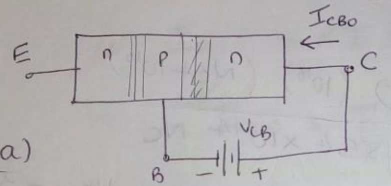
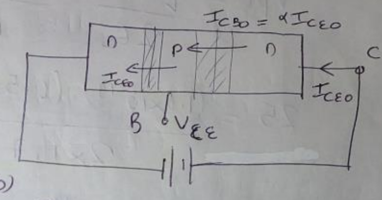
⇒ 2nd breakdown mechanism (Avalanche breakdown):-



(a)



(b)

BV_{CBO} is breakdown voltage of CB junction

For $I_B = 0$ (ie Base open), breakdown voltage at V_{CE} is called BV_{CEO}

fig 6a) Open emitter configuration with saturation current I_{CBO}

b) Open Base configuration with saturation current I_{CEO}

- Fig 6a) is an npn BJT with a R.B V_{BC} applied and with emitter left open. The current I_{CBO} is the R.B junction current.
- Fig 6b) shows npn BJT with an applied V_{CE} and base left open.
- This bias condition also makes the BC junction reverse-biased.
- The current I_{CBO} in fig (6b) is the normal R.B BC junction current. Part of this current is due to flow of minority carrier holes from the collector across the BC depletion region into the base.

Note: (Flow of holes into the base makes Base +ve w.r.t emitter) and BE junction ⇒ F.B, which produces I_{CEO}, due to injection of e̅s from E into Base.

- The injected e̅s diffuse across the base towards the BC junction where it becomes αI_{CEO}.

$$\therefore \quad I_{CEO} = \alpha I_{CEO} + I_{CBO} \quad \text{—①}$$

$$\text{or} \quad \boxed{I_{CEO} \approx \frac{I_{CBO}}{1-\alpha} \approx \beta I_{CBO}} \quad \text{—②}$$

Note: $\beta = \frac{\alpha}{1-\alpha} \approx \frac{1}{1-\alpha}$

Thus the R.B junction current I_{CBO} is multiplied by the current gain β when the transistor is biased in the open-base configuration.

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- When Transistor is biased in open-emitter configuration as in fig 6 a), current I_{CBO} at breakdown becomes $I_{CBO} \rightarrow M I_{CBO}$; where M is the multiplication factor.

$$\boxed{M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}}\right)^m}} \quad — ③$$

Empirical approximation for M.

where, m is an empirical constant ($3 < m < 6$)
and BV_{CBO} is B-C breakdown voltage with the emitter left open.

- When transistor is biased with base open, currents in B-C junction at breakdown are multiplied, so that

$$I_{CEO} = M(\alpha I_{CEO} + I_{CBO})$$

Solving for I_{CEO} $\Rightarrow$ $I_{CEO} \simeq \frac{M I_{CBO}}{1 - \alpha M}$

Thus condition for breakdown corresponds to

$$\alpha M = 1 \quad — ④$$

$$\boxed{M = \frac{1}{\alpha}}$$

$$\Rightarrow \frac{\alpha}{1 - \left(\frac{BV_{CEO}}{BV_{CBO}}\right)^m} = 1 \qquad \text{(Using ③ \& ④)}$$

where, BV_{CEO} is the C-E voltage at breakdown 37. in open base mode.

$$\Rightarrow \frac{BV_{CEO}}{BV_{CBO}} = (1-\alpha)^{1/m} \quad -- \left(\beta = \frac{\alpha}{1-\alpha}\right)$$

$$\therefore \boxed{BV_{CEO} = \frac{BV_{CBO}}{(1+\beta)^{1/m}}} \quad \text{— (A)}$$

---> Relation betn BV_{CEO} & BV_{CBO}.

ie $\boxed{BV_{CBO} >> BV_{CEO}}$

Note:

→ In a transistor ckt, the transistor must be designed to operate under a worst-case situation (eg breakdown) ie why we designer's should know the upper & lower limit of breakdown voltages (ie BV_{CEO} & BV_{CBO})

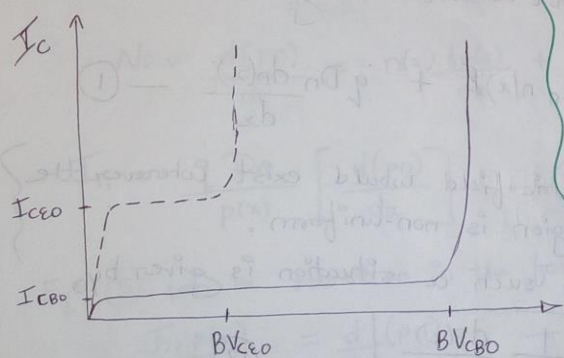

fig 6 d) Relative breakdown voltages and saturation currents of the open base and open emitter configuration.

From eqn (A)

• It means that BV_{CEO} is small by the factor $\sqrt[m]{1+\beta}$ than the actual avalanche junction breakdown voltage.

—X—

* Gummel - Poon model:

- Gummel-poon model takes into account the indepth picture of physical processes taking place within a BJT and is therefore quite capable of handling non-ideal situations (such as non-uniform doping concentration in the base).

- Let us consider an npn transistor.

The minority carrier e current density in the base region is,

$$J_n = q \mu_n n(x) E + q D_n \frac{dn(x)}{dx} \quad \text{— (1)}$$

{* Concept: An Electric field would exist wherever the doping in base region is non-uniform.}

Then, E-field in such a situation is given by,

$$\boxed{E = \frac{KT}{q} \frac{1}{p(x)} \frac{dp(x)}{dx}} \quad \text{— (2)}$$

where, $p(x)$ is the majority carrier hole concentration in the base.

- The direction of this E-field is from collector to emitter which will aid the flow of electrons across the base.

Put eq^n ② in eq^n ①, we get

$$J_n = q\mu_n n(x) \frac{KT}{q} \frac{1}{p(x)} \frac{dp(x)}{dx} + q D_n \frac{dn(x)}{dx} \quad -③$$

From Einstein's relation; $D_n = V_T \mu_n = \frac{KT}{q} \mu_n$ —④

⇒ So eq^n ③ becomes,

$$J_n = \frac{q D_n}{p(x)} \left[n(x) \frac{dp(x)}{dx} + p(x) \left(\frac{dn(x)}{dx} \right) \right]$$

Now $\frac{d(pn)}{dx} = n(x) \frac{dp(x)}{dx} + p(x) \frac{dn(x)}{dx}$] → derivative of pn product.

$$J_n = \frac{q D_n}{p(x)} \left[\frac{d(pn)}{dx} \right] \quad -⑤$$

Eq^n ⑤ can be rewritten in the form,

$$\frac{J_n \, p(x)}{q D_n} = \frac{d}{dx}(pn) \quad -⑥$$

Integrating eq^n ⑥ across the base-region, while assuming that electron current density is constant (ie J_n) and D_n is a constant.

$$\frac{J_n}{q D_n} \int_0^{W_B} p(x)\, dx = \int_0^{W_B} \frac{d}{dx}(pn)\, dx = \int_0^{W_B} n(x) \frac{dp(x)}{dx}\, dx \quad -⑦$$

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$$\therefore \frac{J_n}{q D_n}\int_0^{W_B} p(x)\,dx = n(W_B)\,p(W_B) - n(0)\,p(0) \quad — (8)$$

In active mode, BE junction is forward-bias and BC junction is reverse-bias,

we have $n(0) = n_{B0}\, e^{\left(\frac{V_{BE}}{V_T}\right)}$, $n(W_B) = 0$ — (9)

We know, $pn = n_i^2$ — — — under equilibrium.

Eq^n (8) becomes, (using eq^n (9)), we get

$$\frac{J_n}{q D_n}\int_0^{W_B} p(x)\,dx = 0 - n_{B0}\, e^{\frac{V_{BE}}{V_T}}\, p(0)$$

We know, $\boxed{n_{B0}\, p(0) = n_i^2}$

$$\text{ie } \frac{J_n}{q D_n}\int_0^{W_B} p(x)\,dx = -n_i^2\, e^{\left(\frac{V_{BE}}{V_T}\right)}$$

$$\therefore \boxed{J_n = \frac{-q D_n\, n_i^2\, e^{\left(\frac{V_{BE}}{V_T}\right)}}{\int_0^{W_B} p(x)\,dx}} \quad — (10)$$

In above expression of J_n, $\int_0^{W_B} p(x)\,dx$ is called Gummel number Q_B

ie $\int_0^{W_B} p(x)\,dx$ i.e integral in the denominator is the total integrated majority carrier charge in the base and is known as 'base Gummel number' (Q_B)

ie $$\boxed{Q_B = \int_0^{W_B} p(x)\,dx} \quad — (11).$$

. A similar analysis in the emitter region results in a hole current density given by,

$$\boxed{J_p = \frac{-q\,D_p\,.\,n_i^2\,e^{\left(\frac{V_{BE}}{V_T}\right)}}{\int_0^{W_E} n(x)\,dx}} \quad — (12)$$

where $\int_0^{W_E} n(x)\,dx$ is called the Emitter Gummel number Q_E.

. Gummel-Poon model can also take into account non-ideal effects, such as the "Early effect" and "high-level injection."

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Extra!

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- As B-C voltage changes, neutral base width W_B changes so that Q_B changes.

The change in Q_B with B-C voltage then makes I_n (equation 10) a function of B-C voltage.

- This is the "base-width modulation" (BWM) or "Early effect".

- If V_{BE} becomes too large, Low-level injection no longer applies, which leads to high-level injection.
- In this case, the total hole concentration in base ↑ses because of ↑sed excess hole concentration. This means that Q_B ↑ses (from eq^n 11), ie I_n will also change (from eq^n 10).

∴ The Gummel-Poon model can then be used to describe the basic operation of BJT as well as to describe non-ideal effects.

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