ECE 121 - Electronics (1)

Lecture 7: Bipolar Junction Transistor (BJT)

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Bipolar Junction Transistor (BJT)

Outline

- BJT Structure
- BJT Operation
- BJT Configurations
- Maximum Transistor Ratings
- Transistor Casing and Terminal Identification

BIPOLAR JUNCTION TRANSISTOR (BJT) STRUCTURE

- A BJT transistor has three doped regions: **emitter**, **base**, and **collector**
- Two types : ***npn*** & ***pnp***
- The ***emitter*** is heavily doped.
- The ***base*** is very thin and lightly doped.
- The ***collector*** is moderately doped, The collector is physically the largest of the three regions.
- The transistor has two junctions: emitter-base junction **(EBJ)** & collector-base junction **(CBJ)**.
- The term **bipolar** refers to the use of both holes and electrons as current carriers in the transistor structure.
- A transistor is like **two back-to-back diodes**.

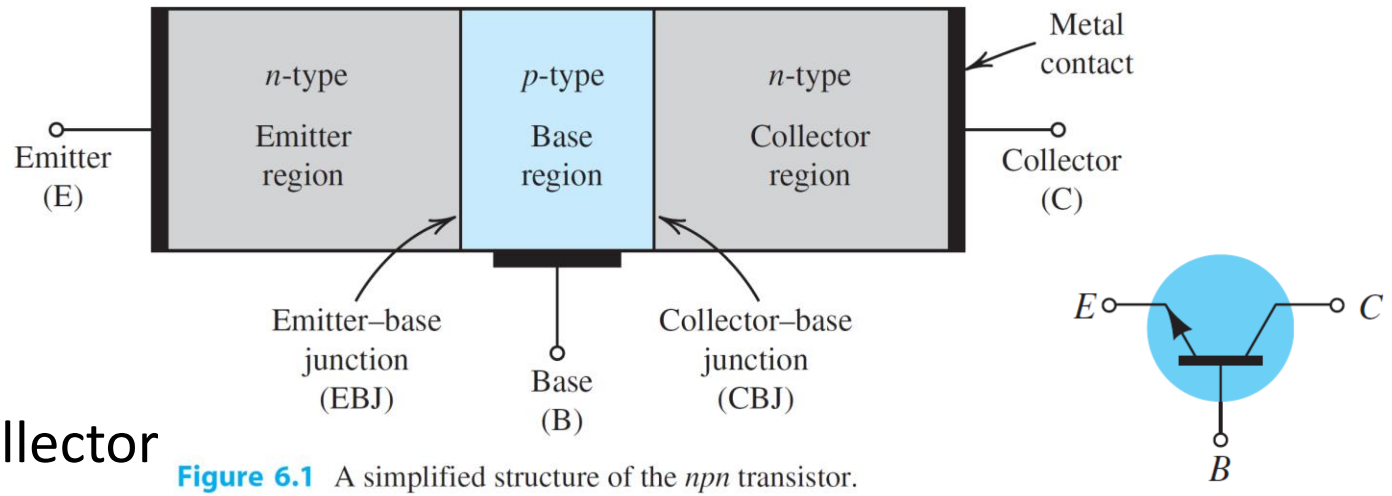


Figure 6.1 A simplified structure of the *npn* transistor.

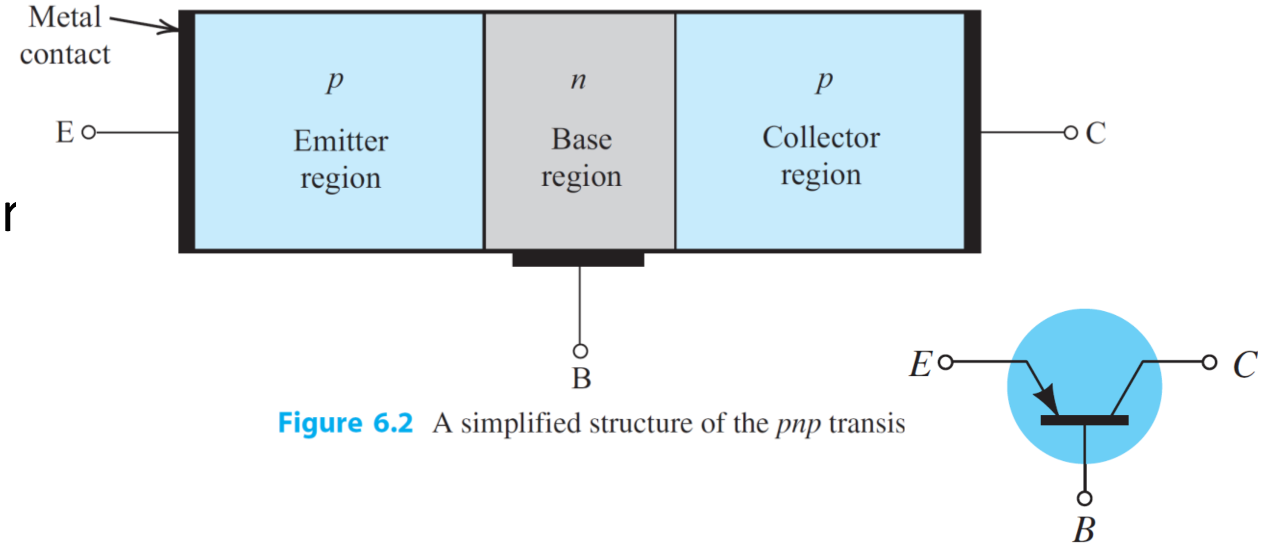


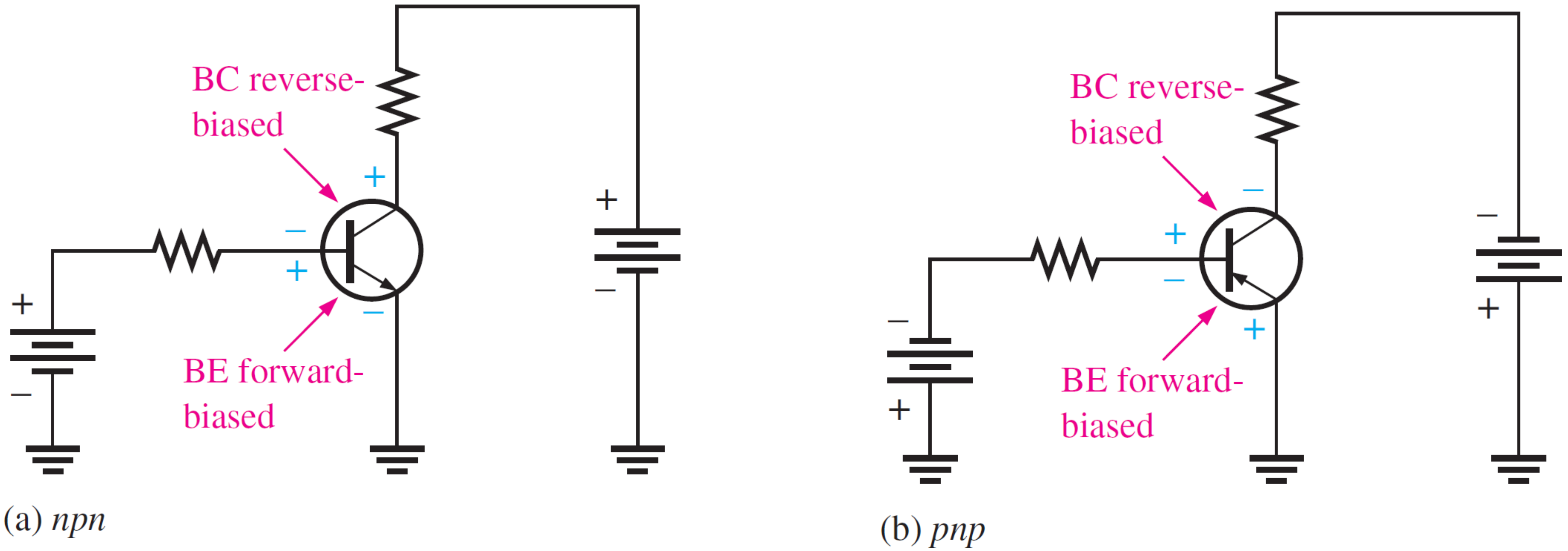
Figure 6.2 A simplified structure of the *pnp* transis

Modes of operation

EBJ	CBJ	Mode	Application
Forward	Reverse	Active	Amplifier
Forward	Forward	Saturation	Switch (ON)
Reverse	Reverse	Cut-off	Switch (OFF)

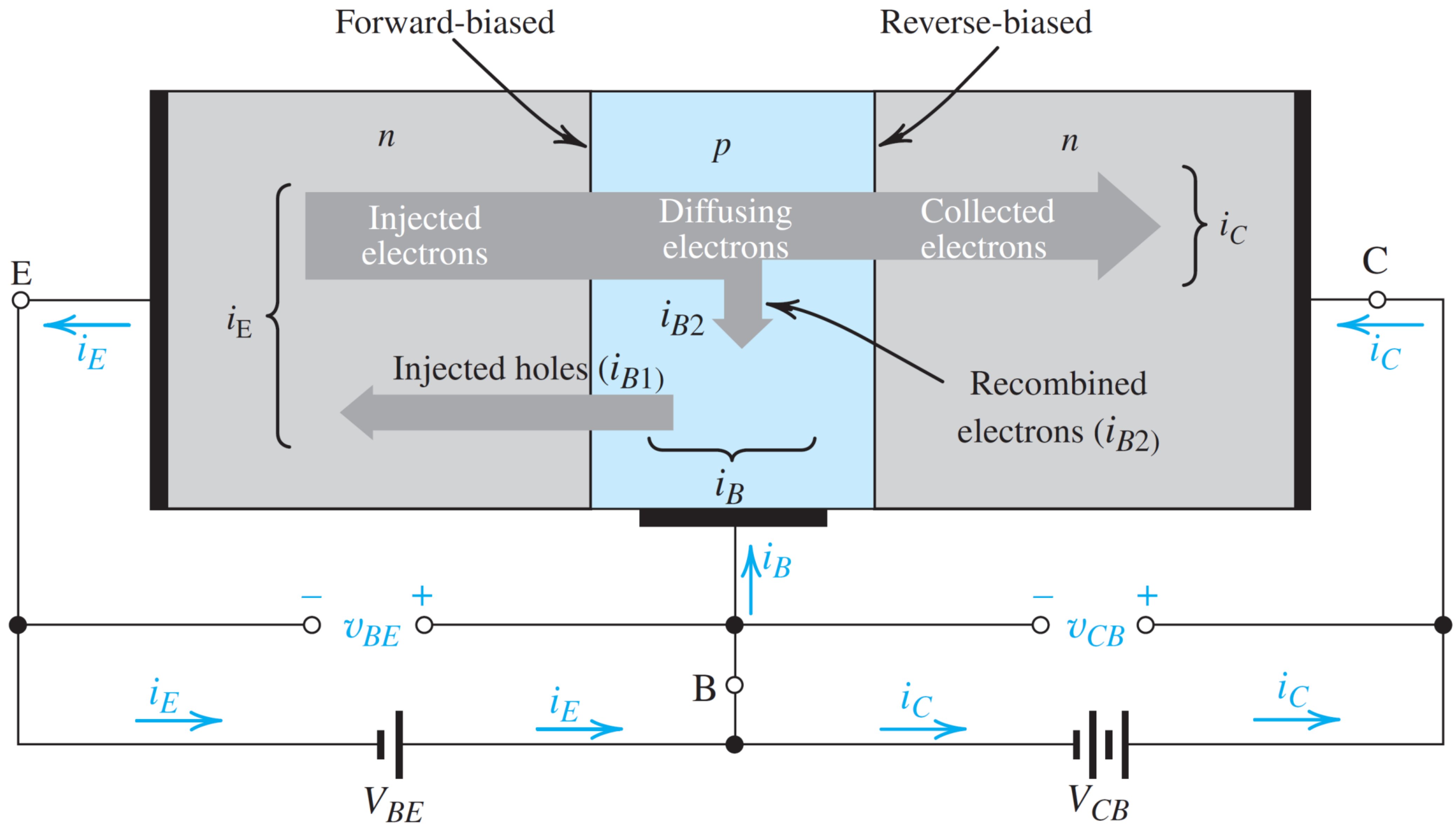
Operation of the *npn* Transistor in the Active Mode

- In normal operation, the EBJ is F.B. and the CBJ is R.B.



- For the *npn* type, the collector is more positive than the base, which is more positive than the emitter.
- For the *pnp type*, the voltages are reversed to maintain the forward-reverse bias.

Operation of the *npn* Transistor in the Active Mode



Current Flow

- The forward bias on the emitter–base junction will cause current to flow across this junction.
- Current will consist of two components: electrons injected from the emitter into the base, and holes injected from the base into the emitter.
- Since the emitter is heavily doped and the base is lightly doped, the device has a high density of electrons in the emitter and a low density of holes in the base.
- The current that flows across the EBJ will constitute the emitter current I_E, as indicated in Fig. The direction of I_E is "out of" the emitter lead (conventional current direction)
- The injected electrons from the emitter into the base will be **minority carriers** in the *p*-type base region. Because their concentration will be highest at the emitter side of the base, the injected electrons will diffuse through the base region toward the collector.
- Some of the electrons will combine with holes, which are majority carriers in the base. Since the base is usually very thin and lightly doped. The proportion of electrons that are "lost" through this **recombination process** will be quite small.
- Thus, most of the diffusing electrons will reach the boundary of the collector–base depletion region.
- Because the collector is more positive than the base, these successful electrons will be swept across the CBJ depletion region into the collector.
- They will thus get collected and constitute the collector current I_C.

The *pnp* Transistor

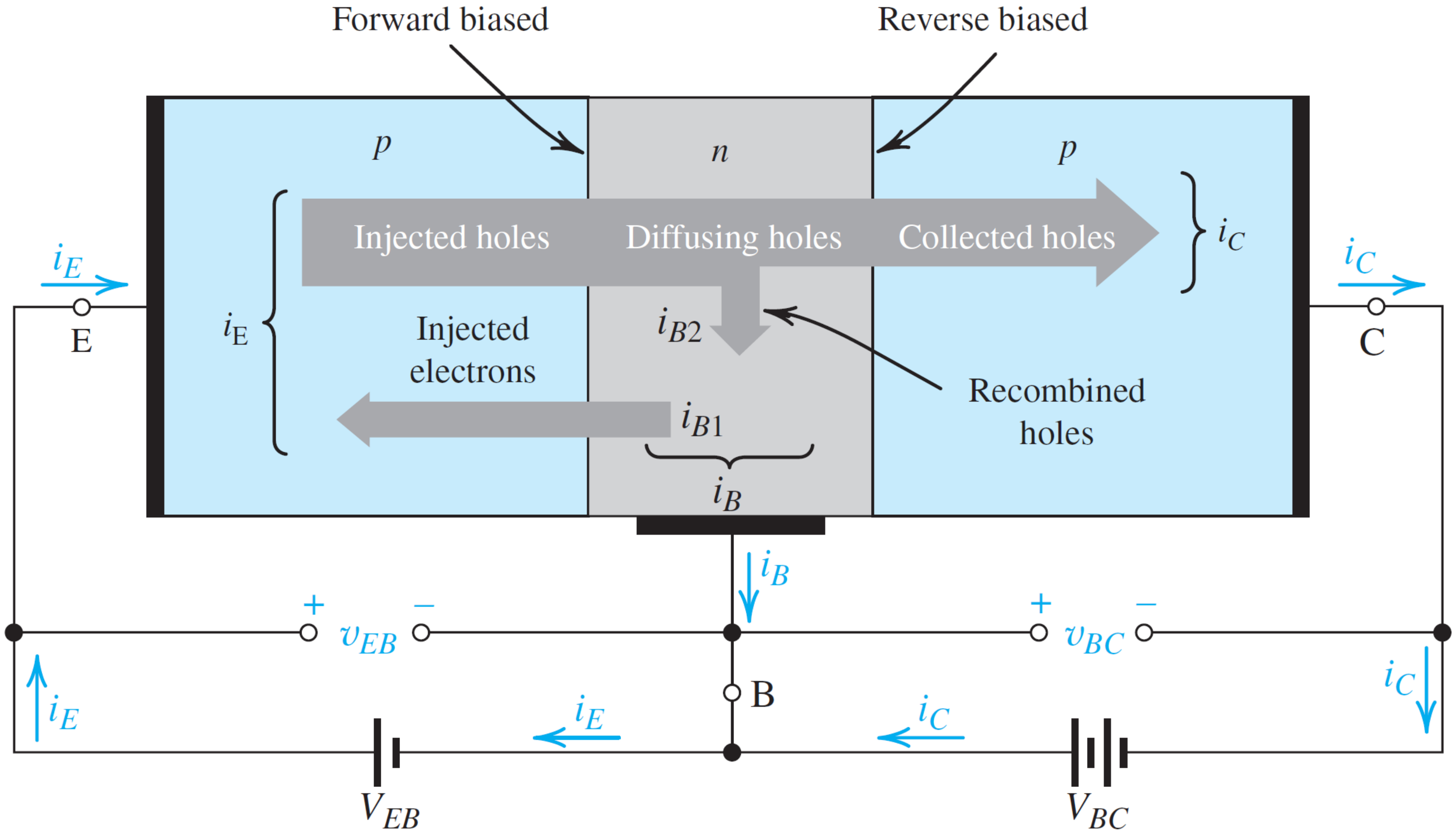


Figure 6.10 Current flow in a *pnp* transistor biased to operate in the active mode.

Transistor Currents

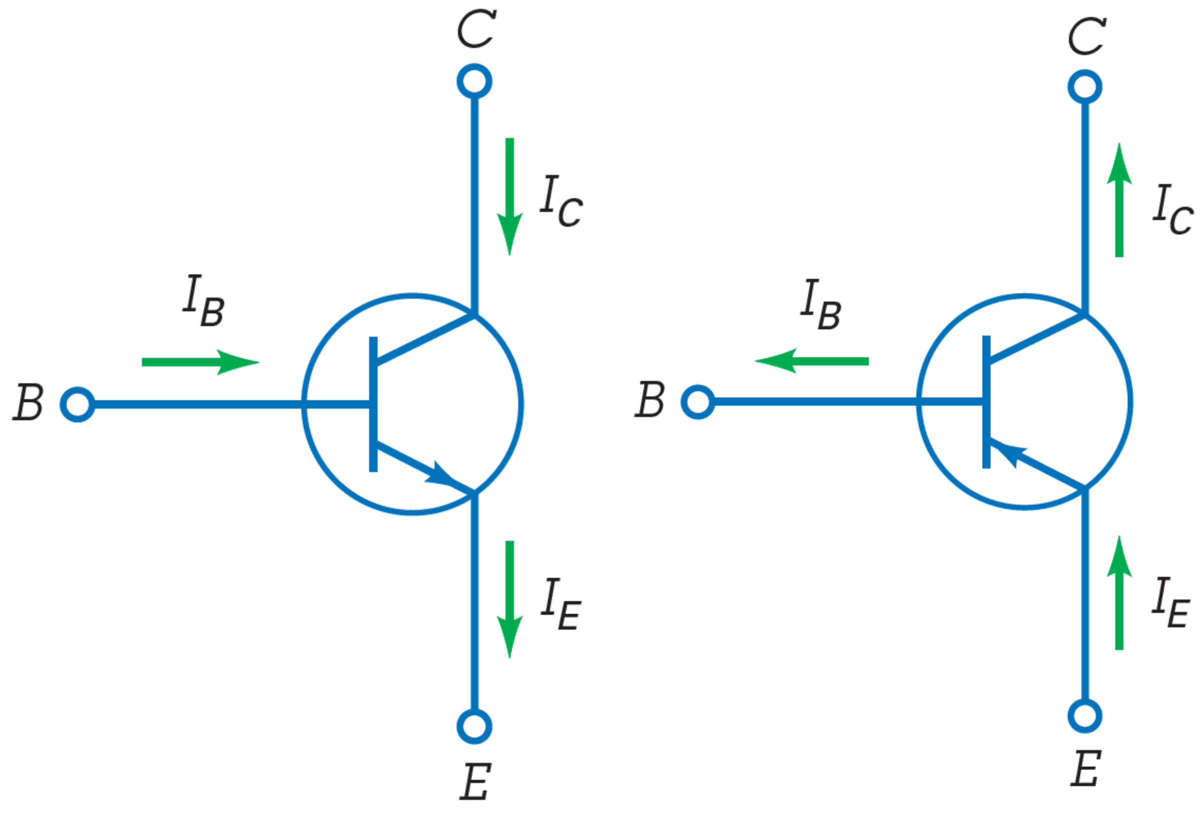
$$\boxed{I_E = I_C + I_B}$$

$$I_C \approx I_E \qquad \boxed{I_C = \alpha I_E} \qquad \boxed{\alpha = \frac{I_C}{I_E}}$$

$$I_B \ll I_C \qquad \boxed{I_C = \beta I_B} \qquad \boxed{\beta = \frac{I_C}{I_B}}$$

$$\boxed{\alpha = \frac{\beta}{\beta + 1}} \qquad \boxed{\beta = \frac{\alpha}{1 - \alpha}}$$

The schematic symbols



(a) ***npn*** tranistor currents (b) ***pnp*** transistor currents

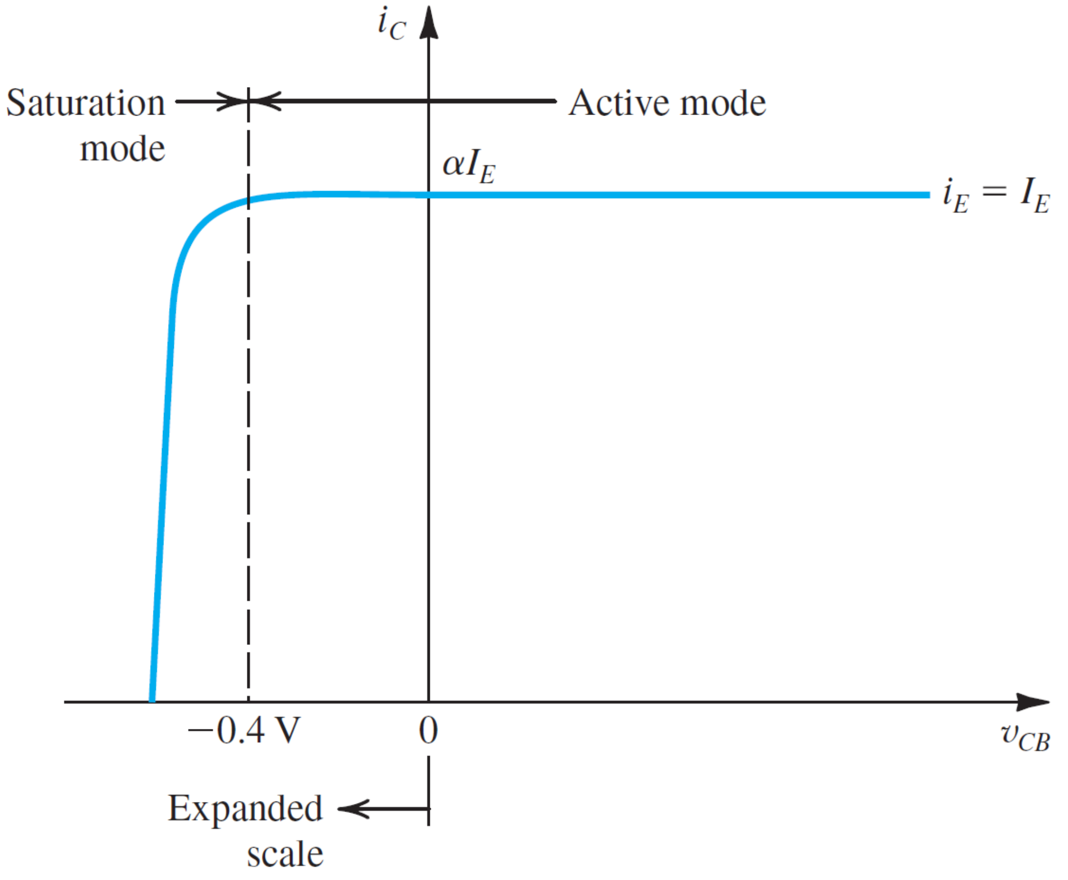
- α is a constant that is less than but very close to unity.
- For instance, if β=100, then α=0.99.
  - β is called the **common-emitter current gain**.
  - α is called the **common-base current gain**.

β ranges from about 50 to over 400

α typically extends from 0.90 to 0.998,

Operation in the Saturation Mode

- Active-mode operation of an *npn* transistor can be maintained for negative v_{CB} down to approximately −0.4 V as illustrated in Fig. (i.e. for $v_{CB} \geq -0.4$)
- For $v_{CB} < -0.4V$, the CBJ begins to conduct sufficiently that the transistor leaves the active mode and enters the saturation mode of operation, where i_C decreases.
- In analyzing a circuit we can determine whether the BJT is in the saturation mode by either of the following two tests:
    1. **Is the CBJ forward biased by more than 0.4 V?**
    2. **Is the ratio $\frac{i_C}{i_B}$ lower than β?**



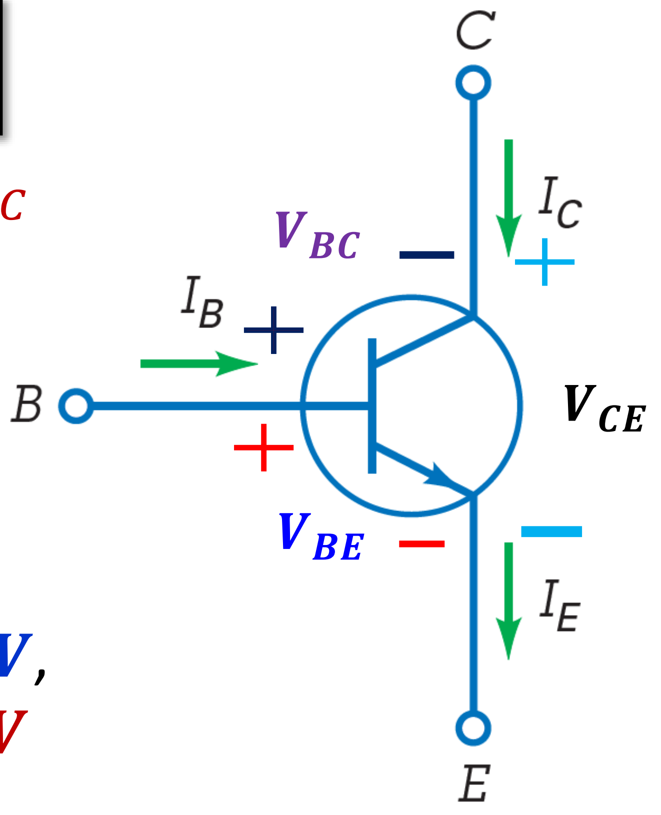
$$\beta_{\text{forced}} = \left.\frac{i_C}{i_B}\right|_{\text{saturation}} \leq \beta$$

Operation in the Saturation Mode

Saturation is the state of a BJT in which the collector current has reached a maximum and is independent of the base current.

V_{CE} of a saturated transistor is:

$$\boxed{V_{CEsat} = V_{BE} - V_{BC}}$$



Recalling that the CBJ has a much larger area than the EBJ, V_{BC} will be smaller than V_{BE} by 0.1 to 0.3 V. Thus,

$$\boxed{V_{CEsat} \simeq 0.1 \text{ to } 0.3 \text{ V}}$$

Typically we will assume that:

- a transistor at the edge of saturation has $V_{CEsat} = 0.3\ V$,
- While a transistor deep in saturation has $V_{CEsat} = 0.2\ V$

$$\boxed{\beta_{\text{forced}} = \left.\frac{i_C}{i_B}\right|_{\text{saturation}} \leq \beta}$$

Solved Problems on BJT

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

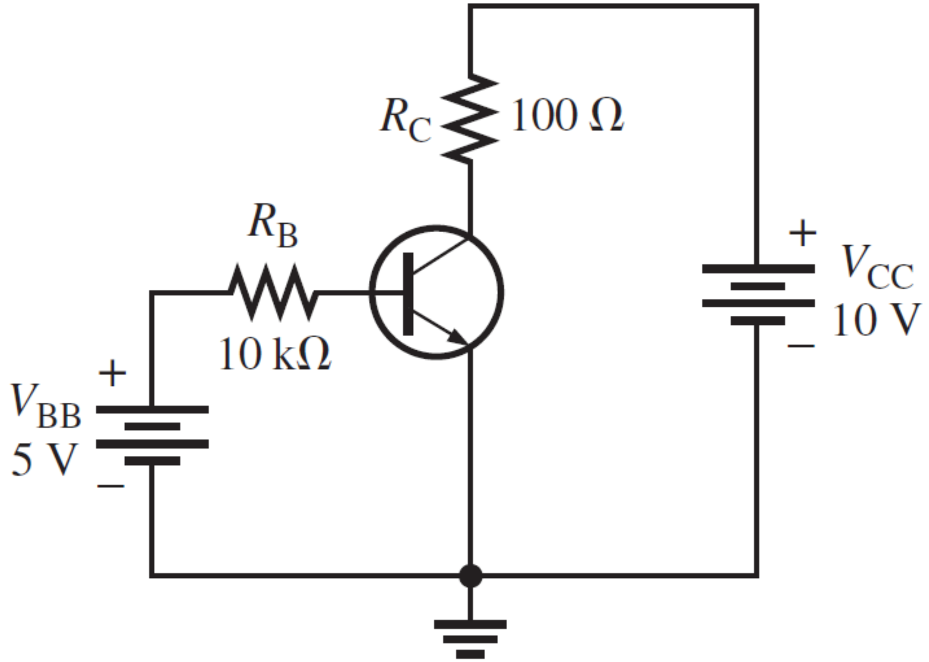
$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

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

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

3) 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 $\beta_{DC} = 150$.

Solution :



$V_{BE} \cong \mathbf{0.7\ V.}$

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

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

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

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

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

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

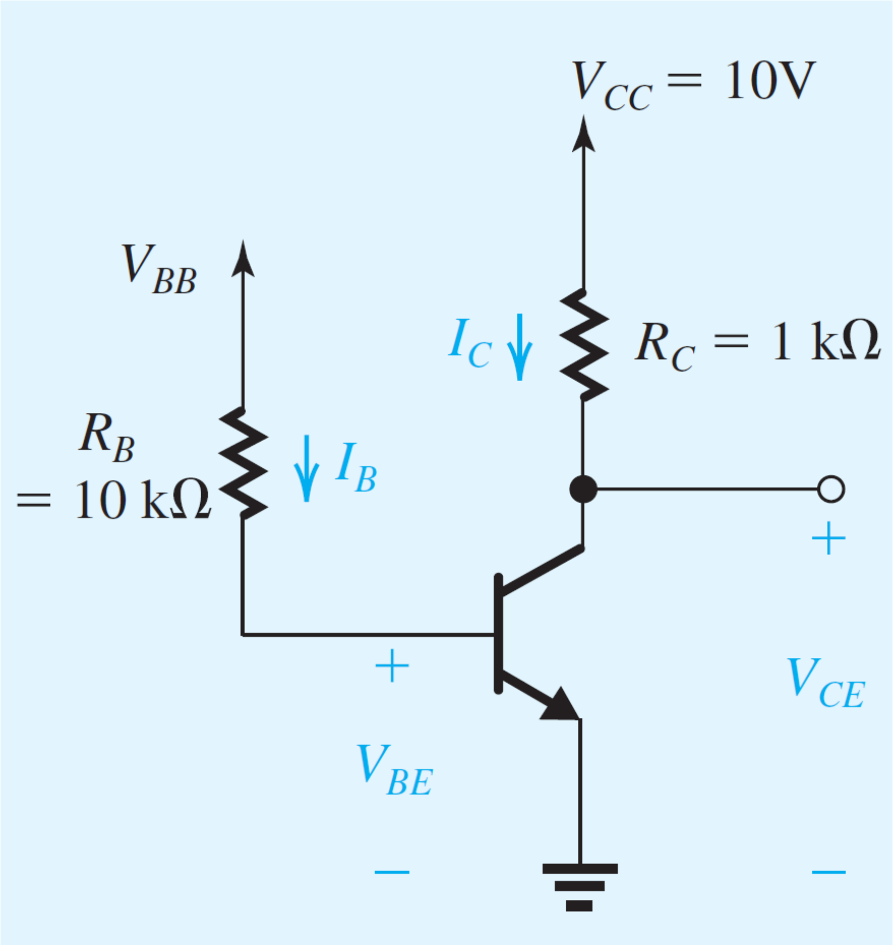
Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

Example 4

For the circuit in Fig. shown, it is required to determine the value of the voltage V_{BB} that results in the transistor operating:

a) in the active mode with $V_{CE} = 5\ V$
b) at the edge of saturation
c) deep in saturation with $\beta_{forced} = 10$

The transistor β is specified to be 50.



Solution

(a) To operate in the active mode with $V_{CE} = 5$ V,

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10 - 5}{1\ \text{k}\Omega} = 5\ \text{mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{5}{50} = 0.1\ \text{mA}$$

Now the required value of V_{BB} can be found as follows:

$$V_{BB} = I_B R_B + V_{BE} \quad = 0.1 \times 10 + 0.7 = 1.7\ \text{V}$$

(b) Operation at the edge of saturation is obtained with $V_{CE} = 0.3$ V. Thus

$$I_C = \frac{10 - 0.3}{1} = 9.7\ \text{mA}$$

Since, at the edge of saturation, I_C and I_B are still related by β,

$$I_B = \frac{9.7}{50} = 0.194\ \text{mA}$$

The required value of V_{BB} can be determined as

$$V_{BB} = 0.194 \times 10 + 0.7 = 2.64\ \text{V}$$

(c) To operate deep in saturation,

$$V_{CE} = V_{CE\text{sat}} \simeq 0.2 \text{ V}$$

Thus,

$$I_C = \frac{10 - 0.2}{1} = 9.8 \text{ mA}$$

We then use the value of forced β to determine the required value of I_B as

$$I_B = \frac{I_C}{\beta_{\text{forced}}} = \frac{9.8}{10} = 0.98 \text{ mA}$$

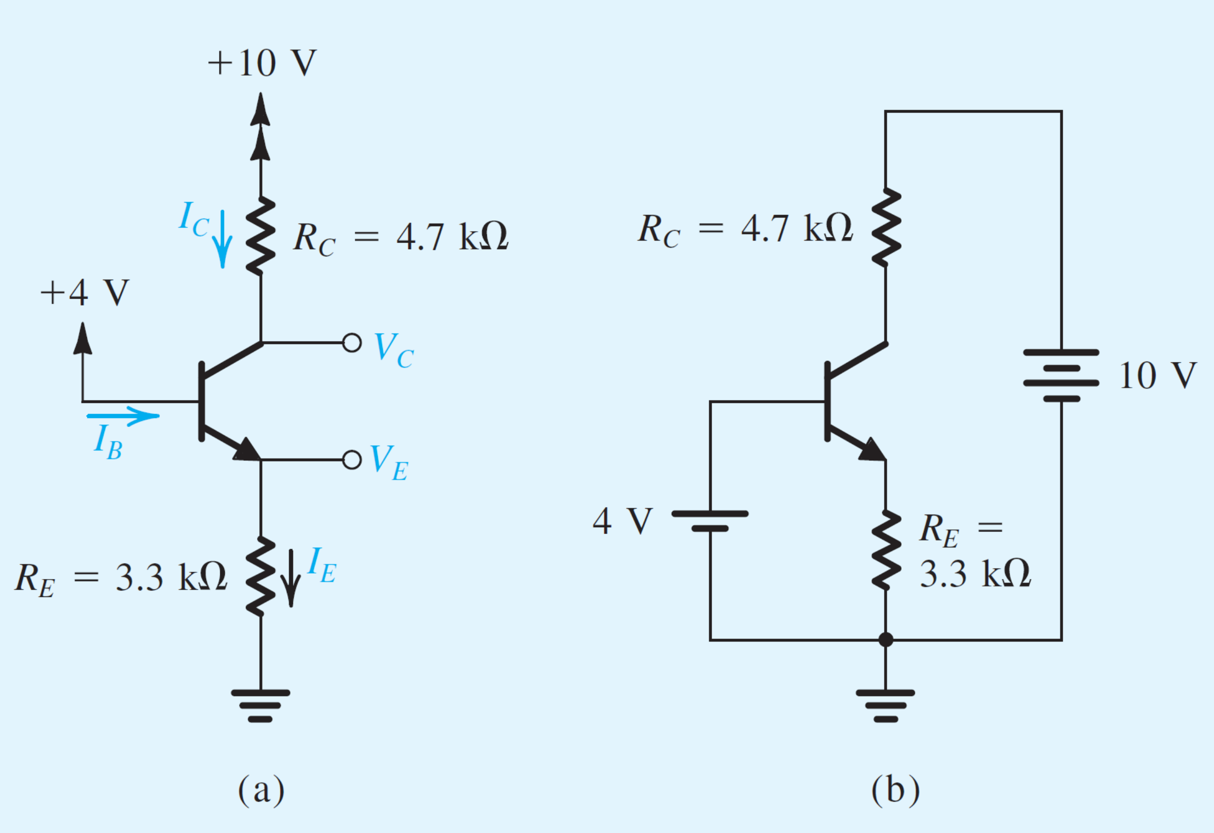
and the required V_{BB} can now be found as

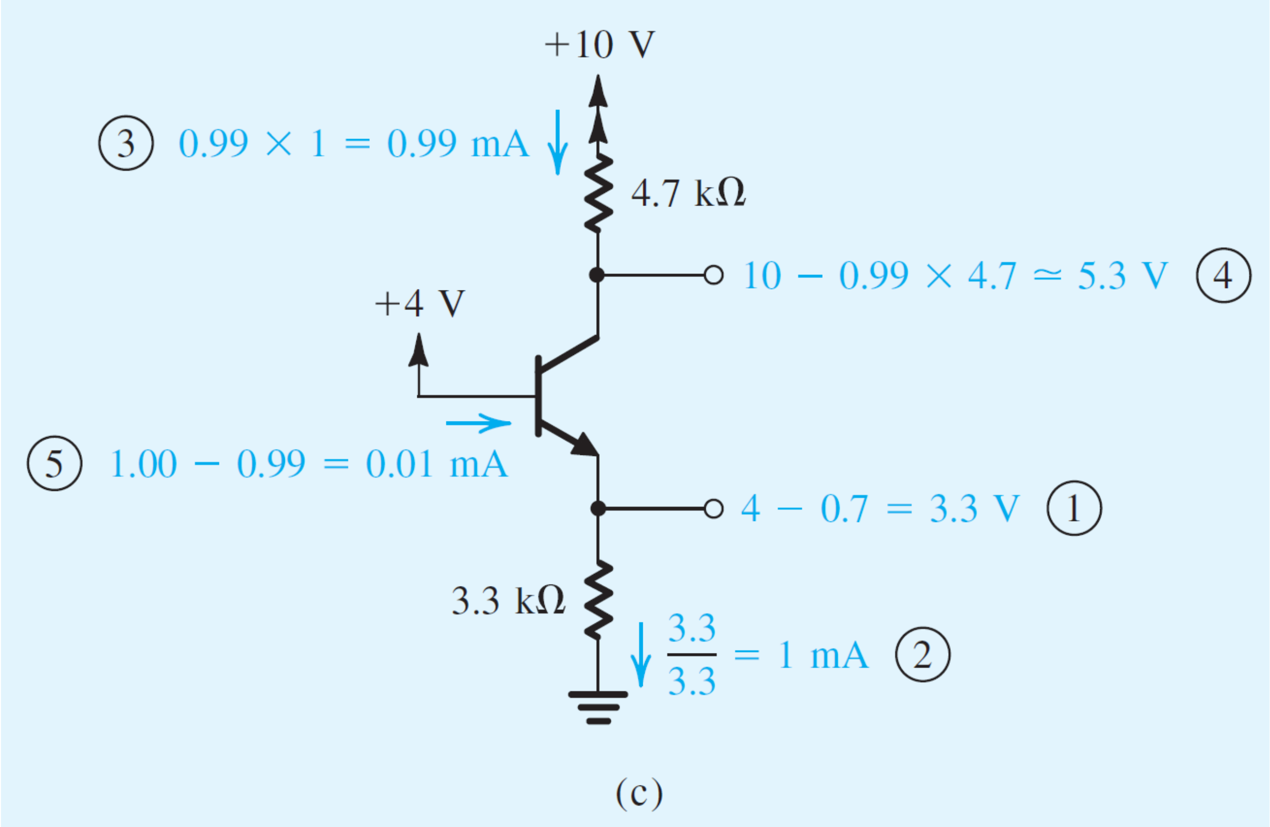
$$V_{BB} = 0.98 \times 10 + 0.7 = 10.5 \text{ V}$$

Observe that once the transistor is in saturation, increasing V_{BB} and thus I_B results in negligible change in I_C since $V_{CE\text{sat}}$ will change only slightly. Thus I_C is said to *saturate*, which is the origin of the name "saturation mode of operation."

Example 5

Consider the circuit shown in Fig. (a), which is redrawn in Fig. (b) . Analyze this circuit to determine all node voltages and branch currents. Assume that β is specified to be 100.





Solution

Glancing at the circuit in Fig. 6.23(a), we note that the base is connected to +4 V and the emitter is connected to ground through a resistance R_E. Therefore, it is reasonable to conclude that the base–emitter junction will be forward biased. Assuming that this is the case and assuming that V_{BE} is approximately 0.7 V, it follows that the emitter voltage will be

$$V_E = 4 - V_{BE} \simeq 4 - 0.7 = 3.3 \text{ V}$$

We are now in an opportune position; we know the voltages at the two ends of R_E and thus can determine the current I_E through it,

$$I_E = \frac{V_E - 0}{R_E} = \frac{3.3}{3.3} = 1 \text{ mA}$$

Since the collector is connected through R_C to the +10-V power supply, it appears possible that the collector voltage will be higher than the base voltage, which implies active-mode operation. Assuming that this is the case, we can evaluate the collector current from

$$I_C = \alpha I_E$$

The value of α is obtained from

$$\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} \simeq 0.99$$

Thus I_C will be given by

$$I_C = 0.99 \times 1 = 0.99 \text{ mA}$$

We are now in a position to use Ohm's law to determine the collector voltage V_C,

$$V_C = 10 - I_C R_C = 10 - 0.99 \times 4.7 \simeq +5.3 \text{ V}$$

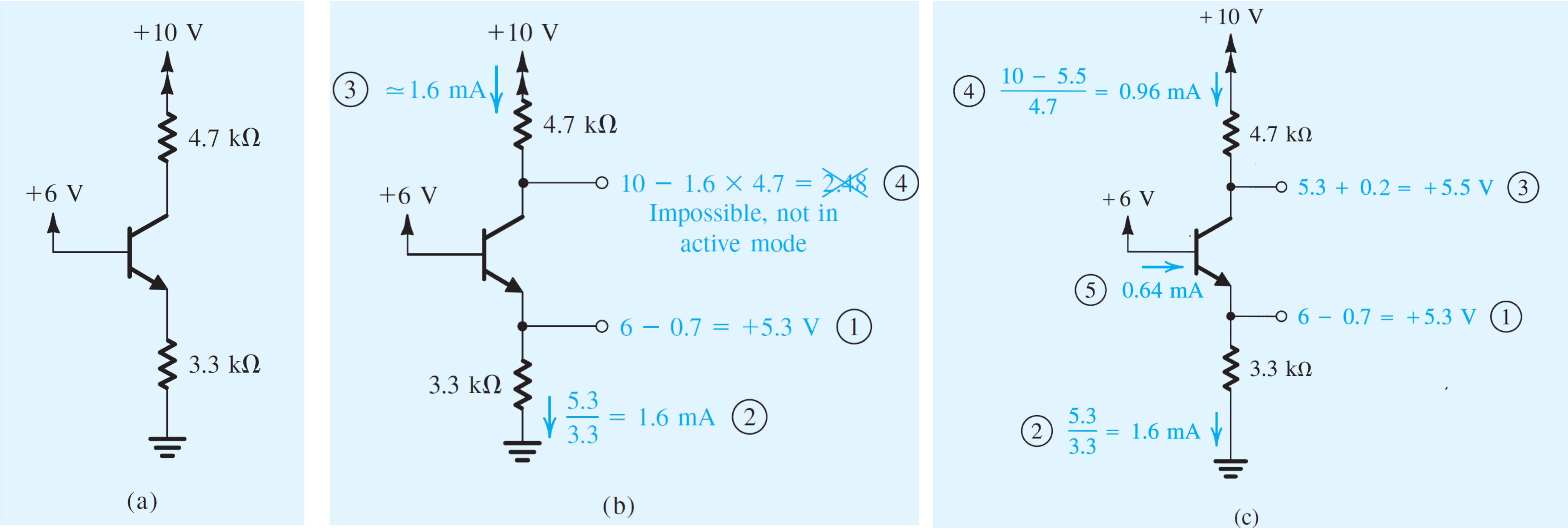
Since the base is at +4 V, the collector–base junction is reverse biased by 1.3 V, and the transistor is indeed in the active mode as assumed.

It remains only to determine the base current I_B, as follows:

$$I_B = \frac{I_E}{\beta+1} = \frac{1}{101} \simeq 0.01 \text{ mA}$$

Before leaving this example, we wish to emphasize strongly the value of carrying out the analysis directly on the circuit diagram. Only in this way will one be able to analyze complex circuits in a reasonable length of time. Figure 6.23(c) illustrates the above analysis on the circuit diagram, with the order of the analysis steps indicated by the circled numbers.

Example 6 Analyze the circuit of Fig. (a) to determine the voltages at all nodes and the currents through all branches. Assume β = 50.



Solution

With +6 V at the base, the base–emitter junction will be forward biased; thus,

$$V_E = +6 - V_{BE} \simeq 6 - 0.7 = 5.3 \text{ V}$$

and

$$I_E = \frac{5.3}{3.3} = 1.6 \text{ mA}$$

Now, assuming active-mode operation, $I_C = \alpha I_E \simeq I_E$; thus,

$$V_C = +10 - 4.7 \times I_C \simeq 10 - 7.52 = 2.48 \text{ V}$$

The details of the analysis performed above are illustrated in Fig. 6.24(b).

Since the collector voltage calculated is less than the base voltage by 3.52 V, it follows that our original assumption of active-mode operation is incorrect. In fact, the transistor has to be in the *saturation* mode. Assuming this to be the case, the values of V_E and I_E will remain unchanged. The collector voltage, however, becomes

$$V_C = V_E + V_{CEsat} \simeq 5.3 + 0.2 = +5.5 \text{ V}$$

from which we can determine I_C as

$$I_C = \frac{10 - 5.5}{4.7} = 0.96 \text{ mA}$$

and I_B can now be found as

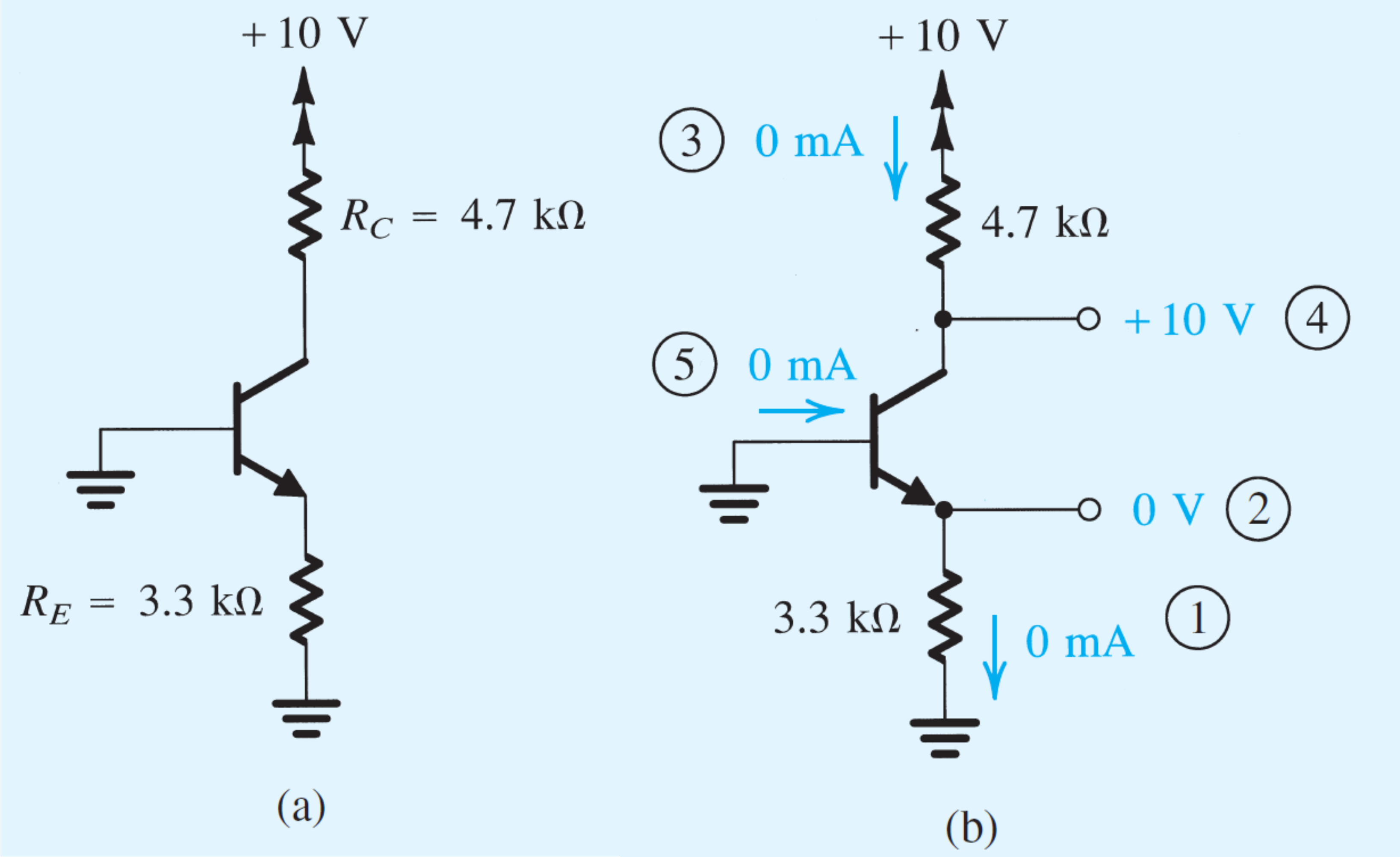
$$I_B = I_E - I_C = 1.6 - 0.96 = 0.64 \text{ mA}$$

Thus the transistor is operating at a forced β of

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{0.96}{0.64} = 1.5$$

Since β_{forced} is less than the *minimum* specified value of β, the transistor is indeed saturated. We should emphasize here that in testing for saturation the minimum value of β should be used. By the same token, if we are designing a circuit in which a transistor is to be saturated, the design should be based on the minimum specified β. Obviously, if a transistor with this minimum β is saturated, then transistors with higher values of β will also be saturated. The details of the analysis are shown in Fig. 6.24(c), where the order of the steps used is indicated by the circled numbers.

Example 7 Analyze the circuit in Fig. (a) to determine the voltages at all nodes and the currents through all branches. Note that this circuit is identical to that considered in Examples 5 and 6 except that now the base voltage is zero.



Solution

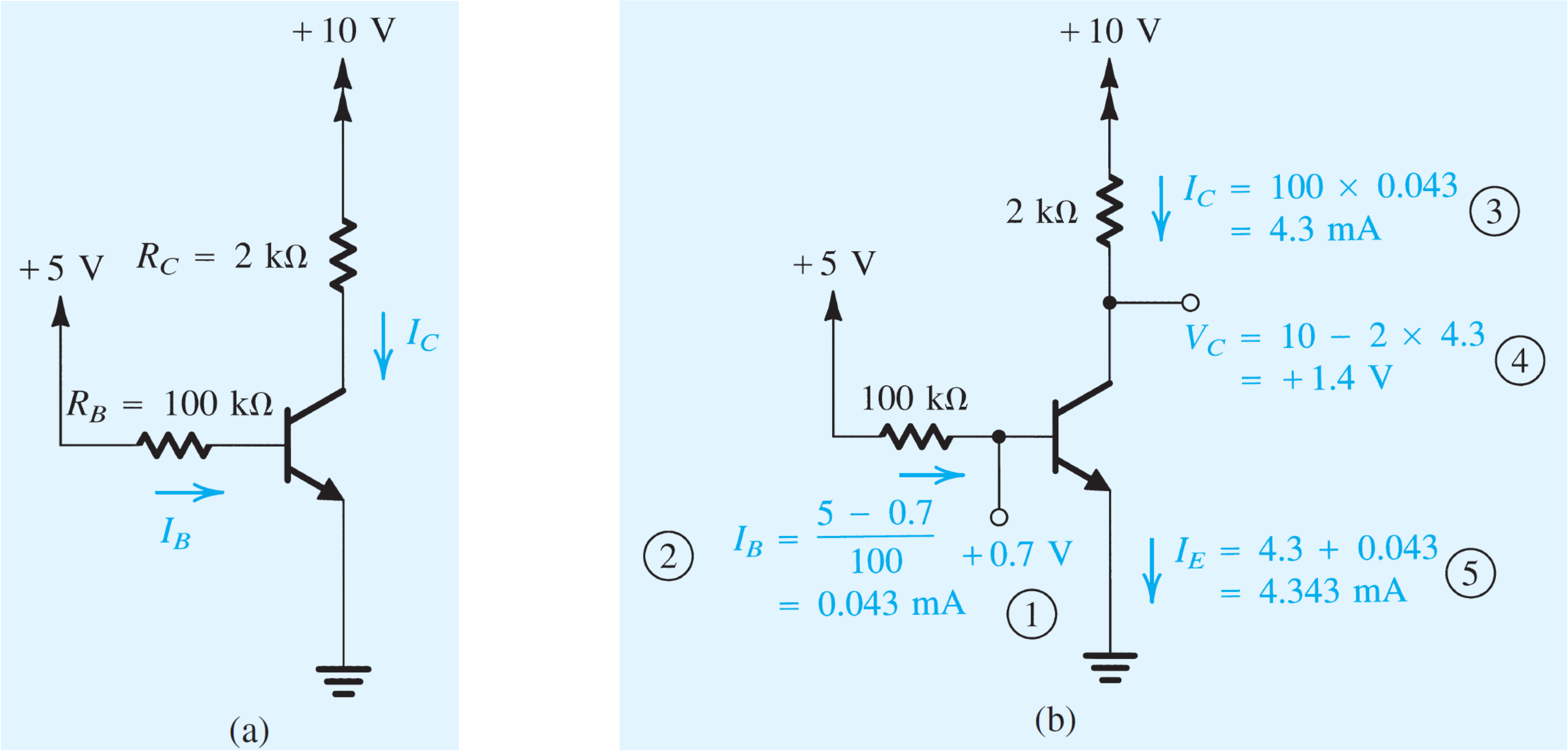
Since the base is at $0V$ and the emitter is connected to ground through R_E, **the BEJ cannot conduct and I_E is zero**.

Also, the CBJ cannot conduct, since the *n*-type collector is connected through R_C to the positive power supply while the *p*-type base is at ground. It follows that I_C will be zero.

I_B will also have to be zero, and **the transistor is in the *cutoff* mode of operation**.

V_E will be zero, while V_C will be equal to +10 V, since the voltage drops across R_E and R_C are zero.

Example 8 We want to analyze the circuit in Fig. 6.27(a) to determine the voltages at all nodes and the currents in all branches. Assume β = 100.



Solution

The base–emitter junction is clearly forward biased. Thus,

$$I_B = \frac{+5 - V_{BE}}{R_B} \simeq \frac{5 - 0.7}{100} = 0.043 \text{ mA}$$

Assume that the transistor is operating in the active mode. We now can write

$$I_C = \beta I_B = 100 \times 0.043 = 4.3 \text{ mA}$$

The collector voltage can now be determined as

$$V_C = 10 - I_C R_C = 10 - 4.3 \times 2 = +1.4 \text{ V}$$

Since the base voltage V_B is

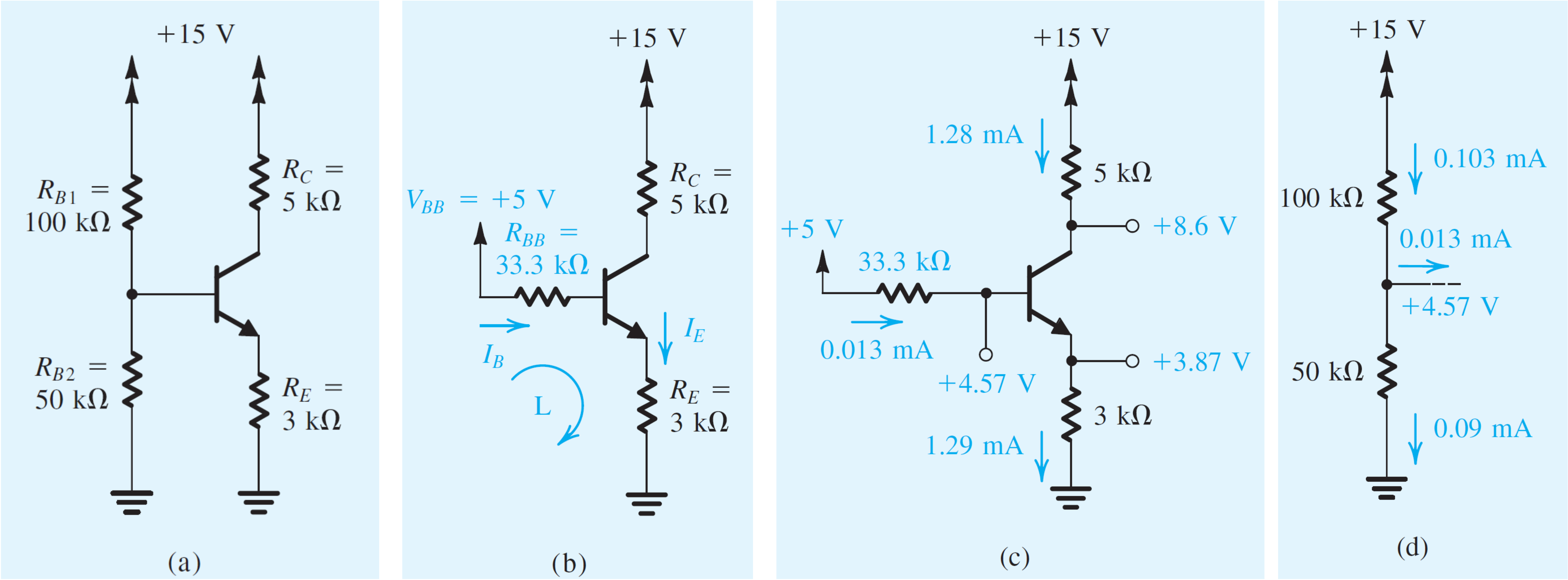
$$V_B = V_{BE} \simeq +0.7 \text{ V}$$

it follows that the collector–base junction is reverse biased by 0.7 V and the transistor is indeed in the active mode. The emitter current will be given by

$$I_E = (\beta + 1) I_B = 101 \times 0.043 \simeq 4.3 \text{ mA}$$

We note from this example that the collector and emitter currents depend critically on the value of β. In fact, if β were 10% higher, the transistor would leave the active mode and enter saturation. Therefore this clearly is a *bad* design. The analysis details are illustrated in Fig. 6.27(b).

Example 9 We want to analyze the circuit of Fig. 6.29(a) to determine the voltages at all nodes and the currents through all branches. Assume β = 100.



Solution

The first step in the analysis consists of simplifying the base circuit using Thévenin's theorem. The result is shown in Fig. 6.29(b), where

$$V_{BB} = +15\frac{R_{B2}}{R_{B1}+R_{B2}} = 15\frac{50}{100+50} = +5\text{ V}$$

$$R_{BB} = R_{B1} \parallel R_{B2} = 100 \parallel 50 = 33.3\text{ k}\Omega$$

To evaluate the base or the emitter current, we have to write a loop equation around the loop labeled L in Fig. 6.29(b). Note, however, that the current through R_{BB} is different from the current through R_E. The loop equation will be

$$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E$$

Now, assuming active-mode operation, we replace I_B with

$$I_B = \frac{I_E}{\beta+1}$$

and rearrange the equation to obtain

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + [R_{BB}/(\beta+1)]}$$

For the numerical values given we have

$$I_E = \frac{5 - 0.7}{3 + (33.3/101)} = 1.29 \text{ mA}$$

The base current will be

$$I_B = \frac{1.29}{101} = 0.0128 \text{ mA}$$

The base voltage is given by

$$\begin{aligned} V_B &= V_{BE} + I_E R_E \\ &= 0.7 + 1.29 \times 3 = 4.57 \text{ V} \end{aligned}$$

We can evaluate the collector current as

$$I_C = \alpha I_E = 0.99 \times 1.29 = 1.28 \text{ mA}$$

The collector voltage can now be evaluated as

$$V_C = +15 - I_C R_C = 15 - 1.28 \times 5 = 8.6 \text{ V}$$

It follows that the collector is higher in potential than the base by 4.03 V, which means that the transistor is in the active mode, as had been assumed. The results of the analysis are given in Fig. 6.29(c, d).