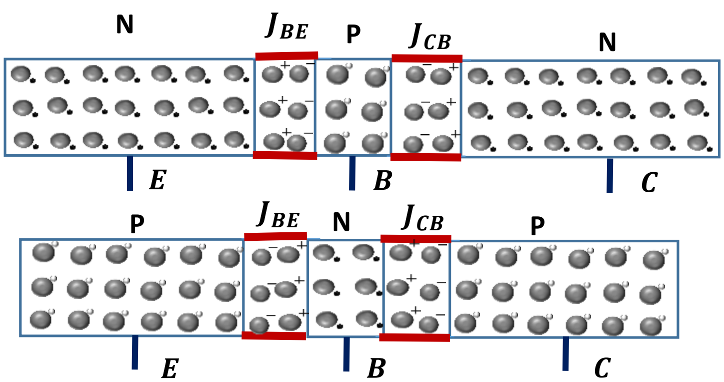
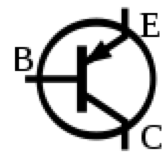
BJT

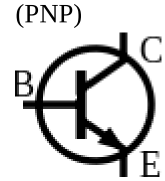
A transistor (BJT) is a three-layer semiconductor device consisting of either two N-type and one P-type layer or two P-type and one N-type layer material. The former is called NPN transistor and the latter is called PNP transistor. Schematic diagrams and circuit symbols are shown in figure. The central layer is very thin and lightly doped as compared to the outer layers and called BASE(B). The outer two layers appear to be identical but the electrical conductivities are different due to different doping level. The heavily doped layer is called the EMITTER(E) and the moderately doped layer is kwon as collector(C).

In typical operation, the base–emitter junction is forward biased, which means that the p-doped side of the junction is at a more positive potential than the n-doped side, and the base–collector junction is reverse biased. In an NPN transistor, when positive bias is applied to the base–emitter junction, the equilibrium is disturbed between the thermally generated carriers and the repelling electric field of the n-doped emitter depletion region. This allows thermally excited electrons to inject from the emitter into the base region. These electrons diffuse through the base from the region of high concentration near the emitter towards the region of low concentration near the collector.





Circuit symbol (PNP)



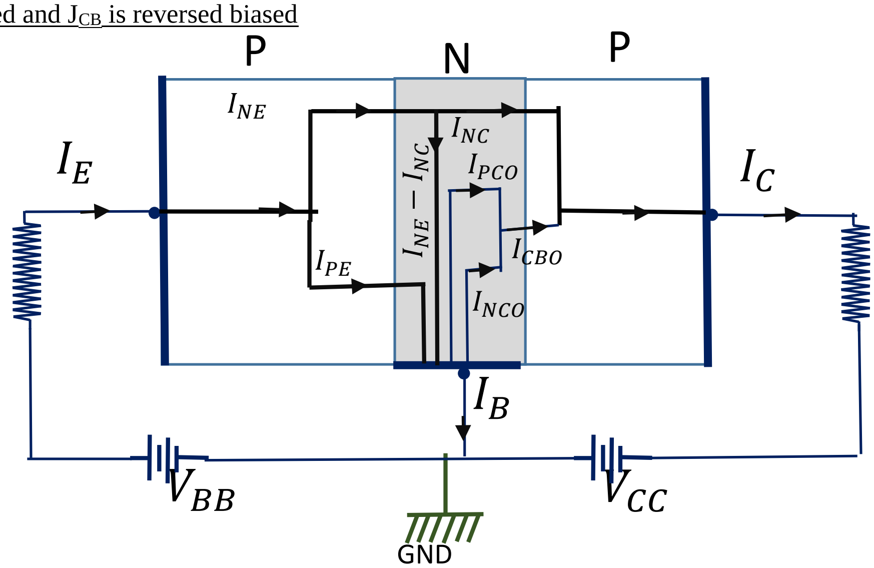
Circuit symbol (NPN)

<u>SOME BASIC FACT ABOUT BJT</u>

1. Emitter is heavily doped; base is poorly doped & collector is moderately doped.
2. The junction between the emitter and the base is called EMITTER-BASE junction (J_{EB}) & the junction between the base and the collector is known as COLLECTOR-BASE junction (J_{CB}).
3. In commercial transistor the area of the COLLECTOR-BASE junction (J_{CB} junction) is made considerably larger than that of EMITTER-BASE junction (J_{EB} junction). Because in most cases J_{CB} junction has to handle more power than J_{EB} junction. So in normal transistor action COLLECTOR and EMITTER cannot be interchanged.
4. For normal operation of a transistor **J_{EB} junction is forward biased** and **J_{CB} junction is reversed biased.**
5. The abbreviation BJT, bipolar junction transistor the term bipolar reflects the fact that holes and electrons participates in the injection process into opposite polarized material. (**Note that Schotly diode, JFET are unipolar device.**)
6. For normal operation of a transistor as the J_{EB} junction is forward biased and the J_{CB} junction is reversed biased. Then dynamical resistance at J_{EB} is small compared to dynamical resistance at J_{CB}. Hence in transistor a current from a low resistance input circuit transferred to high resistance output circuit. (which results power gain)
   The name transistor comes from transfer of resistor. (Transfer + Resistor = Transistor)
7. By design, most of the BJT collector current is due to the flow of charges injected from a high-concentration emitter into the base where there are minority carriers that diffuse toward the collector, and so BJTs are classified as minority-carrier devices.
8. To minimize the percentage of carriers that recombine before reaching the collector–base junction, the transistor's base region must be thin enough that carriers can diffuse across it in much less time than the semiconductor's minority carrier lifetime. **In particular, the thickness of the base must be much less than the diffusion length of the electrons (**for NPN transistor**) or, the diffusion length of the holes (**for PNP).
9. The **thin *shared* base** and **asymmetric collector–emitter doping** are what **differentiates** <u>a bipolar</u> <u>transistor</u> from <u>two *separate* and oppositely biased diodes connected in series.</u>

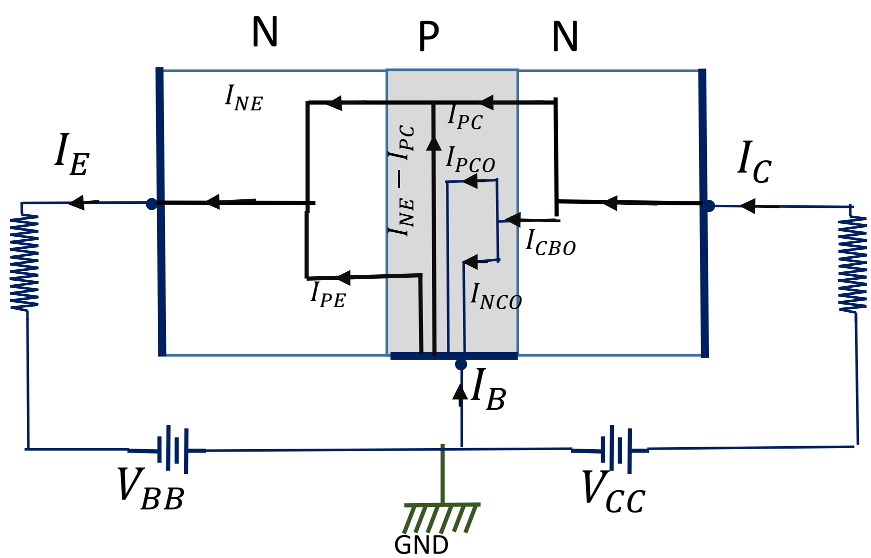
CURRENT COMPONENTS IN A TRANSISTOR

Consider a PNP transistor whose J_{EB} is forward biased and J_{CB} is reversed biased



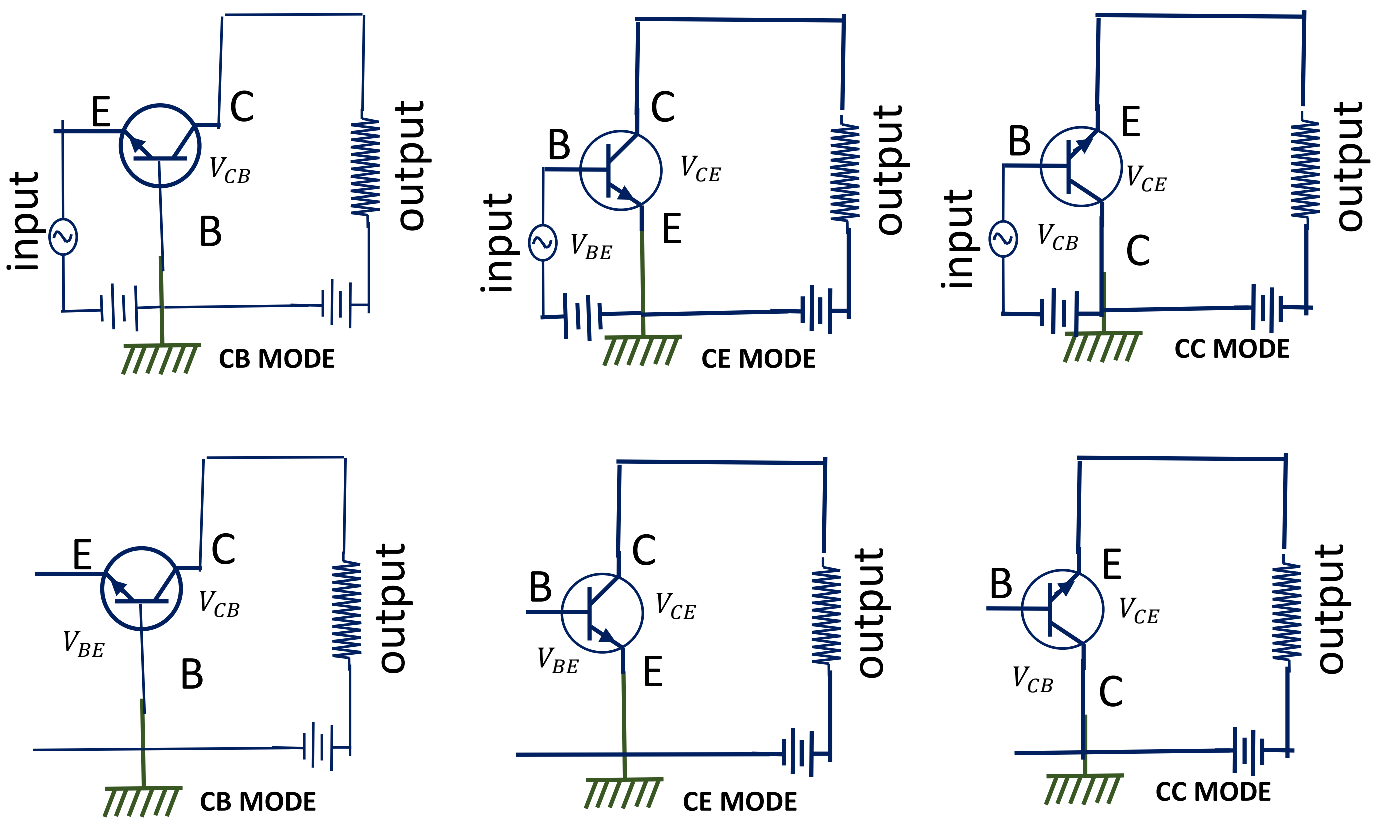
1. The emitter I_E is made up of two components I_{PE}, due to holes injected from the emitter into base and I_{NE} due to electrons crossing from the base into emitter. Thus $I_E = I_{PE} + I_{NE}$. Since doping of emitter is much higher than base then $I_{PE} > I_{NE}$ then $I_E \approx I_{PE}$.
2. Most of the holes injected from the emitter junction (J_{EB}) reach the collector junction producing a hole components of collector current I_{PC}. Remaining hole combine with the electrons in the base giving a recombination hole current ($I_{PE} - I_{PC}$) leaving the base. The base current I_B is due to flow of electrons from battery to the base to maintain charge neutrality of the base region.
3. Since the collector junction is reversed, there is a small collector current even with emitter is open. This reversed saturation current I_{CBO} has two components I_{PCO} & I_{NCO} due to minority holes flowing through N-side to P-side and minority electrons flowing from P-side to N-side. Then $I_{CBO} = I_{PCO} + I_{NCO}$ and $I_C = I_{PC} + I_{CBO}$ [where I_C = collector current]. Then $I_E = I_B + I_C$

Consider a NPN transistor whose J_{EB} is forward biased and J_{CB} is reversed biased



1. The emitter I_E is made up of two components I_{NE}, due to electrons injected from the emitter into base and I_{PE} due to holes crossing from the base into emitter. Thus $I_E = I_{NE} + I_{PE}$. Since doping of emitter is much higher than base then $I_{NE} > I_{PE}$ then $I_E \approx I_{NE}$. Note that the direction of conventional current is opposite to the movement of electrons.
2. Most of the electrons injected from the emitter junction (J_{EB}) reach the collector junction producing a electrons components of collector current I_{NC}. Remaining electron combine with the holes in the base giving a recombination hole current ($I_{NE} - I_{NC}$) leaving the base. The base current I_B is due to flow of electrons from battery to the base to maintain charge neutrality of the base region.
3. Since the collector junction is reversed, there is a small collector current even with emitter is open. This reversed saturation current I_{CBO} has two components I_{PCO} & I_{NCO} due to minority holes flowing through N-side to P-side and minority electrons flowing from P-side to N-side. Then $I_{CBO} = I_{PCO} + I_{NCO}$ and $I_C = I_{NC} + I_{CBO}$ [where I_C = collector current]. Then $I_E = I_B + I_C$

THREE MODES OF CONNECTION



TRANSISTOR α, β i.e, α_{dc}, β_{dc} & α_{ac}, β_{ac}

We know that the collector current I_C consists of two components, (i) the reverse saturation current I_{CBO} and (ii) the predominant portion representing a part of emitter current reaching the collector. In CB mode, $I_C = \alpha I_E + I_{CBO}$ Where α is called transistor $Alpha$. We see in CE mode $I_C = \beta I_B + (\beta + I)\, I_{CBO}$ Where β is known as transistor $Beta$

The ratio of collector current to the emitter current when V_{CB} =0 is known as **common base current gain** $\boldsymbol{\alpha_{dc}}$

i.e, $\alpha_{dc} = \left.\frac{I_C}{I_E}\right|_{V_{CB}=0}$

The ratio of collector current to the base current when V_{CE} =0 is known as **common emitter current gain** $\boldsymbol{\beta_{dc}}$

i.e. $\beta_{dc} = \left.\frac{I_C}{I_B}\right|_{V_{CE}=0}$

i.e, The ratio of change in collector current to the change in emitter current when V_{CB} =constant is known as **small signal common base current gain** $\boldsymbol{\alpha_{ac}}$

i.e, $\alpha_{ac} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB}=Constant}$

The ratio of change in collector current to the change in base current when V_{CE} =constant is known as **small signal common emitter current gain** $\boldsymbol{\beta_{ac}}$

i.e, $\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=Constant}$

RELATION BETWEEN TRANSISTOR α and β i.e, α_{dc} and β_{dc} or, α_{ac} and β_{ac}

We know that $I_E = I_C + I_B$ ………………. (i) Then, $\frac{I_E}{I_C} = \frac{I_C}{I_C} + \frac{I_B}{I_C}$ OR, $\frac{1}{\alpha_{dc}} = \frac{1}{\beta_{dc}} + 1$………………..(ii)

From equation (ii) $\frac{1}{\alpha_{dc}} = \frac{1+\beta_{dc}}{\beta_{dc}}$ or, $\boldsymbol{\alpha_{dc} = \frac{\beta_{dc}}{1+\beta_{dc}}}$

Again from equation (ii) $\frac{1}{\beta_{dc}} = \frac{1}{\alpha_{dc}} - 1 = \frac{1-\alpha_{dc}}{\alpha_{dc}}$ or, $\boldsymbol{\beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}}}$

Similarly from equation (i) $\Delta I_E = \Delta I_C + \Delta I_B$ then $\frac{\Delta I_E}{\Delta I_C} = \frac{\Delta I_C}{\Delta I_C} + \frac{\Delta I_B}{\Delta I_C}$ or, $\frac{1}{\alpha_{ac}} = \frac{1}{\beta_{ac}} + 1$ … … … … … ….…(iii)

From equation (iii) $\frac{1}{\alpha_{ac}} = \frac{1+\beta_{ac}}{\beta_{ac}}$ or, $\boldsymbol{\alpha_{ac} = \frac{\beta_{ac}}{1+\beta_{ac}}}$

Again from equation (iii) $\frac{1}{\beta_{ac}} = \frac{1}{\alpha_{ac}} - 1 = \frac{1-\alpha_{ac}}{\alpha_{ac}}$ or, $\boldsymbol{\beta_{ac} = \frac{\alpha_{ac}}{1-\alpha_{ac}}}$

Note that dc current amplification factor in common collector mode and small signal current amplification factor in common collector mode is defined as $\gamma_{dc} = \frac{I_E}{I_B}\Big|_{V_{CE}=0}$ **&** $\gamma_{ac} = \frac{\Delta I_E}{\Delta I_B}\Big|_{V_{CE}=Constant}$

Relation between γ and α, γ and β

As $\boldsymbol{\gamma = \frac{I_E}{I_B} = \frac{I_B+I_C}{I_B} = 1 + \frac{I_C}{I_B} = 1+\beta = 1 + \frac{\alpha}{1-\alpha} = \frac{1}{1-\alpha}}$

---

1. Expression for collector current in common base connection-

The whole of emitter current does not reach the collector. It is because a small percentage of it, as a result of electron-hole combinations occurring in base area, gives rise to base current. Moreover, as the collector-base junction is reverse biased, therefore, some leakage current flows due to minority carriers. It follows, therefore, that total collector current consists of:

(*i*) That part of emitter current which reaches the collector terminal *i. e.* $\boldsymbol{\alpha I_E}$.

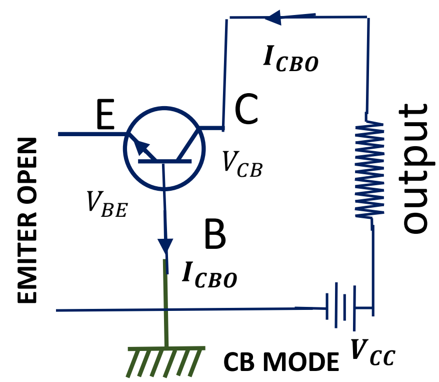
(*ii*) The leakage current $\boldsymbol{Ileakage}$. This current is due to the movement of minority carriers across base-collector junction on account of it being reverse biased.

This is generally much smaller than $\boldsymbol{\alpha \square I_E}$.

∴□Total collector current, $\boldsymbol{I_C = \alpha I_E + Ileakage}$

Now if ***IE* = 0** (*i.e.*, emitter circuit is open), a small leakage current still flows in the Collector circuit.

This $\boldsymbol{Ileakage}$ is abbreviated as ***ICBO,*** meaning collector-base current with emitter open.

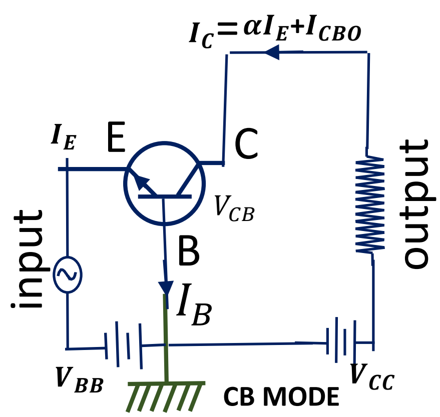


$\therefore \boldsymbol{I_C = \alpha I_E + I_{CBO}}$. … … … … … . . (i) $Now\ IE = IC + IB$

$\therefore I_E = \alpha (I_C + I_B) + ICBO$

$or\ I_C (1 - \alpha) = \alpha I_B + I_{CBO}$

$or\ \boldsymbol{I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}}$ … ……………….. . . (ii)



2. Expression for collector current for common emitter connection-

In common emitter circuit, I_B is the input current and I_C is the output current.

We know $I_E = I_B + I_C$ ....(*i*) and $I_C = \alpha I_E + I_{CBO} \ldots\ldots\ldots\ldots(ii)$

From exp. (*ii*), we get, $IC = \alpha IE + ICBO = \alpha (IB + IC) + ICBO$

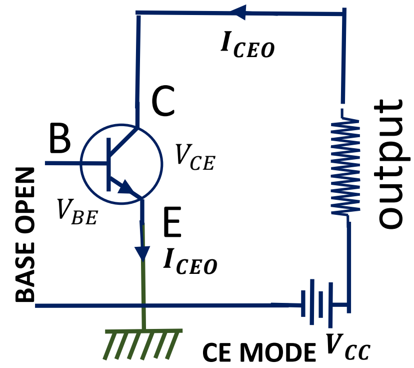
or $I_C\ (1 - \alpha) = \alpha I_B + I_{CBO}$

or $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$......................................(*iii*)

From exp. (*iii*), if $I_B = 0$ (*i.e.* base circuit is open), the collector current will be the current to the emitter. This is abbreviated as I_{CEO}, meaning collector-emitter current with base open.

∴□$I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = (\beta + 1)\ I_{CBO}$ [As $\beta = \frac{\alpha}{1-\alpha}$ then $\beta + 1 = \frac{1}{1-\alpha}$]

Now as $\beta = \frac{\alpha}{1-\alpha}$ then $\boldsymbol{I_C = \beta I_B + I_{CEO} = \beta I_B + (\beta + 1) I_{CBO}}$



Concept of ICEO. In *CE* configuration, a small collector current flows even when the base current is zero. This is the collector cut off current (*i.e.* the collector current that flows when base is open) and is denoted by *ICEO*. The value of *ICEO* is much larger than *ICBO*

3. Expression for emitter current for common collector connection-

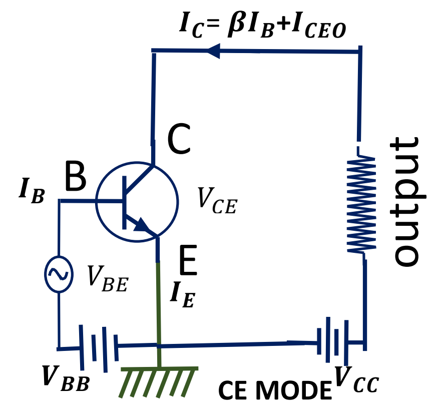
We know that ∴ $\boldsymbol{I_C = \alpha I_E + I_{CBO}}$ and $\boldsymbol{I_E = I_B + I_C}$

Then $I_E = I_B + (\alpha I_E + I_{CBO})$

Then $I_E\ (1-\alpha) = I_B + I_{CBO}$

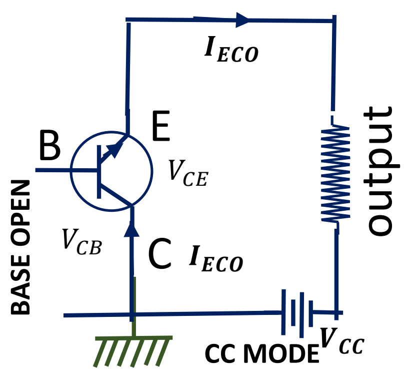
Or, $I_E = \frac{1}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$ [now $\frac{1}{1-\alpha} = \beta + 1 = \gamma$ and $(\frac{1}{1-\alpha}) I_{CBO} = (\beta + 1) I_{CBO} = \boldsymbol{I_{CEO}}$]

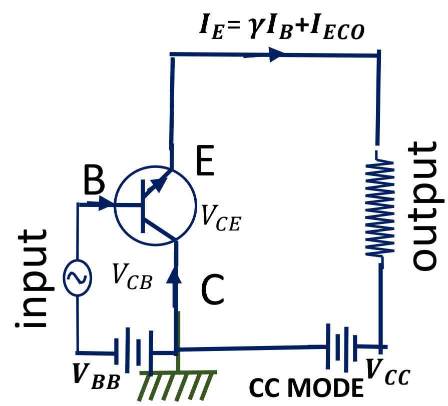
Then $\boldsymbol{I_E = \gamma I_B + I_{CEO} = (\beta + 1) I_B + (\beta + 1) I_{CBO}}$

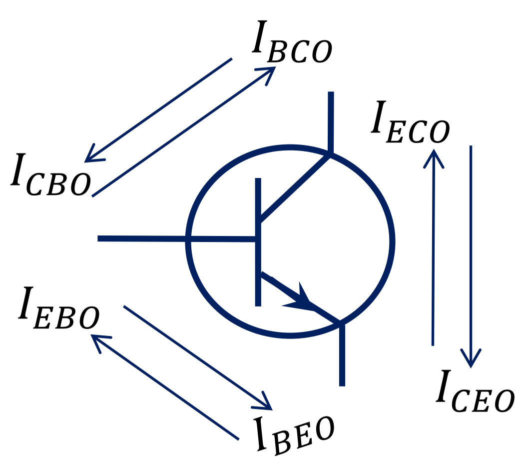


NOTE THAT – when collector is open circuited and emitter- base junction is reversed biased then a small emitter current flows through emitter-base junction. this current is also emitter to base leakage current and denoted as I_{EBO}.

Again note that I_{CBO} is also called collector cut-off current I_{CO}

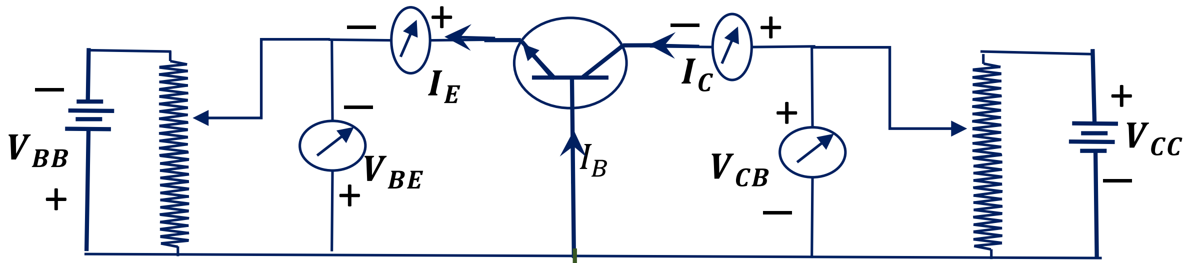






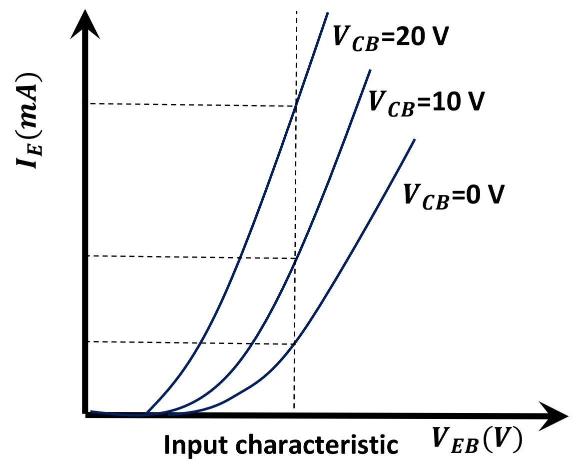
Transistor is a nonlinear device. And we don't have any exact analytical relationship between current and voltage in a transistor. For this we very often take the help of experimentally drawn current voltage characteristic curve.

COMMON BASE CHARACTERISTICS



Circuit diagram to draw CB characteristic curve of a NPN transistor (for PNP just reverse The polarity of the batteries and meters). Fig-I

INPUT CHARACTERISTIC – In CB configuration **the variation of input current (I_E) with input emitter base voltage (V_{EB}) taking output collector base voltage V_{CB} as parameter, gives the static input characteristic.**



In normal operating region of a transistor emitter-base junction is forward biased and the input curve are similar to that of a forward biased PN junction I_E increases exponentially with increase of $|V_{EB}|$.There exists a certain voltage V_γ below which I_E is negligible.

EARLY EFFECT

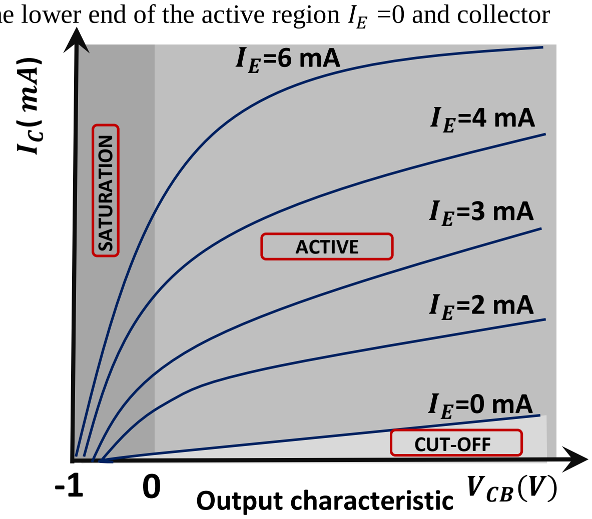
If the reverse biased voltage of the collector-base junction is increased the width of the depletion region of collector-base junction is increases. This reduced the effective width of the base region. **This change of Effective base width by collector-base voltage is known as EARLY EFFECT**.

As a result of Early effect-The minority charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases. Hence I_E increases with $|V_{CB}|$

OUTPUT CHARACTERISTIC CURVE

The **variation of collector current (I_C)with output collector-base voltage (V_{CB}) taking input emitter (I_E) current as parameter,** give the static output characteristic curve. Output characteristic curve has three distinct regions

ACTIVE REGION- In this region emitter junction is forward biased and collector junction is reversed biased. **It is the region to the right of the ordinate $V_{CB} = 0$ and above the characteristic curve I_E =0. At** the lower end of the active region I_E =0 and collector current is simple I_{CBO}. For $I_E > 0$ then $I_C \approx \alpha I_E$.



Since α is close to the unity then I_C is only slightly smaller than I_E.

If the reverse biased voltage of the collector-base junction is increased the width of the depletion region of collector-base junction is increases. This reduced the effective width of the base region (**Early effect**) then (i)Chance of recombination decreases (ii) The minority charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases. Hence I_C increases slightly with V_{CB}.If V_{CB} is increased very much there may be collector junction break down causing a sharp rise in I_C

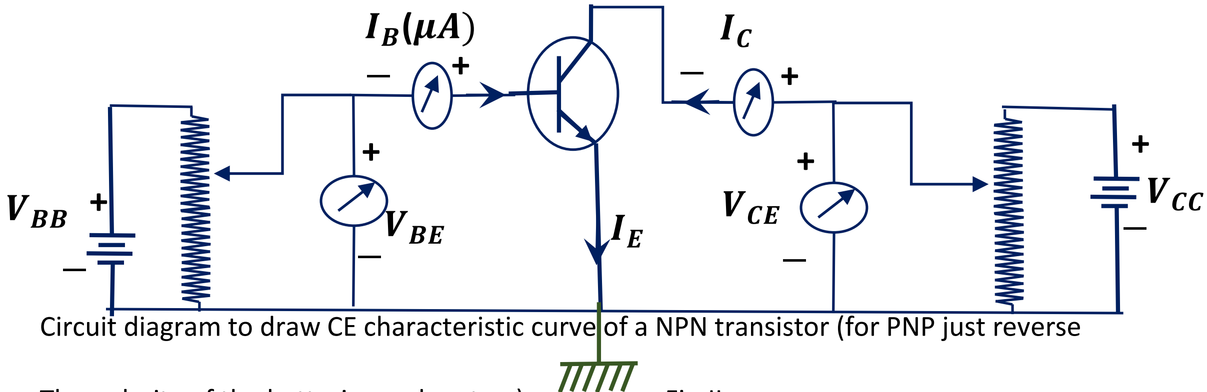
SATURATION REGION -The region when both emitter and collector junction are forward biased. In figure it represents **the region to the left of the ordinate $V_{CB} = 0$ and above the characteristic $I_E = 0$** It is seen that I_E is not zero even when $V_{CB} = 0$ **this happens so because the injected carrier still finds a potential down at collector junction due to contact potential difference.** To reduce to zero, it is necessary to apply a small forward biased to the collector.

CUT-OFF REGION- In this region both emitter and collector junction are reversed biased. **The region right to the ordinate $V_{CB} = 0$ and below the characteristic $I_E = 0$** is the cut-off region.

NOTE THAT-When emitter-base junction is reversed biased and collector-base reversed biased then the transistor is said to be operated in the reverse active region.

COMMON EMITTER CHARACTERISTIC

The circuit arrangement for drawing a common emitter characteristic curve is shown in figure (II)



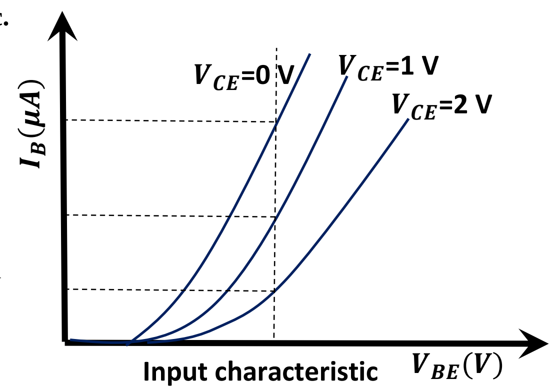
Circuit diagram to draw CE characteristic curve of a NPN transistor (for PNP just reverse The polarity of the batteries and meters). Fig-II

INPUT CHARACTERISTIC – In CE configuration **the variation of input current (I_B) with input base-emitter voltage (V_{BE}) taking output voltage V_{CE} as parameter, gives the static input characteristic.**

In normal operating region of a transistor emitter-base junction is forward biased and the input curve are similar to that of a forward biased PN junction I_B increases exponentially with increase of $|V_{BE}|$.
There exists a certain voltage V_γ below which I_B is negligible.

For a constant V_{BE}, I_B decreases with increase in V_{CE}

Here **increase in V_{CE} decrease the effective base width and probability of recombination of the injected carrier's decreases**. As a result, recombination base current decreases.



OUTPUT CHARACTERISTIC CURVE

The **variation of collector current (I_C) with output voltage (V_{CE}) taking input base (I_B) current as parameter,** give the static output characteristic curve. Output characteristic curve has three distinct regions

ACTIVE REGION- in this region emitter junction is forward biased and collector junction is reversed biased. It is **the region to the right of the ordinate $V_{CE} = V_{CE,sat}$ and above the characteristic curve I_B =0.**

In this region I_C increases significantly with the increase of V_{CE}

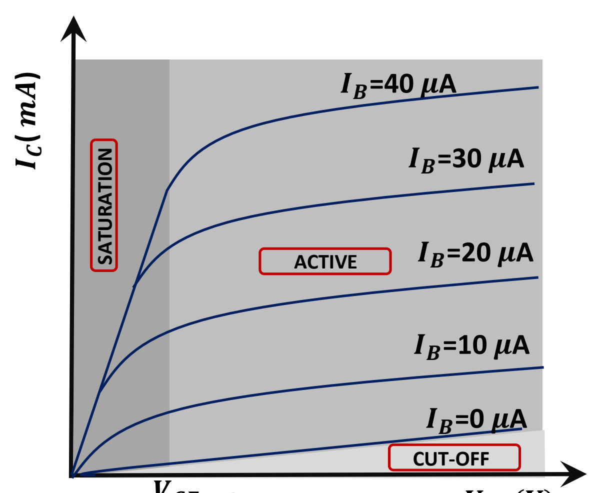
As **$I_C = \beta I_B + (\beta + 1) I_{CBO}$, due to Early effect α increases slightly**

A small change of α causes a large change in β. For this output curves have significant upward slope.

If V_{CE} is increased very much there may be collector junction break down causing a sharp rise in I_C

SATURATION REGION -The region when both emitter and collector junctions are forward biased. In figure it represents **the region to the left of the ordinate $V_{CE} = V_{CE,sat}$ and above the characteristic $I_B = 0$.**

In this region collector current becomes almost independent of base current For a given load and collector supply.



CUT-OFF REGION- In this region both emitter and collector junction are reversed biased. **The region right to the ordinate $V_{CE} = V_{CE,sat}$ and below the characteristic $I_B = 0$ is the cut-off region.**

Note that it is not enough to make I_B= 0 to cut off the transistor since then $I_C = (\beta + 1) I_{CBO}$. As $\beta \gg 1$then I_C has significant value. The cut-off is defined as the condition $I_E = 0, I_B = -I_{CBO}$ and $I_C = I_{CBO}$

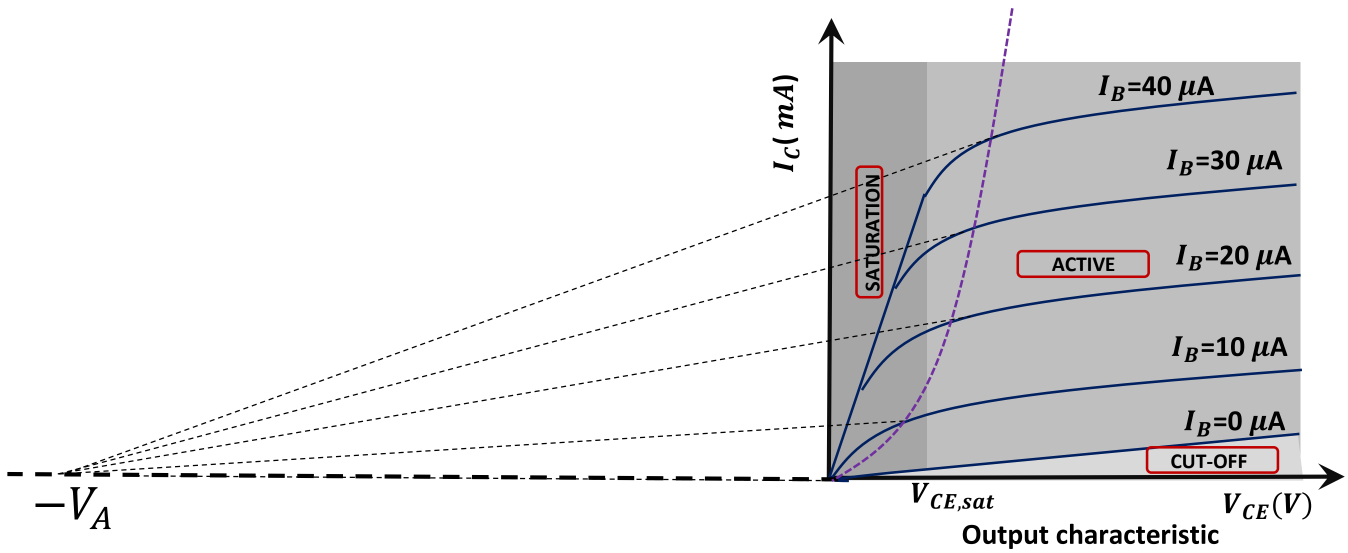
This requires to reverse bias of emitter junction by a voltage of order 0.1 V for Ge and about 0 V for Si transistor

EARLY VOLTAGE-

A greater reverse bias across the collector–base junction, decreasing the width of the charge carrier portion of the base. Base-narrowing has two consequences that affect the current:

(i)There is a lesser chance for recombination within the "smaller" base region.

(ii)The charge gradient is increased across the base, hence the current of Minority carriers injected across the emitter junction increases. Both these factors increase the collector or "output" current of the transistor with an increase in the collector voltage. This increased current is shown in Figure 1.



Tangents to the characteristics at large voltages extrapolate backward to intercept the voltage (V_{CE}) axis at a voltage called the Early voltage, often denoted by the symbol V_A.

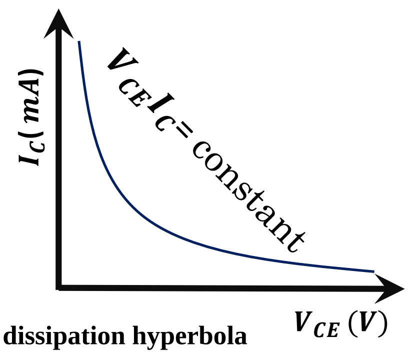
MAXIMUM POWER DISSIPATION HYPERBOLA-

When current passes through the transistor there is always some amount of Joule heating. Again there is also some heat radiation into the surroundings at a rate limited by its design. If the rate of heat generation exceeds the rate of radiation the transistor would be damaged.

The maximum collector dissipation level for CE mode is defined as

$$P_{C,max} = V_{CE}.I_C = constant$$

It represents a hyperbola on the CE output characteristic and called maximum power dissipation hyperbola



MAXIMUM COLLECTOR VOLTAGE-

There is an upper limit to the value of collector junction voltage even if the power rating of a transistor is not exceeded. Because there is possibility of **avalanche breakdown** or **punch through.**

Avalanche breakdown- we have collector multiplication ratio M= $\frac{1}{1-\left(\frac{V_{CB}}{V_B}\right)^n}$ [symbols have their usual meanings]

Then if $V_{CB} \rightarrow V_B$ Then M→ ∞ .Hence the current I_{CBO} passing through the collector junction get multiplied by a factor ∞ hence breakdown occurs.

PUNCH THROUGH- Due to Early effect the effective base width decreases. If the base is very thin it is possible that for a collector voltage far below the breakdown voltage, the active base region disappears and the collector depletion layer meet the emitter base depletion layer. Any further increase of collector base voltage lower the barrier of the emitter junction and result in excessive current as direct injection into wide collector depletion layer. This is known as punch through, which also limit the allowable collector-to-base voltage.

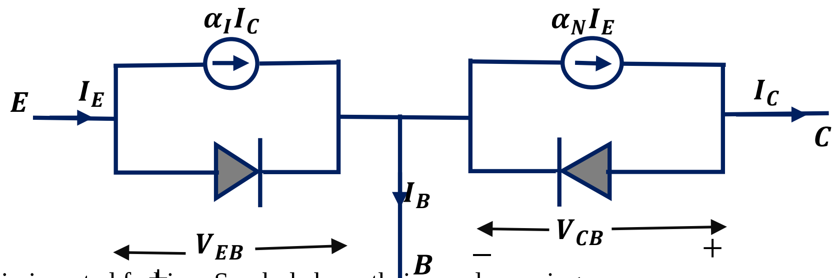
The **maximum collector voltage is limited** by either by **avalanche breakdown** or by **punch through** depending on the base doping level and thickness.

Ebers-Moll model of a transistor-

Consider a normal operation of p-n-p transistor with its E-B junction forward bias by a voltage V_{EB} and J_{CB} is biased by a voltage V_{CB}.As the collector current is equal to the input emitter current plus the current through C-B diode.

Thus $I_C = \alpha_N I_E - I_{CBO}(e^{\frac{eV_{CB}}{kT}} - 1)$……………(i)

The subscript N used to indicate that transistor is operating in normal fashion. Symbols have the usual meanings.



Suppose now the transistor is used in an inverted fashion (role of emitter and collector are interchanged) then, $I_E = \alpha_I I_C + I_{EBO}(e^{\frac{eV_{EB}}{kT}} - 1)$…………………..(ii)

The subscript I used to indicate that transistor is operating in inverted fashion. Symbols have their usual meaning.

These two equation are Ebers-Moll equation, where the four parameters $\alpha_N, \alpha_I, I_{CBO}$ & I_{EBO} are not independent by related as $\alpha_N I_{EBO} = \alpha_I I_{CBO}$. We also have $I_E = I_B + I_c$.

Equation (i) & (ii) may be represent by a circuit shown in figure known as Ebers-Moll model of transistor.

Obviously, the circuit contains two ideal diodes connected back to back and each diode Shunted by a current controlled current source.

The model is valid for both forward and reverse voltages across the junction

Why it is not possible to construct a transistor by simply connecting two isolated diodes back to back?

According to Ebers-Moll model the transistor can be represented by a circuit contains two ideal diodes connected back to back and each diodes is shunted by a current controlled current source. It is not possible to construct a transistor by simply connecting two isolated diodes back to back because if the base width is made much larger than the diffusion length and hence all the minority carriers recombine in the base and none can reach the collector.

In this case $\alpha_N = \alpha_I = 0$ and the current sources are to be eliminated. Hence Ebers moll model is not valid, transistor action ceases.