CHAPTER 4 Bipolar Junction Transistors

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4.1 Bipolar Junction Transistors Structure

4.2 Basic BJT Operation

4.3 BJT Characteristics and Parameters

4.1 Bipolar Junction Transistors (BJT) Structure

- The BJT is constructed with three doped semiconductor regions separated by two pn junctions, as shown in the epitaxial planar structure in Figure 4–1(a). The three regions are called emitter, base, and collector.

- Physical representations of the two types of BJTs are shown in Figure 4–1(b) and (c). One type consists of two n regions separated by a p region (npn), and the other type consists of two p regions separated by an n region (pnp).

The term bipolar refers to the use of both holes and electrons as current carriers in the transistor structure.

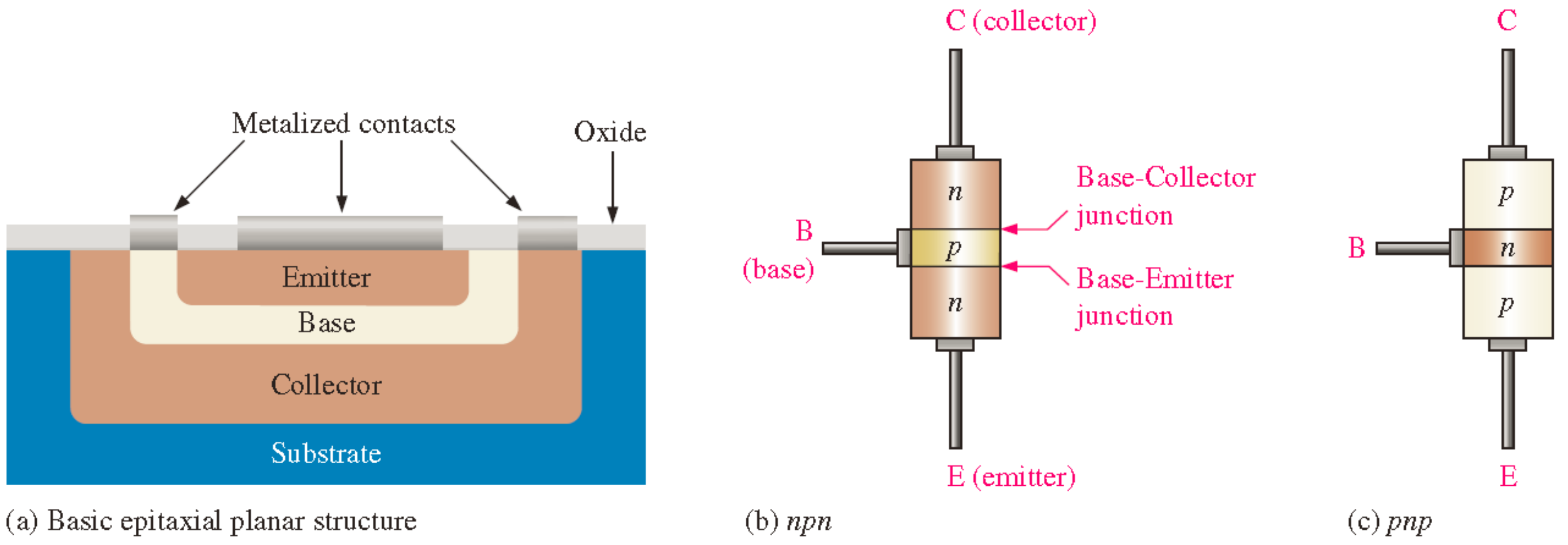


FIGURE 4-1
BJT construction. The substrate is a physical supporting material for the transistor.

Bipolar Junction Transistors (BJT) Structure

- The pn junction joining the base region and the emitter region is called the *base-emitter junction*. The pn junction joining the base region and the collector region is called the *base-collector junction*, as indicated in Figure 4–1(b). A lead connects to each of the three regions, as shown. These leads are labeled E, B, and C for emitter, base, and collector, respectively.
- The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions.

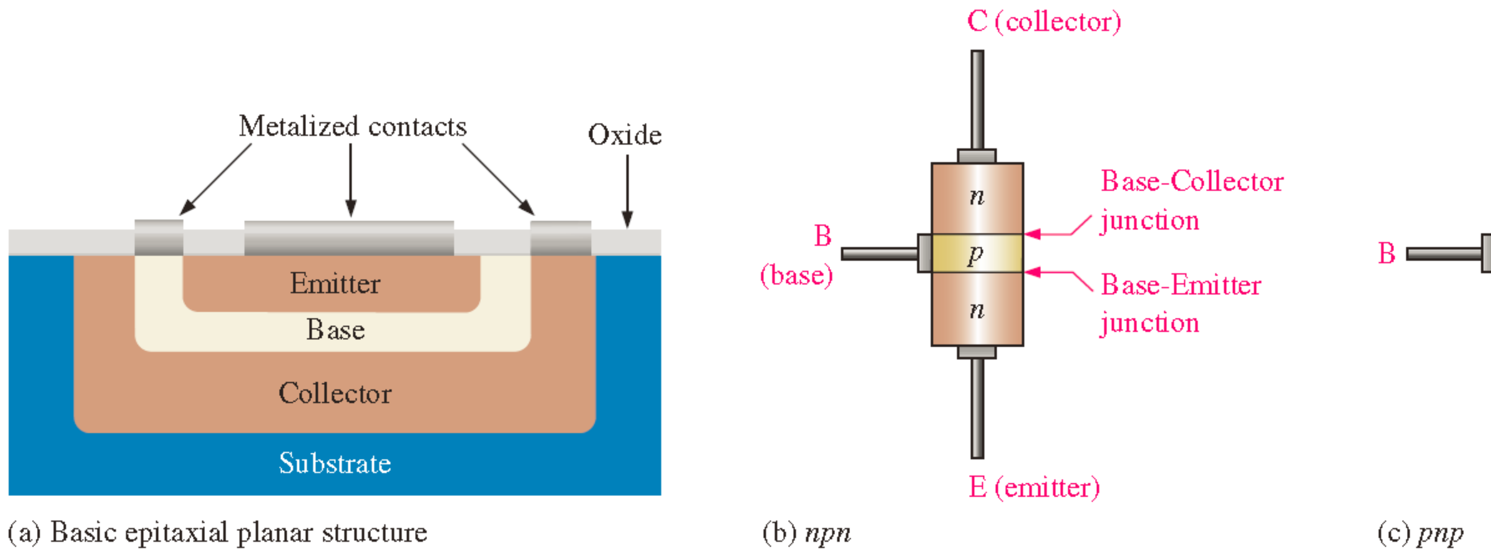


FIGURE 4-1
BJT construction. The substrate is a physical supporting material for the transistor.

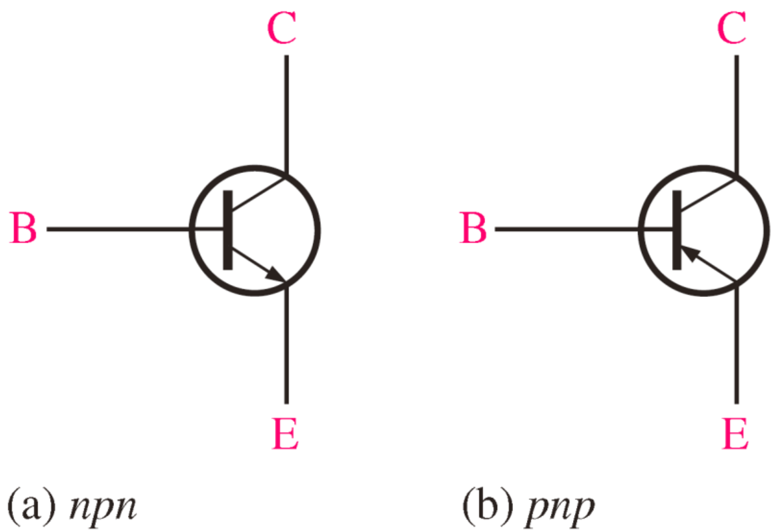


FIGURE 4-2 Standard BJT (bipolar junction transistor) symbols

4.2 Basic BJT Operation

- Biasing: Figure 4–3 shows a bias arrangement for both npn and pnp BJTs for operation as an amplifier. Notice that in both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased.

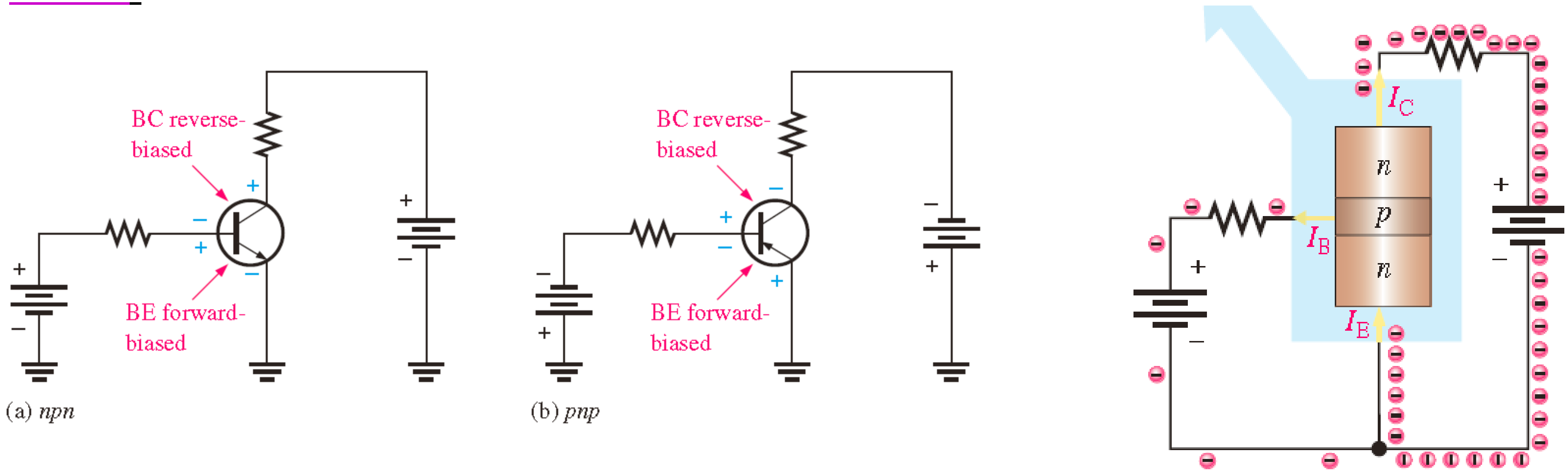


FIGURE 4-3 Forward-reverse bias of a BJT.

Basic BJT Operation

- Free electrons easily diffuse through the forward biased BE junction into the lightly doped and very thin p-type base region. A small percentage of the total number of free electrons injected into the base region recombine with holes.

The rest free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage.

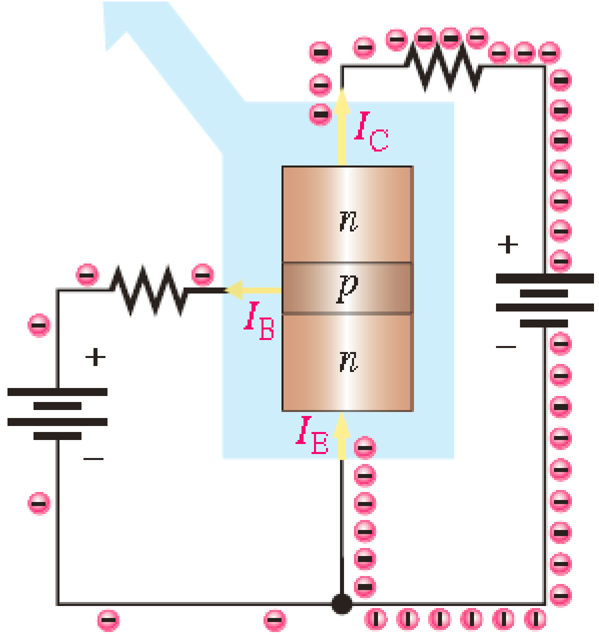


FIGURE 4-4 BJT operation showing electro flow.

Transistor Currents

- The directions of the currents in an npn transistor and its schematic symbol are as shown in Figure 4–5(a);
- These diagrams show that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

$$I_E = I_C + I_B$$

As mentioned before, I_B is very small compared to I_E or I_C. The capital-letter subscripts indicate dc values.

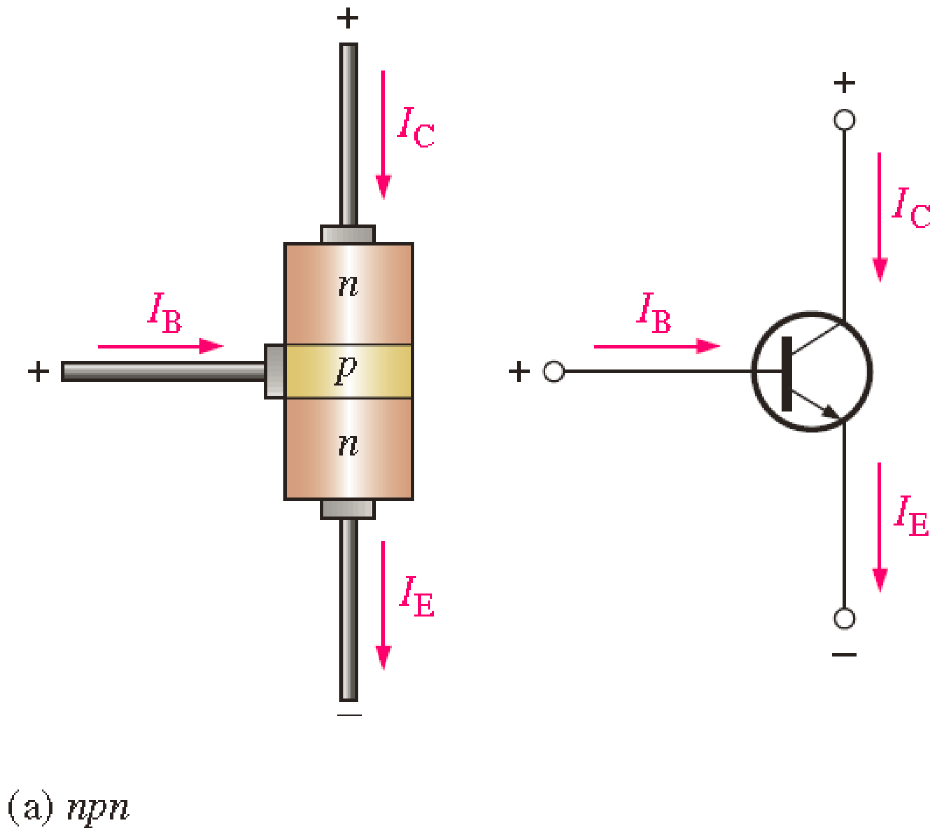


FIGURE 4-5 Transistor currents

4-3 BJT Characteristics and Parameters

$I_B\,/\,mA$	-0.01	0	0.02	0.04	0.06	0.08	0.1
$I_C\,/\,mA$	0.001	0.01	0.7	1.5	2.3	3.1	3.95
$I_E\,/\,mA$	0	0.01	0.72	1.54	2.36	3.18	4.05

$$I_E = I_C + I_B \qquad I_C >> I_B$$

- BJT has current amplifier function. Current amplify gain is almost constant within acceptable varying range.
- The dc current gain of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc beta (β_{DC}).

$$\beta_{DC} = \frac{I_C}{I_B}$$

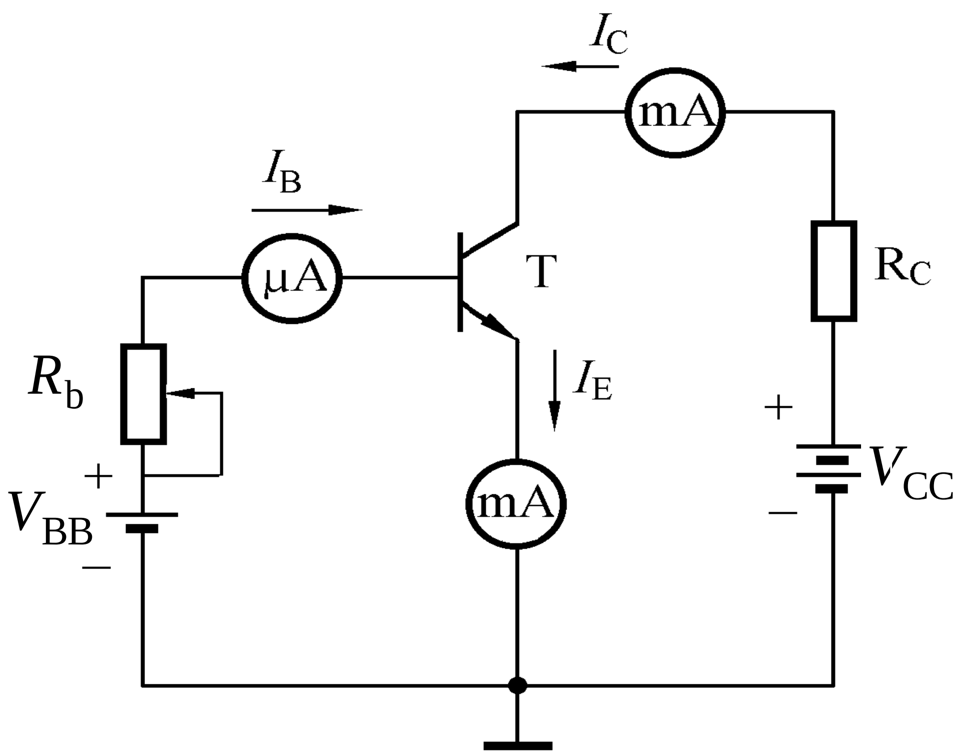


FIGURE 4-6 Testing circuit of Forward-reverse biased BJT.
Through varying the resistor, IB, IC and IE can be varied correspondingly.

Example

EXAMPLE 4–1

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\ mA}$$

*Related Problem** A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current.

Transistor DC Model

- You can view the unsaturated BJT as a device with a current input and a dependent current source in the output circuit, as shown in Figure 4–7 for an *npn transisitor*.
- The input circuit is a forward-biased diode through which there is base current. The output circuit is a dependent current source (diamond-shaped element) with a value that is dependent on the base current, I_B, and equal to $\beta_{DC}I_B$.

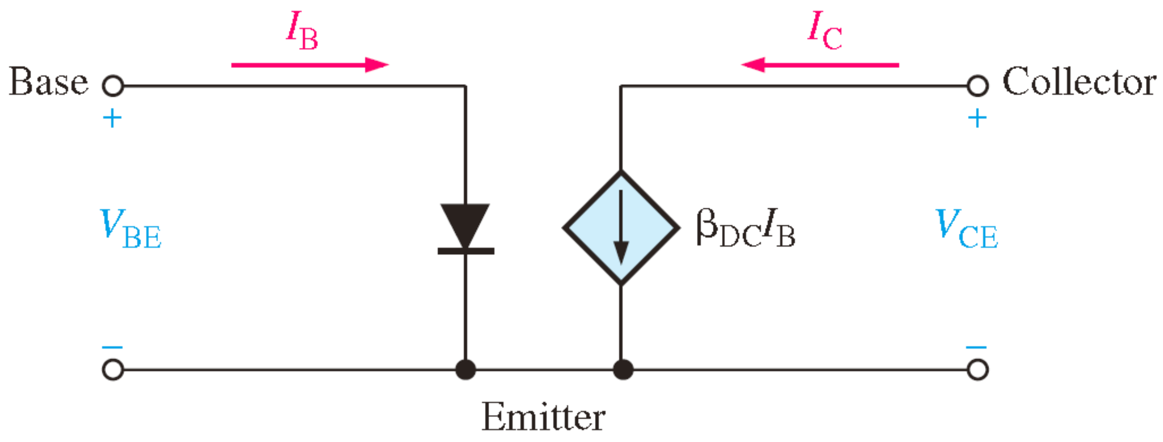


FIGURE 4-7
Ideal dc model of an *npn* transistor

BJT Circuit Analysis

I_B: dc base current

I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter

The base-bias voltage source, V_{BB}, forward-biases the base-emitter junction, and the collector-bias voltage source, V_{CC}, reverse-biases the base-collector junction. When the base-emitter junction is forward-biased, it is like a forward-biased diode and has a nominal forward voltage drop of $V_{BE} \cong 0.7\ \text{V}$

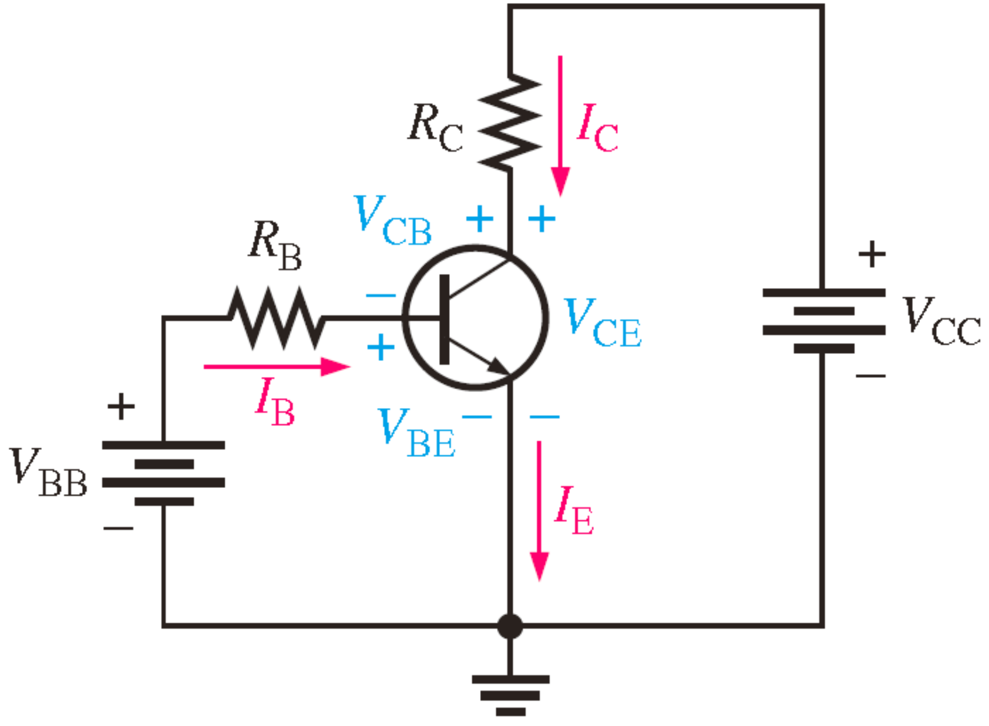


FIGURE 4-8

Transistor currents and voltages.

BJT Circuit Analysis

Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{R_B} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

$$I_B R_B = V_{BB} - V_{BE}$$

Solving for I_B,

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

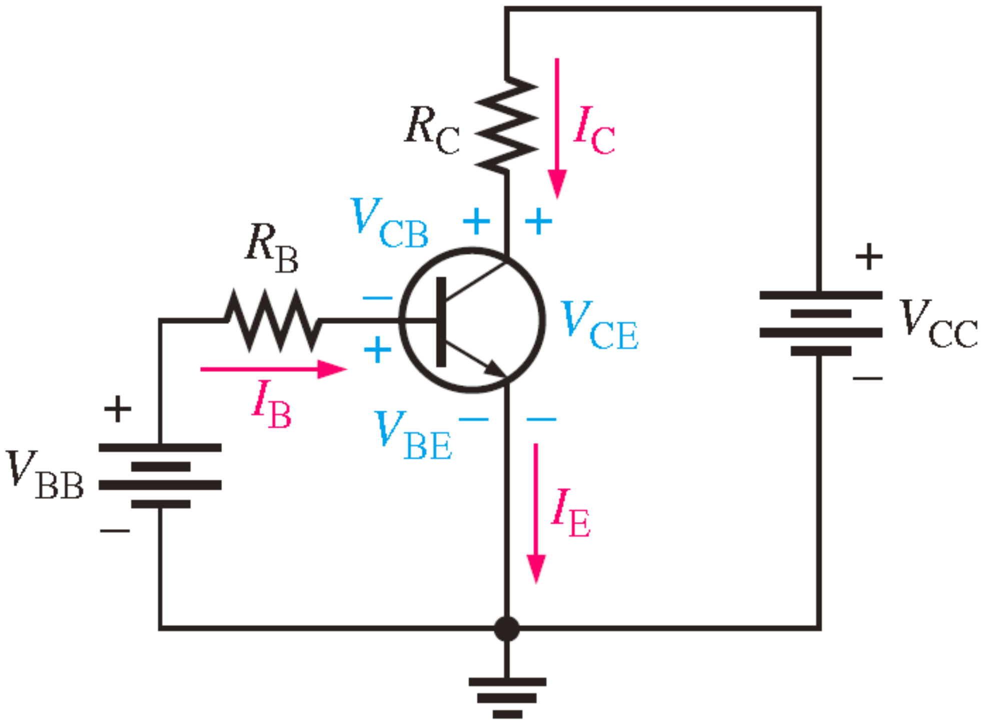


FIGURE 4-8
Transistor currents and voltages.

BJT Circuit Analysis

The voltage at the collector with respect to the grounded emitter is

$$V_{CE} = V_{CC} - V_{R_C}$$

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

the voltage at the collector with respect to the emitter can be written

$$\mathbf{V_{CE} = V_{CC} - I_C R_C}$$

where $I_C = \beta_{DC} I_B$.

The voltage across the reverse-biased collector-base junction is

$$\mathbf{V_{CB} = V_{CE} - V_{BE}}$$

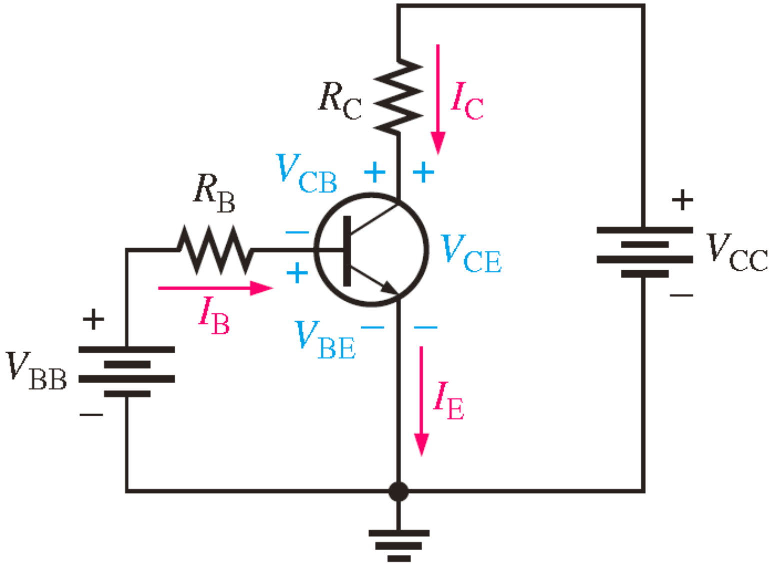


FIGURE 4-8

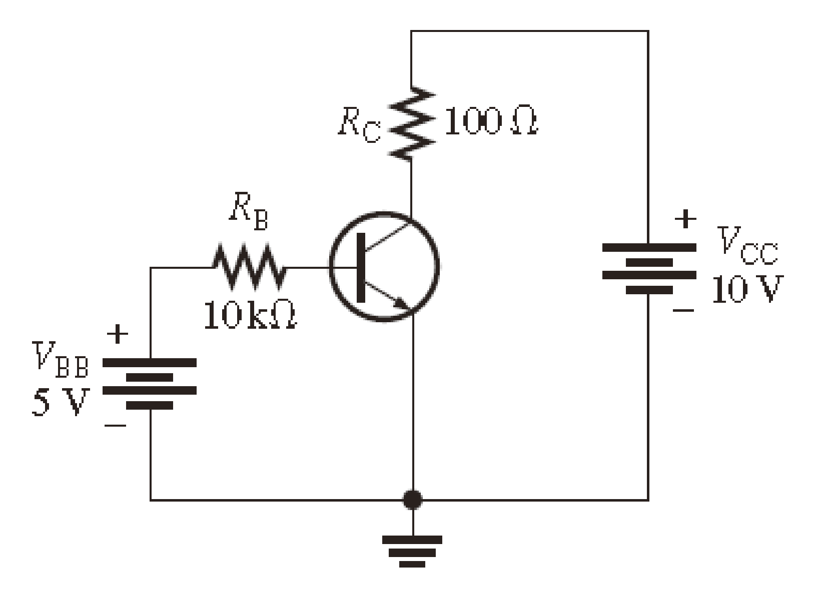
Transistor currents and voltages.

Example

EXAMPLE 4–2

Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–9. The transistor has a $\beta_{DC} = 150$.

▶ FIGURE 4–9



Example

Solution From Equation 4–3, $V_{BE} \cong \mathbf{0.7\ V}$. Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \mathbf{430\ \mu A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = \mathbf{64.5\ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = \mathbf{64.9\ mA}$$

Solve for V_{CE} and V_{CB}.

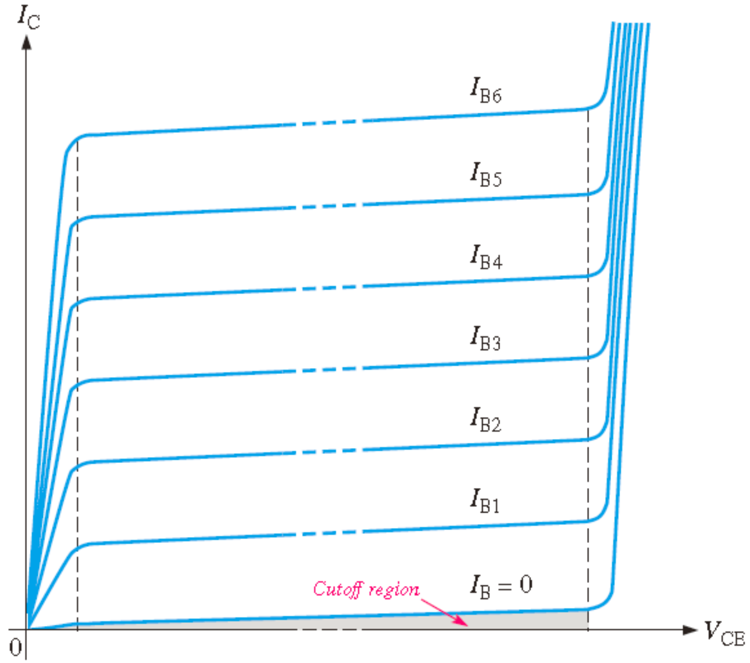
$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = \mathbf{3.55\ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

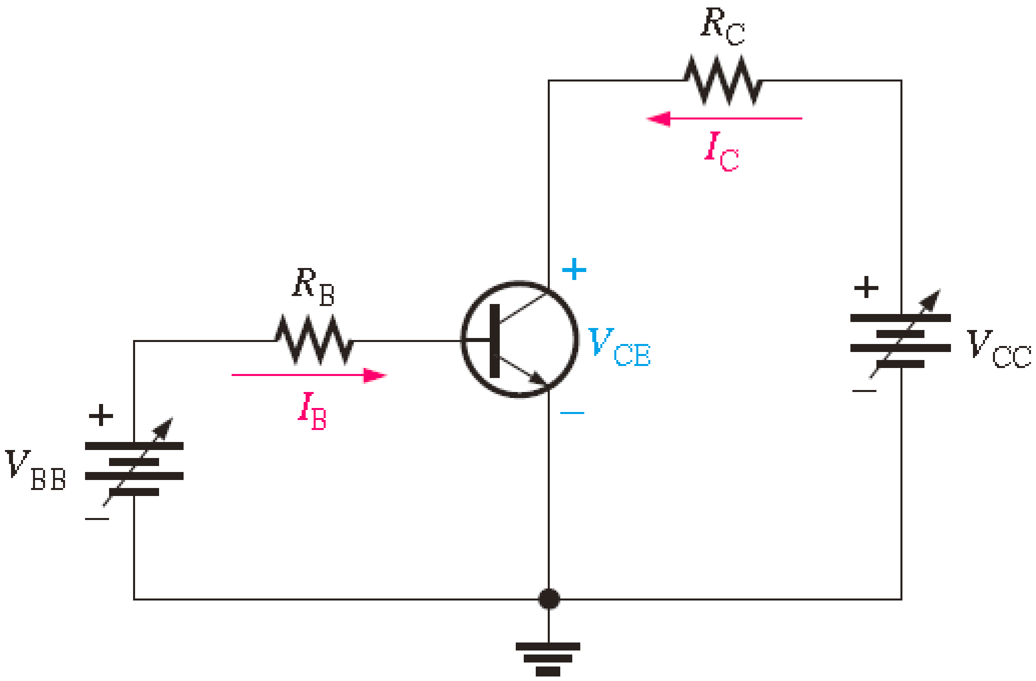
Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

Collector Characteristic Curves

- Using a circuit like that shown in Figure 4–10(a), a set of collector characteristic curves can be generated that show how the collector current, I_C, varies with the collector-to-emitter voltage, V_{CE}, for specified values of base current.



(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)



(a) Circuit

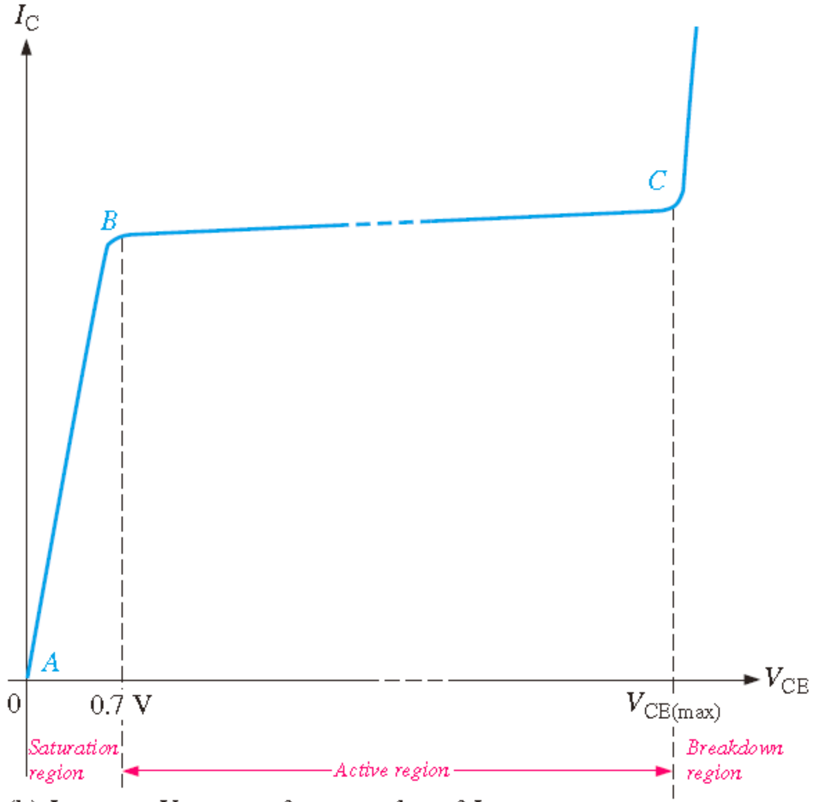
FIGURE 4-10
Collector characteristic curves.

Collector Characteristic Curves

- V_{CE} is near 0 V. When both junctions are forward-biased, the transistor is in the saturation region of its operation. Saturation is the state of a BJT in which the collector current has reached a maximum and is independent of the base current.

- As V_{CC} is increased, V_{CE} increases as the collector current increases. This is indicated by the portion of the characteristic curve between points A and B in Figure 4–10(b).

- I_C increases as V_{CC} is increased because V_{CE} remains less than 0.7 V due to the forward-biased base-collector junction.



(b) I_C versus V_{CE} curve for one value of I_B

FIGURE 4-10

Collector characteristic curves.

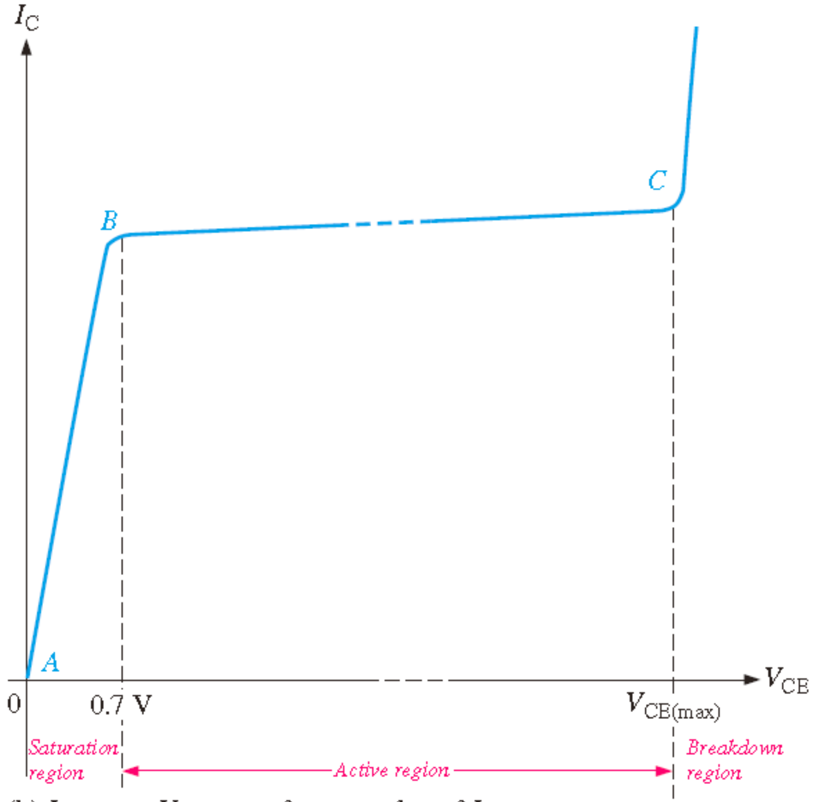
Collector Characteristic Curves

- Ideally, when V_{CE} exceeds 0.7 V, the base-collector junction becomes reverse-biased and the transistor goes into the active, or linear, region of its operation.

- Once the base collector junction is reverse-biased, I_C levels off and remains essentially constant for a given value of I_B as V_{CE} continues to increase.

- This is shown by the portion of the characteristic curve between points B and C in Figure 4–10(b). For this portion of the characteristic curve, the value of I_C is determined only by the relationship expressed as

- $I_C = \beta_{DC} I_B$.



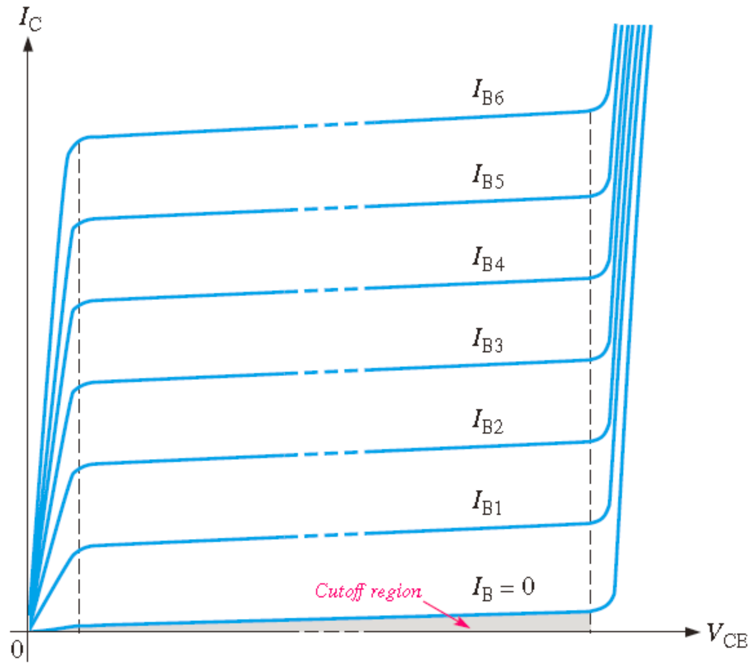
(b) I_C versus V_{CE} curve for one value of I_B

FIGURE 4-10
Collector characteristic curves.

Collector Characteristic Curves

- When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly as indicated by the part of the curve to the right of point C in Figure 4–10(b). A transistor should never be operated in this breakdown region.

- When $I_B = 0$, the transistor is in the cutoff region although there is a very small collector leakage current as indicated. Cutoff is the nonconducting state of a transistor.



(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

FIGURE 4-10
Collector characteristic curves.

Cutoff

- As previously mentioned, when $I_B = 0$, the transistor is in the cutoff region of its operation. This is shown in Figure 4–13 with the base lead open, resulting in a base current of zero.

- Under this condition, there is a very small amount of collector leakage current, I_{CEO}, due mainly to thermally produced carriers. Because I_{CEO} is extremely small, it will usually be neglected in circuit analysis so that $V_{CE} = V_{CC}$. In cutoff, neither the base-emitter nor the base-collector junctions are forward-biased.

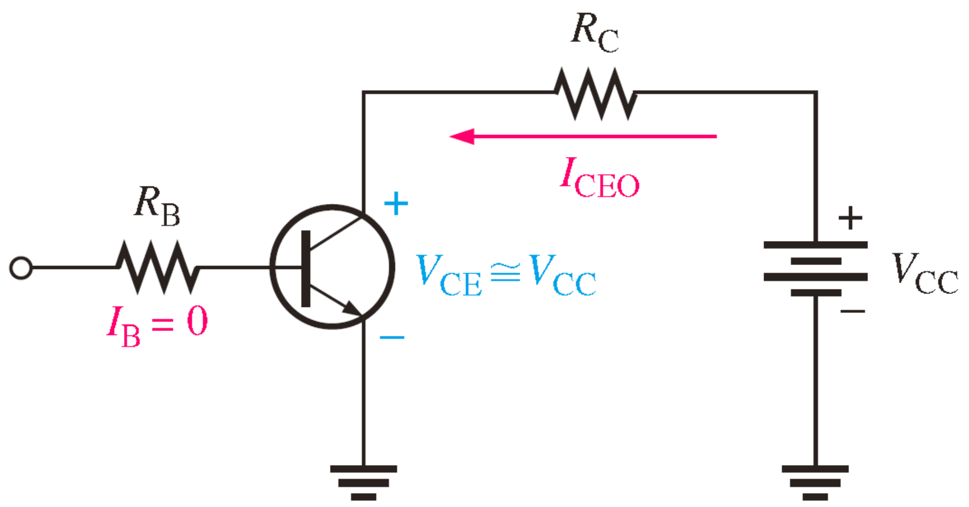


FIGURE 4-11
Cutoff: Collector leakage current (I_{CEO}) is extremely small and is usually neglected. Base-emitter and basecollector junctions are reverse-biased.

Cutoff

- When the base-emitter junction becomes forward-biased and the base current is increased, the collector current also increases ($I_C = \beta_{DC} I_B$) and V_{CE} decreases as a result of more drop across the collector resistor ($V_{CE} = V_{CC} - I_C R_C$). This is illustrated in Figure 4–12.

- When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased and I_C can increase no further even with a continued increase in I_B.
- At the point of saturation, the relation $I_C = \beta_{DC} I_B$ is no longer valid. $V_{CE(sat)}$ for a transistor occurs somewhere below the knee of the collector curves, and it is usually only a few tenths of a volt.

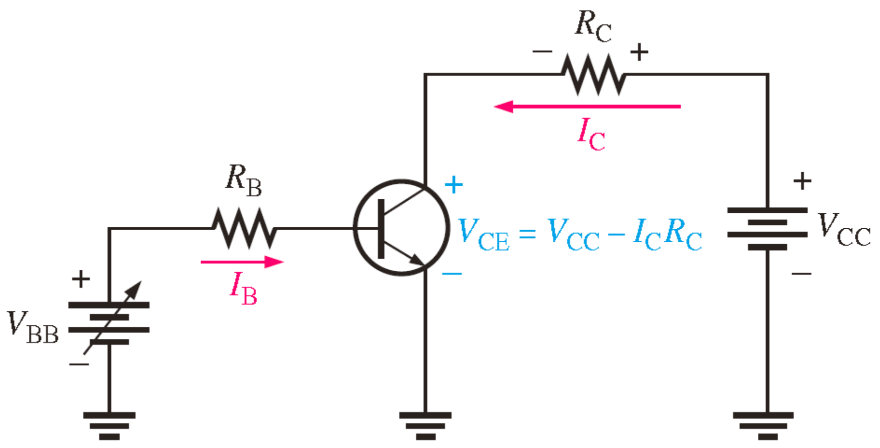


FIGURE 4-12
Saturation: As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across R_C. When the transistor reaches saturation, I_C can increase no further regardless of further increase in I_B. Base-emitter and base-collectorjunctions are forward-biased.