ADVANCED

BJT - PART-3

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PROF. DEVRAJ SINGH
DEPT. OF PHYSICS
RBIPSSR
VBSPU, JNP

STATIC CHARACTERISTICS:

CURRENT-VOLTAGE RELATION

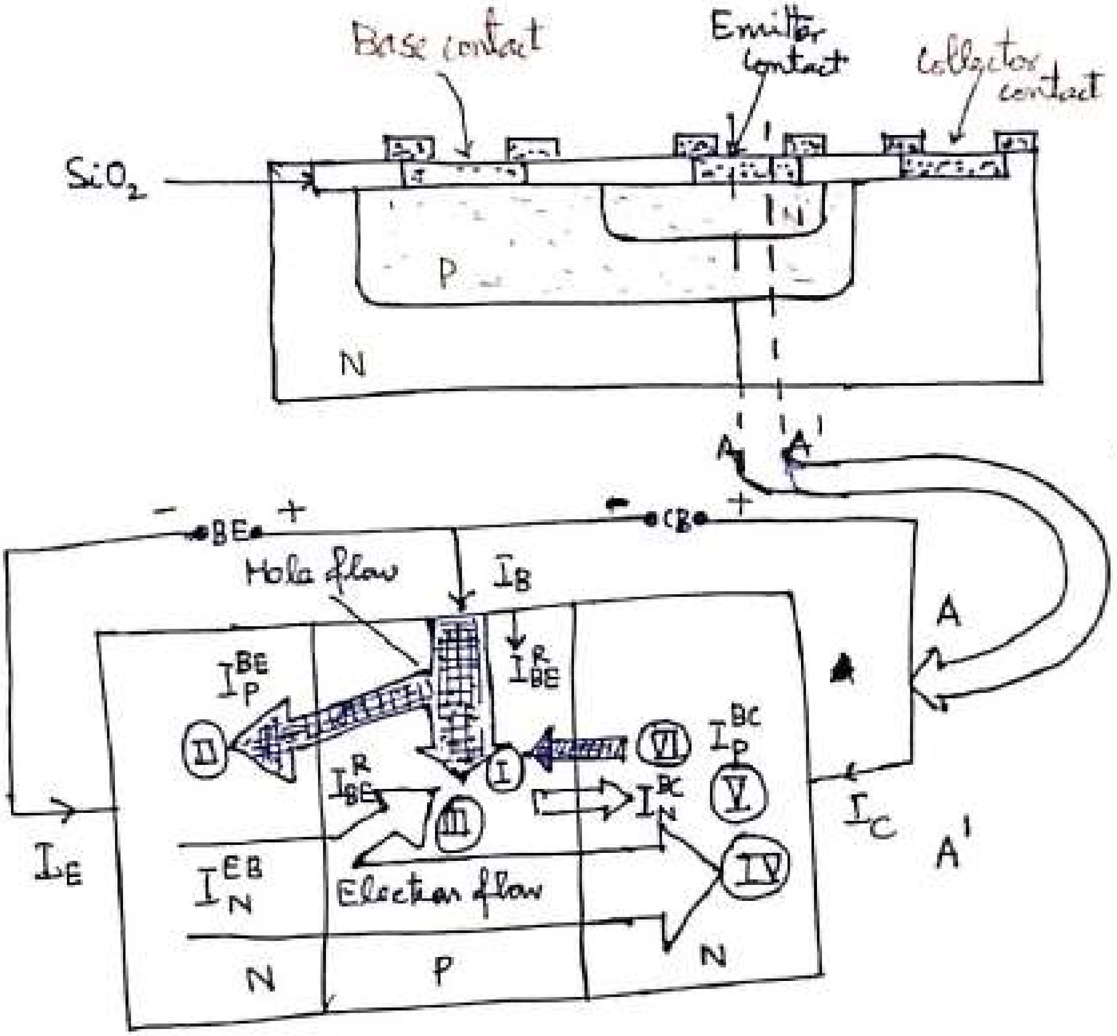
We will now develop a model for the current flow in a BJT. Initially we will use a simple model which captures the essence of the device performance. Later we will discuss secondary issues. In the bipolar device carriers from the emitter are injected "vertically" across the base while the base charge is injected from the "side" of the device, as can be seen in Fig. 13. If we assume that the emitter width is wide, the device can be understood using a one-dimensional analysis. We will use the following assumptions:

Devraj
19/04/20

1. The electron injected from the emitter diffuse across the base region and the field across the base is small enough that there is no drift.
2. The electric fields are nonzero only in the depletion regions and are the bulk materials.
3. The collector injection is negligible when the BJT is reverse biased.
4. In describing voltages, we use the following notation: The first subscript of the voltage symbol represents the contact with respect to which the potential is measured. For example, $V_{BE} > 0$ means the base is positive with respect to emitter.

In general, a number of currents can be identified in the bipolar device (Fig. 13) as follows:

- Base current – is made of holes that recombine with electrons injected from the emitter (Component-I) and



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14/04/20

I_N^{EB} = Emitter current injected into the base $\simeq I_{EN}$

I_P^{BE} = Base current injected into the emitter $\simeq J_{EP}$

I_{BE}^R = Recombination current in the base region

I_P^{BC} = Hole current injected across reverse-biased base collector junction

I_N^{BC} = Electron current injected across reverse-biased base collector junction

I_{nC} = Electron current coming from the emitter ($\simeq I_C$)

Fig. 13. A schematic of an Si BJT showing the three-dimensional nature of the structure and the current flow. Along the section AA', the current flow can be assumed one-dimensional. The various current components in a BJT are discussed in text.

holes that are injected across the emitter-base junction into the emitter (Component II). Once again we ignore the BCJ for the forward active region.

- Emitter current : consists of the electron current that recombines with the holes in the base region (component III), the electron current which is injected into the collector (IV), and the hole current injected from the base into the emitter (II).

Minority electron (V) and hole (VI) currents flow in the base-collector junction and are important when the emitter current goes toward ZERO.

Debjit 14/04/20

In our analysis, we will assume that all the dopants are ionized and the majority carrier density is simply equal to the doping density. The symbols for the doping density are (for the NPN device) —

N_{de} – donor density in the emitter
N_{ab} – acceptor " " " base
N_{dc} – donor " " " collector

If the ionization of the dopants is not complete we need to adjust for the ionization efficiency.

The back to back P-N diodes in the bipolar device can operate in 4 possible biasing modes as shown in Table 1.

Table 1.
Operation modes of the NPN bipolar transistor. Depending upon the particular application, the transistor may operate in one or several modes

MODE OF OPERATION	EBJ BIAS	CBJ BIAS
Forward active	Forward ($V_{BE} > 0$)	Reverse ($V_{CB} > 0$)
Cut off	Reverse ($V_{BE} < 0$)	Reverse ($V_{CB} > 0$)
Saturation	Forward ($V_{BE} > 0$)	Forward ($V_{CB} < 0$)
Reverse active	Reverse ($V_{BE} < 0$)	Forward ($V_{CB} < 0$)

Depending upon the applications, the bipolar device operation may span one or all of these modes.

For Example

For small-signal applications where one needs amplification one only operates in the forward active mode, while for switching applications the device may have to operate under cutoff and saturation modes and pass through the active mode during the switching.

Dr. Singh 14/04/20

o CURRENT FLOW IN A BJT

Since the bipolar device is biased on P-N diodes, we will use our understanding of current flow of P-N diodes. Note that we will assume the emitter width is long compared to hole diffusion length while the base width is small compared to electron diffusion length. We will use the different axes and origin shown in Fig.14. The distances are labeled x_e, x_b and x_c as shown and are measured from the edges of the depletion region. The base width is W_b, but the width of the 'neutral' base region is W_{bn} as shown. We assume that W_b and W_{bn} are equal.

Later we will study the effect of the two widths being different. Using the PN diode theory, we have the following relations for the excess carrier densities in the various regions are

$\delta p_e(x_e=0)$ = excess hole density at the emitter side of the EBJ

$$= p_{e0}\left[\exp.\left[\frac{eV_{BE}}{k_BT}-1\right]\right] \longrightarrow (12)$$

$\delta n_b(x_b=0)$ = excess electron density on the base side of the EBJ

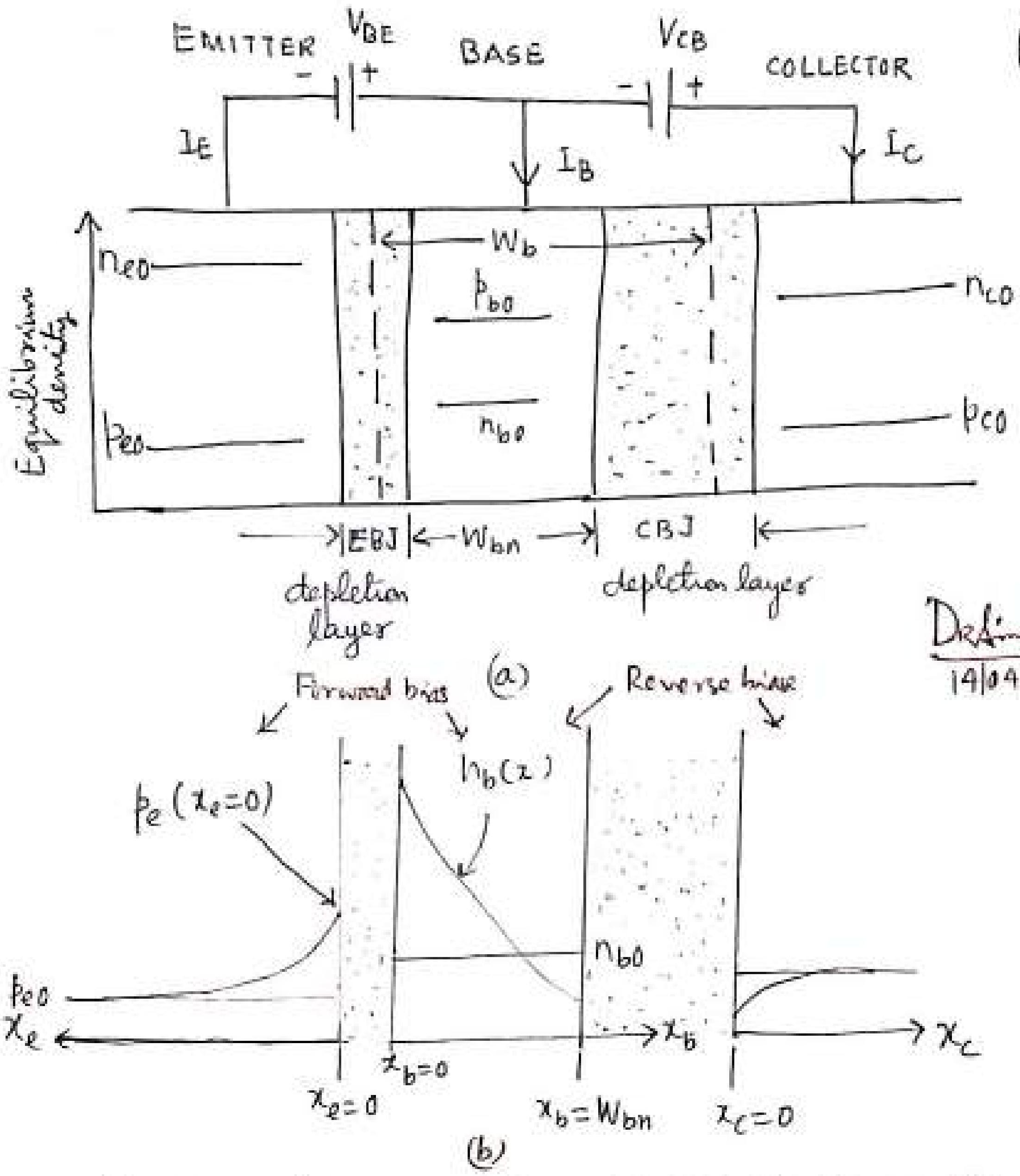
$$= n_{b0}\left[\exp.\left[\frac{eV_{BE}}{k_BT}-1\right]\right] \longrightarrow (13)$$

$\delta n_b(x_b=W_{bn})$ = excess electron density at the base side of CBJ (collector-base junction)

$$= n_{b0}\left[\exp\left(\frac{-eV_{CB}}{k_BT}\right)-1\right] \longrightarrow (14)$$

$\delta p_c(x_c=0)$ = excess hole density at the collector side of CBJ

$$= p_{c0}\left[\exp.\left(\frac{-eV_{CB}}{k_BT}\right)-1\right] \longrightarrow (15)$$



Dr. Singh
14/04/20

Fig. 14. A forward active mode BJT. (a) The equilibrium carrier concentration of electrons and holes and positions of the junction depletion regions in the NPN transistor (b) Minority carrier ~~concentration~~ distributions in the emitter, base and collector regions

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- As shown in Fig. 14 in these expressions the subscripts p_{e0}, n_{b0} and p_{c0} represent the minority carrier equilibrium densities in the emitter, base and collector respectively. The total minority concentrations p_e in emitter, n_b in the base and p_c in the collector as shown in Fig. 14(b).
- Assuming 100% ionization of the dopants, the majority carrier densities are $n_{de} = N_{de}$, $p_{b0} = N_{ab}$ and $n_{c0} = N_{dc}$ for the emitter

base and collector. We will assume that the emitter and collector regions are longer than the hole diffusion lengths L_p, so that the hole densities decrease exponentially away from base regions.

To find the current flow we have to calculate the spatial variation of carrier densities. In the base region the excess electron density is given at the edges of the neutral base region by Eq.(13) and Eq.(14). To obtain the electron density in the base we must solve the continuity equation using these two boundary conditions. The excess minority carrier density in the base region is given by

Drdsingh
14/04/20

$$\delta n_b(x_b) = \frac{n_{b0}}{\sinh\left(\frac{W_{bn}}{L_b}\right)} \left\{ \sinh\left(\frac{W_{bn}-x_b}{L_b}\right)\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] + \sinh\left(\frac{x_b}{L_b}\right)\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right] \right. \longrightarrow (16)$$

The profile of the total minority carrier densities (i.e, background and excess) is shown in Fig. 14(b). The electron distribution in the base is almost linear, as can be seen, and is assumed to be so for some simple applications. Once the excess carrier spatial distributions are known, we can calculate the currents as we did for the PN diode. We assume that the emitter-base currents are due to carrier diffusion once the device is biased. We have, for a device of area A and diffusion coefficients D_b and D_e in the base and emitter, we have, as in the case of a PN diode.

$$I_{En} = I_n^{EB} = eAD_b \frac{d\,\delta n_b(x)}{\delta x_b}\bigg|_{x_b=0} \longrightarrow (17)$$

and $$I_{Ep} = I_p^{BE} = -eAD_e \frac{d\,\delta p(x)}{\delta x_e}\bigg|_{x_e=0} \longrightarrow (18)$$

These are current components shown in Fig 13 and represent the emitter current components II, III and IV. Assuming an exponentially decaying hole density into the emitter, we have, as in the case of a PN diode,

Dr. ... 14/09/20

$$I_{Ep} = -A\left(\frac{eD_e p_{e0}}{L_e}\right)\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] \longrightarrow (19)$$

Using the electron distribution derived in the base, we have for the electron part of the emitter current

$$I_{En} = -\frac{eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}\left\{\cosh\left(\frac{W_{bn}-x_b}{L_b}\right)\left[\exp\left[\left(\frac{eV_{BE}}{k_BT}\right)-1\right]\right.\right.$$
$$\left.\left. - \cosh\left(\frac{x_b}{L_b}\right)\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right]\right\}\Bigg|_{x_b=0}^{at}$$

$$= -\frac{eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}\left\{\cosh\left(\frac{W_{bn}}{L_b}\right)\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right]\right.$$
$$\left. - \left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right]\right\} \longrightarrow (20)$$

For high emitter efficiency we want I_{En} to be much larger than I_{EP}. This occurs if the emitter doping is much larger than the base doping. The total emitter current becomes

$$I_E = I_{En} + I_{Ep} = -\left\{\frac{eAD_b n_{b0}}{L_b}\coth\left(\frac{W_{bn}}{L_b}\right) + \frac{eAD_e p_{e0}}{L_e}\right\}$$
$$\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] + \frac{eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}$$
$$\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right] \longrightarrow (21)$$

The collector current components can be obtained by using the same approach. Thus we have

$$I_n^{BC} = -eAD_b \frac{d\delta n_b(x_b)}{dx_b}\Bigg|_{x_b = W_{bn}} \rightarrow (22)$$

$$I_p^{BC} = eAD_p \frac{d\delta p(x_c)}{dx_c}\Bigg|_{x_c = 0} \rightarrow (23)$$

Using the results shown in the first part of Eq. (20) at $x_b = W_{bn}$, we have

Debasish 14/04/20

$$I_n^{BC} = -\frac{eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] + \frac{eAD_b n_{b0}}{L_b}\coth\frac{W_{bn}}{L_b}\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right] \rightarrow (24)$$

The hole ~~concentration~~ current on the collector side is the same as for a reverse-biased P-N junction

$$I_p^{BC} = -\frac{eAD_c p_{c0}}{L_c}\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right] \rightarrow (25)$$

From the way we have defined the currents, the two current components flow along $+x$ direction. If we define I_c as the total current flowing from the collector into the base, we have

$$-I_c = \left[\frac{eAD_c p_{c0}}{L_c} + \frac{eAD_b n_{b0}}{L_b}\coth\left(\frac{W_{bn}}{L_b}\right)\right]\left[\exp\left(-\frac{eV_{CB}}{k_BT}\right)-1\right] - \frac{eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] \rightarrow (26)$$

The base current is the difference between the emitter and collector currents: $(I_B = I_E - |I_C|)$. It is interesting to point out that if the base region W_{bn} is much smaller than the diffusion length, the electron gradient in the base region can be simplified by using the approximations.

$$\sinh(\alpha) = \frac{e^{\alpha} - e^{-\alpha}}{2} = \alpha + \frac{\alpha^3}{3!} + \frac{\alpha^5}{5!} + \cdots$$

$$\cosh(\alpha) = \frac{e^{\alpha} + e^{-\alpha}}{2} = 1 + \frac{\alpha^2}{2!} + \frac{\alpha^4}{4!} + \cdots$$

For the forward active mode if we ignore the current flow in the reverse-biased BCJ, we get

Debjit 14/04/2020

$$I_E = \frac{-eAD_b n_{b0}}{L_b} \cdot \coth\left(\frac{W_{bn}}{L_b}\right)\left[\exp\left(\frac{eV_{BE}}{k_B T}\right) - 1\right]$$

$$- \frac{eAD_e p_{e0}}{L_e}\left[\exp\left(\frac{eV_{BE}}{k_B T}\right) - 1\right] \longrightarrow (27)$$

Here the first part is due to electron injection from the emitter into the base (III and IV) and the second part due to hole injection from the base into the emitter (II). The collector current is

$$I_C = \frac{-eAD_b n_{b0}}{L_b \sinh\left(\frac{W_{bn}}{L_b}\right)}\left[\exp\left(\frac{eV_{BE}}{k_B T}\right) - 1\right] \longrightarrow (28)$$

Assuming that $W_{bn} << L_b$, we can expand the hyperbolic functions as noted above. The base current is the difference between the emitter and collector current, we find that

$$I_B = \frac{eAD_e p_{e0}}{L_e}\left[\exp\left(\frac{eV_{BE}}{k_B T}\right) - 1\right] + \frac{eAD_b n_{b0} W_{bn}}{2L_b^2}$$

$$\left[\exp\left(\frac{eV_{BE}}{k_B T}\right) - 1\right] \longrightarrow (29)$$

The first part represents the hole current injected from the base into the emitter and the second part represents the hole current recombining with electrons injected from the emitter.

Having derived the current components, in the next section we will examine how material properties and doping levels can be manipulated to improve device performance. It is useful to recast the prefactor of the first term in the emitter current (Eq. (27)) in a different form. The prefactor, which we will denoted by I_s (we assume that $W_{bn} << L_b$, so that $\coth \alpha = \frac{1}{\alpha}$) is

Deb ... 14/04/20

$$I_s = \frac{e A D_b n_{b0}}{W_{bn}} = \frac{e^2 A^2 D_b n_i^2}{e A N_{ab} W_{bn}} = \frac{e^2 A D_b n_i^2}{e Q_G} \longrightarrow (30)$$

Where Q_G is called the Gummel number for the transistor. It has a value

$$Q_G = N_{ab} W_{bn} \longrightarrow (31)$$

and denotes the charge in the base ~~space~~ region of the device (assuming full ionization). As we will see later, the Gummel number has an important effect on the device performance.

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