Lecture-6
Bipolar Junction Transistors (BJT)
Part-I Continued

1. Modes of Operation: Each junction in the BJT can be forward biased, or reverse-biased independently. Thus we have four modes of operation exists as described below,

<table>
<thead>
<tr>
<th>Junction Bias Condition</th>
<th>Mode</th>
<th>Emitter-Base</th>
<th>Collector-Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward active</td>
<td>Forward bias</td>
<td>Reverse bias</td>
<td></td>
</tr>
<tr>
<td>Cut-off</td>
<td>Reverse bias</td>
<td>Reverse bias</td>
<td></td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward bias</td>
<td>Forward bias</td>
<td></td>
</tr>
<tr>
<td>Reverse active</td>
<td>Reverse bias</td>
<td>Forward bias</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Different modes of transistor operation

(a) Forward-active region: In the forward-active region, the bipolar transistor behaves as a controlled source. The conclusion can be reached from Eqns. (14) and (15) of LN-5 for the conditions listed in Table-1. For junction bias voltages of at least several tenths of a volt and assuming that $I_{C0}$ is negligibly small, as is almost always the case, $I_C = -\alpha_F I_E$. Thus control of the input current $I_E$ specifies the output current $I_C$. This is the action of a current-controlled current source as changes in the emitter-base bias level adjust the value of $I_E$ and hence $I_C$. With controlled-Source characteristics obtainable, the BJT can be used as an amplifier and the forward-active mode is prevalent in analog circuits.

(b) Cut-off region: Both junctions are reverse-biased in the cutoff mode: both $I_E$ and $I_C$ are in the order of the diode reverse saturation current. Here the situation is one of nearly zero current with large reverse junction voltages ($V_{CB} \ll V_T$), and behavior approximates an open switch.

(c) Saturation region: With both diodes forward-biased in saturation, the collector current may be appreciable, but only a small voltage exists across the collector junction. This condition is nearly that of a closed switch. Operation of the BJT between cutoff and saturation corresponds to the action of a switch.

(d) Reverse-active region: The reverse-active or inverted mode is similar to the forward-active mode with a significant difference. Although behavior
in the reverse-active region is that of a controlled source \((I_E = -\alpha_R I_C)\), the smaller value of the current again \(\alpha_R\) compared to \(\alpha_F\) makes this mode unsuitable, in general, for amplification. However, the inverted mode has application in digital circuits and certain analog switching circuits.

**Q:** An npn transistor is operated with the collector-base junction reverse-biased by at least a few tenths of a volt and with the emitter-base open-circuited. Determine (a) the mode of operation, (b) the collector and base currents, and (c) the values of \(I_C\) and \(V_{BE}\) at room temperature for \(I_{E0}=10^{-15}\) A, \(I_{C0} = 2 \times 10^{-15}\) A, and \(\alpha_F = 0.99\).

**A:** (a) With the collector-base diode reverse-biased, we can see from the table-1 that the mode of operation is either cut off or forward-active. Which condition exists depends on the state of the emitter-base junction. Using the Eqn.(14) of LN-5, with \(I_E = 0\) (emitter open circuit), we obtain,

\[
I_E = 0 = -I_{E0}(e^{-V_{EB}/V_T} - 1) + \alpha_R I_{C0}(e^{-V_{CB}/V_T} - 1)
\]

as the collector-base junction is reverse biased we can take the approximation \(e^{-V_{CB}/V_T} \ll 1\),

\[
\Rightarrow I_E = 0 = -I_{E0}(e^{-V_{EB}/V_T} - 1) + \alpha_R I_{C0}(1 - 1) \quad (1)
\]

\[
\Rightarrow e^{-V_{EB}/V_T} = 1 - \frac{\alpha_R I_{C0}}{I_{E0}}
\]

using reciprocity condition in the LN-5 Eqn.(9) the above equation reduces to

\[
\Rightarrow e^{-V_{EB}/V_T} = 1 - \alpha_F
\]

Thus taking the logarithm on both sides we have,

\[
\Rightarrow \frac{V_{EB}}{V_T} = \ln \frac{1}{1 - \alpha_F} = \ln (\beta_F + 1) \quad (2)
\]

In the above equation we observe that \(V_{EB}\) is positive, thus reverse-biasing the emitter junction. Consequently, the transistor is cut off.

(b) With \(I_E=0\) the KCL becomes \(I_B = -I_C\). The collector current is obtained from the Eqn.(15) of LN-5, into which Eqn.(1) is substituted:

\[
I_C = -I_B = -\alpha_F \alpha_R I_{C0} + I_{C0}
\]

\[
= (1 - \alpha_F \alpha_R) I_{C0} \quad (3)
\]
(c) Substituting the values given in the Eqn.(2) gives

\[
\frac{V_{EB}}{25 \times 10^{-3}} = \ln \frac{1}{1 - 0.99} = 115 \text{ mV}
\]

The value of \( \alpha_R \) can be obtained from the reciprocity condition Eqn.(9) of LN-5,

\[
\alpha_R = \alpha_F \frac{I_{C0}}{I_{E0}} = 0.99 \frac{10^{-15}}{2 \times 10^{-15}} = 0.495
\]

Thus using the Eqn.(2) we obtain,

\[
I_C = -I_B = (1 - 0.99 \times 0.495) \times 2 \times 10^{-15} = 1.02 \times 10^{-15} \text{ A}
\]

with \( I_E = 0 \), the result indicates that the transistor, between the base and collector terminals, behaves as a diode and the current determined is effective reverse saturation collector current for an open-circuited emitter. Although the value of \( I_C \) obtained is very small, it increases markedly with temperature. The current given by the Eqn.(3) is often referred to as the reverse collector current. It is an important quantity in BJT’s and is usually designated by \( I_{C0}’ \).

Using similar analysis, with collector-base open-circuited and the emitter-base diode reverse-biased, the reverse emitter current \( I_{E0}’ \) is obtained. The two results are stated below,

\[
I_{C0}’ = (1 - \alpha_R \alpha_F)I_{C0} \quad (4)
\]

\[
I_{E0}’ = (1 - \alpha_R \alpha_F)I_{E0} \quad (5)
\]

Figure 1: Common Base circuit showing the bias supplies \( V_{EE} \) and \( V_{CC} \)
Figure 2: Common-base output characteristics for pnp transistor. Note that the positive and negative $V_{CB}$ axis are reversed from normal.

Figure 3: (a) Common-base input characteristics ($V_{EB}$ vs $I_E$) for pnp transistor (b) same characteristics plotted as $I_E$ vs $V_{EB}$. Note that this curve has similarity to the diode curve.
2. Common-Base Configuration:

(a) The Output Characteristics: It is convenient to recast the Ebers-Moll equations directly in terms of $I_E$ and $I_C$ as follows: for a pnp transistor, solve for $I_C( e^{V_{CB}/V_T} - 1 )$ from LN-5 Eqn. (8), substitute this value into LN-5, Eqn.(7), and identify $I_{EO}^\prime$ from Eqn. (5). The result is,

$$I_E = I_{EO}^\prime ( e^{V_{EB}/V_T} - 1 ) - \alpha_R I_C$$

(6)

Proceeding in a similar fashion, we find

$$I_C = -\alpha_F I_E + I_{C0}^\prime ( e^{V_{CB}/V_T} - 1 )$$

(7)

These equations are valid for an npn transistor provided a minus sign is added before $I_C$, $I_E$, $V_{EB}$, and $V_{CB}$. From Eq. (7) we see that $I_C$ depends only on the input current $I_E$ and the output voltage $V_{CB}$. The output characteristics which display this relationship are shown in Fig.2 and constitute the family of curves of $I_C$ versus $V_{CB}$ for different values of $I_E$. To better illustrate behavior in the different modes of operation, only the portion of the characteristics in the vicinity of $V_{CB} = 0$ is shown. These characteristics can be measured by using the circuit shown in Fig.1, where it is assumed that we can vary the amplitudes of each power supply and the values of the two resistances. In the forward-active region (Table-1), $I_E$ is positive, $I_C$ is negative, and $V_{CB}$ is negative. Note that it is customary, as in figure-2, to plot increasing values of $|I_C|$ in the positive $y$ direction and increasing values of the magnitude of the reverse-bias voltage $V_{CB}$ in the positive $x$ direction. The collector current in the forward-active region is independent of $V_{CB}$ and thus constant for a given value of $I_E$. This is evident from Eqn.(7), which, evaluated in the forward active mode yields, ($V_{CB} < 0 \Rightarrow e^{V_{CB}/V_T} \ll 1$)

$$I_C = -\alpha_F I_E - I_{C0}^\prime$$

(8)

Eqn.(8) is valid for an npn transistor if $I_{C0}^\prime$ is changed to $+I_{C0}^\prime$. If $I_E = 0$, then from Eqn.(8), $I_C = -I_{C0}^\prime$ and the BJT is cut off. The characteristic for $I_E = 0$ is technically not coincident with the $V_{CB}$ axis but appears so because $I_{C0}$ is extremely small, Note that since $\alpha_F \approx 1$, $|I_C| \approx |I_E|$. The curves indicate that increasing $V_{CB}$ so that we forward-bias this junction ($V_{CB} > 0.6 \text{ V}$), the collector current increases ($I_C$ becomes less negative). With both diodes forward-biased, the transistor is saturated. The output characteristics of the inverted BJT display $I_E$ versus $V_{EB}$ for different $I_C$ values. Under these conditions $I_C$ (acting as the emitter...
current) is positive and $I_E$ (acting as the collector current) is negative. On the basis of Eqn. (6), a family of curves (not shown) similar to those in Fig.2 is obtained.

(b) The Input Characteristics: The input volt-ampere characteristics are plots of $I_E$ versus $V_{EB}$ for various values of $V_{CB}$. As seen in Fig.3, these curves represent the characteristics of the emitter-base diode at different collector-base voltages. An evident feature of these characteristics is the existence of a cut-in, turn-on, or threshold voltage $V_\gamma = 0.5 \, \text{V}$ below which $I_E$ is extremely small. If, with the collector open-circuited, we plotted the reverse-bias characteristic ($V_{EB} < 0$), we would observe a saturation current equal to $I_{E0}$. A second feature of this curve is that the emitter-base diode characteristic is affected by changing $V_{CB}$. We now consider the phenomenon, which accounts for the shape of the curves in Fig.3.

(c) The Early Effect or Base-Width Modulation: We know that the width of the depletion region of a junction increases as the magnitude of the reverse-bias voltage increases. We need only consider effects due to the collector-base junction as the emitter-base diode is forward biased. Consequently, the effective base width $W$ decreases with increasing $V_{CB}$; this modulation of base width is known as the “Early effect”. We can attribute three consequences to base-width modulation; (1) the narrower base width means that there is less chance for recombination, causing $\alpha_F$ to increase as $|V_{CE}|$ increases; (2) the concentration gradient of minority carriers within the base increase (as diffusion current is proportional to the concentration gradient, $I_E$ increases with the reverse-bias voltage at the collector-base diode); and (3) for extremely large voltages, $W$ may be reduced to zero, causing voltage breakdown of the BJT. This phenomenon, referred to as punch-through. At a constant value of $V_{EB}$, the Early effect predicts that $I_E$ increases as we increase $|V_{CB}|$. This conclusion accounts for the shift in the input characteristics shown in Fig.3.