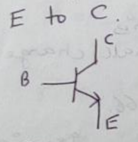
01

Module 02 : Bipolar Devices (20-25M)

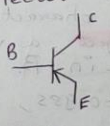
10/08/2014 R

BJT : The bipolar transistor action, minority carrier distribution, Low-Frequency common base current gain, non-ideal effects (doping conc^n, early effect), Ebers-Moll model, Gummel-Poon model, Hybrid-Pi model, Frequency Limitations (parasitic effects)

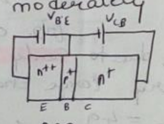
- A BJT is a 3 terminal SD in which the operation depends on the interaction of both majority and minority carriers and hence the name bipolar.
- BJT → npn, → pnp } EB J^n is F.B, CB J^n is R.B
- Emitter is heavily doped so that it can inject a large no. of charge carriers into the base. Base is lightly doped and v. thin. It passes most of the injected charge carriers from E to C. Collector is moderately doped.



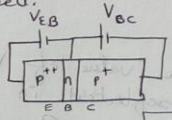
npn



pnp



npn



pnp

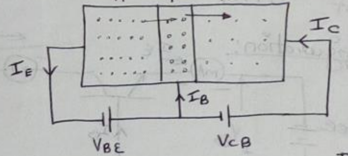
$$\boxed{\beta = \frac{\alpha}{1-\alpha}}$$

- Operation of npn Transistor

$$\alpha = \frac{I_C}{I_E} \quad (\alpha \; +ve)$$

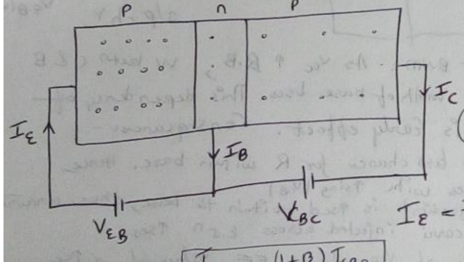
(CB configuratn) current gain

(0.9 to 0.995)



$$\boxed{I_E = I_C + I_B}$$

This eq^n gives the fundamental relationship bet^n the currents in a BJT.



$$I_E = I_C + I_B$$

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

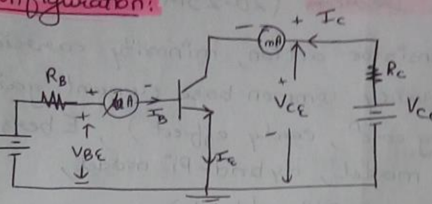
(CE config^n) → $\boxed{I_C = \beta I_B + I_{CEO}}$

$$\boxed{I_{CEO} = (1+\beta) I_{CBO}}$$

$$I_C = -\alpha I_E + I_{CBO}\left(1 - e^{V_C/V_T}\right)$$

$$\boxed{I_C = -\alpha I_E + I_{BO}} \quad \text{(CB config)}$$

CE configuration:



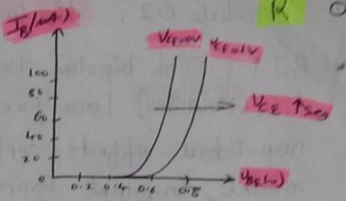


fig CE i/p characteristics.

- EB J^n → F.B, so J^n behaves as a F.B diode.
- when V_{CE} is ↑sed, width of DL at the R.B CB J^n will ↑se, Hence effective width of base will ↓se. This effect causes a ↓se in I_B.
- Hence, to get same value of I_B as that for $V_{CE}=0$, V_{BE} shld be ↑sed.

∴, the curve shifts to the right as V_{CE} ↑ses.

- O/P characteristics: $\boxed{\beta = \frac{I_C}{I_B}}$

I_C Vs $V_{CE} \big|_{I_B = \text{constant}}$

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

$$I_C = (1+\beta) I_{CBO} + \beta I_B$$

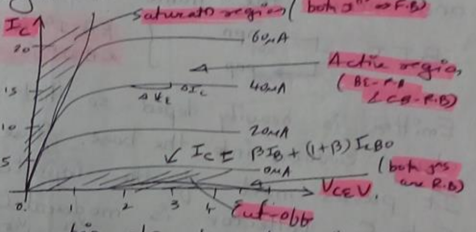


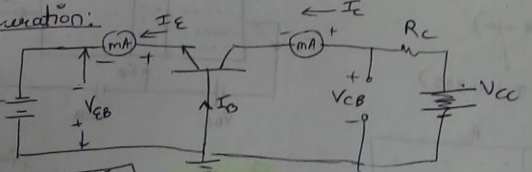
fig. o/p characteristics

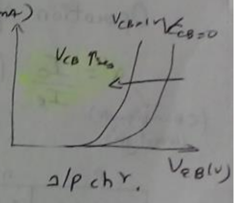
- For larger value of V_{CE}, due to Early effect, a v-small change in α is reflected in a very large change in β.

eg $\alpha = 0.98$, $\beta = \frac{\alpha}{1-\alpha} = 49$; $\alpha = 0.985$, $\beta = 66$.

∴ A slight ↑se in α by about 0.5% results in an ↑se in β by about 34%.

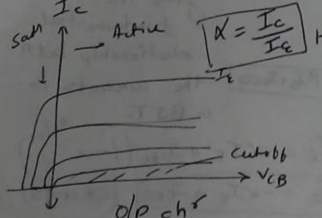
CB configuration:





i/p chr.

$\boxed{\alpha = \frac{I_C}{I_E}}$



o/p chr

1- Early effect or BWM :- As V_{CC} ↑ R.B, w betn C & B ↑ses, thus eff width of base ↓ses. This dependency of W_B on V_{CE} is Early effect. Consequences -

a) There is less chance for R within base. Hence α ↑ses with ↑sing $|V_{CB}|$

b) Charge gradient is ↑sed within the base, thus current of min carri injected across E J^n ↑ses.

For high values of V_{CB}, due to EE, value of α ↑ses

Property	CB	CE	CC
I/p resist^{n}	Low (100 Ω)	Moderate (750 Ω)	High (750K)
o/p resist^{n}	High (450K)	Moderate (45K)	Low (25 Ω)
Current gain	1	High	High
Voltg gain	~150	~500	< 1
Phase shift bet^{n} i/p & o/p vltg	0 or 360°	180°	0 or 360°
Applica^{tns}	For high freq^{n} ckts	For audio freq^{n} ckts	For impedance matching.

$\alpha = \frac{\Delta I_C}{\Delta I_E}$; $\beta = \frac{\Delta I_C}{\Delta I_B}$; $\gamma = \frac{\Delta I_E}{\Delta I_B}$.

$\beta = \frac{\alpha}{1-\alpha}$. ; $\alpha = \frac{\beta}{1+\beta}$

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

- CE configuration is used for almost all transistor appl^{n}s becoz of its high current gain β.

—— × ——

Module 02: BJT

Introduction

R

The *p-n* junction studied so far is an important milestone in the understanding of solid state electronics. The phenomenal growth of this field is, however, due to the invention of transistor, which led to a large scale replacement of the then-dominating vacuum tubes. We start our study of the transistor with the bipolar junction transistor in this chapter. In simple terms, a bipolar junction transistor (BJT) consists of three differently doped semiconductor regions. Two of these regions are doped with one type dopant (acceptor or donor) and the third with the another type. A BJT essentially consists of two *p-n* junctions placed back to back. The word 'bipolar', is used to indicate the role of both the types of charge carriers, namely, electrons and holes. We will see in this chapter how such a simple structure can result in a host of effects such as current gain, power gain, etc. Some important models that have been used to explain the characteristics of a BJT will also be briefly discussed in this chapter. Some important limitations of this device would be taken care of in other types of transistors, which will be discussed in subsequent chapters.

8.1 Fundamentals of Bipolar Junction Transistors

As already mentioned a bipolar junction transistor consists of two *p-n* junctions placed back to back. The two *p-n* junctions are coupled to each other by a semiconducting region, which is common to both the junctions. This common region is known as the *base* region of the transistor. The other two regions of the same conductivity type are called the *emitter* and the *collector*. Thus the junction between the emitter and the base is one of the *p-n* junctions comprising the transistor. This junction is referred to as the *emitter junction*, whereas the junction between the collector and the base is called the collector junction. Under no external applied bias and in thermal equilibrium the Fermi energy levels in all the three regions must lie along the same line. Figure 8.1 shows a diagram of an *n-p-n* transistor alongwith its zero-bias energy band diagram.

In Fig. 8.1 the emitter and collector regions are of *n*-type, whereas the base region is of *p*-type, such a transistor is called an *n-p-n* transistor. The other type of transistor is called a *p-n-p* transistor. In the *p-n-p* transistor, the emitter and collector regions are *p*-type and the base region is *n*-type.

At zero bias the net current density is zero throughout the transistor. The net electron-current density, due to diffusion and drift, is equal to zero. Similarly, the net hole current density is also zero. To understand the basic control action of a transistor, let us assume the emitter junction to be forward biased and the collector junction to be reverse biased. It so happens that this also is the most common state of operation of a transistor. This biasing arrangement alongwith the energy band diagram is shown in Fig. 8.2.

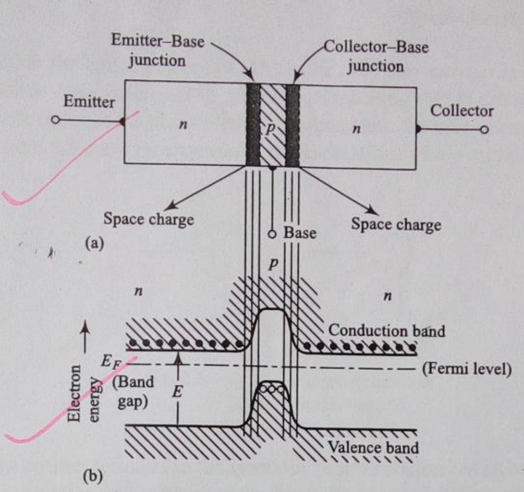


Fig. 8.1 (a) Schematic diagram of an *n-p-n* transistor, (b) zero-bias energy band diagram

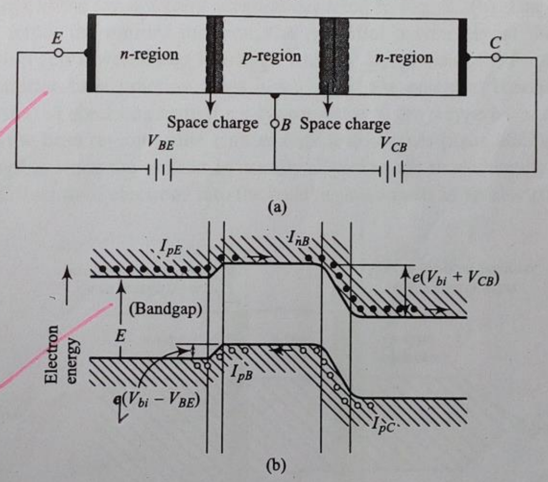


Fig. 8.2 Biasing arrangement and energy band diagram of an *n-p-n* transistor

Electrons are injected from the emitter region, where they happen to be majority carriers, into the base region, where they are minority carriers. In the base region, a small fraction of these electrons recombine with the majority carrier holes. The rest of the electrons diffuse across the thin base region and reach the space charge region of the collector junction. The *n*-type collector region is positively biased, due to which the electrons are collected by the collector. The collected electrons dominate the collector current. Thus, *the collector current is controlled by the emitter-to-base voltage*. The power gain resulting due to the transistor action is possible because the base-to-emitter voltage and the base current are very small.

Figure 8.3 shows the symbolic representations of *n-p-n* and *p-n-p* transistors.

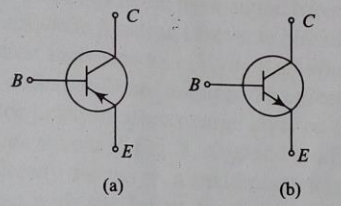


Fig. 8.3 Symbolic representation of
(a) *p-n-p* transistor and
(b) *n-p-n* transisor

The emitter terminal in the symbolic representation has an arrow which points in the direction of emitter current (opposite to the direction of electron flow).

To understand the physical mechanism of a bipolar junction transistor, let us go back to the energy band diagram depicted in Fig. 8.2(b). Due to the forward bias across the emitter junction, the potential barrier across the emitter–base junction gets lowered to $q(V_{bi} - V_{BE})$, where V_{BE} represents the forward bias across the emitter–base junction. This lowering of the potential barrier results in the diffusion of electrons from the *n*-type emitter to the *p*-type base. A flow of holes from the base region to the emitter region also takes place but can be treated as negligible since the emitter is usually doped much more heavily than the base. The diffusion of electrons into the base region results in an electron profile in the

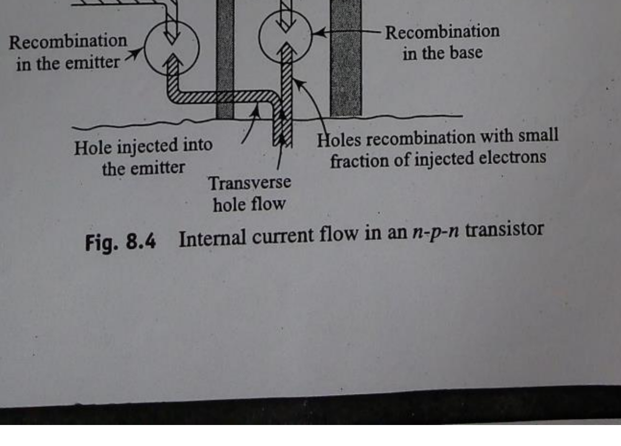


Fig. 8.4 Internal current flow in an *n-p-n* transistor

base that has a higher density at the emitter end of the base than at the collector end. The minority carrier electrons in the base region traverse through this region by diffusion. The collector–base junction is reverse biased and thus the potential barrier across this junction increases to $q(V_{\mathrm{bi}} + V_{CB})$ where V_{CB} represents the applied bias across the collector–base junction. The electrons that arrive at the beginning of the collector junction space charge layer on the base side then slide down the potential hill, as shown in Fig. 8.2(b), and are finally collected by the collector terminal. As already discussed, a small percentage of electrons injected into the base recombine with the holes present in the base. Under thermal equilibrium conditions, these lost electrons are replenished by the base current.

The base current is kept low by ensuring a thin base having high carrier lifetimes. [redacted]

Module 02: Bipolar Junction Transistor

01 R
16/08/2014

Topic: Minority Carrier Distribution (MCD)

- MCD is very important in deciding BJT characteristics
- We are ultimately interested in calculating currents in the BJT.
- Since diffusion currents are produced by minority carrier gradients, we will determine MCD in each of the three transistor regions.

→ Notations used in the analysis of BJT

A] For both npn and pnp BJT:

i) N_E, N_B, N_C : Doping concentrations in Emitter (E), base (B) and collector (C).

ii) W_E, W_B, W_C : Widths of neutral emitter, base and collector.

iii) D_E, D_B, D_C : Minority carrier diffusion co-efficients in emitter, base and collector.

iv) L_E, L_B, L_C : Minority carrier diffusion lengths in emitter, base and collector regions.

v) $\tau_{E0}, \tau_{B0}, \tau_{C0}$: Minority carrier lifetimes in E, B and C.

For npn BJT:

i) p_{E0}, n_{B0}, p_{C0} : Thermal equilibrium minority carrier hole, electron and hole concentrations in the E, B and C.

ii) $p_E(x'), n_B(x), p_C(x'')$: Total minority carrier hole, electron and hole concentrations in the E, B and C.

iii) $\delta p_E(x'), \delta n_B(x), \delta p_C(x'')$: Excess minority carrier hole, electron and hole concentrations in the E, B and C.

INDERJIT SINGH

A] MCD in forward-Active mode:- (npn, BJT) 02

- Consider a uniformly doped npn BJT with the geometry shown in fig(1.1).

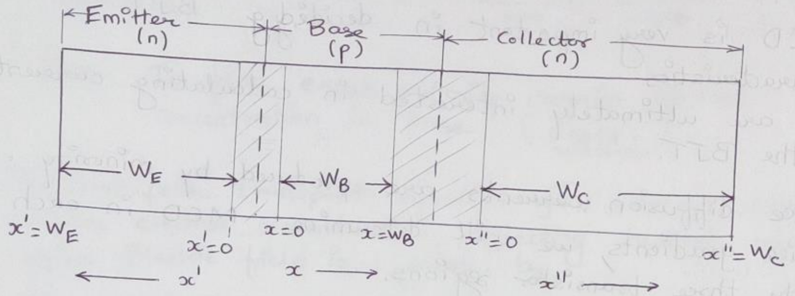


fig1.1 : Geometry of npn BJT used to calculate the MCD

- When we consider the individual emitter, base and collector regions, we will shift the origin to the edge of the space-charge region as shown in fig(1.1).

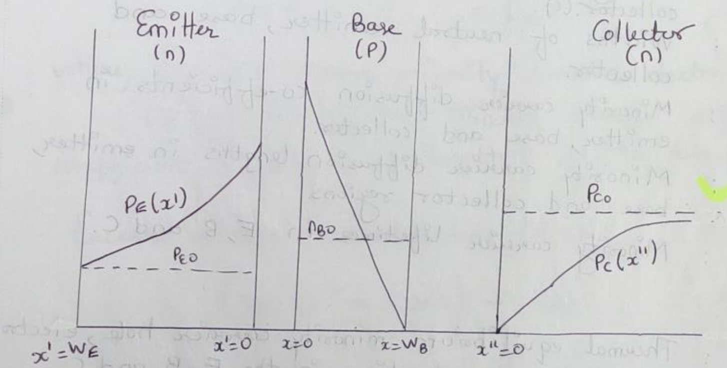
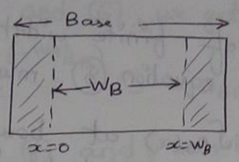


fig 1.2: MCD in an npn BJT operating in forward active mode.

- Assumptions:
  - a) W_C is long compared to L_C in collector.
  - b) Excess minority carrier conentration at $x'=W_E$ is zero ie $p_E(x'=W_E)=p_{E0}$.

I] BASE Region :



- (To make analysis simpler, we will treat each region separately).

- Aim : To find excess minority carrier electron concentration in base ($\underline{\underline{\delta n_B(x)}}$) :

The ambipolar transport equation for excess minority carrier electron concentration, neglecting neutral base region Electric field is given by,

$$D_B \frac{\partial^2(\delta n_B(x))}{\partial x^2} - \frac{\delta n_B(x)}{\tau_{B0}} = 0$$

ie $$\frac{\partial^2(\delta n_B(x))}{\partial x^2} - \frac{\delta n_B(x)}{L_B^2} = 0 \quad — ①$$

$\{ L_B^2 = D_B \tau_{B0}$

where, $\delta n_B(x)$ – excess minority carrier electron concentration.

D_B, τ_{B0} and L_B – Minority carrier diffusion co-efficient, lifetime and length in the base region.

- Excess electron concentration is :

$$\delta n_B(x) = n_B(x) - n_{B0} \quad — ②$$

- The general solution to eq^n ① is :

$$\delta n_B(x) = A\, e^{(x/L_B)} + B\, e^{(-x/L_B)} \quad — ③$$

(The base is of finite width so both exponential terms in equation ③ must be retained).

- Evaluate $\delta n_B(x)$ at boundary conditions ie at two edges of neutral base region. (ie at $x=0$ and at $x = W_B$) $\Rightarrow$ From eq^n ③, we get

$$\delta n_B(x=0) = A + B \quad \text{— (4.a)}$$

$$\delta n_B(x=W_B) = A\, e^{(W_B/L_B)} + B\, e^{(-W_B/L_B)} \quad \text{— (4.b)}$$

Since, B-E junction is forward-bias, boundary condition at $x=0$ is,

$$\delta n_B(x=0) = n_B(0) - n_{B0}$$

$$\Rightarrow n_B(0) = n_{B0}\, e^{\left(\frac{V_{BE}}{V_T}\right)}$$

$$\therefore \delta n_B(0) = n_{B0}\left[e^{\left(\frac{V_{BE}}{V_T}\right)} - 1\right] \quad \text{— ⑤}$$

Now
Since, B-C junction is reverse-bias, boundary condition at $x = W_B$ is,

$$\delta n_B(x=W_B) = n_B(x=W_B) - n_{B0}$$

$$= 0 - n_{B0}$$

$$\therefore \delta n_B(W_B) = -n_{B0} \quad \text{— ⑥}$$

Using equation (4.a) and ⑤, we get

$$A + B = n_{B0}\left[e^{\left(\frac{V_{BE}}{V_T}\right)} - 1\right] \quad \text{— ⑦}$$

Also, using equation (4.b) and (6), we get

$$A\, e^{(W_B/L_B)} + B\, e^{(-W_B/L_B)} = -n_{BO} \qquad \text{— ⑧}$$

Now, using equation ⑦ and ⑧ and solving for co-efficient A and B yield,

$$A = \frac{n_{BO}\, e^{-\left(\frac{W_B}{L_B}\right)} \left[e^{\frac{V_{BE}}{V_T}} - 1 \right] + n_{BO}}{e^{-\left(\frac{W_B}{L_B}\right)} - e^{\left(\frac{W_B}{L_B}\right)}} \qquad \text{— ⑨}$$

$$B = \frac{-n_{BO}\, e^{\left(\frac{W_B}{L_B}\right)} \left[e^{\frac{V_{BE}}{V_T}} - 1 \right] - n_{BO}}{e^{-\left(\frac{W_B}{L_B}\right)} - e^{\left(\frac{W_B}{L_B}\right)}} \qquad \text{— ⑩}$$

Recollect ⇒ $\sinh z = \dfrac{e^{z} - e^{-z}}{2}$ — ⑪

Using eq^n ⑪ in ⑨ and ⑩, we get

$$A = \frac{-n_{BO}\, e^{-\left(\frac{W_B}{L_B}\right)} \left[e^{\frac{V_{BE}}{V_T}} - 1 \right] - n_{BO}}{2 \sinh\left(\frac{W_B}{L_B}\right)} \qquad \text{— ⑫}$$

$$B = \frac{n_{BO}\, e^{\left(\frac{W_B}{L_B}\right)} \left[e^{\frac{V_{BE}}{V_T}} - 1 \right] + n_{BO}}{2 \sinh\left(\frac{W_B}{L_B}\right)} \qquad \text{— ⑬}$$

Substituting the values of A and B from ⑫ and ⑬ into equation ③,

$$\delta n_B(x) = \frac{n_{B0}\left\{\left[e^{\frac{V_{BE}}{V_T}} - 1\right]\sinh\left(\frac{W_B - x}{L_B}\right) - \sinh\left(\frac{x}{L_B}\right)\right\}}{\sinh\left(\frac{W_B}{L_B}\right)} \quad \text{—⑭}$$

Equation ⑭ represents excess minority carrier electron concentration in the base region.

- If we assume $W_B << L_B$, then we can use the approximation $\sinh(x) \approx x$ (for $x << 1$)

  ie $\sinh\left(\frac{W_B}{L_B}\right) \simeq \frac{W_B}{L_B}$ -------(for $W_B << L_B$) — ⑮

Extra!

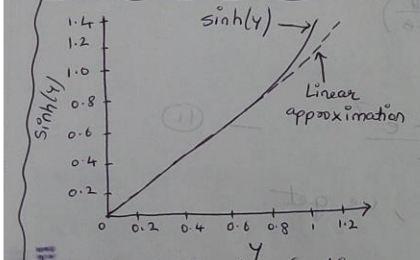


fig: Hyperbolic sine function & its Linear approximation

→ Plot shows sinh(y) for $0 \le y \le 1$ & also shows the Linear approximation for small values of y.

If $y < 0.4$, sinh(y) function differs from its linear approximation by less than 3 percent.

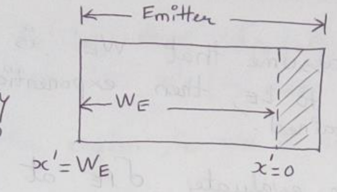
- Thus, we can conclude that "the excess electron concentration δn_B" in equation ⑭ is approximately a Linear function of x through the neutral base region.

Using eq^n ⑮ in eq^n ⑭, we get,

$$\delta n_B(x) \simeq \frac{n_{B0}}{W_B}\left\{\left[e^{\frac{V_{BE}}{V_T}} - 1\right](W_B - x) - x\right\} \quad \text{—⑯}$$

II] EMITTER Region:

· Aim: To find excess minority carrier hole concentration in emitter ($\delta p_E(x')$):



(Emitter region has only one depletion layer, so edge of depletion layer is defined to be $x' = 0$ and edge of emitter region is $x' = W_E$)

· The ambipolar transport equation for excess minority carrier concentration, neglecting any electric field in neutral emitter region is given by,

$$D_E \frac{\partial^2(\delta p_E(x'))}{\partial x'^2} - \frac{\delta p_E(x')}{\tau_{E0}} = 0$$

$$\text{ie} \quad \frac{\partial^2(\delta p_E(x'))}{\partial x'^2} - \frac{\delta p_E(x')}{L_E^2} = 0 \quad — ①$$

where D_E, L_E, τ_{E0} are minority carrier diffussion coefficient, length and minority carrier lifetime in the emitter.

Excess hole concentration is given by,

$$\delta p_E(x') = p_E(x') - p_{E0} \quad — ②$$

· General solution of equation ①,

$$\delta p_E(x') = C\, e^{\left(\frac{x'}{L_E}\right)} + D\, e^{\left(\frac{-x'}{L_E}\right)} \quad — ③$$

where, $L_E^2 = D_E \tau_{E0}$

(If we assume that W_E is not necessarily long compared to L_E, then exponential term in eqⁿ ③ must be retained.)

Now, we evaluate δp_E at $x' = 0$ and $x' = W_E$:-

$$\therefore \delta p_E(x'=0) = C + D \quad \text{— ④}$$

Also, $$\delta p_E(x'=W_E) = C e^{\left(\frac{W_E}{L_E}\right)} + D e^{\left(-\frac{W_E}{L_E}\right)} \quad \text{— ⑤}$$

Since B-E junction is forward-bias (F.B), we have

$$\delta p_E(x'=0) = p_E(x'=0) - p_{E0}$$
$$= p_{E0}\left(e^{\frac{V_{BE}}{V_T}}\right) - p_{E0}$$

$$\therefore \delta p_E(x'=0) = p_{E0}\left[e^{\frac{V_{BE}}{V_T}} - 1\right] \quad \text{— ⑥}$$

Also, $$\delta p_E(x'=W_E) = p_E(x'=W_E) - p_{E0}$$
$$= p_{E0} - p_{E0}$$
$$\delta p_E(x'=W_E) = 0 \quad \text{— ⑦}$$

$$\left\{\begin{array}{l} p_E(W_E) = p_{E0} \\ \text{from fig}(1.2) \end{array}\right\}$$

Solving for C and D using equation ④ to ⑦ and substituting into equation ③, we get

$$\delta p_E(x') = \frac{p_{E0}\left[e^{\frac{V_{BE}}{V_T}} - 1\right]\sinh\left(\frac{W_E - x'}{L_E}\right)}{\sinh\left(\frac{W_E}{L_E}\right)} \quad \text{— ⑧}$$

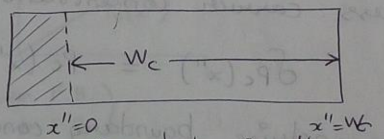
If W_E is comparable to L_E, then $\delta p_E(x')$ shows an exponential dependence on x'. (as seen in eqⁿ ⑧)

Assuming a thin emitter region, ie W_E is small, eqⁿ ⑧ becomes,

$$\delta p_E(x') \approx \frac{P_{EO}}{W_E}\left[e^{\frac{V_{BE}}{V_T}} - 1\right](W_E - x') \quad \text{— 09}$$

From eqⁿ ⑨, it is evident that, the excess hole concentration in the emitter will vary approximately Linearly with distance if W_E is small.

III COLLECTOR Region :



Transport equation for minority carrier holes in the collector region is,

$$D_c \frac{\partial^2(\delta p_c(x''))}{\partial x''^2} - \frac{\delta p_c(x'')}{\tau_{co}} = 0$$

$$\text{ie} \quad \frac{\partial^2(\delta p_c(x''))}{\partial x''^2} - \frac{\delta p_c(x'')}{L_c^2} = 0 \quad \text{— ①}$$

where, L_c, D_c, τ_{co} → are the minority carrier diffusion length, co-efficient and minority carrier lifetime in the collector region.

where, $L_c^2 = D_c \tau_{co}$

General solution to eqⁿ ① is,

$$\delta p_c(x'') = A_1 e^{x''/L_c} + A_2 e^{-x''/L_c} \quad — ②$$

If we assume, collector is long, then the co-efficient A_1 must be zero, since the excess concentration must remain finite. ie $A_1 = 0$

Then, Eqⁿ ② becomes,

$$\delta p_c(x'') = A_2 e^{-\frac{x''}{L_c}} \quad — ③$$

Excess carrier concentration $\delta p_c(x'')$ is

$$\delta p_c(x'') = p_c(x'') - p_{c0} \quad — ④$$

Now, applying boundary condition at the edge of space-charge region is,

$$\therefore \delta p_c(x''=0) = p_c(x''=0) - p_{c0}$$

$$\delta p_c(0) = 0 - p_{c0} = -p_{c0} \quad — ⑤$$

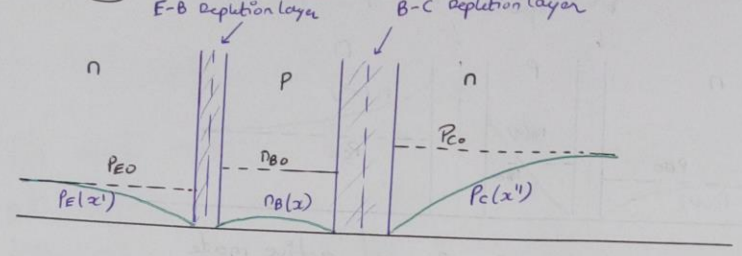
$$\therefore A_2 = -p_{c0} \quad — ⑥$$

∴ Excess minority carrier hole concentration in the collector is

$$\boxed{\delta p_c(x'') = -p_{c0} e^{-\frac{x''}{L_c}}} \quad — ⑦$$

—×—

1. Minority Carrier distribution (MCD) in an npn BJT operating in cut-off mode:

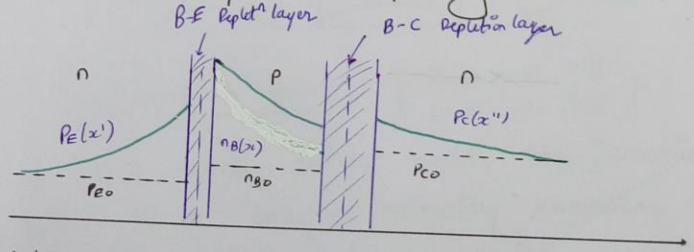


- When BJT is operated in Cut-off mode,
  → both B-E and B-C junctions are reverse-biased.

∴ The minority carrier conc^{n}s are zero at each depletion layer edge.

- Since $W_B \ll L_B$ (assumed), all minority carriers are "swept out" of the base region.

2. MCD in an npn BJT operating in saturation mode:

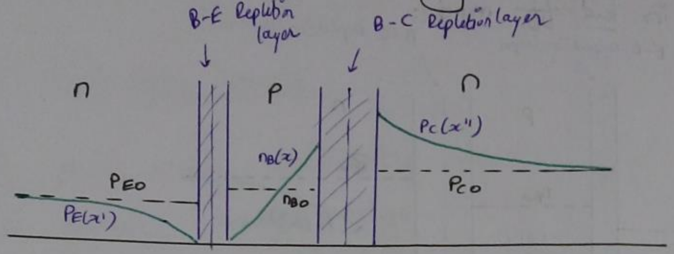


- When BJT is operated in saturation mode,
  → both B-E and B-C junctions are forward-biased.

∴ Excess minority carriers exist at the edge of each depletion layer.

- However, since a collector current still exists when the transistor is in saturation, a gradient will still exist in the minority carrier electron conc^n in the base

3. MCD in an npn BJT operating in inverse-active mode.



- BJT when operated in inverse-active mode
  - → B-E is Reverse-biased & B-C is forward biased
- → Electrons From the collector are now injected into base.
- → The gradient in the minority carrier e^- concⁿ in the base is in the opposite direction compared to forward-active mode,
- → so the emitter and collector currents will change direction.

—x—

1. A Si npn transistor consists of emitter and base regions uniformly doped to $5\times10^{18}/cm^3$ and $5\times10^{16}/cm^3$ respectively. The base-emitter forward bias voltage is 0.6 V. The neutral base width is $3\mu m$ and the minority carrier electron diffusion length in base region is $15\ \mu m$.

Calculate the excess minority carrier concentration in the base region at

a) $x = W_B | 3$ b) $x = 0$

Solution: Given data: $N_E = 5\times10^{18}/cm^3$, $N_B = 5\times10^{16}/cm^3$

$W_B = 3\mu m = 3\times10^{-4}\ cm$, $L_B = 15\mu m = 15\times10^{-4} cm$

a) $$n_{B0} = \frac{n_i^2}{N_B}$$

$$\approx \frac{(1.5\times10^{10})^2}{5\times10^{16}} \approx 4500\ cm^{-3}$$

$$\delta n_B(x) \approx \frac{n_{B0}}{W_B}\left[\left(e^{\frac{V_{BE}}{V_T}} - 1\right)(W_B - x) - x\right] \quad -①$$

At $x = W_B/3$, eq^n ① changes to

$$\delta n_B\left(x = \frac{W_B}{3}\right) \approx \frac{4.5\times10^3}{3\times10^{-4}}\left[\left(e^{\frac{0.6}{0.026}} - 1\right)\left(W_B - \frac{W_B}{3}\right) - \frac{W_B}{3}\right]$$

$$\boxed{\delta n_B\left(x = \frac{W_B}{3}\right) \approx 3.157\times10^{13}\ cm^{-3}}$$

b) At $x=0$, from eqn ③, we get

$$\delta n_B(x=0) = \frac{n_{B0}}{\cancel{W_B}}\left[\left[e^{\frac{V_{BE}}{V_T}}-1\right](\cancel{W_B})\right]$$

$$= 4.5\times10^{3}\left(e^{\frac{0.6}{0.026}}-1\right)$$

$$\boxed{\delta n_B(x=0) = 4.73\times10^{13}\ \text{cm}^{-3}}$$

2. A Si npn BJT has emitter and base regions uniformly doped to $5\times10^{18}\ \text{cm}^{-3}$ and $5\times10^{16}/\text{cm}^3$ respectively. V_{BE} is 0.6 V and neutral emitter width is 3µm. Calculate excess minority carrier concentration at emitter edge of B-E space-charge region.

Soln: [Hint :] →

$$\left\{\text{Use } \delta p_E(x') = \frac{p_{E0}}{W_E}\left(e^{\frac{V_{BE}}{V_T}}-1\right)\left(W_E-x'\right)\right\}$$

$$\Rightarrow \delta p_E(x'=0) = ? \quad ; \quad p_{E0} = \frac{n_i^2}{N_E} = \frac{(1.5\times10^{10})^2}{5\times10^{18}} = 45$$

$$\delta p_E\Big|_{x'=0} = \frac{p_{E0}}{\cancel{W_E}}\left(e^{\frac{V_{BE}}{V_T}}-1\right)(\cancel{W_E})$$

$$= 45\left(e^{\frac{0.6}{0.026}}-1\right)$$

$$\boxed{\delta p_E(x'=0) = 4.736\times10^{11}\ /\text{cm}^3}$$