

The Bipolar Junction Transistor

Topics: Bipolar junction transistor (BJT), BJT types, operating modes of the BJT, BJT configurations, analysis of internal currents, the Ebers-Moll model, the BJT as an amplifier, operational (quiescent) point analysis

Transistors: Before the invention of transistors, electrical signals were amplified using vacuum tubes, which are large, heavy and expensive components. Electronic instruments and appliances were simple and large and their use was limited. Transistors were invented in the 1940's. Their first use was in amplifier circuits for analog signals, where they replaced vacuum tubes. The first widespread electronic device employing transistors was the "transistor radio." Transistors are small and versatile, and they are inexpensive to manufacture. They rapidly made their way into existing electronic systems and many new systems were designed to take advantage of their properties. The introduction of integrated circuit (IC) fabrication techniques further increased the significance of transistors, because with these techniques, thousands of transistors can be implemented on a single semiconductor chip. They remained a key component in the design of analog circuits, but more importantly, they became the building block of all digital circuits. Today, transistors are in all electronic systems, from home appliances to computers.

The Bipolar Junction Transistor (BJT): The BJT is the most common transistor. It consists of three sections of semiconductors: an *emitter*, a *base* and a *collector* (**Figure 3.1**). In an *npn-type* BJT, the emitter and the collector are made of n-type semiconductors and the base is made of a p-

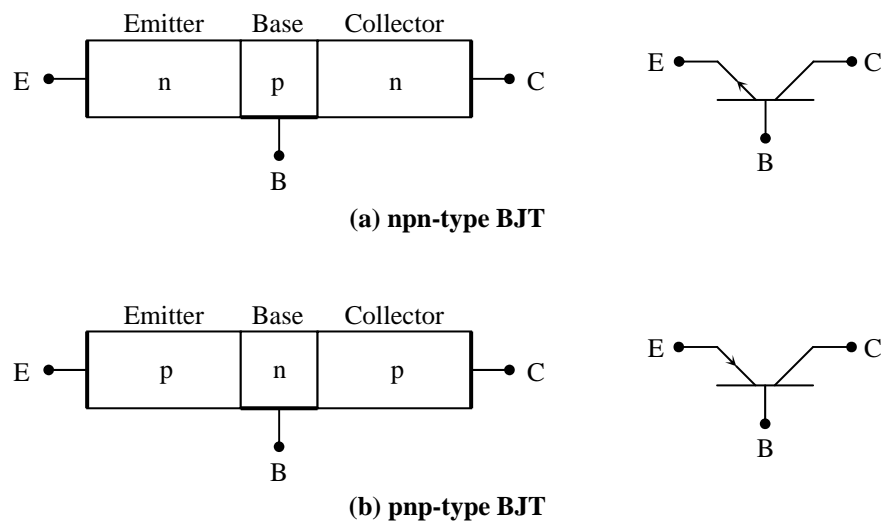


Figure 3.1 Schematic Diagram and Circuit Symbol of the BJT

type semiconductor. In a *pnp-type* BJT, it is the other way round. The three sections of a BJT form two p-n junctions: the *emitter-base junction* and the *collector-base junction*. Individually, these junctions are not different from the p-n junction in a diode. The unique characteristics of the BJT originate from an *interaction* between these two junctions.

Operating modes of the BJT: The *operating mode* of a BJT depends on how its junctions are biased (**Table 3.1**). The BJT is biased to operate in the *active* mode in applications where it is used as an amplifier. In the *cut-off* and *saturation* modes, the BJT behaves like an open and closed switch, respectively. Most BJTs in digital circuits (logic gates, memory) operate in these two modes. The *reverse active* mode is rarely used and is listed here for reference.

Operating mode	Emitter-Base junction	Collector-Base junction
Active	forward biased	reverse biased
Cut-off	reverse biased	reverse biased
Saturation	forward biased	forward biased
Reverse active	reverse biased	forward biased

Table 3.1 Operating Modes of the BJT

BJT configurations: In a typical transistor circuit, the transistor is connected to an input circuit and an output circuit or load (**Figure 3.2**). (Additional components are often necessary to *bias* the BJT.) One of the terminals of the BJT (E, B or C) is connected to both the input and the output circuit. The configuration of a BJT in a circuit is named after this common terminal. Thus, we speak of *common-emitter*, *common-base* and *common-collector* configurations.

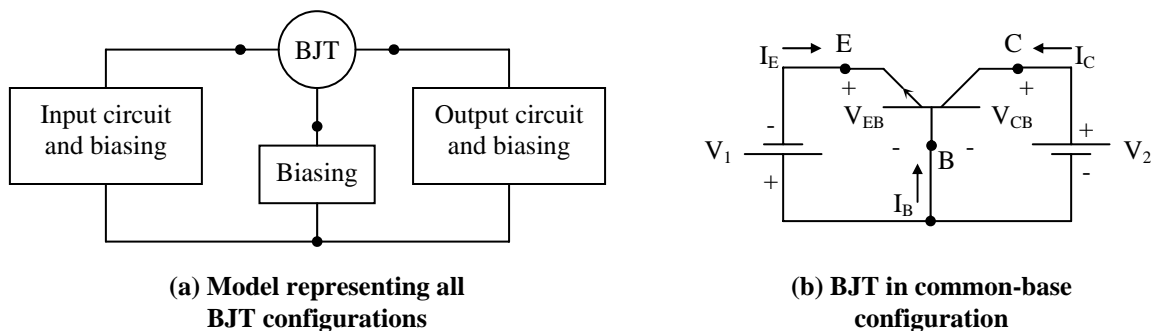


Figure 3.2 BJT Configurations

Analysis of internal currents: The internal currents in an npn-type BJT biased to operate in the active mode are shown in **Figure 3.3**. The emitter-base junction is forward biased by the voltage V_1 . In the emitter, the electron current resulting from this bias is larger than the hole current (indicated by the thickness of the arrows representing the currents), because in a BJT the emitter is more heavily doped than the base. The hole current follows the path that it would follow in a forward biased diode. The electron current, however, behaves differently than it would in a forward biased diode. In a diode, all of the electrons entering the p-side would recombine with the holes there. In Figure 3.3, it is indicated that only a fraction of the electrons from the emitter recombine with the holes in the base. Most of the electrons from the emitter travel through the base and reach the collector. There are two reasons for that: 1.) As mentioned above, the base is more lightly doped than the emitter. Thus, the number of holes in the base is not enough to accept all the electrons diffusing from the emitter. 2.) The base in a BJT is so narrow, that its width is comparable to the *diffusion length* of the electrons from the emitter. The diffusion length is the average distance that charge carriers travel after they diffuse across a p-n junction and before they recombine with the charge carriers on the opposite side. Hence, most of the electrons from the emitter reach the base-collector junction, before they have a chance to recombine with the holes in the base. Once they reach the base-collector junction, they are accelerated into the collector because of the charge build-up on both sides of the junction. The base-collector junction is reverse biased by the voltage V_2 . Therefore, there is a negative charge build-up on the base side, which pushes the emitter electrons into the collector; and there is a positive charge build-up on the collector side, which pulls them in.

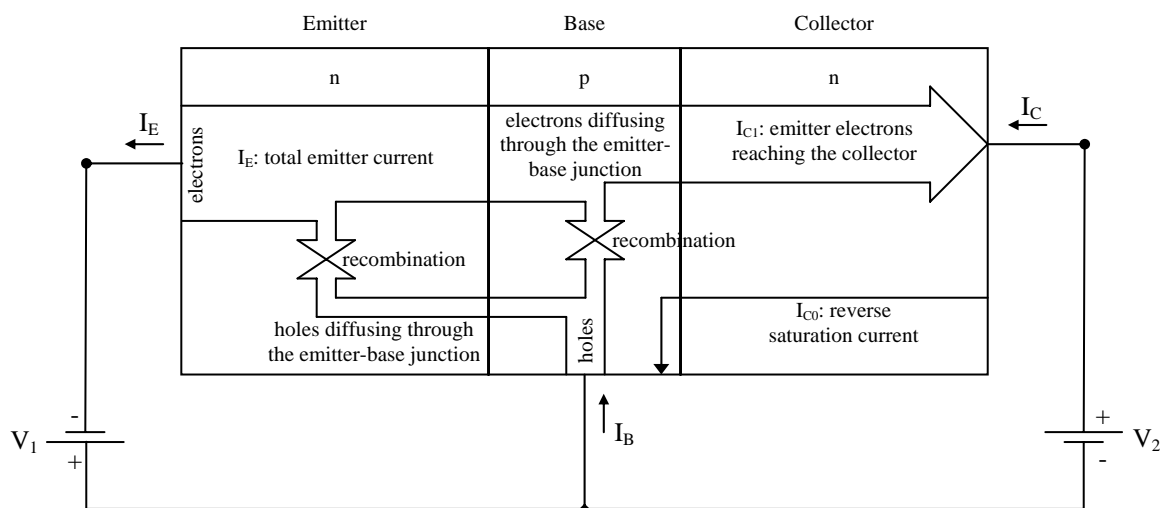


Figure 3.3 Internal Currents in an npn-type BJT in the Active Mode

The interaction between the emitter and the collector is basic principle behind the operation of the BJT. A BJT, in which the base is as wide as, and as heavily doped as the emitter would not work, because the electrons from the emitter would never reach the collector. This kind of a BJT would be nothing but two diodes put together back to back.

The fraction of the total emitter current that reaches the collector is known as the large-signal forward current gain (α_F). Thus:

$$I_{C1} = \alpha_F \cdot I_E$$

The collector current I_C has two components: I_{C1} and I_{C0} , the reverse saturation current. Since the reverse saturation current is much smaller than the forward currents, we can write:

$$I_C = I_{C1} + I_{C0} \approx I_{C1}$$

$$I_C \approx \alpha_F \cdot I_E$$

Applying KCL to the BJT in Figure 3.3 yields:

$$I_B = I_E - I_C \approx I_E - \alpha_F \cdot I_E$$

$$I_B \approx (1 - \alpha_F) \cdot I_E$$

BJTs are manufactured such that α_F is very close to unity. Its value is typically larger than 0.900 and can be as high as 0.997. Thus, in an npn-type BJT, most of the current flowing out of the emitter comes from the collector, with only a small contribution from the base. Similarly, in a pnp-type BJT most of the current entering at the emitter leaves through the collector, with only a small portion exiting through the base.

The Ebers-Moll Model: The above discussion of the internal currents in a BJT is valid only for the active mode. The Ebers-Moll model (**Figure 3.4**) was developed to represent the currents in a BJT in all operational modes. According to this model, the emitter and the collector currents have two components: the “diode current” (I_{DE} and I_{DC}) and the “interaction current” (represented by the dependent current sources). The diode current is the current that would flow through each junction if it were a single diode. This current is determined by the biasing of the junction and

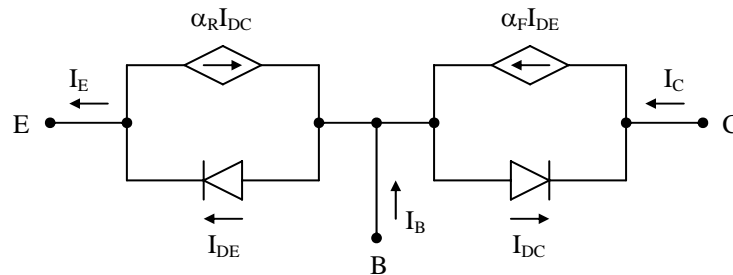


Figure 3.4 The Ebers-Moll Model of an npn-type BJT

does not take the interaction between the junctions into account. The currents resulting from the interaction between the emitter and the collector are represented by the dependent current sources. α_R is the large-signal reverse current gain. It has an effect only in the reverse active mode. In the other three modes the collector-base is reverse biased and I_{DC} is very small. Therefore, the collector cannot have an effect on the current flowing through the emitter. BJTs are not designed to operate in the reverse active mode. Unlike the forward current gain, the value of the reverse current gain is much less than unity.

In the cut-off mode, both junctions in the BJT are reverse biased and both diode currents equal to the reverse saturation current. According to the model, this also reduces the interaction currents to the level of reverse saturation current. Since the emitter and collector currents are the sum of their respective diode and interaction currents, they are also at the level of reverse saturation current. No significant currents flow through the BJT; it is “cut-off.”

In the saturation mode, both junctions are forward biased and both diode currents are large. Consequently, the interaction currents are also large. Large currents flow both through the emitter and the collector; the BJT is “saturated.”

Beta analysis of the operating point: If we assume that the BJT in Figure 3.8 is operating in the active mode, we can write: $I_C = \alpha_F I_E$

Applying KCL to the transistor yields: $I_E = I_C + I_B$

Substituting for I_E :
$$\frac{I_C}{\alpha_F} = I_C + I_B$$

$$\left(\frac{1}{\alpha_F} - 1 \right) \cdot I_C = I_B$$

$$\frac{1 - \alpha_F}{\alpha_F} \cdot I_C = I_B$$

$$I_C = \frac{\alpha_F}{1 - \alpha_F} \cdot I_B$$

We define:
$$\beta = \frac{\alpha_F}{1 - \alpha_F}$$

Then:
$$I_C = \beta \cdot I_B$$

$$I_E = (\beta + 1) \cdot I_B$$

The variable β is another way of expressing the large signal forward current gain. In common-emitter configurations, it is more convenient to use than α_F . The following examples show how beta can be used to calculate the operating point of a BJT.

Example 3.1:

Find I_C and V_{CB} in the circuit shown in **Figure 3.8**. Ignore reverse saturation currents and let $V_1 = 5V$, $V_2 = 10V$ and $\beta = 100$.

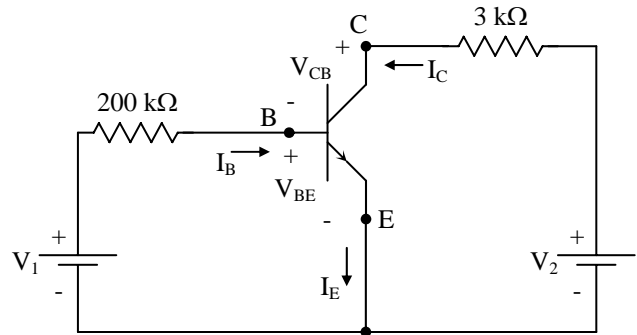


Figure 3.8 npn-type BJT in Common-emitter Configuration

Assuming that the BJT is in the active mode, we can set $V_{BE} = 0.7 V$. (We have to verify this assumption later.)

$$\text{From the input circuit: } I_B = \frac{5V - 0.7V}{200k\Omega} = \frac{4.3V}{200k\Omega} = 21.5 \mu A$$

$$I_C = \beta \cdot I_B = 2150 \mu A = 2.15 mA$$

$$I_E = I_C + I_B = 2.15 mA + 21.5 \mu A = 2.18 mA$$

$$\text{From the output circuit: } V_2 = I_C \cdot 3k\Omega + V_{CB} + V_{BE}$$

$$\text{Solving for } V_{CB}: V_{CB} = V_2 - I_C \cdot 3k\Omega - V_{BE} = 10V - (2.15mA) \cdot (3k\Omega) - 0.7V$$

$$V_{CB} = 10V - 6.45V - 0.7V$$

$$V_{CB} = 2.85V$$

V_{CB} is positive. The collector-base junction is reverse biased. The assumption was correct.

Example 3.2:

Find I_C and V_{CB} in the circuit shown in **Figure 3.9**. Ignore reverse saturation currents and let $V_1 = 5V$, $V_2 = 10V$ and $\beta = 100$.

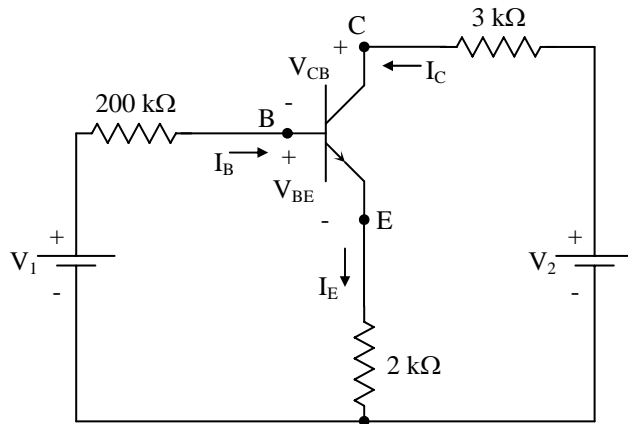


Figure 3.9 npn-type BJT in Common-emitter Configuration, with Emitter Resistance