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Module - 3

Bipolar Junction Transistor

Fundamentals of BJT operation, Amplification with BJTs BJT Fabrication, The Coupled Diode Model (Ebers-Moll Model) Switching operation of a Transistor, Cut-off, Saturation, Switching Cycle, Specifications, Drift in the base region, Base narrowing, Avalanche Breakdown.

Text book 1:

Ben. G. Streetman, Sanjay Kumar Banerjee, "Solid State Electronic Devices", 7th Edition, Pearson Education, 2016, ISBN 978-93-325-5508-2.

Fundamentals of BJT operation.

< operation of PNP transistor >

< formation of PNP transistor >

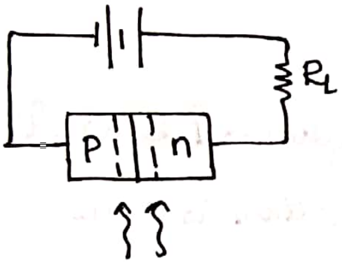


fig (a)
optical generation

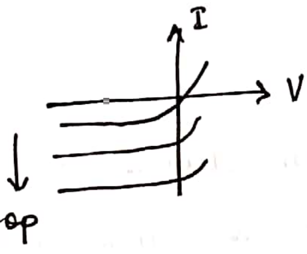


fig (b)
I-V charac as func of EHP generation

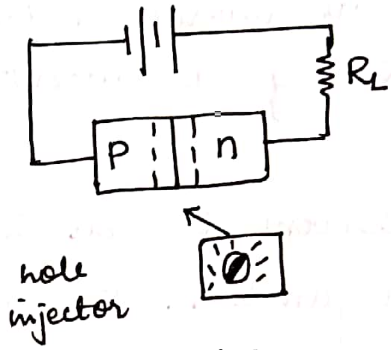


fig (c)
minority carrier injection by a hypothetical device.

* W.K.T the reverse saturation current through the diode depends on the rate at which minority carriers are generated in the neighborhood of the junction.

* Reverse current through the diode can be increased by increasing the rate of EHP generation (fig b). One convenient method for accomplishing this is optical excitation of EHPs with light ($h\nu > E_g$) and the reverse current is directly proportional to the optical generation rate gop.

* It is also possible to inject minority carriers into the neighborhood of the junction electrically instead of optically.

* If a hypothetical hole injection device is considered as shown in fig (c) and hole can be injected at a predetermined rate into the n-side of the junction, the effect on the junction current will resemble the effects of optical generation.

* The current from n to p will depend on the hole injection rate and will be essentially independent of the bias voltage.

* There are several obvious advantages to such an external control of a current.

* A convenient hole injection device is a forward biased p^+-n junction. The current in such a junction is due primarily to holes injected from p^+ region into the n material.

  If n side of forward biased junction is made same as n side of the reverse biased junction, the p^+-n-p structure is formed.

* With this configuration, injection of holes from the p^+-n junction into the center n region supplies the minority carrier holes to participate in the reverse current through n-p junction.

  It is important that the injected holes do not recombine in the n-region before they can diffuse to the depletion layer of the reverse biased junction. Thus n-region is made narrow compared with a hole diffusion length.

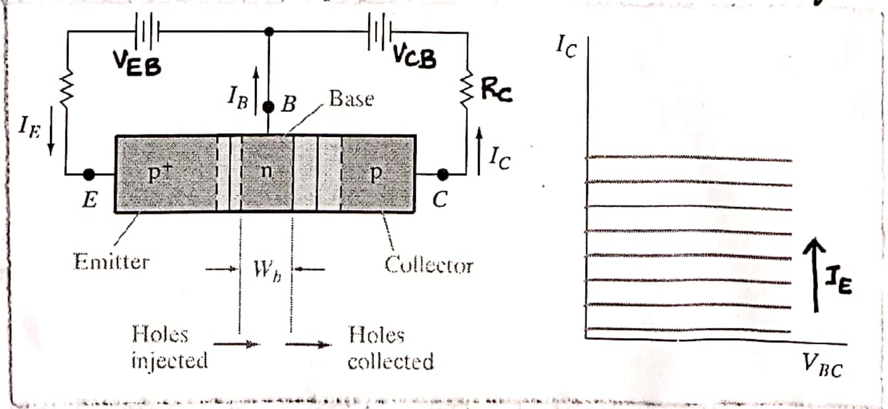


fig: PNP device with FB emitter junction & RB collector Junc & its charac

* The structure is P-n-P BJT. The forward biased junction that injects holes into the center n-region is called the emitter junction, the reverse biased junction that collects the injected holes is called the collector junction.

p^+ - emitter, n - base and p - collector. The biasing arrangement is called common base configuration.

* characteristics of good p-n-p transistor.

* almost all the holes injected by emitter into the base be collected.
* n-type base must be narrow and hole lifetime τ_p should be long which can be obtained by specifying $W_b << L_p$. where W_b = length of the neutral 'n' material of the base and L_p = diffusion length for holes in the base.

$$L_p = \sqrt{D_p \tau_p}$$

* when $L_p = \sqrt{D_p \tau_p}$ is satisfied then an average hole injected at the emitter junction will diffuse to the depletion region of the collector junction without recombination in the base.

* second requirement is that the current I_E crossing the emitter junction should be composed almost entirely of holes injected into the base rather than electrons crossing from base to emitter. this requirement is satisfied by doping the base region lightly compared with the emitter so that p^+-n emitter junction as shown in fig results.

* fig 3 : summary of holes and electron flow in a p-n-p transistor with proper biasing.

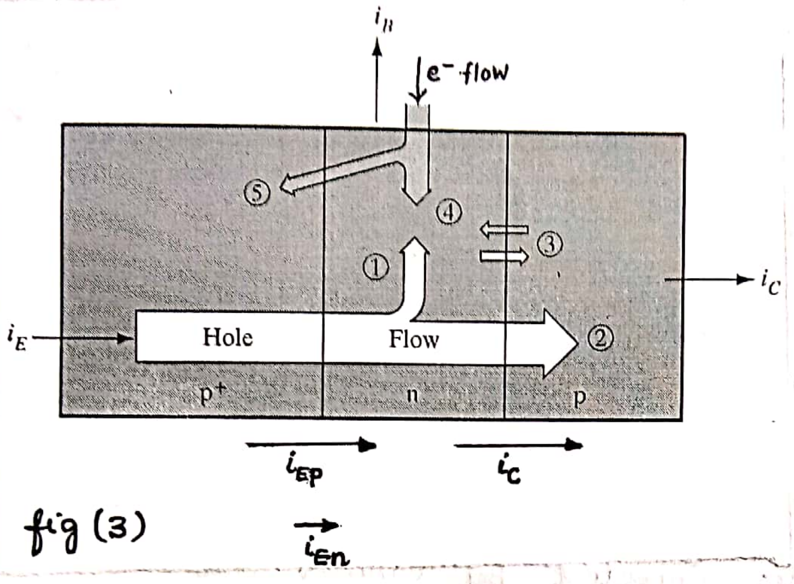


fig (3)

with proper biasing,

In fig,

① injected holes lost to recombination in the base.

② holes reaching the reverse biased collector junction.

③ thermally generated electrons and holes making up the reverse saturation current of the collector junction.

④ e^-s supplied by the base contact for recombination with holes.

⑤ e^-s injected across the forward biased emitter junction.

* It is clear that current I_E flows into the emitter of a properly biased p-n-p transistor and that I_C flows out at the collector, since the direction of hole flow is from the emitter to collector.

* In a good transistor the base current will be very small since I_E is essentially hole current and the collected current I_C is almost equal to I_E.

* Base current I_B can be considered by three dominant mechanisms :

① There must be some recombination of injected holes with electrons in the base, even with $W_b \ll L_p$. The electrons lost to recombination must be resupplied through the base current.

(2) Some electrons will be injected from n to p in the forward-biased emitter junction, even if the emitter is heavily doped compared with the base. These electrons must also be supplied by I_B.

(3) Some electrons are swept into the base at the reverse-biased collector junction due to thermal generation in the collector. This small current reduces I_B by supplying electrons to the base.

In well designed transistor, I_B will be a very small fraction of I_E.

In n-p-n transistor the three current directions are reversed, since electrons flow from the emitter to collector and holes must be supplied to the base.

[M. Sushma]

Amplification with BJTs

* The transistors are useful in amplifiers because the currents at the emitter and collector are controllable by the relatively small base current.

* Collector current is made up entirely of those holes injected at the emitter, which are not lost to recombination in the base. Thus i_c is proportional to the hole component of the emitter current i_{EP}

i.e $i_C \propto i_{EP}$

$$\boxed{i_c = B\, i_{EP}} \longrightarrow (1)$$

Proportionality factor B is the fraction of injected holes which make it across the base to the collector.

B is called base transport factor.

* The total Emitter current i_E is made up of the hole component i_{EP} and the electron component i_{En}, due to electrons injected from the base to emitter.

∴ The emitter injection efficiency γ is

$$\boxed{\gamma = \frac{i_{EP}}{i_{En} + i_{EP}}} \longrightarrow (2)$$

* For an efficient transistor, B and γ are very near to unity that is emitter current should be mostly due to holes $(\gamma \simeq 1)$ and most of the injected holes should be eventually participate in the collector current $(B \simeq 1)$.

* The relation between the collector and emitter currents is

$$\frac{i_C}{i_E} = \frac{B\, i_{EP}}{i_{En} + i_{EP}} = B\gamma \equiv \alpha \longrightarrow (3)$$

The product $B\gamma$ is defined as the factor α, called the current transfer ratio which represents the emitter-to-collector current amplification.

As α is smaller than unity, hence there is no real amplification between these currents.

< Note : Transistor in common base configuration cannot be used as an amplifier as $\alpha \leq 1$ >

* The relation between i_C and i_B is more promising for amplification.

[To account for base current, the rates at which electrons are lost from the base by injection across the emitter junction (i_{En}) and the rate of electron recombination with holes in the base must be included. The lost electrons must be resupplied through the base current i_B.]

* If the fraction of injected holes making it across the base without recombination is B, it follows that $(1-B)$ is the fraction recombining in the base. Thus the base current is

$$i_B = i_{En} + (1-B)\, i_{EP} \longrightarrow (4)$$

* The relation between the collector and base currents is

$$\frac{i_C}{i_B} = \frac{B\, i_{EP}}{i_{En} + (1-B)\, i_{EP}} = \frac{B\left(i_{EP}/i_{En} + i_{EP}\right)}{1 - B\left(i_{EP}/i_{En} + i_{EP}\right)} = \frac{B\gamma}{1-B\gamma} = \frac{\alpha}{1-\alpha} = \beta$$

$$\boxed{\frac{i_c}{i_B} = \frac{\alpha}{1-\alpha} = \beta} \longrightarrow (5)$$

The factor β relating the collector current to the base current is the base-to-collector current amplification factor.

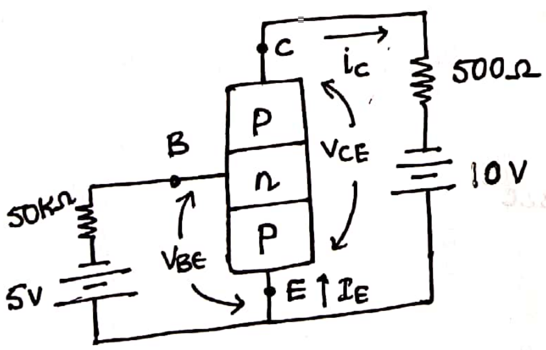
Since α is near to unity, β can be large for a good transistor, and the collector current is large compared with the base current.

<Note : Transistor in Common Emitter Configuration is used as an amplifier As β is large>

$$\boxed{I_c = \beta \cdot I_B} \longrightarrow (6)$$

Eq^n (6) represents that the collector current i_c can be controlled by variations in the small current i_B.

* Consider the circuit where i_B can be determined by the biasing circuit



Assuming $\beta = 100$

$$i_B = \frac{V_{BB}}{R_B} = \frac{5}{50K} = 0.1\,mA$$

$$i_c = \beta\, i_B = 100(0.1m) = 10\,mA$$

$$\left[\text{i.e } \beta = \frac{i_c}{i_B} = \frac{10m}{0.1m} = 100\right] \text{assume}$$

$$V_{CE} - I_c R_c - V_{CE} = 0$$

$$V_{CE} = V_{CC} - I_c R_c = 10 - (10m)500 = 5V$$

<OR>

Given $\tau_p = 10\,\mu sec$, $\tau_t = 0.1\,\mu sec$

$$\beta = \frac{\tau_p}{\tau_t} = \frac{10\mu}{0.1\mu} = \boxed{100}$$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \boxed{0.1\,mA} \quad \text{neglecting } V_{BE}$$

$$I_C = \beta I_B = 100(0.1m) = \boxed{10\,mA}$$

$$V_{CC} - I_C R_C - V_{CE} = 0$$

$$V_{CE} = V_{CC} - I_C R_C = 10V - (10m \times 500) = \boxed{5V}$$

* The average excess holes ~~ex / transit~~ spends a time τ_t defined as the transit time from the emitter to collector. Since the base width W_b is made small compared with L_p, this transit time is much less than the average hole life time τ_p in the base (τ_p = life time of the hole in n-region)

Thus the ratio of collector current to the base current is expressed as

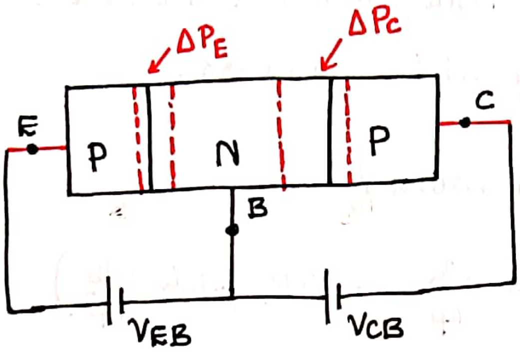
$$\boxed{\frac{i_c}{i_B} = \beta = \frac{\tau_p}{\tau_t}}$$

Let $\tau_p = 100\,\mu sec$ $\tau_t = 0.1\,\mu sec$

$$\therefore \beta = \frac{100\mu}{0.1\mu} = 100$$

[M. Sushma]

The Coupled - Diode Model ⟨ Ebers - Moll Model ⟩



* The excess hole concentration at the edge of the emitter depletion region ΔP_E and the corresponding concentration on the collector side of the base ΔP_C are given by

$$\Delta P_E = P_n \left(e^{\frac{qV_{EB}}{KT}} - 1 \right) \longrightarrow ①$$

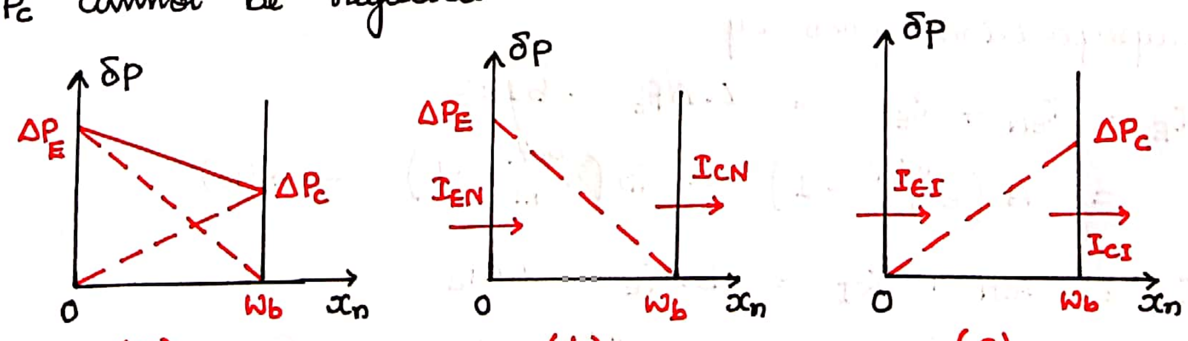
$$\Delta P_C = P_n \left(e^{\frac{qV_{CB}}{KT}} - 1 \right) \longrightarrow ②$$

If the emitter junction is strongly forward biased $\left(V_{EB} >> \frac{KT}{q}\right)$ and the collector junction is strongly reverse biased $(V_{CB} << 0)$

$$\therefore \; \Delta P_E \simeq P_n \, e^{\frac{qV_{EB}}{KT}} \longrightarrow ③$$

$$\Delta P_C \simeq -P_n \longrightarrow ④$$

* If the collector junction of a transistor is forward biased, ΔP_C cannot be neglected.



(a) approximate hole distribution in base with J_E and J_C forward biased.

(b) component due to injection and collection in the normal mode.

(c) component due to the inverted mode.

* fig a) illustrates a situation in which the emitter and collector junctions are both forward biased, so that ΔP_E and ΔP_c are positive numbers.

For a symmetrical transistor,

$$I_E = qA\frac{D_P}{L_P}\left(\Delta P_E \operatorname{ctnh}\frac{W_b}{L_P} - \Delta P_c \operatorname{csch}\frac{W_b}{L_P}\right) \longrightarrow (5)$$

$$I_c = qA\frac{D_P}{L_P}\left(\Delta P_E \operatorname{csch}\frac{W_b}{L_P} - \Delta P_c \operatorname{ctnh}\frac{W_b}{L_P}\right) \longrightarrow (6)$$

$$I_B = I_E - I_c = qA\frac{D_P}{L_P}\left((\Delta P_E + \Delta P_c)\tanh\frac{W_b}{2L_P}\right) \longrightarrow (7)$$

where D_P = hole diffusion co-efficient.

* For a symmetrical transistor, defining,

$$a \equiv \left(qA\frac{D_P}{L_P}\right)\operatorname{ctnh}\left(\frac{W_b}{L_P}\right) \longrightarrow (8)$$

$$b \equiv \left(qA\frac{D_P}{L_P}\right)\operatorname{csch}\left(\frac{W_b}{L_P}\right) \longrightarrow (9)$$

then $I_{EN} \equiv a\,\Delta P_E$ and $I_{CN} = b\,\Delta P_E$ with $\Delta P_c = 0$

$I_{EI} = -b\,\Delta P_c$ and $I_{CI} = -a\,\Delta P_c$ with $\Delta P_E = 0$

These above 4 components are combined by linear superposition given by

$$I_E = I_{EN} + I_{EI} = a\,\Delta P_E - b\,\Delta P_c$$

$$= A\left(e^{\frac{qV_{EB}}{KT}} - 1\right) - B\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \longrightarrow (10)$$

$$I_c = I_{CN} + I_{CI} = b\,\Delta P_E - a\,\Delta P_c$$

$$= B\left(e^{\frac{qV_{EB}}{KT}} - 1\right) - A\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \longrightarrow (11)$$

where $A \equiv a p_n$ and $B \equiv b p_n$

Note : These equations show that a linear superpositions of the normal and inverted components does give the result for a a symmetrical transistor.

* To relate the four components of current by factors which allow for asymmetry in the two junctions.

For example, the emitter current in the normal mode can be written as,

$$I_{EN} = I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right) \quad , \Delta P_c = 0 \longrightarrow (12)$$

where I_{ES} is the magnitude of the emitter saturation current in the normal mode.

$\Delta P_c = 0$ in this mode implies $V_{CB} = 0$ in the eq^n.

* Similarly the collector current in the inverted mode is

$$I_{CI} = -I_{CS}\left[e^{\frac{qV_{CB}}{KT}} - 1\right] \quad , \Delta P_E = 0 \longrightarrow (13)$$

where I_{CS} is the magnitude of collector saturation current with $V_{EB} = 0$. Minus sign with I_{CI} means that in the inverted mode holes are injected opposite to the defined direction of I_c.

* The corresponding collected currents for each mode of operation can be written by defining a new α for each case:

$$I_{CN} = \alpha_N I_{EN} = \alpha_N I_{ES}\left[e^{\frac{qV_{EB}}{KT}} - 1\right] \longrightarrow (14)$$

$$I_{EI} = \alpha_I I_{CI} = \alpha_I I_{CS}\left[e^{\frac{qV_{CB}}{KT}} - 1\right] \longrightarrow (15)$$

where α_N and α_I are the ratios of collected current to injected current in each mode.

* The total current can again be obtained by superposition of the components.

$$I_E = I_{EN} + I_{EI} = I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right) - \alpha_I I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \rightarrow (16)$$

$$I_C = I_{CN} + I_{CI} = \alpha_N I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right) - I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \rightarrow (17)$$

The above equation is referred to as Ebers-moll equations.

* An interesting feature of Ebers-moll equation is that I_E and I_C are described in terms resembling diode relation (I_{EN} & I_{CI}) plus terms that provide coupling between properties of emitter and collector (I_{EI} & I_{CN})

where,

$$I_E = I_{ES}\frac{\Delta P_E}{P_n} - \alpha_I I_{CS}\frac{\Delta P_C}{P_n} \rightarrow (18)$$

$$I_C = \alpha_N I_{ES}\frac{\Delta P_E}{P_n} - I_{CS}\frac{\Delta P_C}{P_n} \rightarrow (19)$$

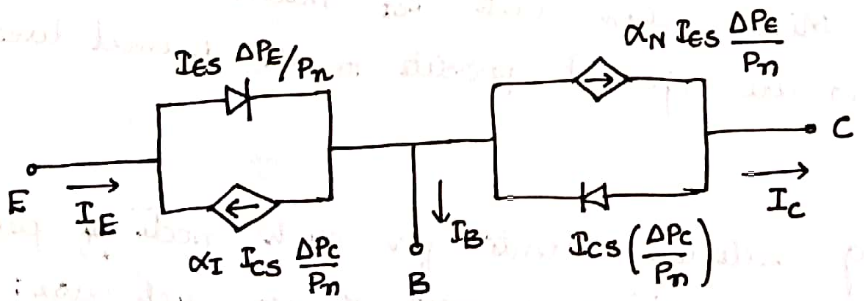


fig : Equivalent circuit synthesizing Ebers moll equations.

when $\alpha_I I_{CS} = \alpha_N I_{ES} \rightarrow (20)$

$$I_E = I_{ES}\frac{\Delta P_E}{P_n} - \alpha_N I_{ES}\cdot\frac{\Delta P_C}{P_n} = \frac{I_{ES}}{P_n}\left(\Delta P_E - \alpha_N \Delta P_C\right) \rightarrow (21)$$

$$I_C = \alpha_I I_{CS}\frac{\Delta P_E}{P_n} - I_{CS}\frac{\Delta P_C}{P_n} = \frac{I_{CS}}{P_n}\left(\alpha_I \Delta P_E - \Delta P_C\right) \rightarrow (22)$$

* The saturation current from the coupling term can be eliminated by considering (Eq^n 17 $-$ $\alpha_N \cdot$ eq^n 16)

i.e $\quad I_C = \alpha_N I_E - (1-\alpha_N\alpha_I)\, I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \longrightarrow$ (23)

and (eq^n 16 $-$ α_I eq^n 17)

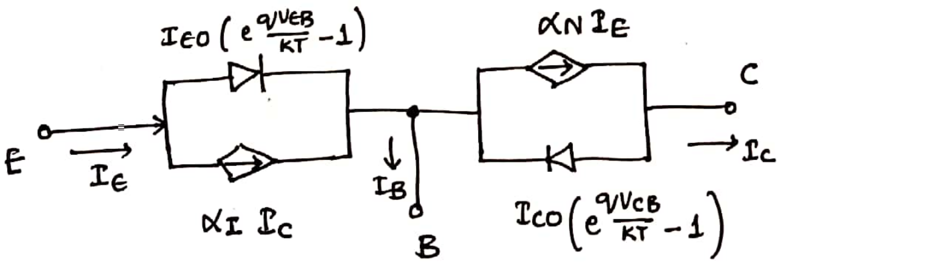
$$I_E = \alpha_I I_C + (1-\alpha_N\alpha_I)\, I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right) \longrightarrow (24)$$

If the terms $(1-\alpha_N\alpha_I) I_{CS} = I_{CO}$ and $(1-\alpha_N\alpha_I) I_{ES} = I_{EO}$ where I_{EO} is the magnitude of Emitter Saturation current with collector junction open and I_{CO} is the magnitude of collector saturation current with emitter junction open.

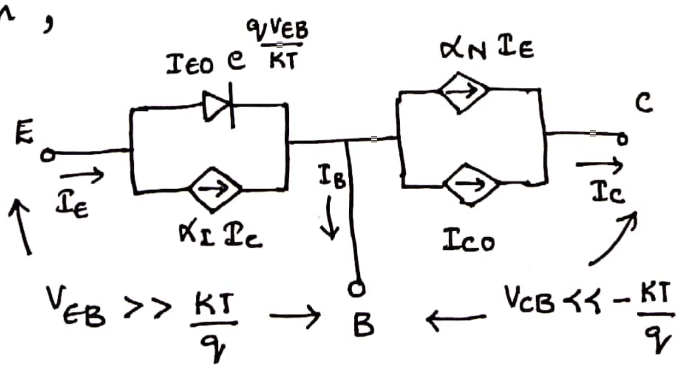
* The Ebers Moll equations then become

$$I_E = \alpha_I I_C + I_{EO}\left(e^{\frac{qV_{EB}}{KT}} - 1\right) \longrightarrow (25)$$

$$I_C = \alpha_N I_E - I_{CO}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) \longrightarrow (26)$$



* under normal biasing the equivalent circuit reduces to the form ,



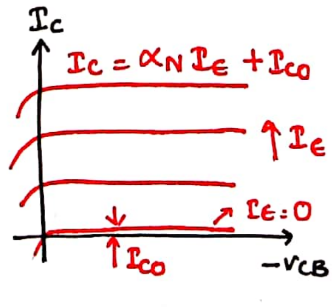


fig : collector charac with normal biasing,

Switching Operation of a Transistor.

* In switching operation a transistor is usually controlled in two conduction states i.e 'ON' state and 'OFF' state.

* Ideally, a switch appears as a short circuit when turned ON and an open circuit when turned off.

* It is always desirable to switch the device from one state to the other with no lost time in between.

* Two states of a transistor in switching can be seen considering Common Emitter Configuration.

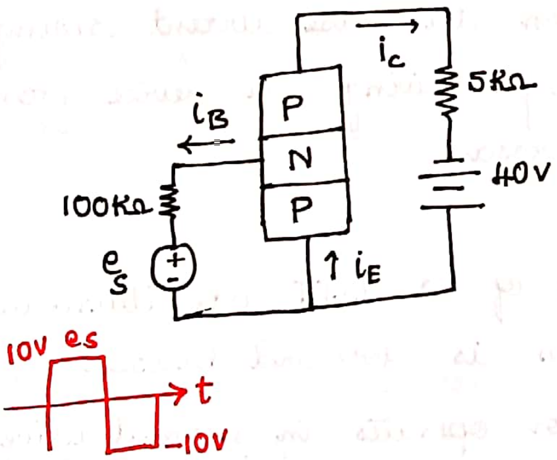


fig a) CE biasing ckt

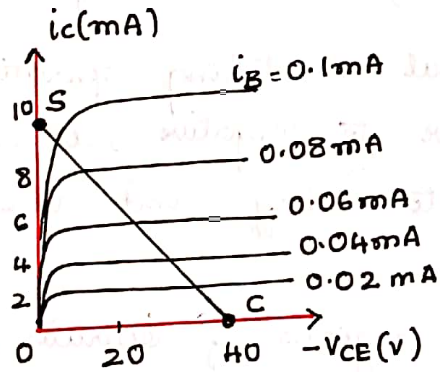


fig b) collector characteristics and load line for the circuit with cut-off and saturation indicated

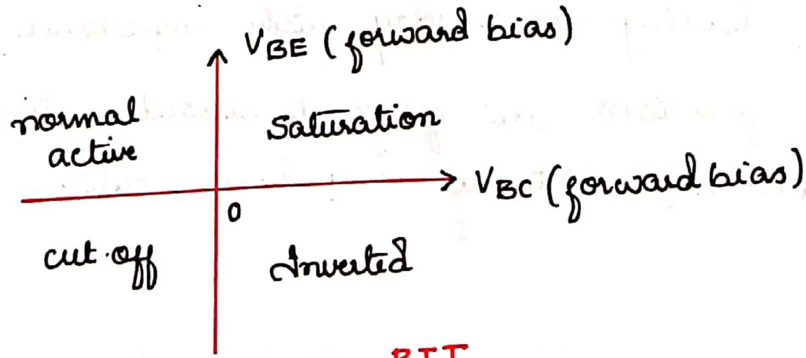


fig c) operating regimes of a BJT

* When emitter junction is forward biased and collector is reverse biased with a reasonable value of i_B, transistor operates in the normal active mode. (fig - b)

* If base current is zero or negative, the point C is reached at the bottom end of the load line and the collector current is negligible. This is 'off' state of the transistor and the device is said to be operating in the cut-off regime.

* If base current is positive and sufficiently large, the device is driven to the saturation regime, marked S. This is the ON-state of the transistor in which a large value of i_C flows with only a very small voltage drop V_{CE}

* In a typical switching operation the base current swings from positive to negative, thereby driving the device from saturation to cut off and vice versa.

* The various regions of operation of a BJT are illustrated in fig C. If the emitter junction is forward biased and collector reverse biased, transistor operates in normal active mode, the opposite gives inverted mode of operation.

If both junctions are reverse biased, transistor operates in cut-off leading to a very high impedance state of BJT.

If both junctions are forward biased, transistor operates in saturation with low impedance state.

** Cut-off **

If emitter junction and collector junction is reverse biased the transistor operates in cut-off mode.

W.K.T, $\Delta P_E = P_n \left(e^{\frac{qV_{EB}}{KT}} - 1\right)$ for RB, $V_{EB} << \frac{KT}{q}$

$$\therefore \Delta P_E = -P_n$$

$\Delta P_c = P_n \left(e^{\frac{qV_{CB}}{KT}} - 1\right)$ for RB, $V_{CB} << \frac{KT}{q}$

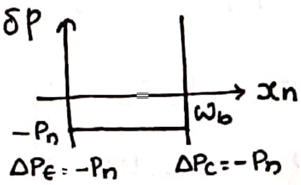
$$\therefore \Delta P_c = -P_n$$

* In cut-off regime, the excess hole concentration at the edges of the reverse biased emitter and collector junction is

$$\frac{\Delta P_E}{P_n} \simeq \frac{\Delta P_c}{P_n} \simeq -1 \quad \text{which implies } p(x_n) = 0$$

* The excess hole distribution in the base is approximately constant at $-P_n$. The base current i_B can be approximated for a symmetrical transistor on a charge storage basis as $-qAP_n\frac{W_b}{\tau_p}$.

* Small saturation current flows from n to p in each reverse biased junction.

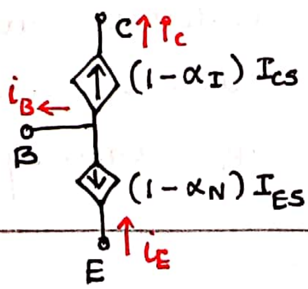


* W.K.T Eber's Moll equations

$$i_E = I_{ES}\frac{\Delta P_E}{P_n} - \alpha_I I_{CS}\frac{\Delta P_c}{P_n} = -I_{ES} + \alpha_I I_{CS} \boxed{= -I_{ES}(1-\alpha_N)}$$

$$i_C = \alpha_N I_{ES}\frac{\Delta P_E}{P_n} - I_{CS}\frac{\Delta P_c}{P_n} = -\alpha_N I_{ES} + I_{CS} \boxed{= I_{CS}(1-\alpha_I)}$$

$$\left(\because \frac{\Delta P_E}{P_n} \simeq \frac{\Delta P_c}{P_n} \simeq -1 \text{ and } \alpha_N I_{ES} = \alpha_I I_{CS}\right)$$



$$\therefore i_B = i_E - i_C = -(1-\alpha_N)I_{ES} - (1-\alpha_I)I_{CS}$$

of short circuit saturation currents I_{ES} and I_{CS} are small and α_N and α_I are both near to unity, the currents will be negligible and the cut-off regime will closely approximate the 'off' condition of an ideal switch.

** Saturation **

* The saturation regime begins when the reverse bias across the collector junction is reduced to zero and it continues as the collector becomes forward biased.

* The excess hole distribution in this case is illustrated in fig as shown below.

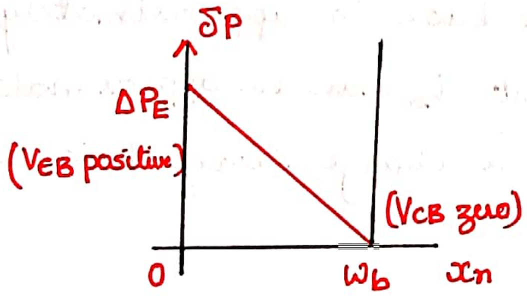


fig (a) beginning of Saturation

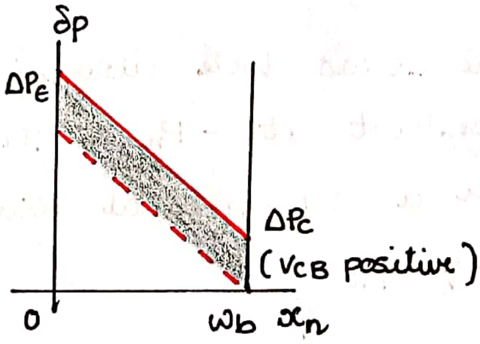


fig (b) over saturation.

* The device is saturated when $\Delta P_c = 0$ and forward bias of collector junction (fig b) leads to a positive ΔP_c, driving the device further into saturation.

* As the device is driven deeper into saturation, the collector current stays essentially constant while the base current increases. In this saturation condition the transistor approximates the 'ON' state of an ideal switch.

* The degree of 'over saturation' fig b) does not affect the value of i_c significantly, it is important in determining the time required to switch the device from one state to the other.

** Switching Cycles. **

* The various mechanisms of a switching cycles are illustrated in the fig.

* If the device is originally in the cut-off condition, a step increase of base current to I_B causes the hole distribution to increase approximately, as shown in fig (b)

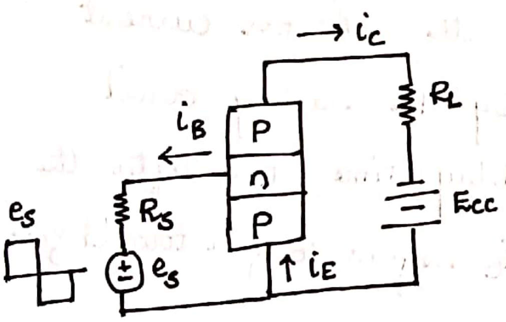


fig a) Circuit diagram

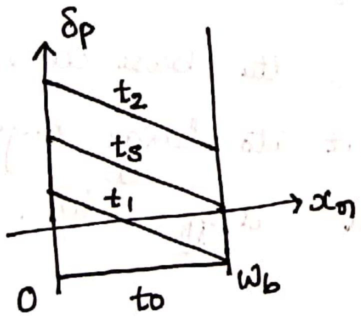


fig b)

to = cutoff
t_1 = normal active region
t_s = beginning of saturation
t_2 = Final Saturated State

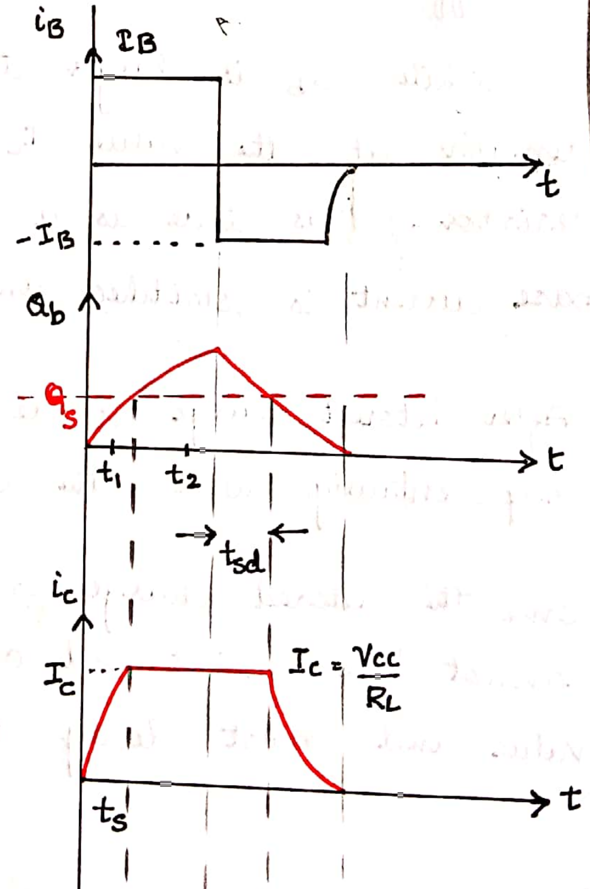


fig c) base current, stored charge and collector current during a turn on and turn off transient.

* At time t_s the device enters saturation and the hole distribution reaches its final state at t_2.

* As the stored charge in the base Q_b increases, there is an increase in the collector current i_c. The collector current does not increase beyond its value at the beginning of saturation t_s.

* The saturated collector current $I_C \simeq \frac{E_{CC}}{R_L}$. There is an essentially exponential increase in the collector current while Q_b rises to its value Q_s at t_s.

* When the base current is switched negative $(-I_B)$, the stored charge must be withdrawn from the base before cut-off is reached.

While Q_b is larger than Q_s, the collector current remains at the value I_c, fixed by the battery and resistor. Thus there is a storage delay time t_{sd} after the base current is switched and before i_c begins to fall toward zero.

* After stored charge is reduced below Q_s, i_c drops exponentially with the characteristic fall time.

* Once the stored charge is withdrawn, the base current cannot be maintained any longer at its large negative value and must decay to a small cut off value.

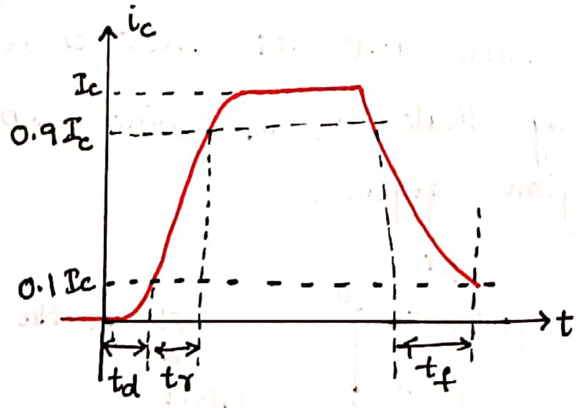
[M. Sushma]

** Specifications for Switching Transistors **

* t_s and t_{sd} can be determined by solving for the time dependent base current $i_B(t)$

* Charging time of the emitter junction capacitance in going from cut-off to saturation cannot be neglected.

* Since the emitter junction is reverse biased in cutoff, it is necessary for the emitter space charge layer to be charged to the forward bias condition before collector current can flow. Therefore delay time td must be included to account for this effect.



td = Delay time while jxnc capacitance is charging.

t_r = Rise time from 0.1 to $0.9 I_c$

t_f = fall time from 0.9 to $0.1 I_c$

* Typical values of td are given in the specification information of most switching transistors where td is time duration at jxnction capacitor charges.

* Rise time t_r defined as the time required for the collector current to rise from 10 to 90% of its final value.

$\therefore t_{on} = t_d + t_r$.

* Third specification is the fall time t_f required for i_c to fall through a similar fraction of its turn-off excursion.

Other Important Effects

1. Drift in Base Region

In this method there is a fairly sharp discontinuity in the doping profile. When the donor concentration in the base region becomes smaller than the constant p-type background doping in the collector.

Similarly the emitter is assumed to be a heavily doped (p^+) shallow region providing a second rather sharp boundary for the base. Within the base region itself, however the net doping concentration ($N_d - N_a \equiv N$) varies along a profile that decreases from the emitter edge to the collector edge.

It can be clearly seen that the effect of an impurity gradient by assuming that $N(x_n)$ varies exponentially within the base region fig(b).

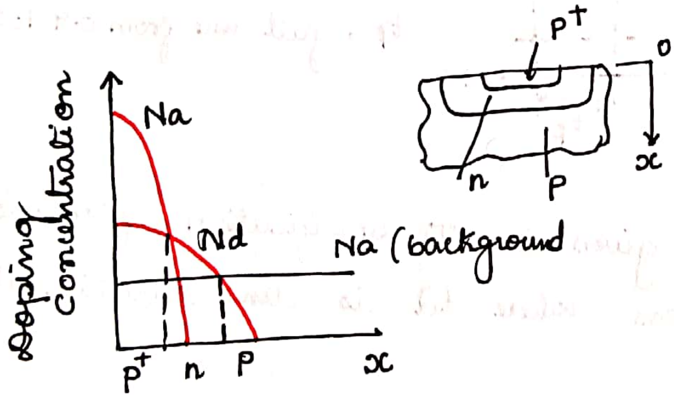


fig a) Typical doping profile

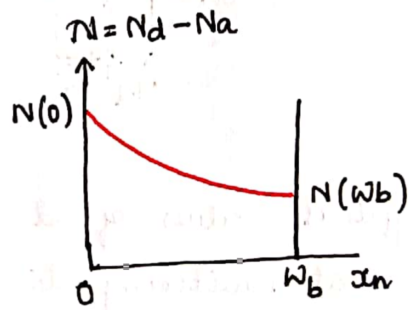


fig b) Exponential distribution of the net donor.

Graded Doping in base region of p-n-p transistor

* One important result of a graded base region is that a built in electric field exists from emitter to collector (for a p-n-p), thereby adding a drift component to the

the transport of hole across the base.

* If the net donor doping of the base is large enough to allow the usual approximation $n(x_n) \simeq N(x_n)$, the balance of electron drift and diffusion currents at equilibrium requires

$$I_n(x_n) = qA\mu_n N(x_n)\mathcal{E}(x_n) + qAD_n \frac{dN(x_n)}{dx_n} = 0 \longrightarrow ①$$

∴ the built-in electric field is,

$$\mathcal{E}(x_n) = -\frac{D_n}{\mu_n}\frac{1}{N(x_n)}\frac{dN(x_n)}{dx_n} = -\frac{KT}{q}\frac{1}{N(x_n)}\cdot\frac{dN(x_n)}{dx_n} \longrightarrow ②$$

* For a doping profile $N(x_n)$ that decreases in the positive x_n-direction, this field is +ve directed from emitter to collector.

For an exponential doping profile, the electric field $\mathcal{E}(x_n)$ turns out to be constant with position in the base.

$$\therefore \mathcal{E}(x_n) = \frac{KT}{q}\frac{a}{W_b} \longrightarrow ③$$

where exponential distribution is represented as

$$N(x_n) = N(0)\, e^{\frac{-ax_n}{W_b}} \quad \text{where } a \equiv \ln\frac{N(0)}{N(W_b)}$$

* Since this field (eqn ③) aids the transport of holes across the base region from emitter to collector, the transit time τ_t is reduced below that of a comparable uniform base transistor.

* Similarly, electron transport in p-n-p is aided by the built in field in the base. This shortening of the transit time can be very important in high-frequency devices.

2. Base Narrowing / Base width Modulation / Early Effect.

* Effective base width W_b is essentially dependent of the bias Voltages applied to the collector and emitter junctions. i.e p^+-n-p^+ transistor is affected by the reverse bias applied to the collector.

* If the base region is lightly doped, the depletion region at the reverse biased collector junction can extend significantly into the n-type base region as shown in fig.

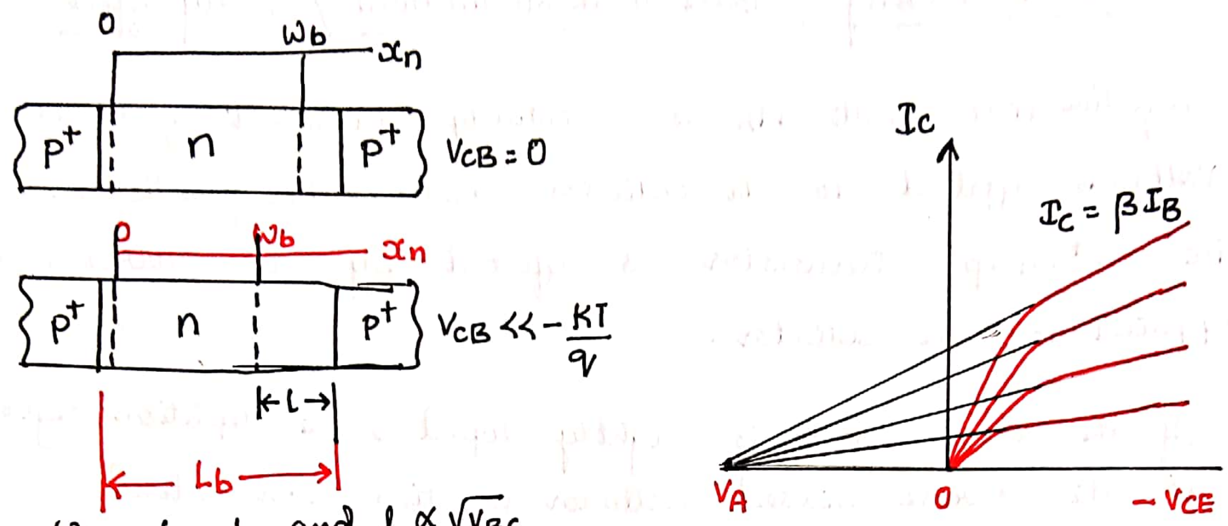
* As the collector voltage is increased, the space charge layer takes up more of width of the base L_b thereby reducing the effective base width W_b. This effect is called base narrowing, base-width modulation and Early effect.

* This decrease in W_b causes β to increase. As a result the collector current I_c increases with collector voltage rather than staying constant.

* The slope introduced by the early effect is almost linear with I_c and the common-emitter characteristics extrapolate to an intersection with the voltage axis at V_A, called Early voltage.

* for p^+-n-p^+ device shown in figure, length l of collector junction depletion region in the n material is given by

$$l = \left(\frac{2\epsilon V_{BC}}{q N_d}\right)^{1/2}$$



$W_b = L_b - l$ and $l \propto \sqrt{V_{BC}}$

If the reverse bias on the collector junction is increased far enough, it is possible to decrease W_b to the extent that the collector depletion region essentially fills the entire base.

This condition is called punch-through where holes are swept directly from the emitter region to the collector, transistor action is lost.

* punch through is a breakdown effect that is generally avoided in circuit design.

Avalanche Breakdown.

* Before punch through occurs in most transistors, avalanche multiplication at the collector junction becomes important.

* when CB (common-Base) and CE (common emitter) configuration are considered, the collector current increases sharply at a breakdown voltage BV_{CBO} and BV_{CEO} respectively.

* BV_{CEO} is significantly smaller than BV_{CBO}.

These effects can be understood by considering breakdown for the condition $I_E = 0$ (in CB) and for $I_B = 0$ in the common-emitter case.

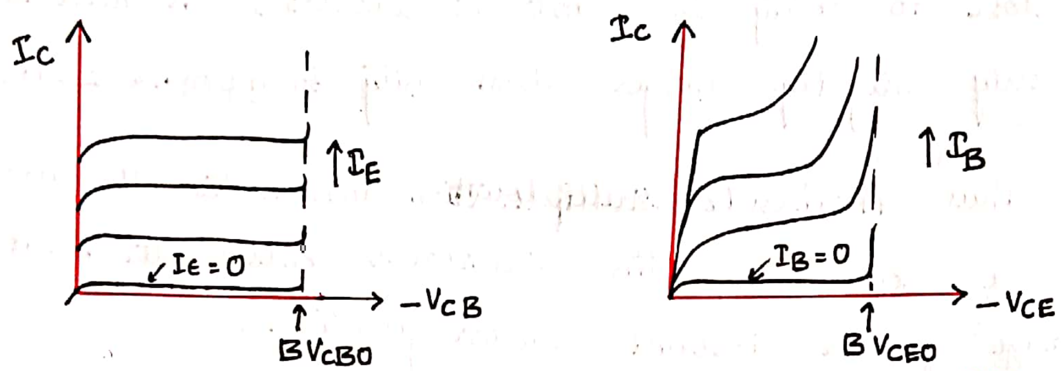


fig a) Common Base   fig b) Common emitter

* In each case the terminal current I_c is the current entering the collector depletion region multiplied by the factor M (multiplication factor)

$$I_c = (\alpha_N I_E + I_{co}) M = (\alpha_N I_E + I_{co}) \left(\frac{1}{1 - \left(\frac{V_{BC}}{BV_{CBO}}\right)^n} \right)$$

$$\because M = \frac{1}{1 - \left(\frac{V}{V_{bT}}\right)^n}$$

* In common Base case, $I_E = 0$

$$\therefore \; I_c = \alpha_N \cancel{I_E}^{\,0} M + M I_{co}$$

$\boxed{I_c = M I_{co}}$ and the term BV_{CBO} signifies the collector junction breakdown voltage.

* In common Emitter Case, $I_B = 0$ $\quad I_E = \cancel{I_B}^{\,0} + I_c \quad I_E = I_c$

$$\therefore \; I_c = \alpha_N I_c M + I_{co} M$$

$$\therefore \; \boxed{I_c = \frac{I_{co} M}{1 - M\alpha_N}}$$

* It can be noticed that in case of CE, I_C increases indefinitely when $\alpha_N M$ approaches unity

By contrast, M must approach infinity in the common base case before BV_{BO} is reached. Since α_N is close to unity in most transistors, M need to be only slightly larger than unity to approach Breakdown.

Thus Avalanche Multiplication dominates the current in a common emitter transistor below the breakdown voltage of the isolated collector junction.

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