BASIC OF ELECTRONICS

Pavol Galajda, KEMT, FEI, TUKE
Pavol.Galajda@tuke.sk

Bipolar Transistors

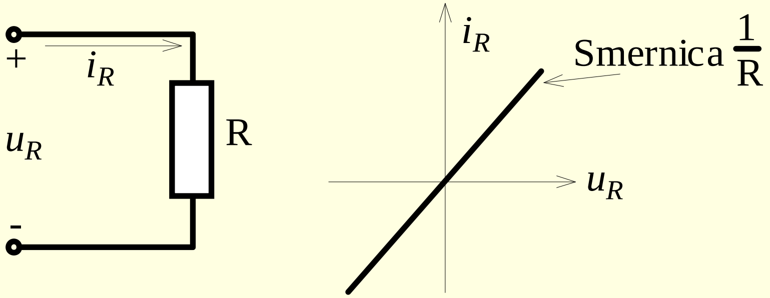
- 2.1 Bipolar Transistors- Introduction
- 2.2 Transistor Operation
- 2.3 Transistor Circuits
  - Common Circuit Configurations
  - Characteristic Curves

2 Bipolar Transistors

- The simplest linear circuit element is the resistor. The voltage across this element is related to current through it by Ohm's law. This relationship is graphically depicted by a straight line. The slope of the line is the conductance of the resistor, i.e., the ratio of current to voltage. The reciprocal of this slope is the resistance in ohms. If the resistor is connected in any circuit, the operating point must fall somewhere on this curve.

- In last presentation we have discussed diode construction and have had a brief introduction to practical diode models and differences between practical and ideal diodes.

- **Now we shall explore the Bipolar Tranzistor**



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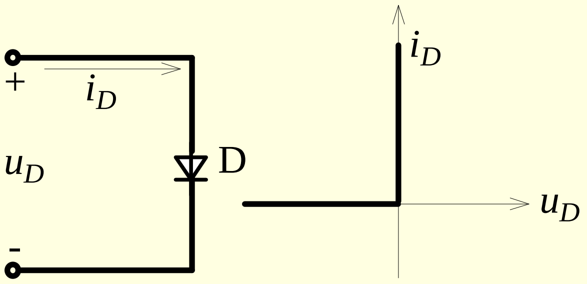
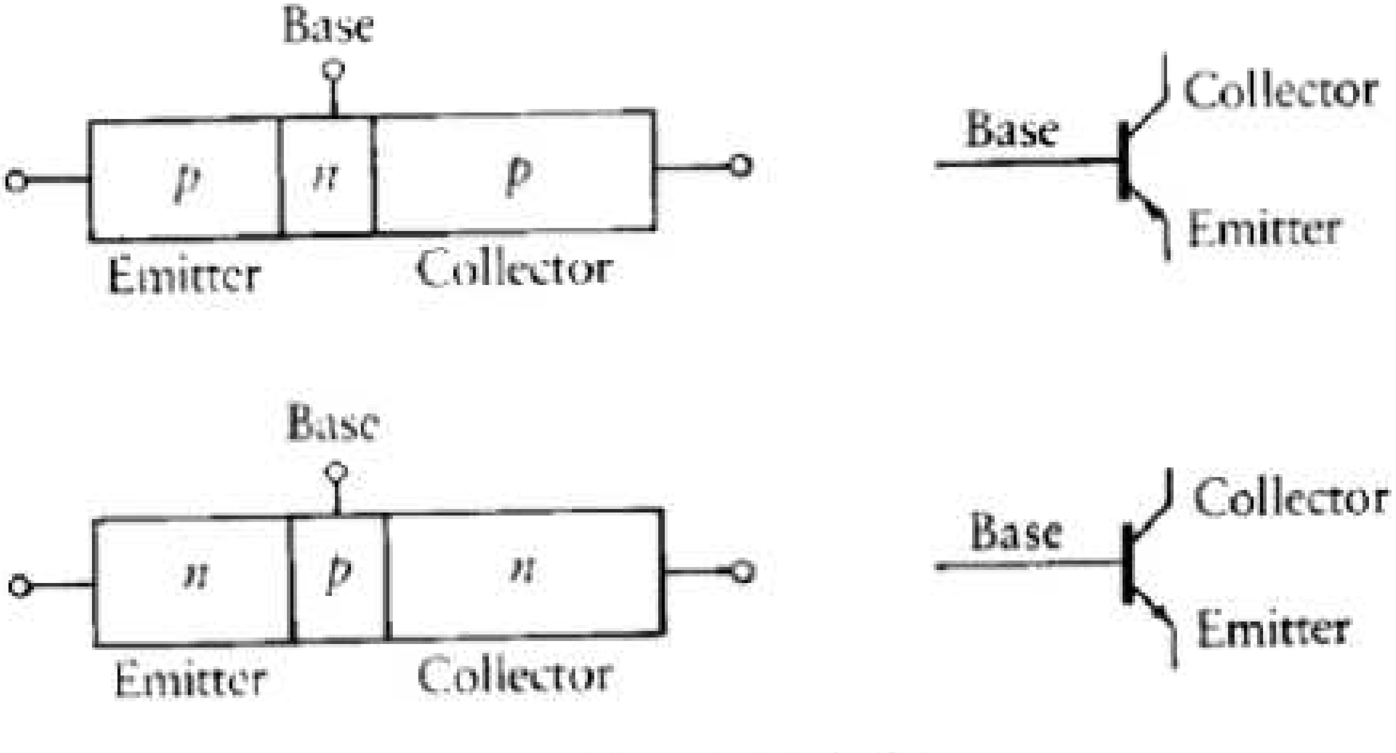


b)

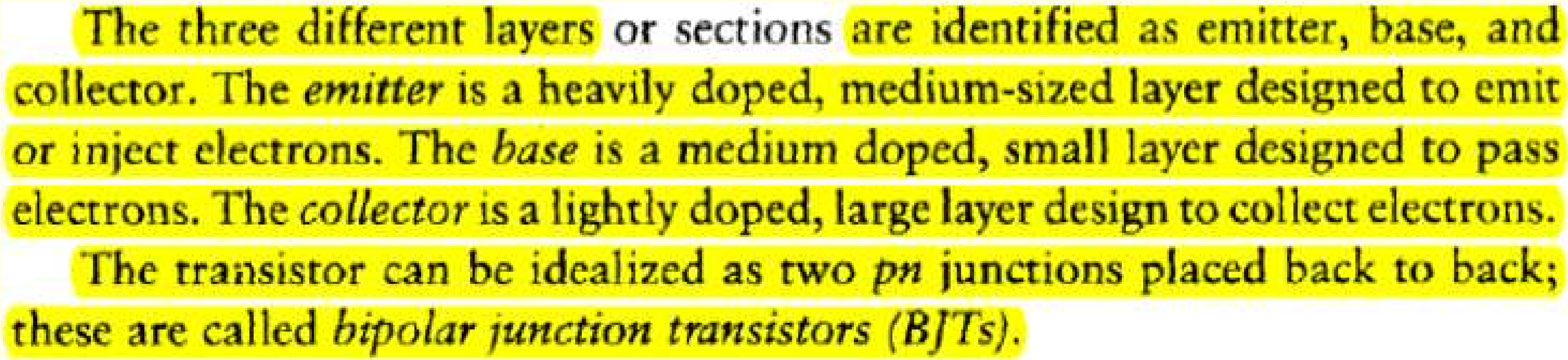
2.1 Bipolar Transistors

The transistor is a three-terminal device, in contrast to the diode, which is a two-terminal device. The diode consists of a *p*-type material and an *n*-type material; the transistor consists of two *n*-type materials separated by a *p*-type material (*npn* transistor) or two *p*-type materials separated by an *n*-type material (*pnp* transistor). Figure 2.4(a) illustrates the schematic representation of a transistor [22].



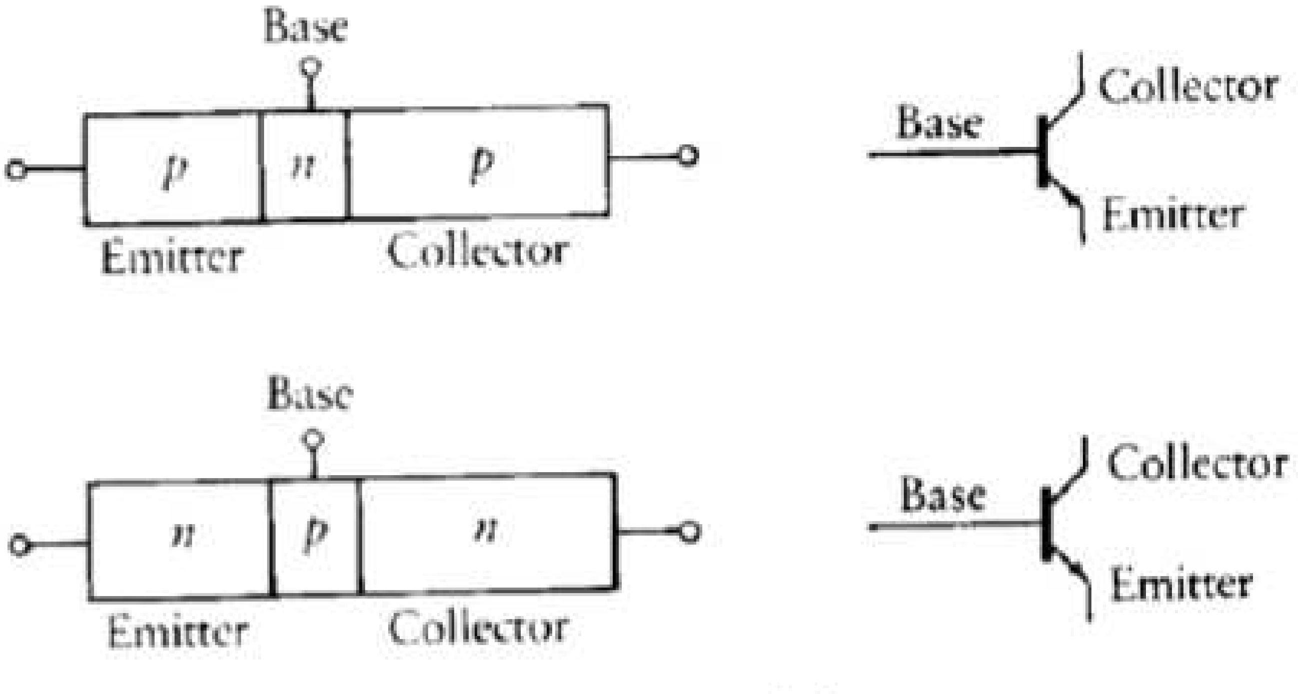
(a) Circuit symbols

2.1 Bipolar Transistors



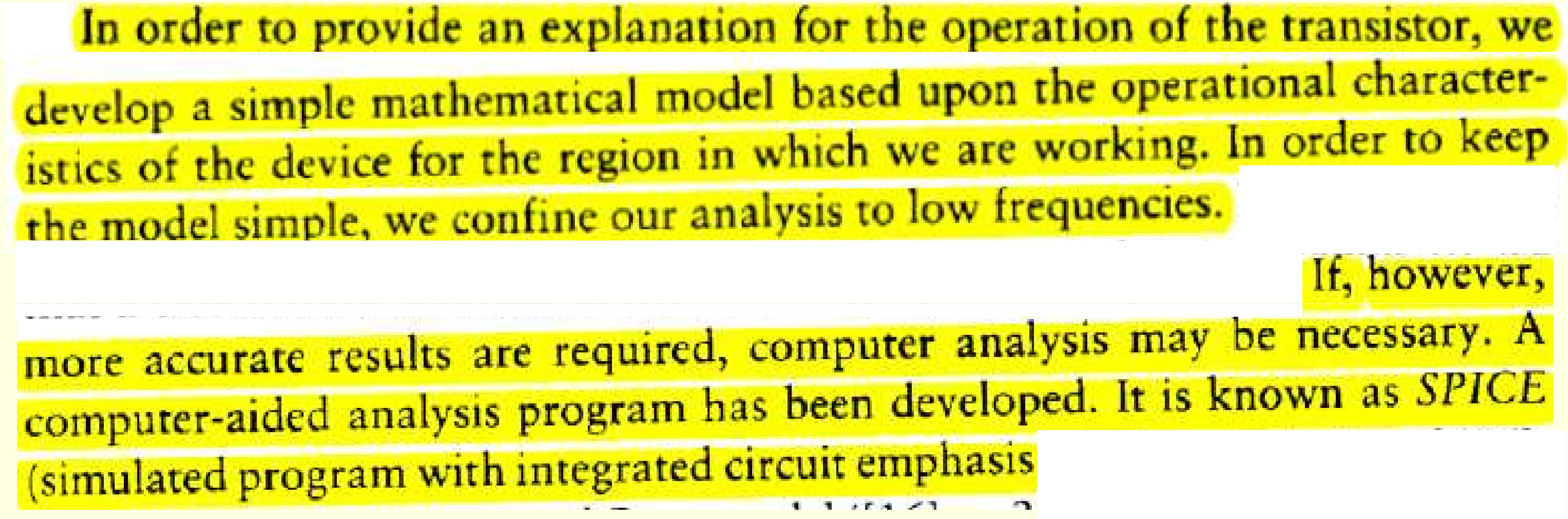
The three different layers or sections are identified as emitter, base, and collector. The *emitter* is a heavily doped, medium-sized layer designed to emit or inject electrons. The *base* is a medium doped, small layer designed to pass electrons. The *collector* is a lightly doped, large layer design to collect electrons.

The transistor can be idealized as two *pn* junctions placed back to back; these are called *bipolar junction transistors (BJTs)*.



(a) Circuit **symbols**

2.1 Bipolar Transistors

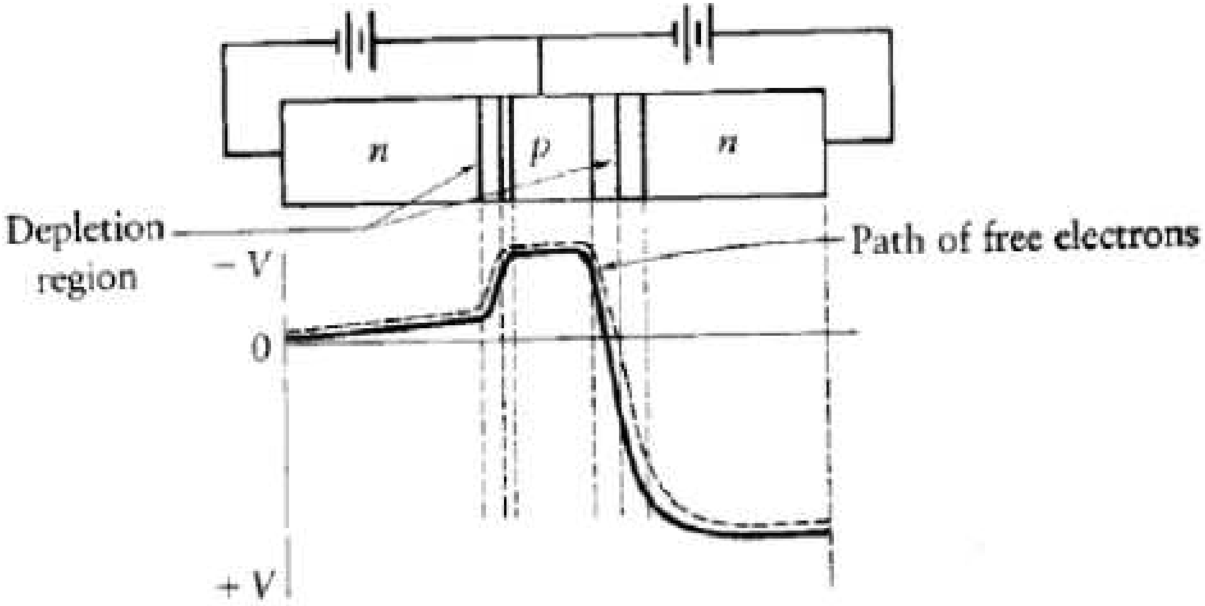


In order to provide an explanation for the operation of the transistor, we develop a simple mathematical model based upon the operational characteristics of the device for the region in which we are working. In order to keep the model simple, we confine our analysis to low frequencies.

If, however, more accurate results are required, computer analysis may be necessary. A computer-aided analysis program has been developed. It is known as *SPICE* (simulated program with integrated circuit emphasis

2.2 Transistor Operation

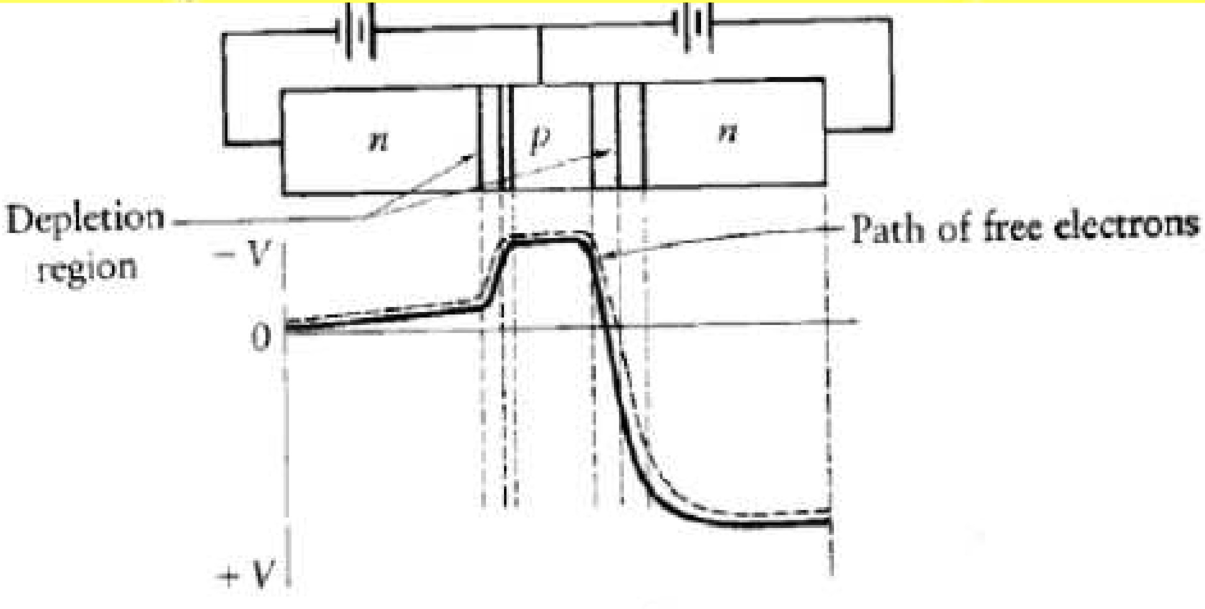
A simple but effective explanation of the *npn* transistor operation is developed using the potential-hill diagram technique of Figure 2.4(b). This approach illustrates a simplified visual picture of the basic operation of a bipolar transistor so that simple circuit applications can be understood. When the base-emitter junction is biased in the forward direction and the base-collector junction is biased in the reverse direction, electrons leaving the *n*-material of the emitter will see only a small potential hill at the *np* junction. Since the potential hill is small, most of the electrons have enough energy to progress to the top of the hill.



(b) Potential-hill diagram

2.2 Transistor Operation

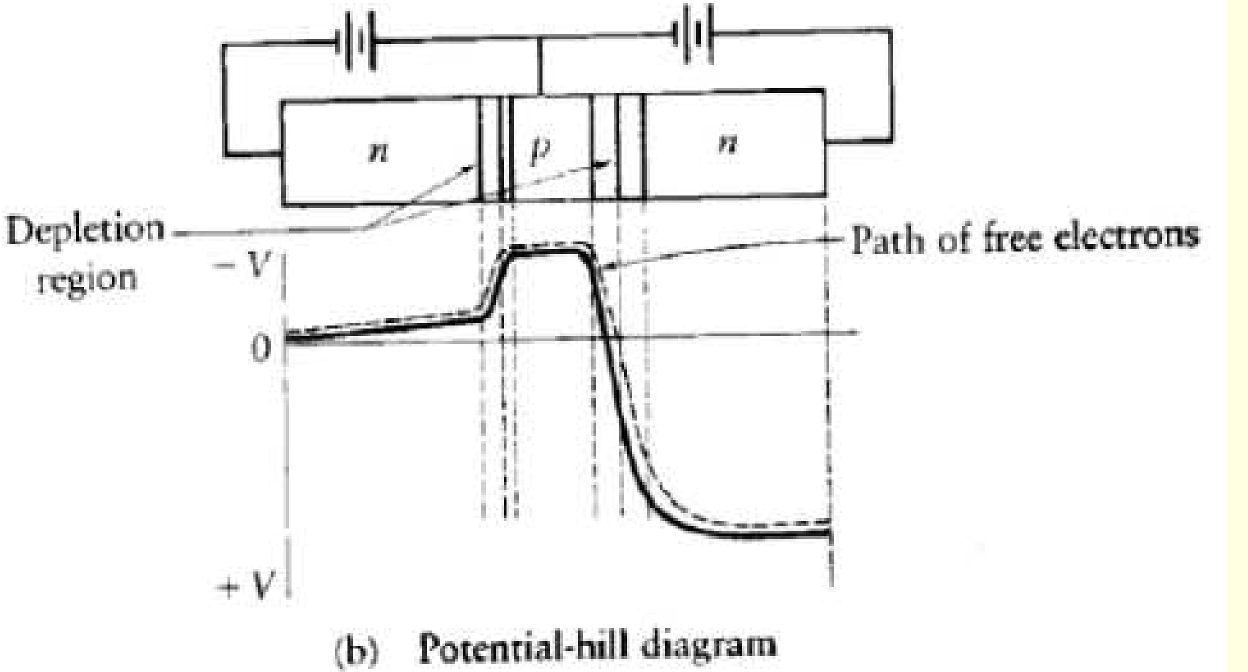
Once on top of the potential hill, the electrons move easily through the *p*-material (base) to the *pn*- (base-collector) junction. When they approach that junction, the electrons are under the influence of the positive supply voltage and move forward rapidly as they move down the potential hill. If the forward bias on the base-emitter junction is reduced, the height of the potential hill is raised. Electrons leaving the emitter will have more difficulty in reaching the top. The electrons reaching the top are the ones with the highest amount of energy, and these will progress to the collector. The reduction of forward bias thus causes the current through the transistor to be considerably reduced.



(b) Potential-hill diagram

2.2 Transistor Operation

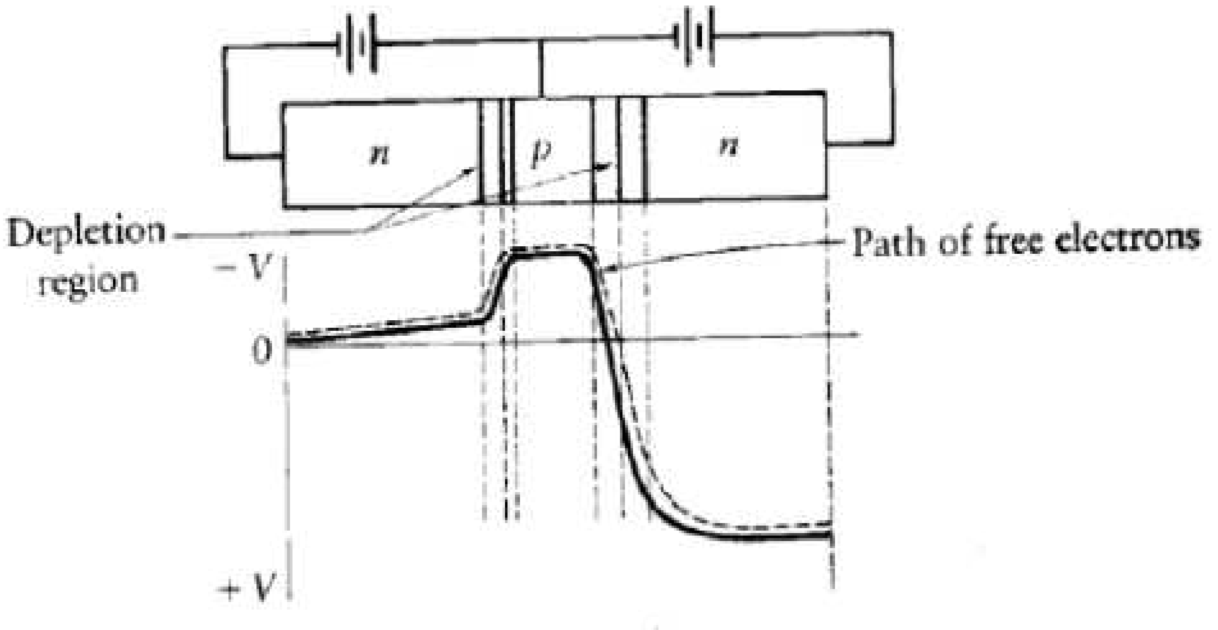
On the other hand, increasing the forward bias on the base-emitter junction will reduce the potential hill and allow more emitter electrons to flow through the transistor.



(b) Potential-hill diagram

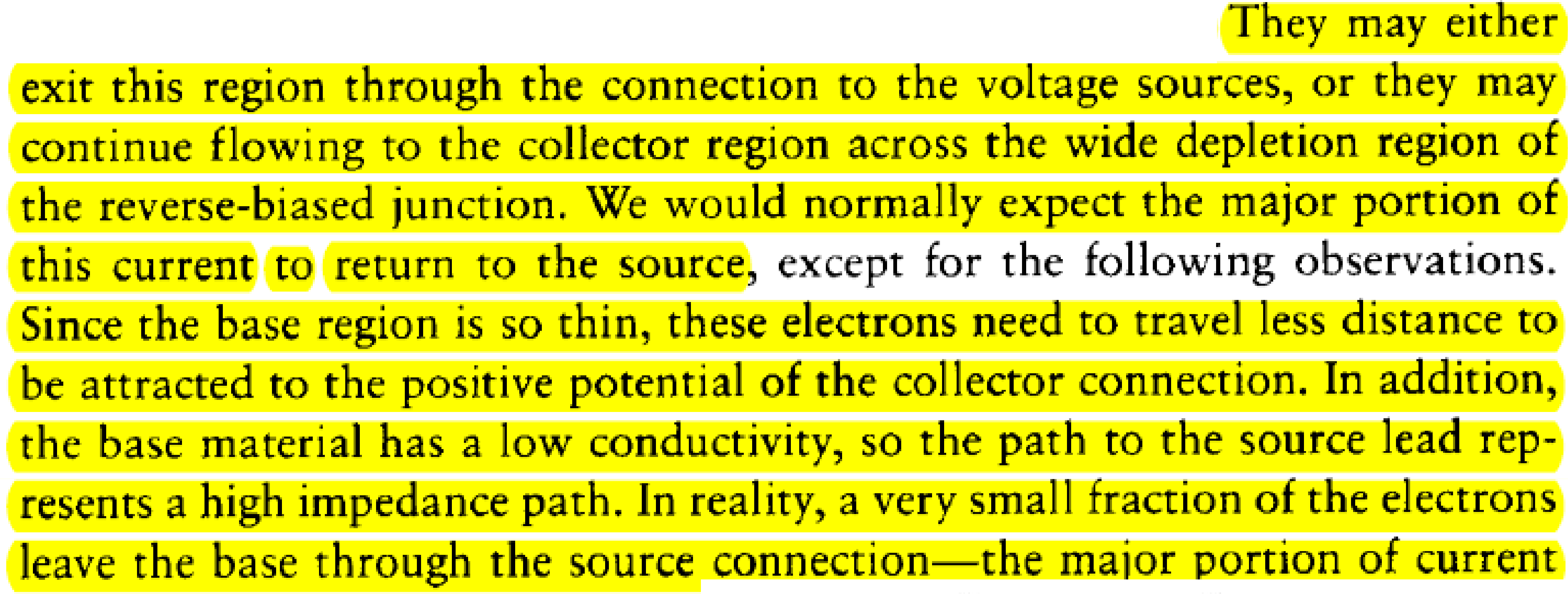
2.2 Transistor Operation

The current flow in a junction transistor can also be understood by examining charge-carrier behavior and the depletion regions. The depletion regions have been indicated on Figure 2.4(b). Note that since the base-emitter junction is forward-biased, the depletion region is relatively narrow. The reverse is true for the base-collector junction. A large number of majority carriers (electrons) will diffuse across the base-emitter junction, since this is forward-biased. These electrons then enter the base region and have two choices.

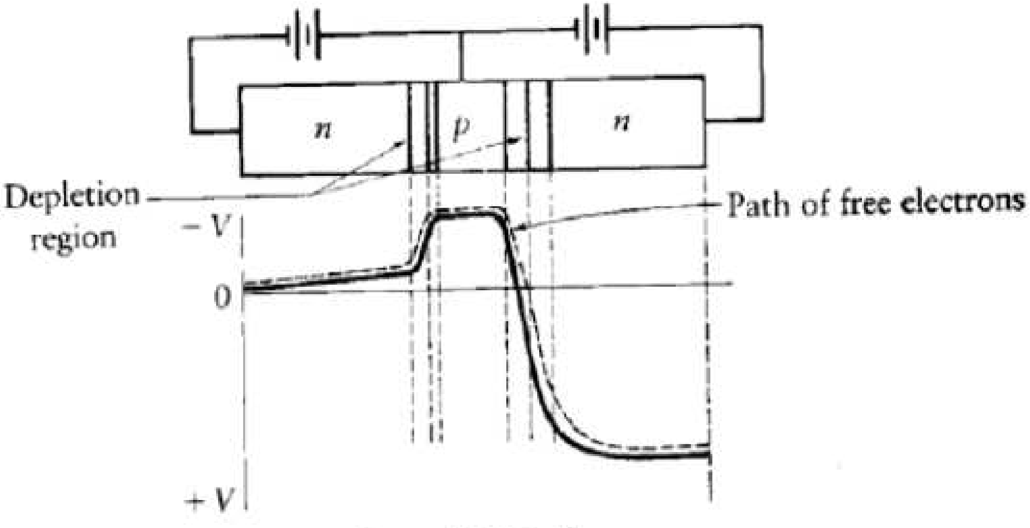


(b) Potential-hill diagram

2.2 Transistor Operation



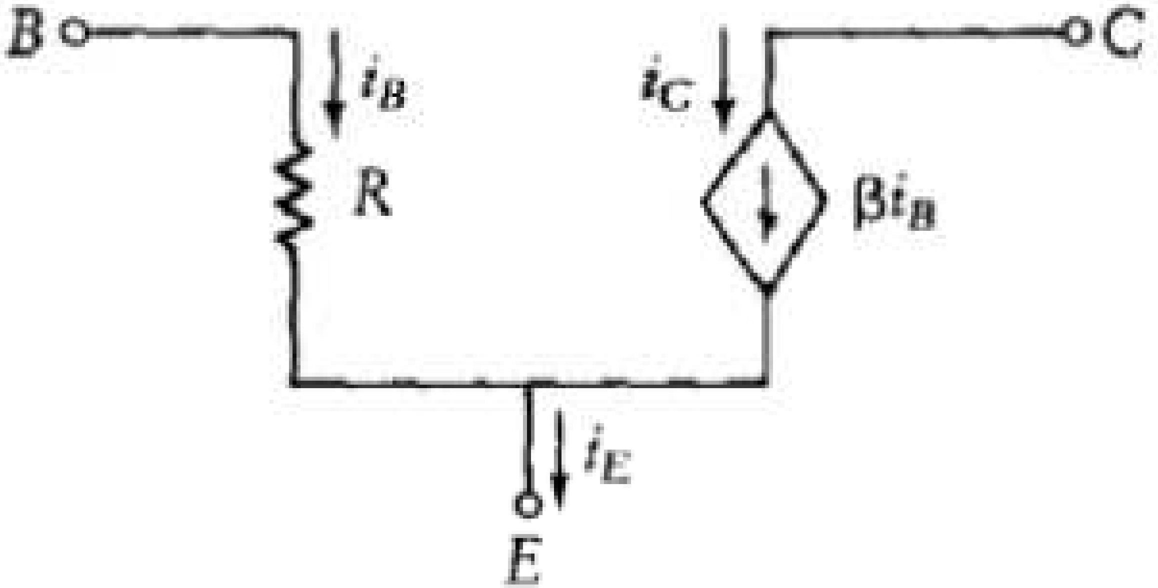
They may either exit this region through the connection to the voltage sources, or they may continue flowing to the collector region across the wide depletion region of the reverse-biased junction. We would normally expect the major portion of this current to return to the source, except for the following observations. Since the base region is so thin, these electrons need to travel less distance to be attracted to the positive potential of the collector connection. In addition, the base material has a low conductivity, so the path to the source lead represents a high impedance path. In reality, a very small fraction of the electrons leave the base through the source connection—the major portion of current does flow into the collector.



(b) Potential-hill diagram

2.2 Transistor Operation

The bipolar junction transistor exhibits a current gain, which can be used to amplify signals. A simplified *npn* transistor equivalent circuit is shown in Figure 2.5. This model is usually adequate for design and analysis of most circuits.

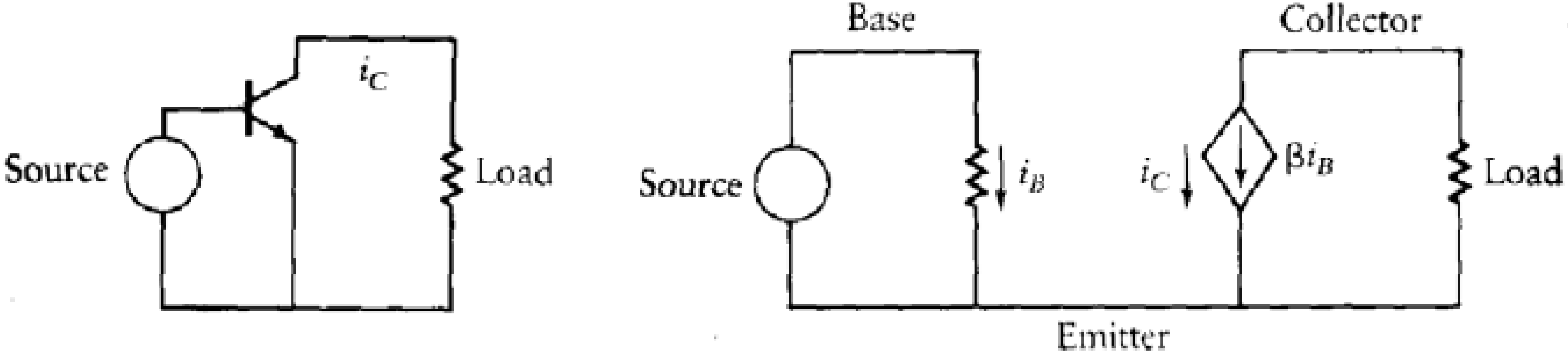


i_B = base current
i_C = collector current
i_E = emitter current
R = resistance between base and emitter

2.2 Transistor Operation

Figure 2.6 shows a simple circuit for producing current gain. A source voltage is applied across the base-emitter, and a load resistance is connected between the collector and emitter. Figure 2.6(b) shows the same circuit, where the transistor is replaced by the model of Figure 2.5. Because of the presence

the collector to the emitter. The collector current source is dependent upon the base current, i_B. As i_B is increased, the collector current, i_C, increases proportionally. The proportionality constant is given the name *beta* (β).



(a) (b)

2.2 Transistor Operation

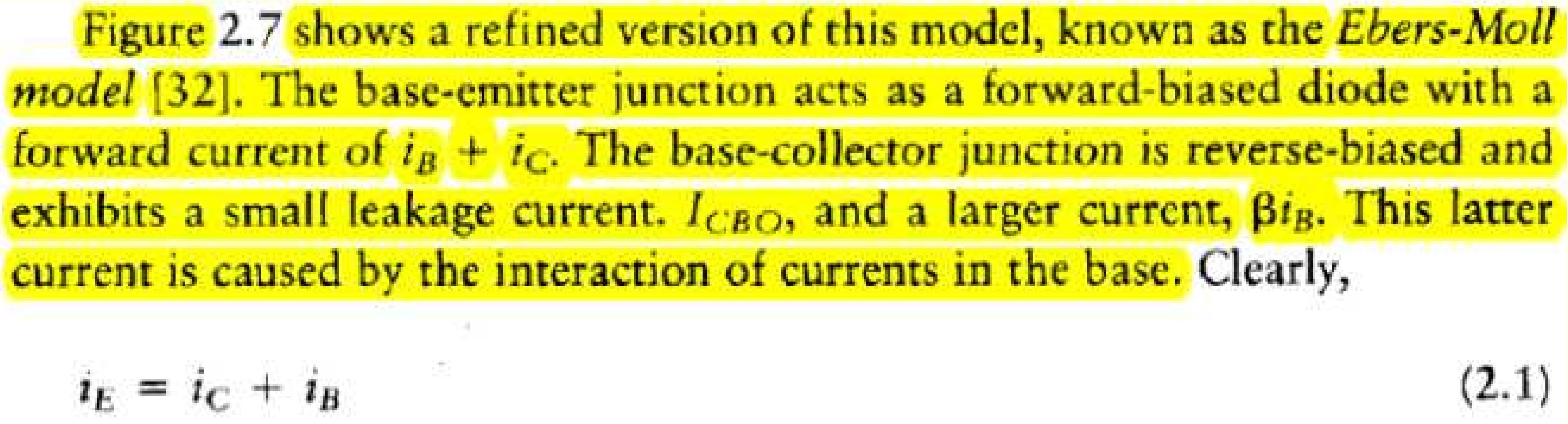
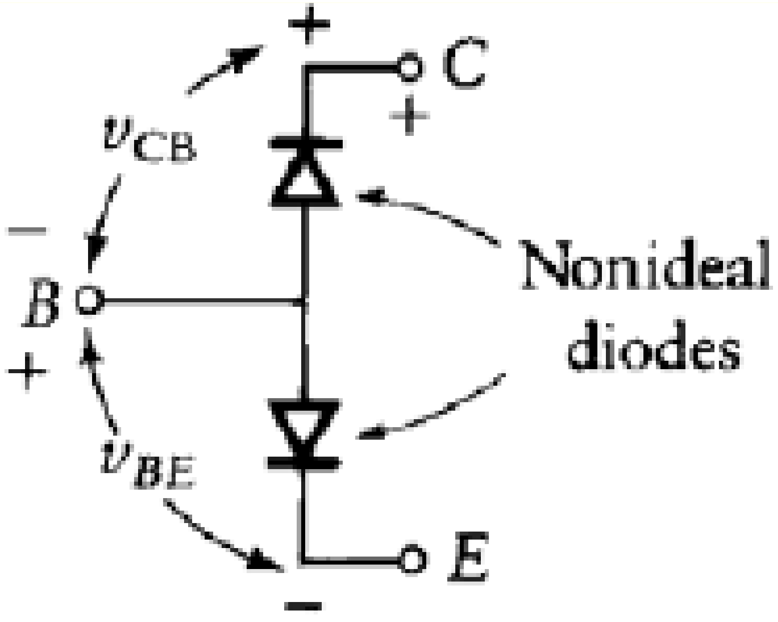
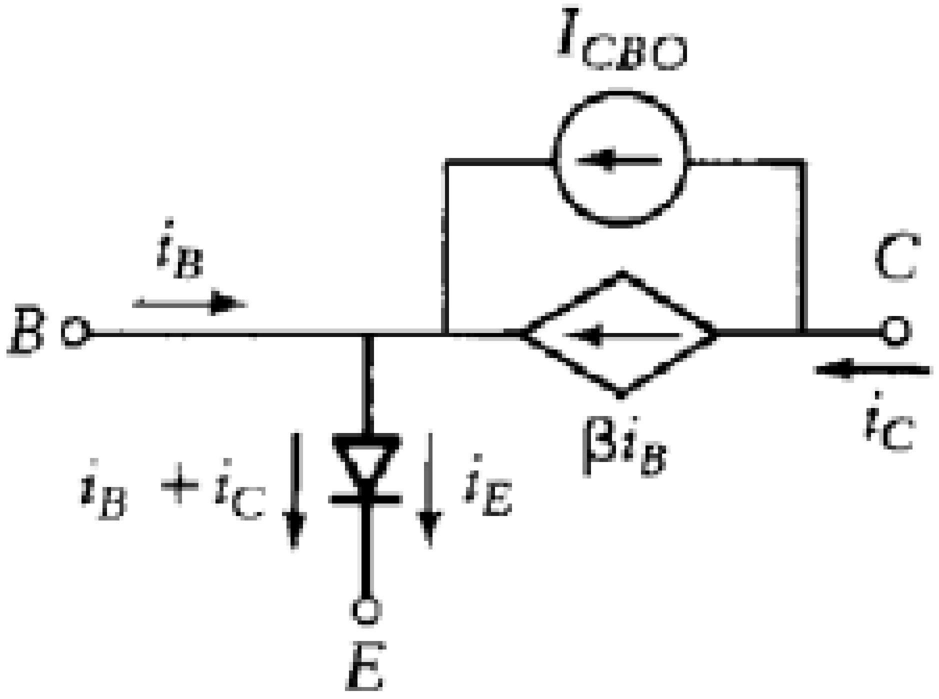


Figure 2.7 shows a refined version of this model, known as the *Ebers-Moll model* [32]. The base-emitter junction acts as a forward-biased diode with a forward current of $i_B + i_C$. The base-collector junction is reverse-biased and exhibits a small leakage current, I_{CBO}, and a larger current, βi_B. This latter current is caused by the interaction of currents in the base. Clearly,

$$i_E = i_C + i_B \tag{2.1}$$

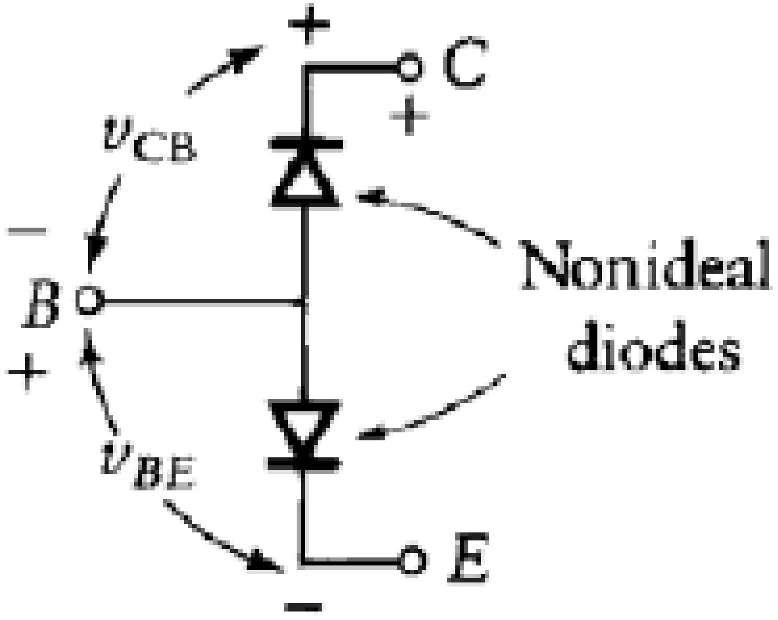


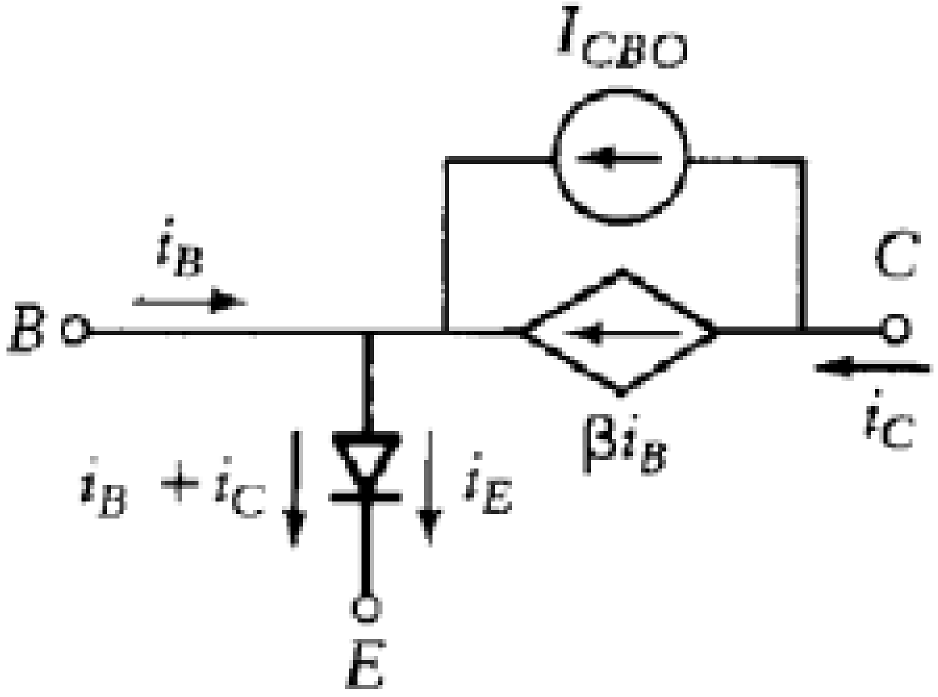


2.2 Transistor Operation

Note that the positive direction of base and collector currents are defined to be *into* the transistor, whereas the reverse is true for the emitter current. This is simply a convention,

directions. The Ebers-Moll model includes a current, I_{CBO}, which is independent of the base current.





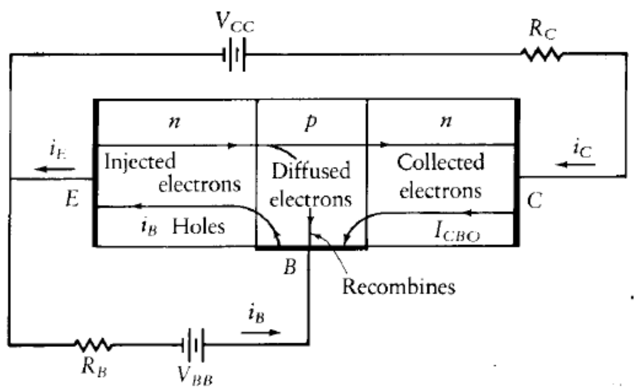
2.2 Transistor Operation

The *common-base current gain*, α, is defined as the ratio of the change in collector current to the change in emitter current, assuming that the voltage between collector and base is a constant. Thus,

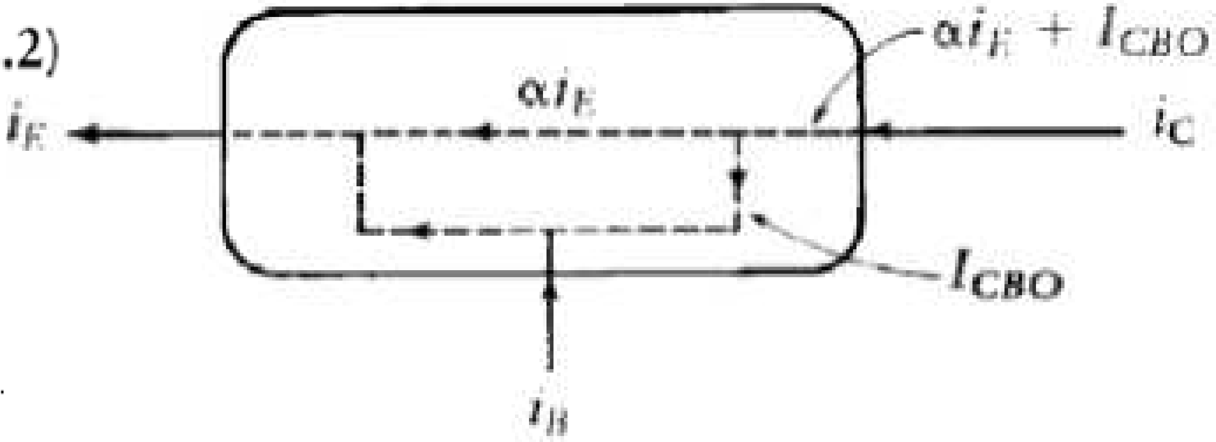
$$\alpha = \left.\frac{\Delta i_C}{\Delta i_E}\right|_{v_{CB} = \text{constant}}$$

This is shown pictorially in Figure 2.8 where I_{CBO} is the leakage current between base and collector. We wish to find a relationship between the collector and base currents. The collector current is found by viewing Figure 2.8(b):

$$i_C = \alpha i_E + I_{CBO} \qquad (2.2)$$



(a) Detailed inside view



(b) Simplifed view

2.2 Transistor Operation

Combining equation (2.1) with equation (2.2) yields the **emitter current,**

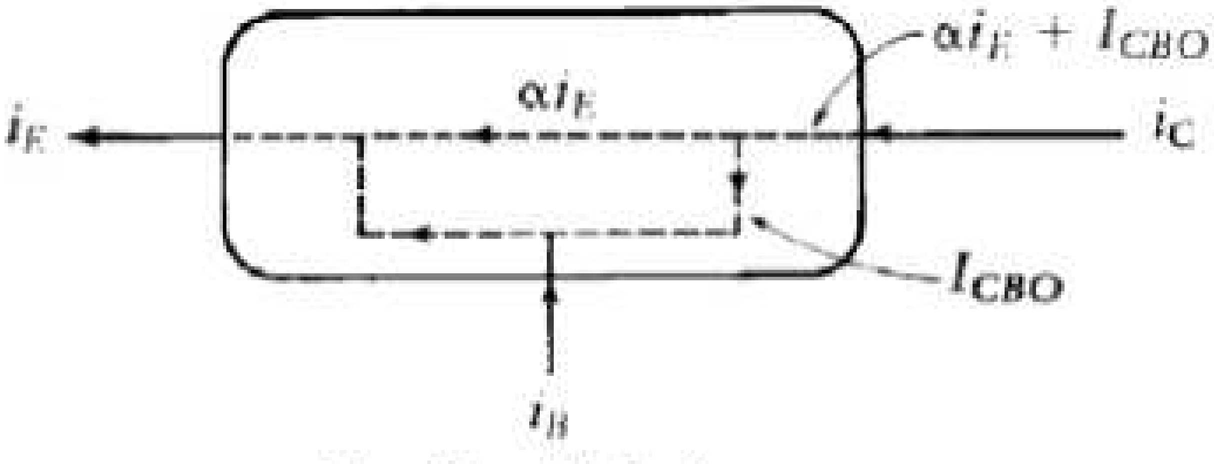
$$i_E = \alpha i_E + I_{CBO} + i_B$$

and solving for the base current,

$$i_B = i_E(1 - \alpha) - I_{CBO} \qquad (2.3)$$

We can eliminate i_E from equation **(2.3) by rewriting equation** (2.2) as

$$i_E = \frac{i_C - I_{CBO}}{\alpha}$$



(b) Simplifed view

2.2 Transistor Operation

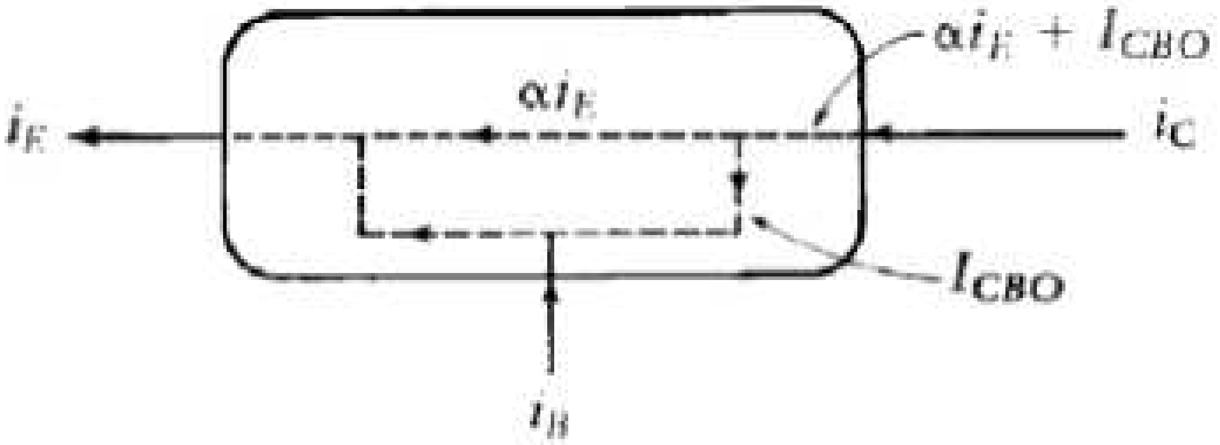
Finally, this is substituted in equation (2.3) to yield a relationship between i_B, i_C, and I_{CBO}:

$$i_B = \frac{(i_C - I_{CBO})(1 - \alpha)}{\alpha} - I_{CBO} \qquad (2.4)$$

$$= \frac{(1 - \alpha)i_C}{\alpha} - \frac{I_{CBO}}{\alpha}$$

The common-base current gain, α, usually lies in the range from 0.8 to 0.999. Therefore, the reciprocal can often be approximated as unity, thus yielding

$$i_B = \frac{(1 - \alpha)i_C}{\alpha} - I_{CBO}$$



(b) Simplified view

2.2 Transistor Operation

Beta (β) was used earlier (see Figure 2.6) to define the ratio of changes in collector current to changes in base current. That is,

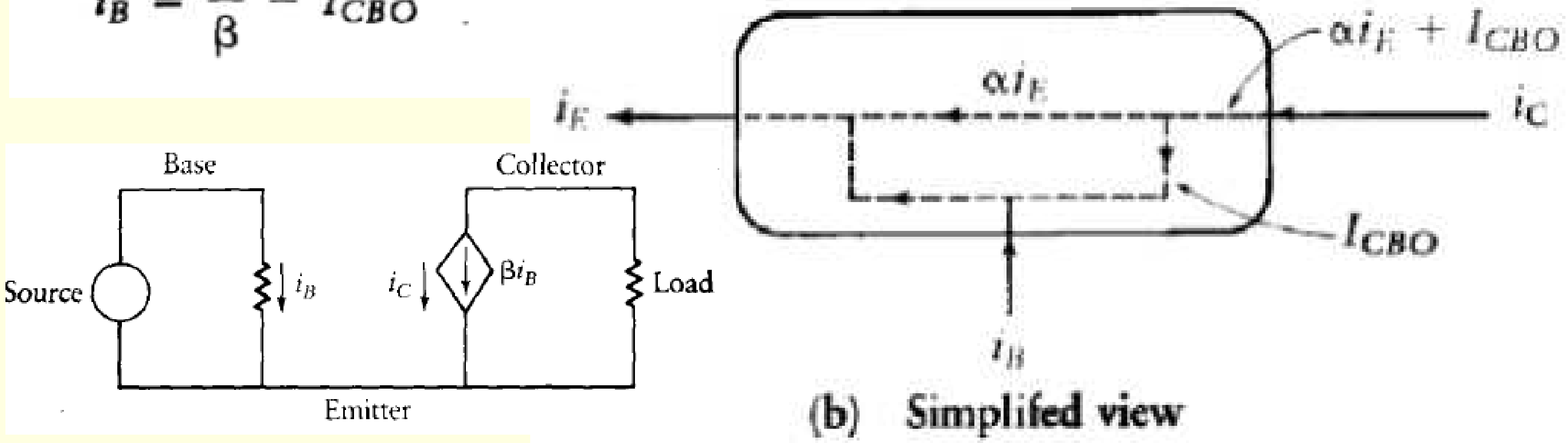
$$\beta = \frac{\Delta i_C}{\Delta i_B}$$

Therefore, we differentiate equation (2.4) and rearrange terms.

$$\beta = \frac{\alpha}{1 - \alpha}$$

Typical values of β range from 10 to 600. Making the substitution for β yields

$$i_B = \frac{i_C}{\beta} - I_{CBO}$$



(b) Simplified view

2.2 Transistor Operation

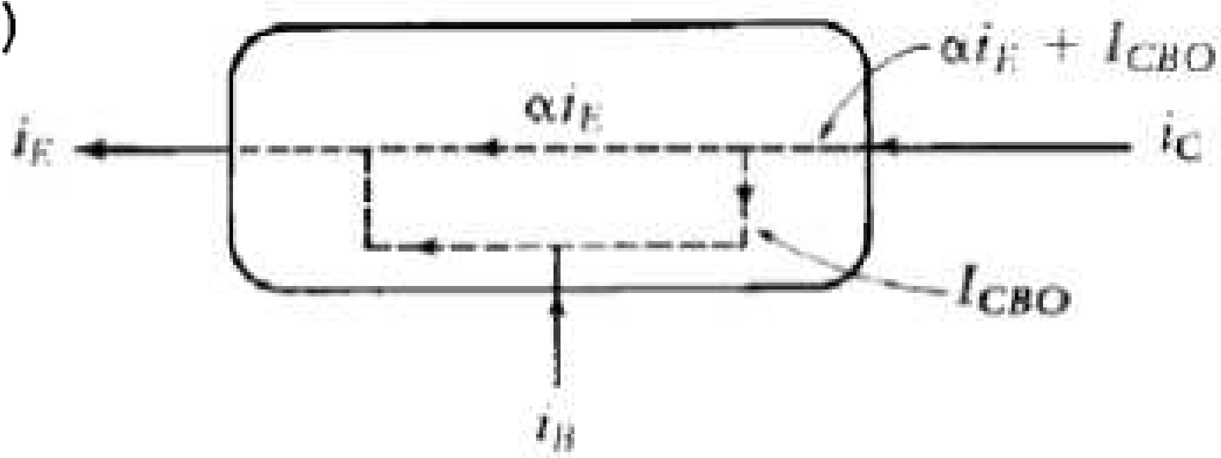
We can usually neglect I_{CBO}, since it is small in magnitude. Thus,

$$i_C \approx \beta i_B \tag{2.5}$$

The term β is referred to as the *large-signal amplification factor*, or the *dc amplification factor*. Thus we are back to our original simplified model. In

Another simplifying assumption often made is that the collector current is approximately equal to the emitter current. That is, since I_{CBO} is small compared to i_C and since α ranges from 0.9 to 0.999, we have

$$i_C \approx i_E \tag{2.6}$$

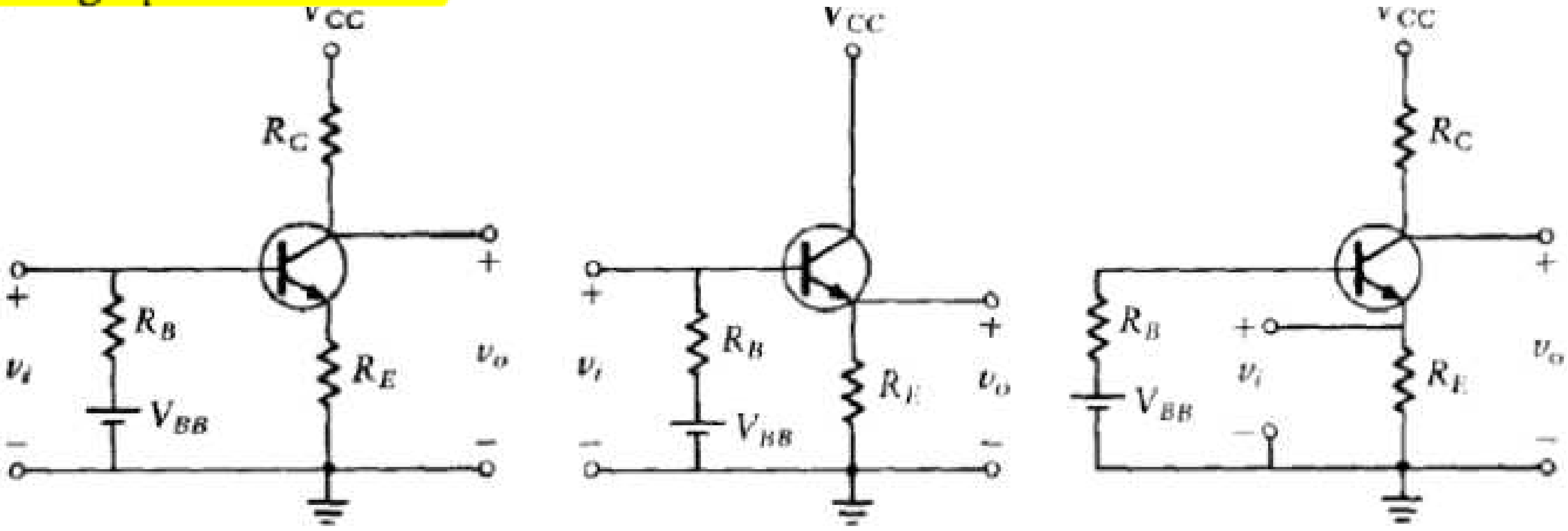


(b) Simplifed view

2.3 Transistor Circuits

Common Circuit Configurations

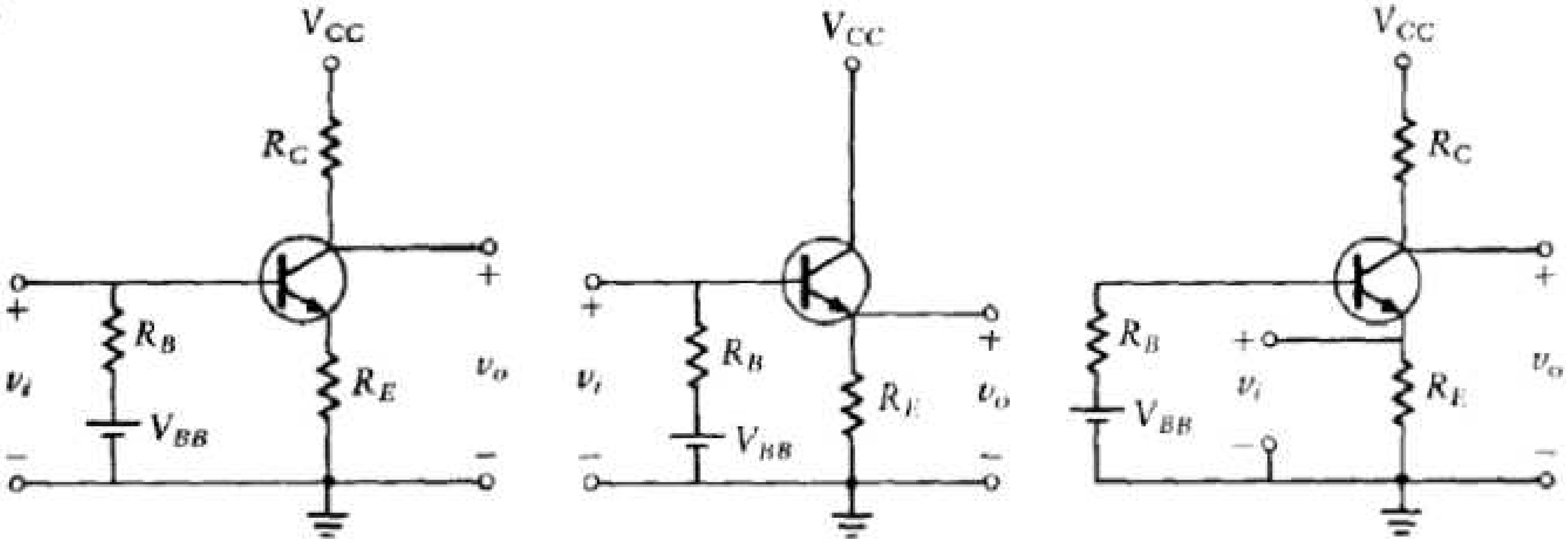
There are three general configurations utilized in transistor circuits. The most often used is the *common-emitter* (CE) *amplifier*, so called because the emitter is in both the input and output loops. The next most widely used circuit is the *common-collector* (CC) configuration, also known as the *emitter follower*. The third configuration is the *common-base* (CB) circuit. Examples of these amplifier configurations are shown in Figure 2.9, where we have illustrated the circuits using *npn* transistors.



(a) Common emitter (b) Common collector (emitter follower) (c) Common base

2.3 Transistor Circuits

In this chapter we consider the design of the bias, or dc circuit. This is characterized by the base resistor, R_B, the emitter resistor, R_E, the collector resistor, R_C, and the source voltage, V_{CC}. The bias technique for the CE amplifier is the same as that for the CB configuration, so these are considered together. The CC configuration is considered separately. When we use *pnp* transistors, the voltage polarities of V_{BB} and V_{CC} are reversed, but the ac equivalent circuits remain the same.



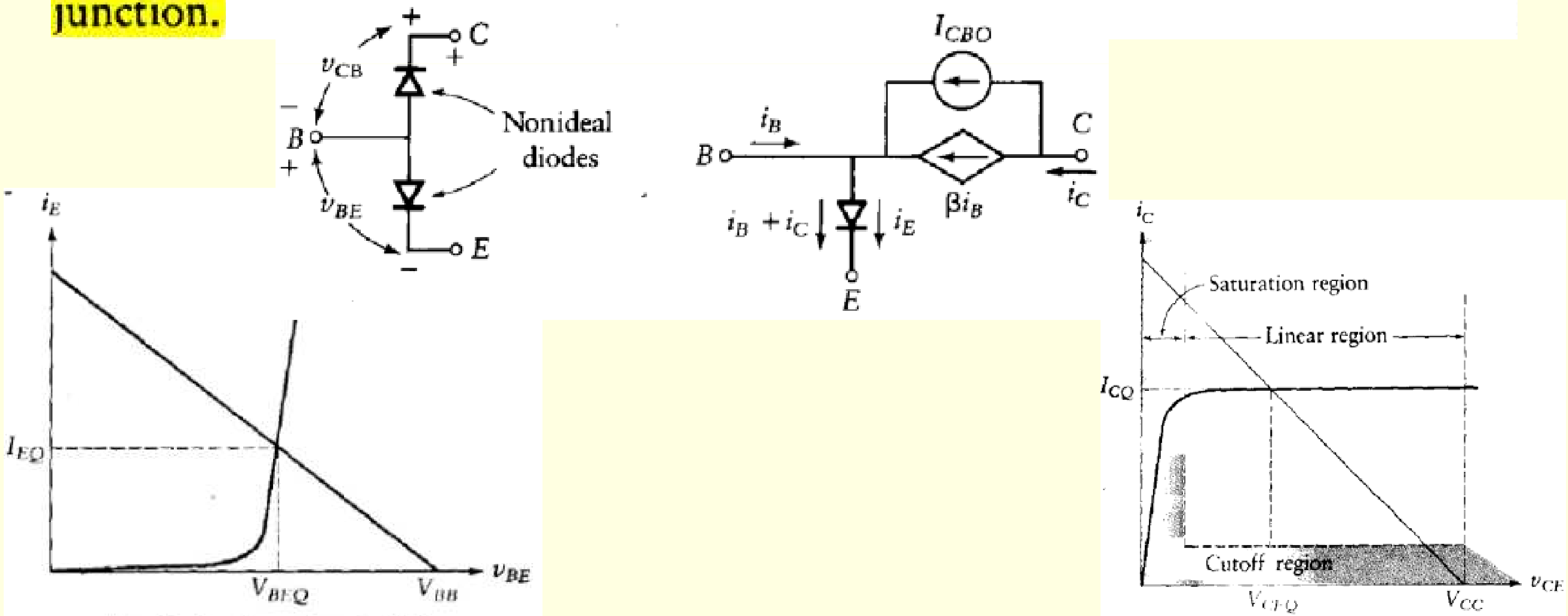
(a) Common emitter

(b) Common collector (emitter follower)

(c) Common base

2.3 Transistor Circuits- Characteristic curves

Since the transistor is a nonlinear device, one way to define its operation is with a series of characteristic curves in a manner similar to that used for diodes at least three variables. Therefore, *parametric curves* are usually used to describe transistor behavior. Figure 2.10 shows two typical plots. Figure 2.10(a) shows the emitter current as a function of the voltage between base and emitter when v_{CE} is held constant. Note that, as we might have expected, this curve is similar to the curve for a diode, since it is the characteristic of the current in the single junction.



(a) Emitter-base characteristics

(b) Collector-emitter characteristics

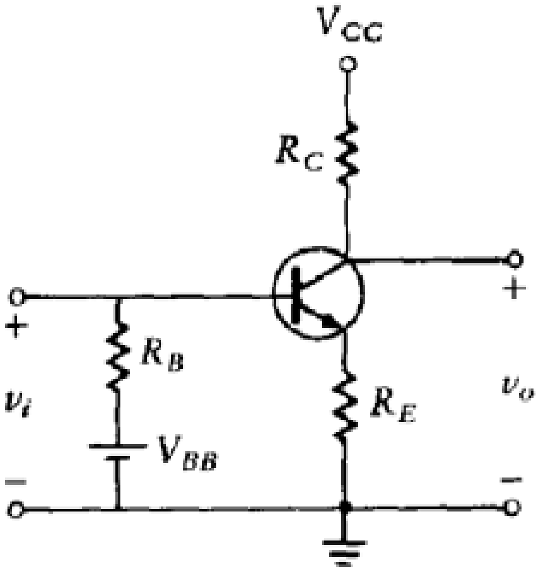
2.3 Transistor Circuits- Characteristic curves

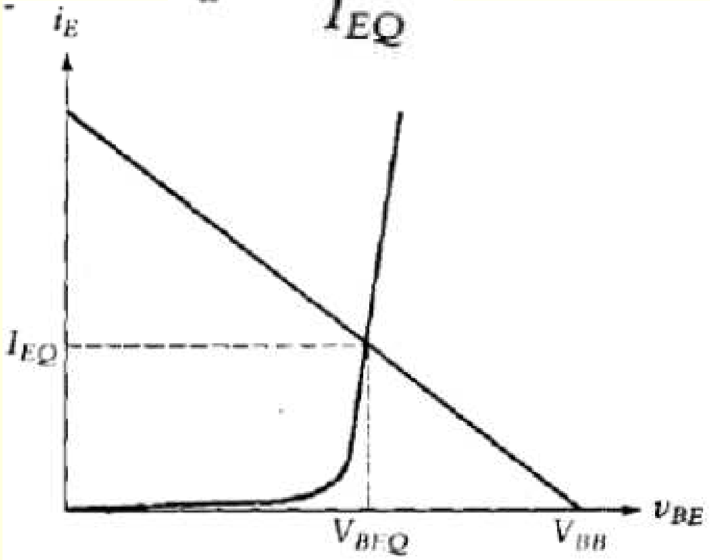
A load line is drawn using the two axis intercepts. When $i_E = 0$, $v_{BE} = V_{BB}$. The other intercept is found by setting $v_{BE} = 0$. The point where the load line crosses the i_E versus v_{BE} curve is called the *quiescent point*, or simply *Q-point*. The slope of the load line is $-1/(R_E + R_B)$. That is, the equivalent resistance seen by the base and emitter terminals is simply $R_E + R_B$. The slope of the characteristic curve is $1/r_d$, where r_d is the *dynamic resistance* of the transistor emitter-base junction. This slope can be calculated

the derivative of equation (1.1) and performing appropriate simplifications, we find the dynamic resistance to approximately equal

$$r_d \approx \frac{0.026}{I_{EQ}}$$

$$i_D = I_0\left(\exp\left(\frac{q \cdot u_D}{n \cdot k \cdot T}\right) - 1\right)$$





(a) Emitter-base characteristics

where I_{EQ} is the emitter current at the Q-point.

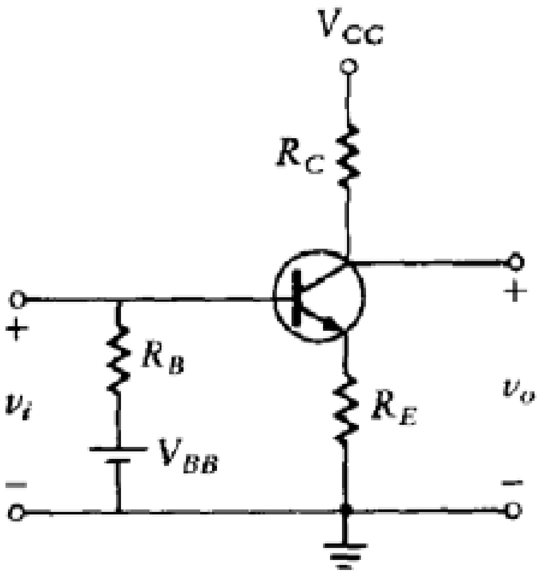
2.3 Transistor Circuits- Characteristic curves

Since $i_B = i_C/\beta$, the base-emitter junction is similar to that of a diode. Therefore, for the forward-biased junction,

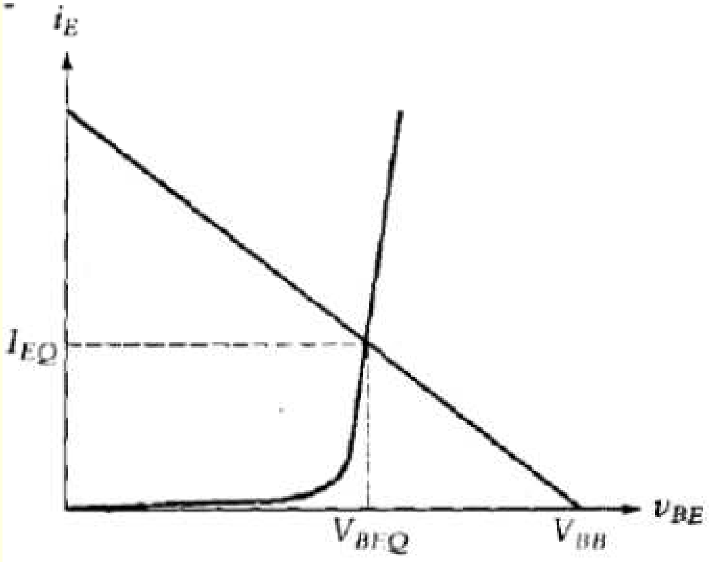
$$i_B \approx \left(\frac{I_o}{\beta}\right) \exp\left(\frac{v_{BE}}{nV_T}\right)$$

we use $n = 1$ and $nV_T = 26$ mV for silicon transistors.

A straight-line extension of the characteristic curve would intersect the v_{BE} axis at 0.7 V for silicon transistors, 0.2 V for germanium, and 1.2 V for gallium arsenide devices.



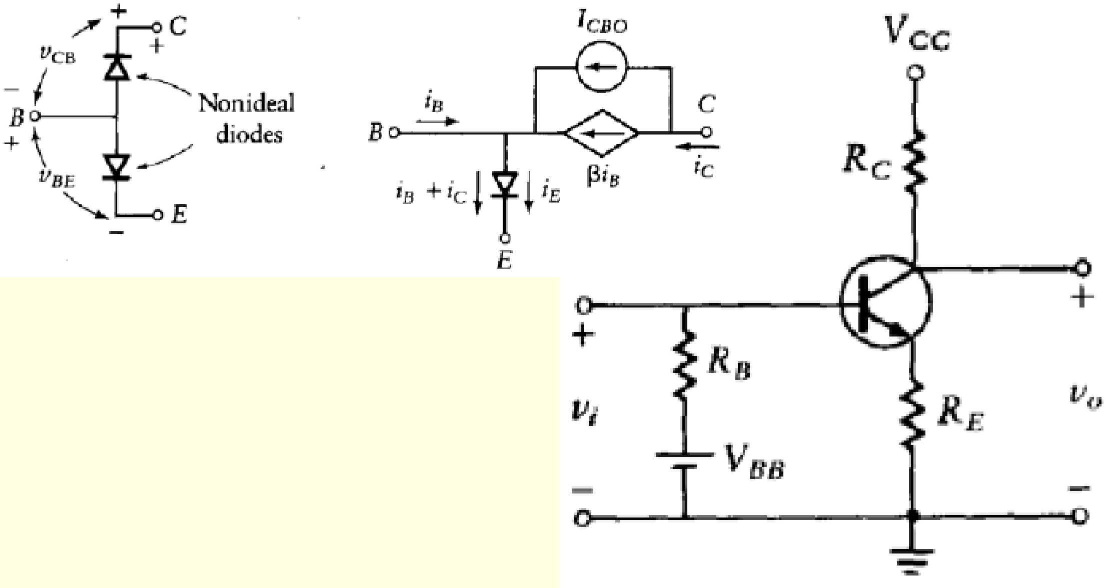
(a) Common emitter



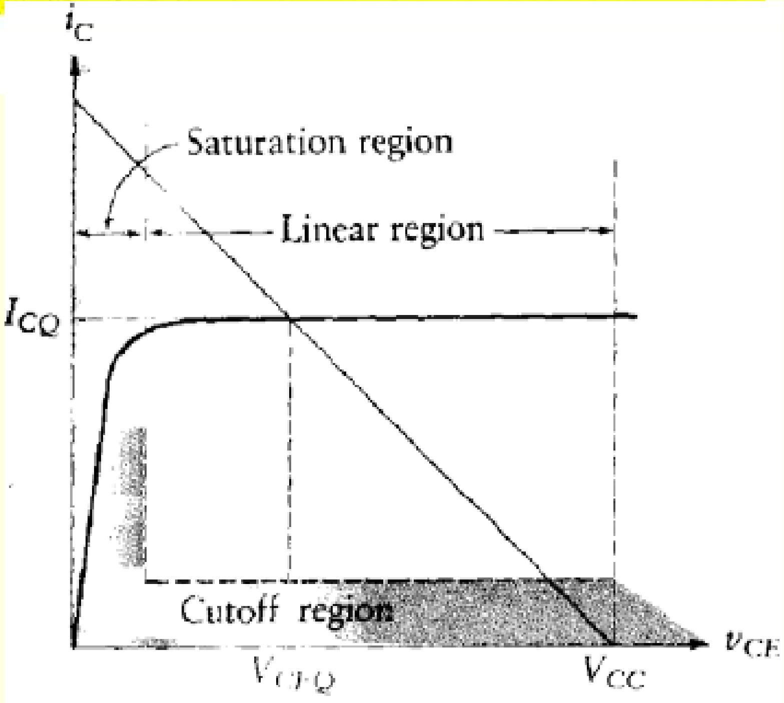
(a) Emitter-base characteristics

2.3 Transistor Circuits- Characteristic curves

If we now hold i_B constant, the collector-emitter junction is defined by the curve of i_C versus v_{CE} shown in Figure 2.10(b). As can be seen from this typical curve, the collector current is almost independent of the voltage between the collector and the emitter, v_{CE}, throughout the "linear range" of operation. When i_B is close to zero, i_C approaches zero in a nonlinear manner. This is known as the *cutoff region* of operation. For the section of the characteristic curves where v_{CE} is near zero, i_C is maximum. This region, known as the *saturation region*, is also not usable for amplification because of nonlinear operation.



(a) Common emitter



(b) Collector-emitter characteristics

2.3 Transistor Circuits- Characteristic curves

Transistor characteristic curves are parametric curves of i_C versus v_{CE}, where i_B is a parameter. Figure 2.11 shows an example of a family of such curves. Each transistor type has its own unique set of characteristic curves.

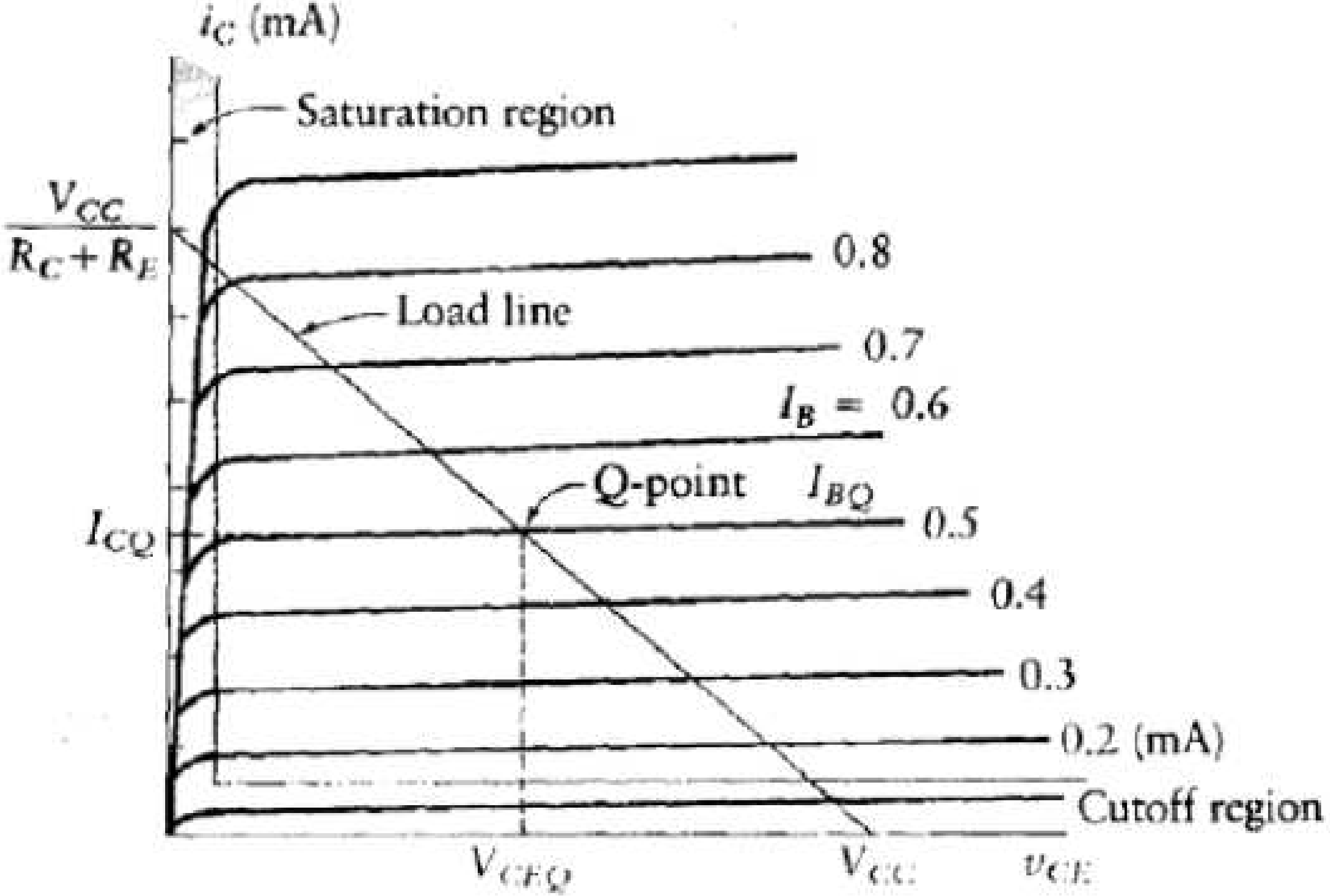


Figure 2.11 Family of transistor characteristic curves.

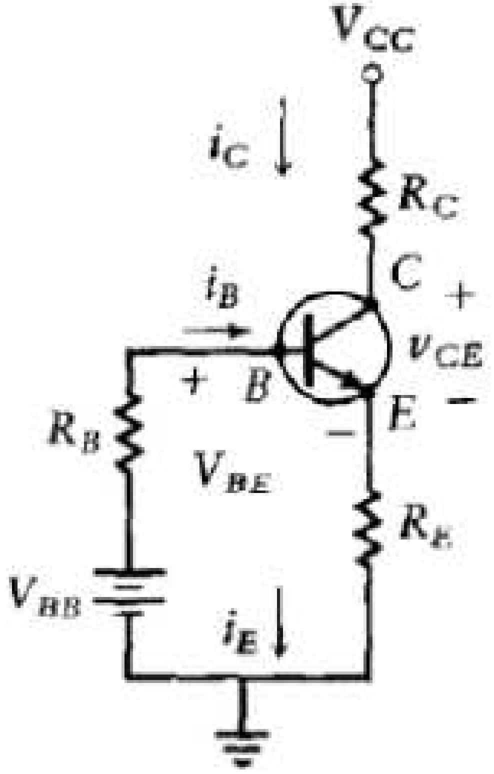


Figure 2.12 Simple transistor circuit.