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,

	Junction Bias Condition	
Mode	Emitter-Base	Collector-Base
Forward active	Forward bias	Reverse bias
Cut-off	Reverse bias	Reverse bias
Saturation	Forward bias	Forward bias
Reverse active	Reverse bias	Forward bias

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 α_R compared to α_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 $e^{-V_{CB}/V_T} \ll 1$,

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

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

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,

$$\Rightarrow \frac{V_{EB}}{V_T} = \ln \frac{1}{1 - \alpha_F} = \ln\ (\beta_F + 1) \tag{2}$$

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:

$$\begin{aligned} I_C &= -I_B \\ &= -\alpha_F \alpha_R I_{C0} + I_{C0} \\ &= (1 - \alpha_F \alpha_R) I_{C0} \end{aligned} \tag{3}$$

(c) Substituting the values given in the Eqn.(2) gives

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

The value of α_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,

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

with $I_E = 0$, the result indicates that the transisto, 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 oftem referred to as the *reverse collector current*. It is 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,

$$I'_{C0} = (1 - \alpha_R \alpha_F) I_{C0} \tag{4}$$

$$I'_{E0} = (1 - \alpha_R \alpha_F) I_{E0} \tag{5}$$

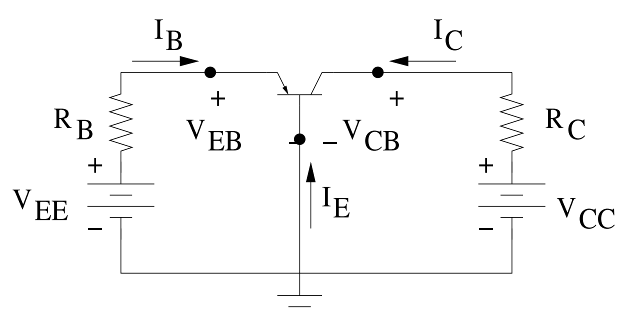

Figure 1: Common Base circuit showing the bias supplies V_{EE} and V_{CC}

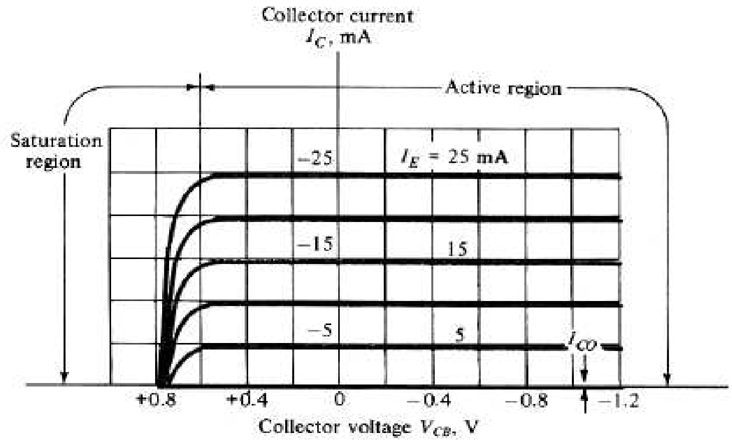

Figure 2: Common-base output characteristics for *pnp* transistor. Note that the positive and negative V_{CB} axis are reversed from normal

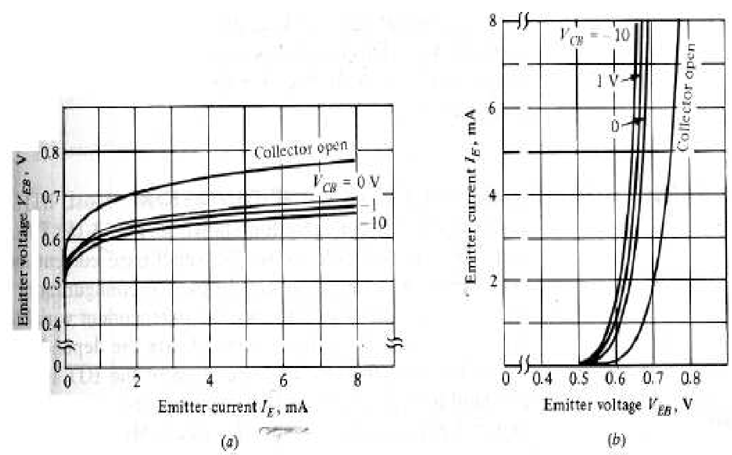

Figure 3: (a)Common-base input characteristics (V_{EB} vs I_E) for *pnp* transistor (b) same characteristics plotted as I_E vs V_{EB}. Note that this curve has similarity to the diode curve

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 $I_{C0}(e^{V_{CB}}/V_T - 1)$ from LN-5 Eqn. (8), substitute this value into LN-5, Eqn.(7), and identify I'_{EO} from Eqn. (5). The result is ,

$$I_E = I'_{EO}(e^{V_{EB}/V_T}1) - \alpha_R I_C \tag{6}$$

   Proceeding in a similar fashion, we find

$$I_C = -\alpha_F I_E + I'_{C0}(e^{V_{CB}/V_T} - 1) \tag{7}$$

   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, $(V_{CB} < 0 \Rightarrow e^{V_{CB}/V_T} \ll 1)$

$$I_C = -\alpha_F I_E - I'_{C0} \tag{8}$$

   Eqn.(8) is valid for an *npn* transistor if I'_{C0} is changed to $+I'_{C0}$. If $I_E = 0$, then from Eqn.(8), $I_C = -I'_{C0}$ 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 ($V_{CB} > 0.6\ V$), 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 $V_\gamma = 0.5\ V$ 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 α_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.