

Lecture-5

Bipolar Junction Transistors (BJT)

Part-I

1. **The Ideal Current-Controlled Source:** Electronic amplifiers and switches exploit the properties of controlled sources to achieve their function. Transistors are extensively used in such circuits because they exhibit controlled source characteristics. To focus attention on some important aspects of transistor operation, it is beneficial to examine the circuit properties of controlled sources and how these can be used as amplifying and switching devices. An ideal current-controlled current source, depicted in Fig.1(a), is a circuit element consisting of three terminals, one of which is common to both input and output. The input terminal pair (1-3) provides the control current i_1 , and a current source of strength Ai_1 acts as the output terminal pair (2-3). Parameter A relates the strength of the source to the control current and is often referred to as the current gain. Physically, A is related to the processes which occur within the device used to obtain the controlled source. It is evident in Fig.1(a) that the effect of i_1 is transmitted to the output by means of the source, whereas signals applied at the output terminals do not affect the control current. This unilateral behavior allows the portions of a circuit where the control signal is applied to be isolated from circuit elements connected to the output. In the circuit shown in Fig.1(b), a signal source v_s in series with a resistance R_s is connected to the input and a load resistance R_L is placed across the output of the controlled source. The control current is $i_1 = v_s/R_s$, and the output voltage v_2 is

$$v_2 = -Ai_2R_L = \frac{-AR_L}{R_s}v_s \quad (1)$$

thus if

$$\left| \frac{-AR_L}{R_s} \right| > 1$$

then $|v_2| > v_s$ this gives the voltage amplification. The output volt-ampere characteristics are a convenient method for displaying the dependence of source strength on the control variable. These characteristics are shown in the figure-2. In the graph, the horizontal characteristics indicates that i_2 is independent of v_2 (ideal current source). Now writing KVL in the output loop of figure-3, we get

$$v_2 = V_{22} - i_2R_2 \quad (2)$$

if $i_1 = 0$ then $i_2 = 0 \Rightarrow v_2 = V_{22}$. Thus we get the point on x -axis. Similarly if $v_2 = 0$ the $i_2 = V_{22}/R_2$ which is the point on the y -axis. By joining these point

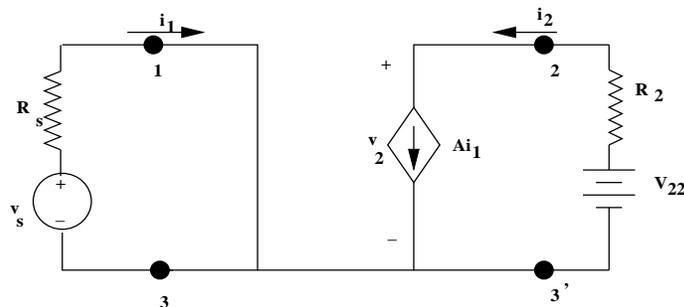


Figure 3: Current Source used as an Amplifier

we get a linear line of slope $-1/R_2$. This line is called *load line*. The points of the intersection of load line with output characteristics are called *quiescent points* or *operating points*.

2. **Junction Transistor:** The bipolar junction transistor (BJT), also called the *junction transistor* or *bipolar transistor*, is a three-element device formed from two junctions which share a common semiconductor layer. The two types of bipolar transistors are pictorially represented in figure-4. In the *pn*p transistor in figure-4(a), the common *n*-type region is sandwiched between two *p*-type layers. Analogously, a *p* region is common to two *n*-type layers in the *n**pn* transistor in figure-4(b). The three elements of a BJT are referred to as the emitter, base, and collector and are indicated in the circuit symbols in figure-5. The arrow on the emitter lead specifies the direction of current when the emitter-base junction is forward-biased. In both cases, the assumed positive direction for the terminal currents I_E , I_B , and I_C is into the transistor. The voltage between each pair of terminals is also indicated in figure-5 by means of the double subscript notation. For example, V_{CB} represents the voltage drop between collector and base. Figure-4 represents the symmetrical structure and allows us to choose either *n*-region as emitter. However in practical in the planar *n**pn*, the emitter and collector regions differ markedly. The term “Planar transistor” refers to the fact that the three output leads *C*, *B*, and *E* are connected to aluminum contacts for the collector, base and emitter respectively, with all three contacts lying in the single plane. The emitter area is considerably smaller than the collector area. This difference is due mainly to the fact that in most prevalent uses of BJT’s, the collector region must handle more power than the emitter. Hence more surface area is required for heat dissipation. A second difference is the doping densities of emitter and collector regions. The emitter generally serves as the source of mobile charge. A high doping is used (thus n^+ or p^+) to enhance the ability to make

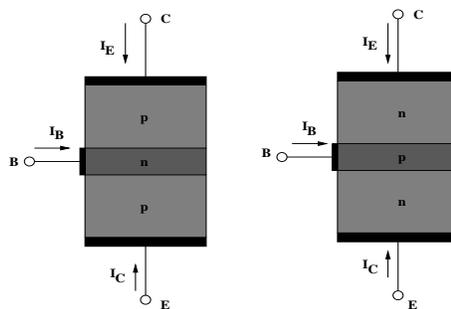


Figure 4: (a) *pnp* and (b) *npn* transistors

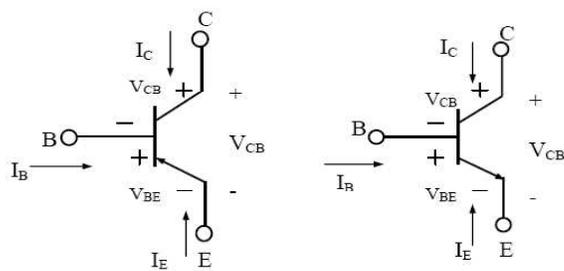


Figure 5: Circuit symbols for (a) *pnp* and (b) *npn* transistors

many carriers available. That is if emitter-base junction is forward -biased, the emitter injects electrons into the base where they move towards collector. If the collector-base diode is reversed-biased, the minority carrier electrons in the base are swept into the collector region. The collector as its name implies, is normally not required to provide many carriers, and so its doping levels need not be as high as that of emitter.

3. **The physical behavior of BJT:** The essential features of a BJT as an active circuit element can be appreciated by considering the situation depicted in figure-6. Here a *npn* transistor is shown with voltage source which serve to bias the emitter-base junction in the forward direction (V_{EB} positive) and the collector-base junction in the reverse direction (V_{CB} negative). The electric field is confined to the depletion region, and the field is zero in the rest of the semiconductor. Hence the potential is constant within each region (emitter, base, or collector) and no conduction (drift) currents exist. Consequently, *the current components in a BJT are all diffusion currents.* Let us for the

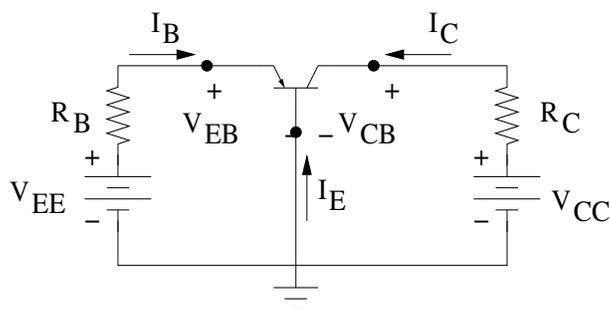


Figure 6: Common Base circuit showing the bias supplies V_{EE} and V_{CC}

moment assume an idealized transistor whose base is so lightly doped compared to the emitter region that we can neglect all currents due to electrons. We also assume that the width of the base region is small compared with the diffusion length so that recombination in this region can be neglected. For this ideal transistor, a forward voltage V_{EB} injects holes into the base, and all these holes travel through the base and into the collector region. This action results in the collector current being equal to the emitter current $|I_C| = |I_E|$ for all values of reverse collector voltage V_{CB} . This transistor exhibits precisely the characteristic of the current-controlled current source, with unity current gain ($A = 1$). The output characteristics of this ideal transistor are those indicated in figure-2 with $i_2 = -I_C$, $i_1 = I_E$, and $v_2 = -V_{CB}$. Now let us consider the behavior of a practical (non-ideal) transistor in the circuit shown

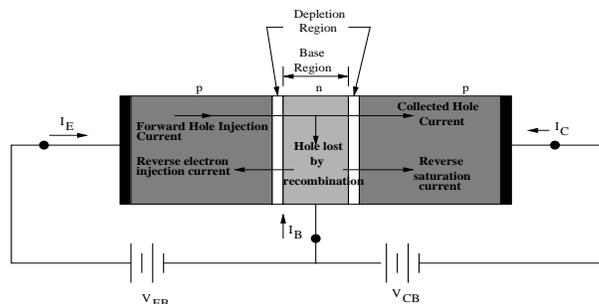


Figure 7: Transistor carrier components for a forward biased emitter-base junction and reverse biased collector-junction

in figure-6. We can no longer neglect recombination or the effects of the electron concentration in a real transistor. Figure-7 shows the various current components of a *pnp* transistor biased to correspond to the circuit shown in figure-6. For this situation we again assume that no electric field exist in the semiconductor regions outside the depletion regions so that the voltages V_{EB} and V_{CB} appear across the emitter and collector junctions, respectively. The forward-biased emitter-base junction injects many holes into the base (forward injection) is kept small in transistor design by doping the base less heavily than the emitter. In the narrow base region, holes diffuse toward the collector-base junction. A small number of injected holes diffuse toward the collector-base junction are swept into the collector because of the reverse bias. Under the bias condition shown in figure-7, these holes form the major component of I_C . However, there is another (small) contribution to the collector current due to thermally generated carriers. Holes so generated in the base region cross into the collector section and electrons, thermally generated in the collector, cross the junction into the base layer. These two thermal currents constitute the reverse saturation current of the collector-base junction indicated in figure-7. Consequently, as shown in figure-7, it is clear that the collector current consists of two components, one due to injected holes at the emitter-base diode and the other attributed to thermally generated carriers crossing the collector-base junction.

4. **The Ebers-Moll representation of the BJT:** The behavior of the bipolar transistor can be described in both conceptual and quantitative terms by observing that this device consists of two coupled *pn* junctions. The base region is common to both junctions and forms the coupling between them. Bipolar transistors are constructed with very narrow base regions (considerably smaller than one diffusion length). The current components which comprise

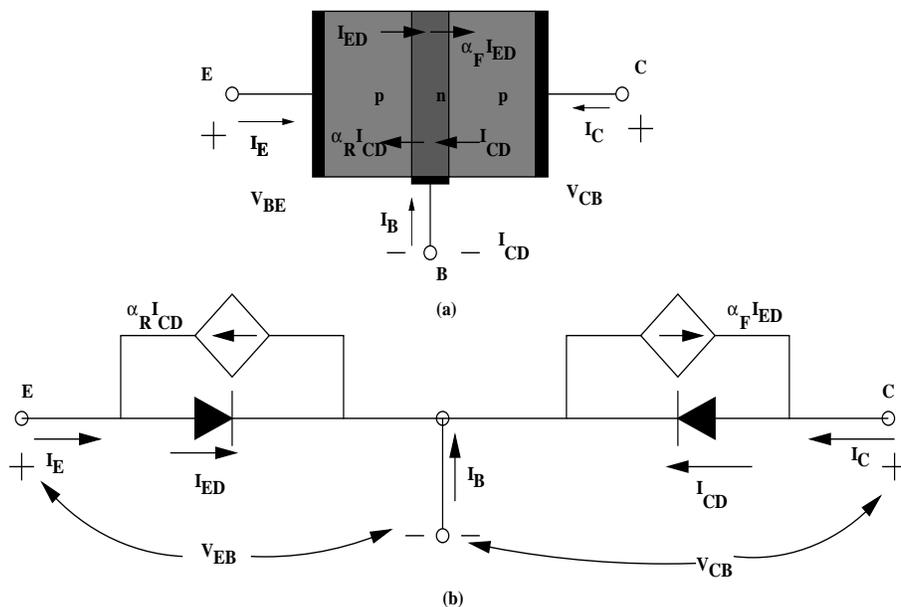


Figure 8: (a) Current components in *pnp* transistor (b) Large-signal (Ebers-Moll) representation of a *pnp* transistor

the terminal currents I_E and I_C are shown for a *pnp* transistor in figure-8(a). The voltages V_{EB} and V_{CB} are the voltage drops from emitter to base and collector to base, respectively. Assuming that there is no voltage drop across the bulk semiconductors forming the emitter, base, and collector regions, these voltages appear across the respective junctions. With both voltages measured with respect to the base, this connection is called the common-base(CB) configuration. The emitter current in figure-7(a) has two components. The current associated with the emitter-base diode is designated I_{ED} and that with the collector-base diode, I_{CD} . The component $\alpha_R I_{CD}$ is the portion of I_{CD} that is coupled through the base to the emitter. Similarly, $\alpha_F I_{ED}$ is the fraction of I_{ED} coupled into the collector. On the basis of the considerations in the preceding paragraph we can construct the Ebers-Moll model in figure-8(b). The two back-to-back diodes (whose cathodes are connected) represent the junctions of the bipolar transistor, whereas the two controlled sources indicate the coupling between junctions. The currents I_{ED} and I_{CD} are related to V_{EB} and V_{CB} by the diode volt-ampere relation given in Eqn.(22) of LN(Lecture notes)-4 . Thus we have

$$I_{ED} = I_{E0}(e^{V_{EB}/V_T} - 1) \quad (3)$$

$$I_{CD} = I_{C0}(e^{V_{CB}/V_T} - 1) \quad (4)$$

where I_{E0} I_{C0} are the reverse saturation currents. By applying KCL we have,

$$I_E = I_{ED} - \alpha_R I_{CD} \quad (5)$$

$$I_C = -\alpha_F I_{ED} + I_{CD} \quad (6)$$

substituting Eqn.(3) and (4) in (5) and (6) we get,

$$I_E = I_{E0}(e^{V_{EB}/V_T} - 1) - \alpha_R I_{C0}(e^{V_{CB}/V_T} - 1) \quad (7)$$

$$I_C = -\alpha_F I_{E0}(e^{V_{EB}/V_T} - 1) + I_{C0}(e^{V_{CB}/V_T} - 1) \quad (8)$$

The Eqns. (7) and (8) are called ‘‘Ebers-Moll Equations’’ for the *pnp* transistor. The values α_F and α_R are each less than unity, since not all the current from one diode is coupled to the other junction. The subscripts refers to forward transmission (F) from the emitter to collector and reverse transmission (R) from collector to emitter. I_{E0} , I_{C0} , α_F and α_R are found from the theory and are related by the equation,

$$\alpha_F I_{E0} = \alpha_R I_{C0} \quad (9)$$

This condition is often called *reciprocity condition* for BJT. The base current can be calculated by applying KCL at the transistor (i.e., treating the transistor as node, so sum of all currents entering the node is zero.) Hence we have

$$I_B + I_C + I_E = 0 \quad (10)$$

$$\Rightarrow I_B = -(I_C + I_E) \quad (11)$$

For transistor with small dimensions used we have,

$$0.98 \leq \alpha_F \leq 0.998 \quad (12)$$

$$0.4 \leq \alpha_R \leq 0.8 \quad (13)$$

and the currents I_{E0} , I_{C0} , are of the order of 10^{-15} A. Similarly the Ebers-Moll equations can be obtained for *nnp* transistor as shown in figure-9(a) and (b) as follows,

$$I_E = -I_{E0}(e^{-V_{EB}/V_T} - 1) + \alpha_R I_{C0}(e^{-V_{CB}/V_T} - 1) \quad (14)$$

$$I_C = \alpha_F I_{E0}(e^{-V_{EB}/V_T} - 1) - I_{C0}(e^{-V_{CB}/V_T} - 1) \quad (15)$$

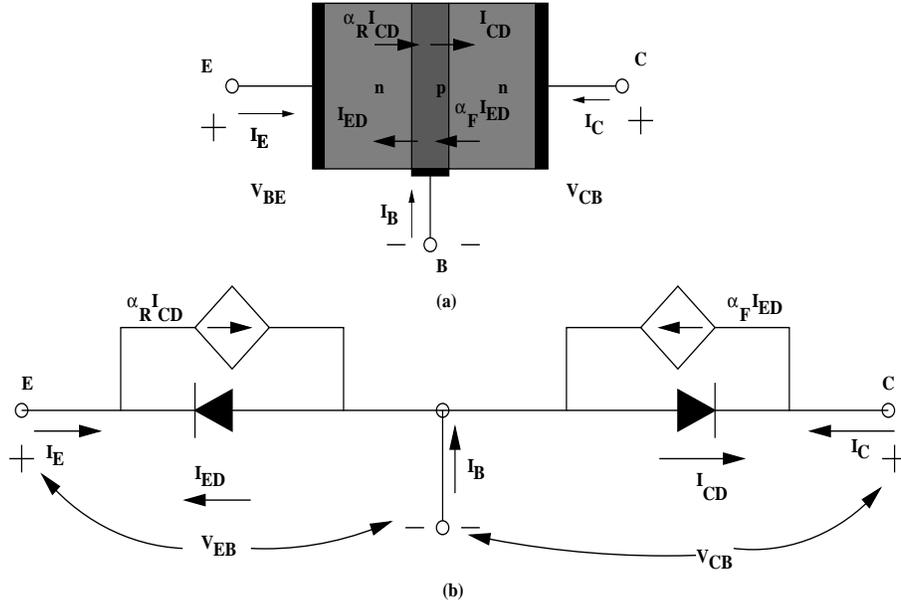


Figure 9: (a) Current components in *npn* transistor (b) Large-signal (Ebers-Moll) representation of a *npn* transistor

5. **Large Signal Current Gains:** Let us consider an *npn* transistor for the situation that emitter-base junction is forward biased (V_{EB}) and the collector-base are short circuited ($V_{CB} = 0$). Substituting these values in the Eqns.(14) and (15)

$$-I_E = I_{E0}(e^{-V_{EB}/V_T} - 1)$$

and

$$\alpha_F I_{E0}(e^{-V_{EB}/V_T} - 1)$$

Hence eliminating $I_{E0}(e^{-V_{EB}/V_T} - 1)$ we get $I_C = \alpha_F I_E$. Thus we define,

$$\alpha_F = -\frac{I_C}{I_E} \Big|_{V_{CB} = 0} \quad (16)$$

The quantity α_F is called “common-base forward short circuit current gain”. Similarly when $V_{CB} < 0$, and $V_{EB} = 0$ we have “common-base reverse short circuit current gain”.

$$\alpha_R = -\frac{I_E}{I_C} \Big|_{V_{EB} = 0} \quad (17)$$

For *npn* devices I_C is positive, while I_E is negative. $I_B = -(I_C + I_E)$ is

positive and hence it have the same sign of I_C ; similarly for pnp transistors I_C is negative, I_E is positive which implies I_B is negative. Thus for any BJT, I_B and I_C have same sign and opposite to that of I_E . Substituting Eqn.(16) in (11) we have,

$$I_B = -(1 - \alpha_F)I_E \quad (18)$$

If α_F is almost unity then I_B is quite small compared with I_E and hence magnitudes of I_C and I_E are almost same.

It is often convenient to express the collector and emitter currents in terms of much smaller base currents.

$$\begin{aligned} I_C &= -\alpha_F I_E \\ &= -\alpha_F \left(-\frac{1}{(1 - \alpha_F)} \right) I_B \text{ from Eqn.(18)} \\ &= \frac{\alpha_F}{1 - \alpha_F} I_B \\ \Rightarrow I_C &= \beta_F I_B \end{aligned} \quad (19)$$

where β_F is called “common-emitter forward short circuit current gain”, given by

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F} \quad (20)$$

Similarly reverse condition yields the “common-emitter reverse short circuit current gain” as

$$\beta_R = \frac{\alpha_R}{1 - \alpha_R} \quad (21)$$

β_F lies between 50 to 250 and β_R is between 1 to 5.