long base diode approximation (which gives quite satisfactory result for all practical purposes for moderate value of operating voltages). The built in potential at the junction due to the charged depletion region is responsible for the discontinuity. This potential barrier allows majority carrier to flow only when the applied voltage is greater than it. The majority carrier flow is blocked for all the voltages less than that ($Va < V\gamma \rightarrow I_f = 0$). It is obvious that under revers bias (Va = -ve) condition majority carrier flow will be stopped.

However, the junction potential is not a hindrance for minority carrier flow. The minority carriers can flow without any attenuation and becomes saturated quickly and gives a fiat response. (fig 2 a).

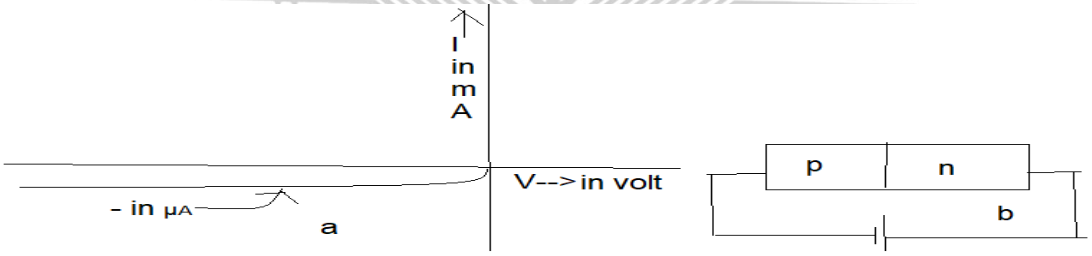


Fig 2 response of reverse biased diode and the circuit connection

The value of this current is of the order of nA for Silicon device and becomes order of µA for Germenium device. At moderate temperature (30 or 40°C) the the value of the reverse current achieves a value of few µA. Still now the value is small and comparing the magnitude in the forward bias current (mA) and can be neglected.

So in a nutshell we can consider the diode as closed switched or in ON condition when it is in forward bias and OFF when it is in reverse bias,

The problems with diode switch are:

1) To make it ON we need at least Vγ, volt (for silicon 0.7 volt = 700 mV).

2) We have to neglect, reverse saturation current under OFF condition which may not be negligible for higher temperature. We cannot take any protective arranpement for such increment from outside.

3) A minimum time is required to get it in OFF condition from ON conditions which is referred as reverse recovery time (t_{rr}). The time depends on the carrier concentration on both sides. There is no way to reduce this time interval. So we have to choose the frequency of operation in such a way that it should not be less than t_{rr}.

Thus one can control the carriers with the pn junction under the constraints mentioned above.

What type of control can be achieved?

Answer is "Flow can be either stopped or allowed."

Can we decrease or enhance the carrier flow?

Answer is "NO".

But this type of device is essential for practical application, because for the circuit with multi sections one need to amplify the signal value. For this purpose single pn junction is of no help.

Previously in vacuum technology we had such type of device which was used to amplify the signal. This was triode. Here an additional terminal was provided to control the carrier flow. The basic features of the device was that for small change of voltage in the controlling terminal (grid) a family of I-V curves were generated which can be approximated as linear for a quite considerable range,

Under this situation the transistor was discovered to get a device for amplification in semiconductor technology.

The philosophy of transistor:-

The proper observation reveals that the I-V response is linear under reverse bias condition. The main problem is that the magnitude of current is very low. If some minority carrier can be injected from any side in controlled manner a family of curves can be generated.

Fig 2b shows a pn junction in reverse biased condition and the corresponding curves is depicted in adjacent figure. The minority carrier of n type semiconductor is hole and for p type semiconductor it is electron. If we attach a hole generator to the n type semiconductor, injected holes will increase the minority carriers in n. automatically the reverse current will be increased. The proposal is shown in fig 3a

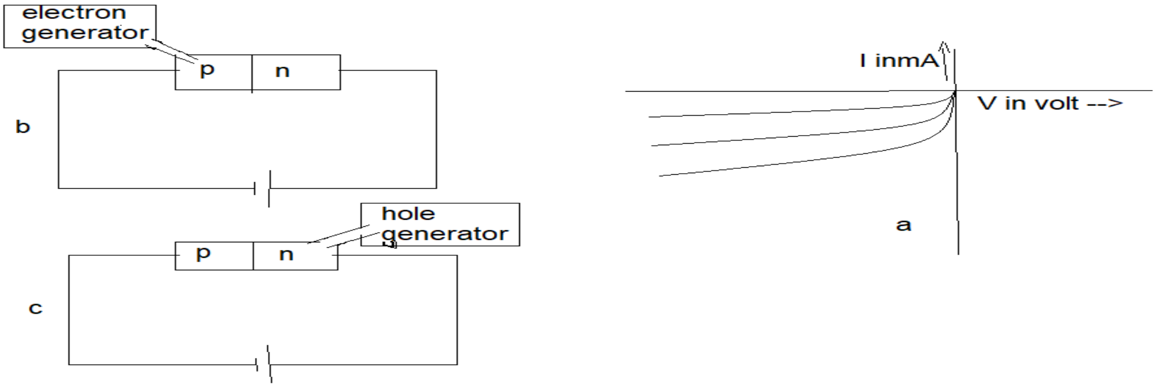


Figure 3: (a) enhanced I-V characteristics after injection of minority carriers, (b) the minority electron injection (c) the minority hole injection.

Alternatively an electron generator can be attached with p side as a minority injector (fig 3 c). Again a family of curves can be generated.

Now the millions dollar question arises: ***What will be that generator***?

The clue is again lies with the pn junction. A forward bias pn junction can generate huge amount of carriers. Under such condition we can expect plenty of electrons from the n side of a pn junction under conduction which becomes minority in the p end. Similarly the n side of a pn junction diode can supply majority holes injected from p side. The mode of connection is shown in (fig .4 a). If we agree to merge the two a layer i.e, n layer of electron generator and n layer of reversed pn junction then we readily get a pnp structure in fig 4 b. The npn structure also described in fig 4 a.

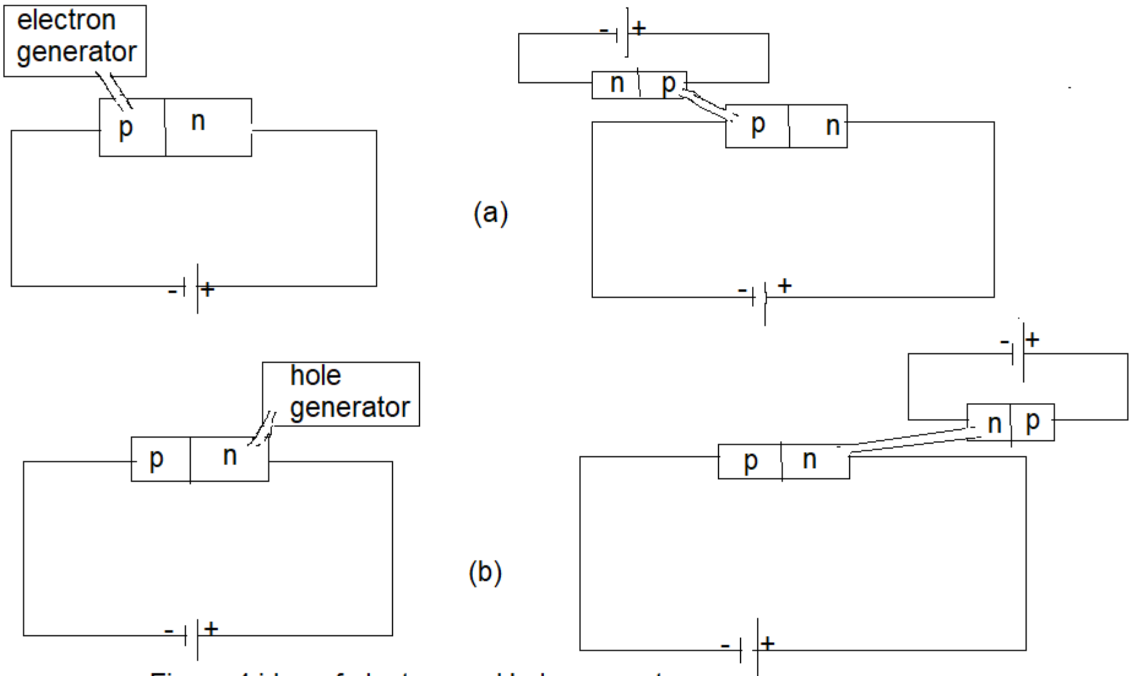
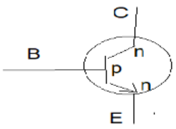
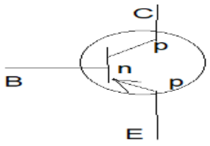


Figure 4 idea of electron and hole generator

Figure 4: use of forward bias pn junction as minority carrier injector

Though we have two p layers on either side of a n layer (in pnp transistor) *both of them are not used for same purpose*. One p end is used to generate carriers and to inject in the other layer as minority. This p end is referred as **emitter**. In the other p layer that carriers are collected This p end is known as **collector**. The middle one (n layer) which is common to the generator junction and collector junction is commonly referred as base. Actually on either side of this layer emitter and collector are grown and used as base layer. Emitter is used to emit the carriers. So doping concentration is high than the other player. Base layer size is very small along with its doping concentration. So by heart it is a device of p$^+$np or if n$^+$pn structure. +ve sign indicates higher doping concentration.



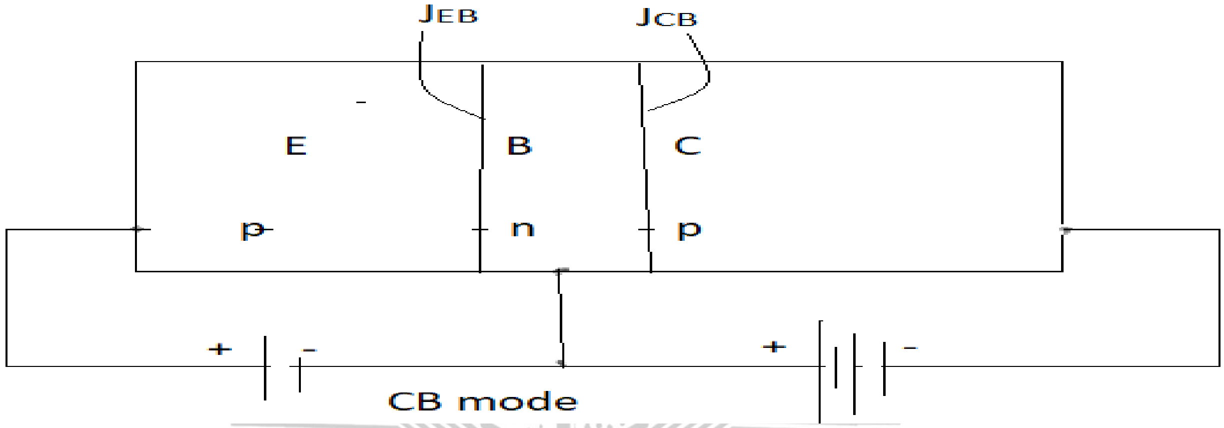


Basic operation mode of transistor will be such that emitter base junction will be in forward bias and collector base junction will be reverse bias. In the reverse bias junction there is a possibility of generation of heat. So to dissipate that heat collector region is fabricated with large area. Also heat sinks are attached with the collector end for power transistor.

Current component through the junctions

A transistor has two junctions' emitter base junction (J_{EB}) and collector base junction (J_{CB}). Emitter base junction is forward biased and collector base junction is reversed bias when the transistor is operated in the active region. When the transistor is used (e.g., as amplifier) it is operated mainly in the active region so we want to discuss the behaviour of the junction or the current flow across the junction under active region operation.

A transistor can be connected in three modes: common base (CB mode), common emitter (CE mode) and common collector (CC mode) (**which one is common to both input and output circuit**). Since the biasing batteries are directly applied across these two junction and the potential difference of the two junctions can be identified as the battery voltages we discuss the whole situation under common base biasing. The circuit connection is shown in the diagram below.



CB mode

Here we choose a pnp transistor. So the emitter and collector are of p type. The majority carrier is hole in these two, where electron is minority carrier in both of them. Emitter is highly doped than collector. Therefore the hole concentration in emitter is greater than the collector.

Hole is minority carrier in the n type base. Though electron is the majority carrier but the number of carriers present in the base region is very small due to narrow width of lightly doped base.

Total current will be governed by the hole flow and current direction is along the direction of the flow of the holes.

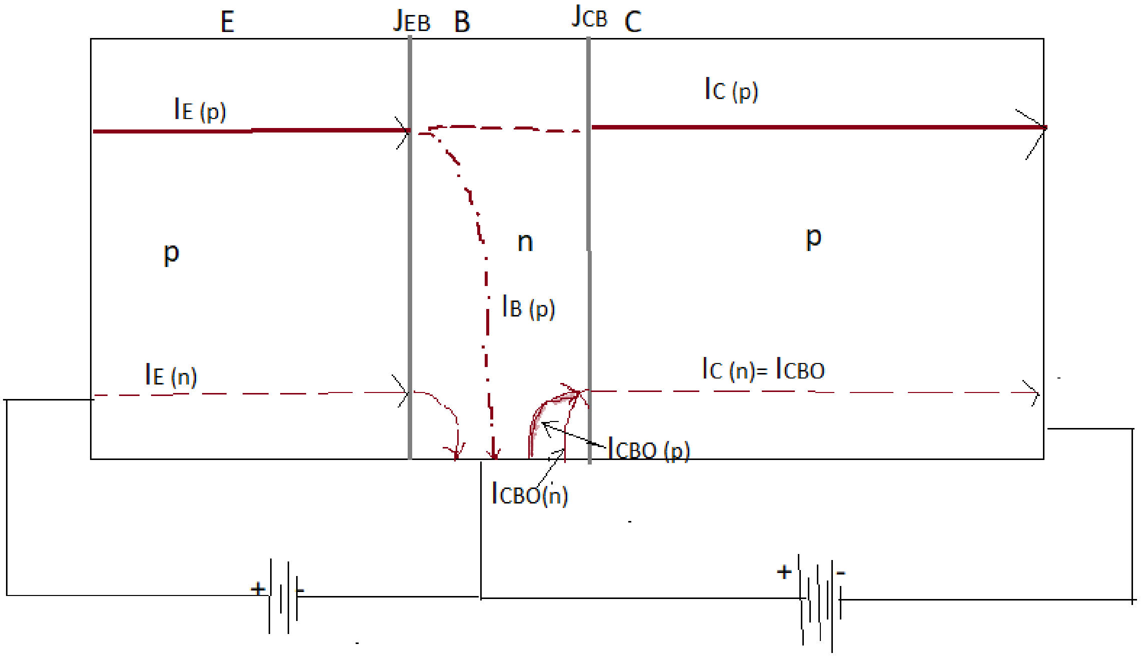


fig 5 All possible current in CB mode

Figure 5: current component of a pnp transistor under active biases condition (cont line => majority carrier current, dotted line => minority carrier current, bold line=> hole current , lighter line => electron current

Currents at (J_{EB})

I_E(p): Emitter current due to holes, the majority carriers of the emitter. Holes will move from emitter to base under the action of forward bias V_{EB}.

I_E(n): Emitter current due to electrons. Electron is majority carrier of base. They are injected from the base to emitter and minority electrons of emitter also accompany with them constituting this current from emitter to base (current direction is opposite to carrier flow).

I_B (p): Some of the holes injected from emitter will follow the recombination inside the base. Rest of the holes will pass through J_{CB} and form the collector current I_C(p).

I_B (p) = I_E(p) – I_C(p)

I_B (n): Current due to electrons moving from base to emitter which is already discussed and denoted as I_E(n).

I_E (n) = I_B (n)

Currents at (J_{CB})

Ic (p): Collector current due to holes. Holes are majority carriers and will be attracted towards the collector terminal and shows a current in outer direction in the collector due to reverse bias of the collector base junction. Holes crossing the base after recombination will add themselves with the stream and under steady state condition these holes maintains the Ic (p).

Ic (n) = I_{CBO}: Minority carriers of p type collector is electron. Electrons move from collector to base and generate a current Ico (n) from base to collector (current direction is opposite to carrier flow) under reverse bias voltage. This current will flow even if the base emitter junction is kept open. So one 'O' is added in the subscript to mention input open. Here in the common base mode the battery for biasing of J_{CB} and J_{EB} are totally different. So even if the emitter base junction is in forward bias it has nothing to do with this Ico (This Ico is solely controlled by V_{CB}, the biasing voltage for collector to base bias. To ensure this situation generally this Ico is denoted as I_{CBO} ,*the minority carrier current in the collector region with input open connected in common base mode*. The subscript 'B' represent the common terminal.

I_{CBO} (n): This is the current due to majority carrier (n) of the base when J_{EB} is open. The electrons will be attracted towards positive base terminal (offered by V_{CB}). This will generate a current from base to collector. This will join with the electron current (minority) of collector

I_{CBO} (p): The minority carriers (p) of the base will be repelled by the positive base terminal (offered by V_{CB}). These holes will be injected into collector. This also will give current to collector.

These two components I_{CBO} (n) and I_{CBO} (p) are nothing but reverse saturation current of the base collector pn junction and formed by the minority carriers of both. Since the number of carriers is a function of temperature these currents also increases with increase of temperature.

In summary

Emitter current: $IE = IE(p) + IE(n) \approx IE(p)$.   as $IE(n) << IE(p)$

Collector current: $IC = IC(p) + ICBO \approx IC(p)$.   as $ICBO << IC(p)$

Cut off current: $ICBO = [ICBO(n) + ICBO(p)]$

Base Current: $IB = IE(p) - IC(p) = IE - IC$.

Here $IB = IB(p)$. as $IB(n) = IE(n)$ is already neglected.

$IE = IB + IC$ ------------------(1)

This is one of the widely used equation of the transistor. The equation possess that the emitter current is the main current and which is divided into two parts. Main current is the collector current and other current is the base current, which is indeed. This is a continuity equation of the emitter current. The name emitter is really becomes suggestive here: which can emit the hole (majority carriers). The emitted carriers will be injected to the collector through base and ultimately form the collector current.

So carriers start their journey from emitter and ended at collector losing some of them in the base.

Here we can define the emitter injection efficiency $\gamma = \frac{IE(p)}{IE}$ the fraction or part of the emitter current which is injected to the base.

$$\boldsymbol{\gamma = \frac{IE(p)}{IE} = \frac{IE(p)}{IE(p)+IE(n)}}$$

Again some part of the IE (p) will cross the junction J_{CB} to form collector current.

$$IC = IC(p) = B\, IE(p)$$

The B represents the fraction of IE (p) transferred to the collector from the base and known as Base transport factor.

The base current becomes

IB = IB (n) + IB (p) = IB (n) + (1 - B) IE (p)

Neglecting IB (n) it can be written as IB = (1 - B) IE.

We can define two current gains

$$\boldsymbol{\alpha = \frac{IC}{IE}}$$

And

$$\boldsymbol{\beta = \frac{IC}{IB}}$$

These two equations indicates collector is the output of the device which is really true and either of the two terminals base or emitter can be considered as input terminals. Now

$$\boldsymbol{\alpha = \frac{IC}{IE} = \frac{B\,IE(p)}{IE(p) + IE(n)} = \gamma B}$$

Again

$$\boldsymbol{\beta = \frac{IC}{IB} = \frac{B\,IE(p)}{(1 - B)IE(p) + IB(n)}}$$

$$\boldsymbol{= \frac{\frac{B\,IE(p)}{IE(p) + IE(n)}}{\frac{(1 - B)IE(p) + IB(n)}{IE(p) + IE(n)}}}$$

$$\boldsymbol{= \frac{\gamma B}{\frac{(1 - B)IE(p) + IE(n)}{IE(p) + IE(n)}}}$$

As IE(n) is nearly equal to IB(n)

$$\boldsymbol{= \frac{\gamma B}{\frac{IE(p) + IE(n)}{IE(p) + IE(n)} - \frac{BIE(p)}{IE(p) + IE(n)}}}$$

$$\beta = \frac{\boldsymbol{\gamma B}}{1 - \boldsymbol{\gamma B}} = \frac{\alpha}{1 - \alpha}$$

The last one shows the interrelationship between **α** and **β**. So that if **α** is known to anybody **β** can be calculated easily. It can be shown that

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

Which can be used to find α from β.

From the above discussions it is clear that the value of α is always less than one simply because always collector current is formed by the carrier less than the carriers injected to base. On the other hand β possess a high value because base current is really very small compared to the collector currents. The standard value of α becomes ~ 0.997 and corresponding β comes out to be 332.

Current convention

We here want to give the stress on the continuity equation. We have just discussed the current components in the pnp transistor where emitter currents in from emitter to the base i.e., inward and base current and the collector current are outward from the respective terminals. In the npn transistor it is just reversed because the majority carriers of the emitter are electrons and are injected towards base. That means emitter current is outward and obviously base and collector current are inwards. So for pnp transistor we can say emitter current breaks into two components whereas for npn-transistor the correct version will be base current and collector currents compose the emitter current. Whatever may be the case always carriers are emitted from the critter and divided into two parts in base and collector[1]

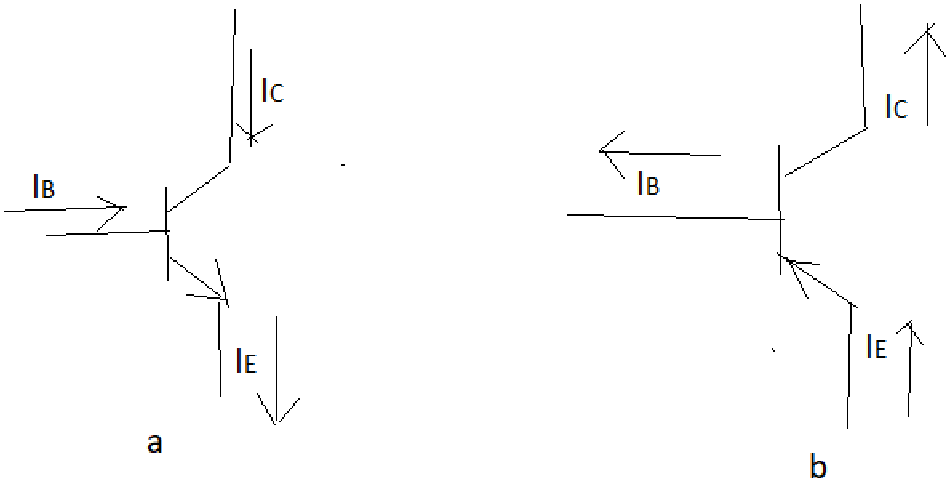


figure 6 currents in npn (a) and (b) transistors

Figure 6: currents in npn (a) and pnp (b) transistors

We have already mentioned the forward bias or reverse bias of the junction. The voltage of the junction with proper polarity should be mentioned for fruitful discussions. We will elaborate this after discussing the different mode of connections of the transistor. The only thing that can be mentioned here is the junction is denoted in as subscript in voltage expression and the terminal potential of which is seeking precedes whereas the reference terminal comes later. e.g., V_{CB} will indicate voltage of the collector (C) with respect to base (B).

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[1] 'In some books e.g., Miliman Halkias the convention is taken as all the currents inward. If the actual current is outward then it is represented with a negative sign. For example for common base the current equation in that convention becomes

$IE = - (IB + IC)$

That means for pnp transistor emitter current is inward whereas base current and collector current is inward.