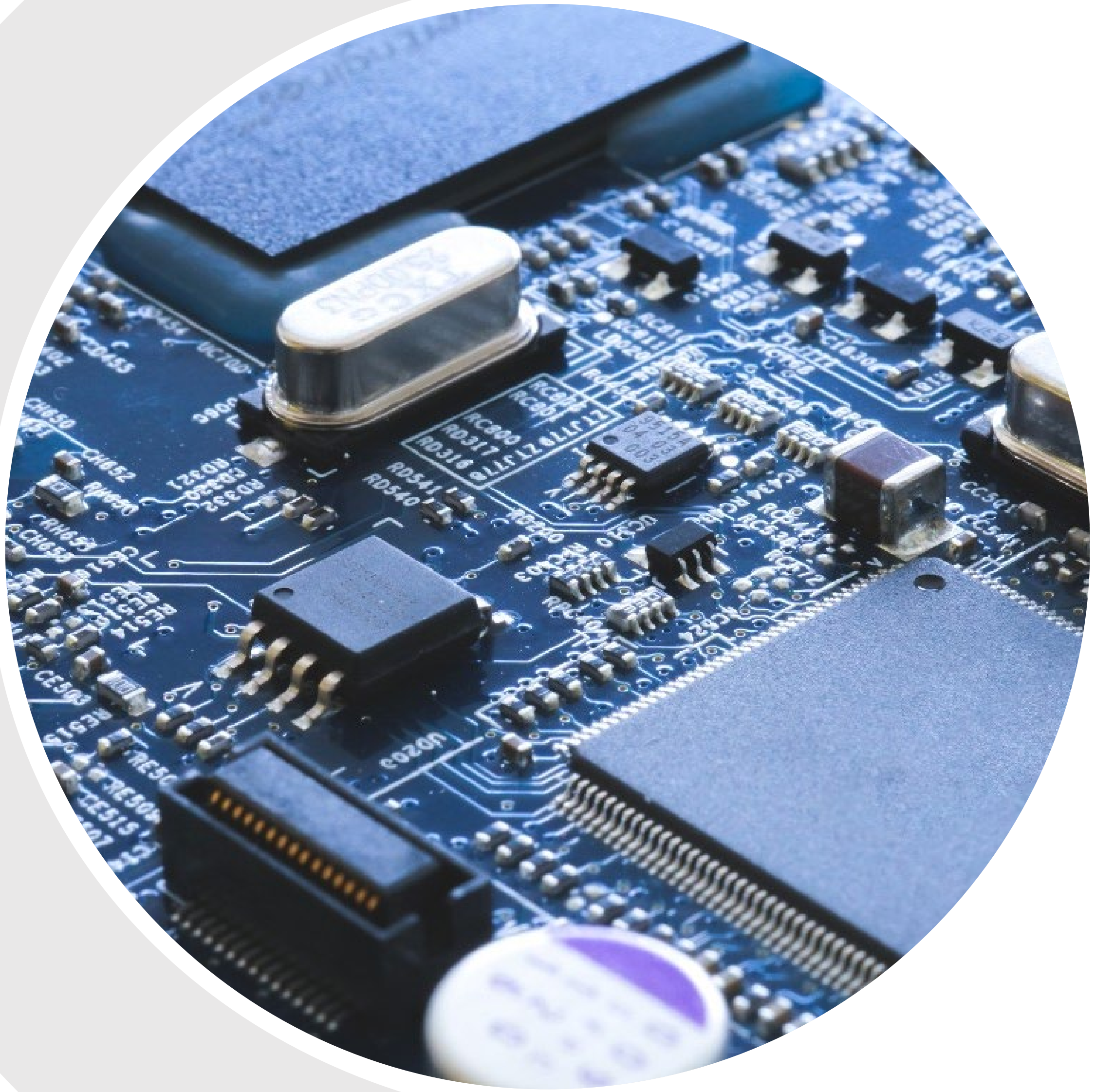

ANJUMAN
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BASIC ELECTRONICS

(BBEE103/BBEE203)

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MODULE – 2

Bipolar Junction Transistors

Syllabus

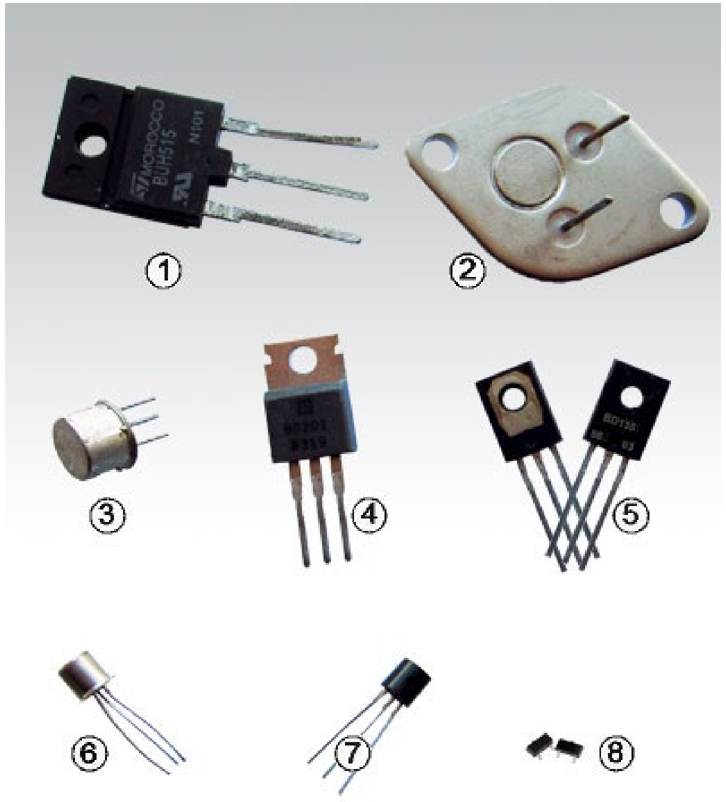
Bipolar Junction Transistors:

Introduction, BJT Voltages & Currents, BJT Amplification, Common Base Characteristics, Common Emitter Characteristics, Common Collector Characteristics, BJT Biasing: Introduction, DC Load line and Bias point

Introduction

- A Bipolar Junction Transistor (BJT) is a three-terminal semiconductor device.
- Transistor = Transfer+Resistor
- A BJT is a sandwich of one type of semiconductor material between two layers of the opposite type.
- A BJT has three terminals: *Base* (B), *Collector* (C) and *Emitter* (E)
- BJT is a current controlled device
  - A small base current controls the current flow from emitter to collector.
- In BJT, the current flow is because of both majority as well as minority charge carriers. Hence the name *bipolar*.

Introduction



Commercially available BJTs

Introduction

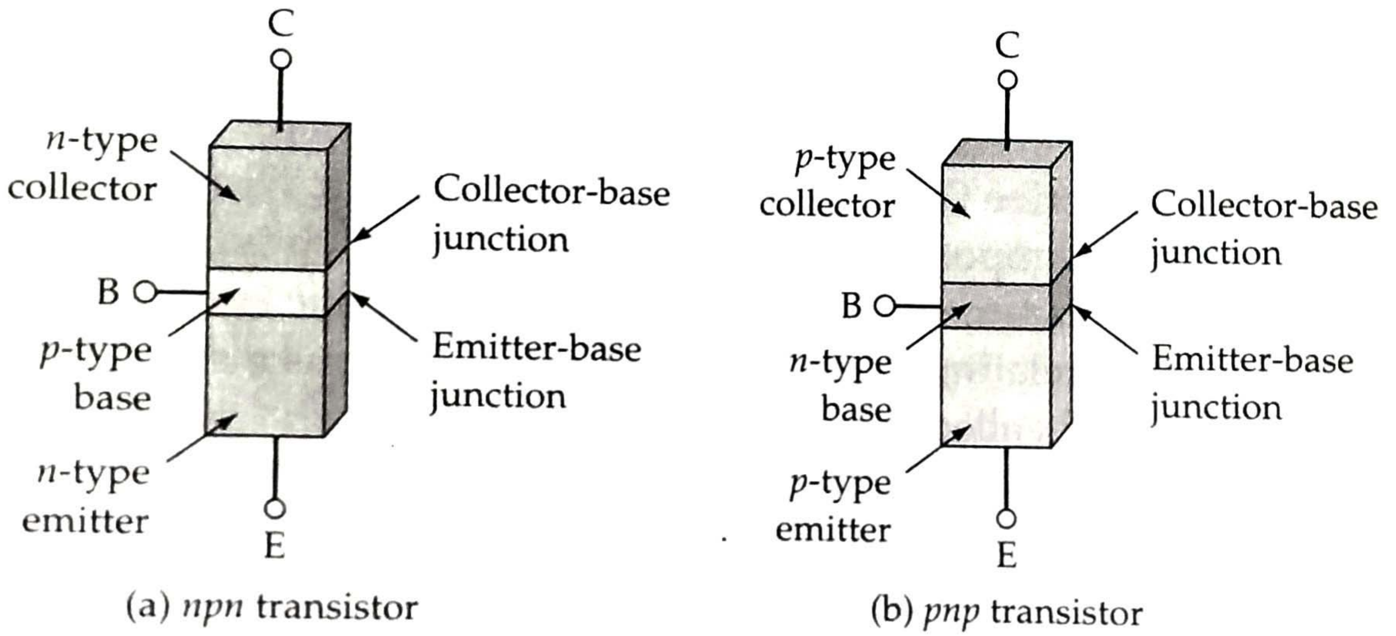
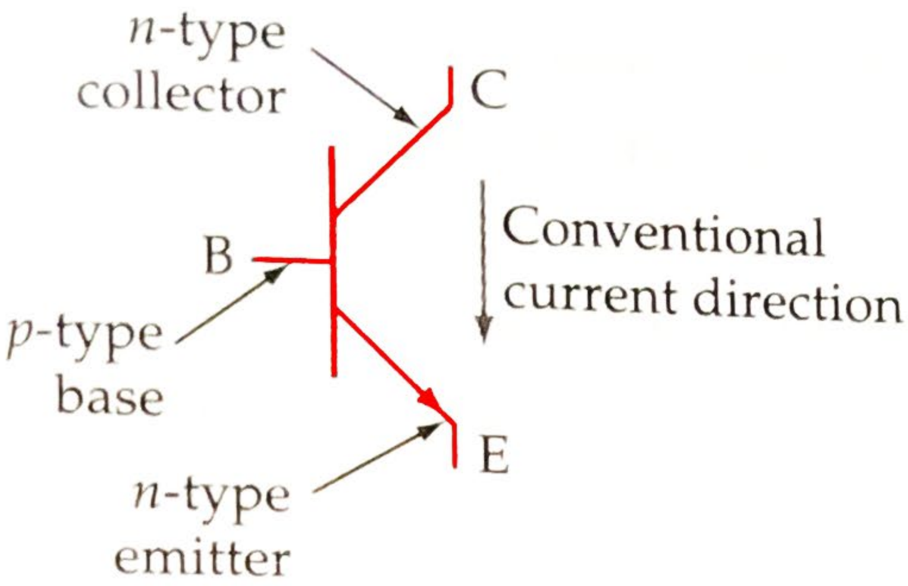


Figure 4-1 Block representation of *npn* and *pnp* bipolar junction transistors (BJTs). Each device is made up of a layer of one type of semiconductor material sandwiched between two layers of the other type.

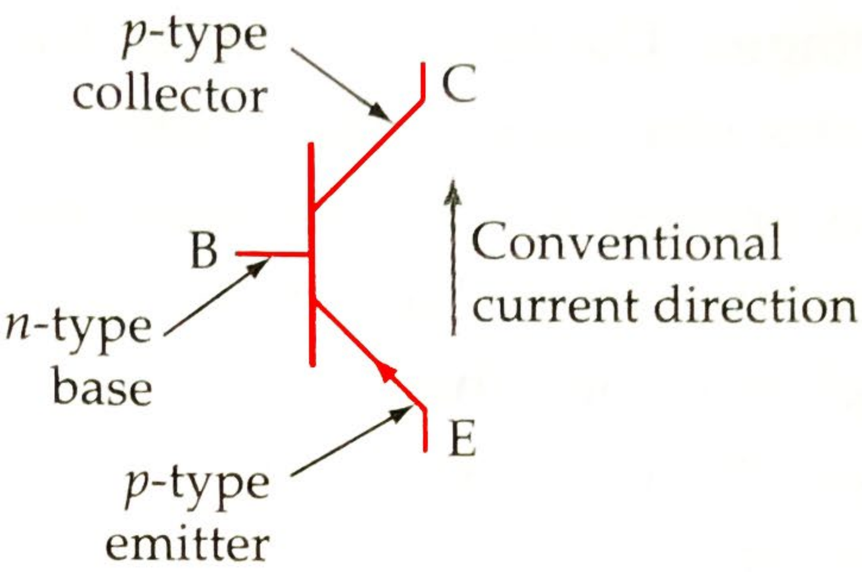
Introduction

- Three layers of BJT
  - Centre layer is called the *Base*
  - One of the outer layer is called the *Emitter*
  - The other outer layer is called the *Collector*
- In an *npn* transistor, base is of *p*-type material and emitter and collector are of *n*-type.
- In an *pnp* transistor, base is of *n*-type material and emitter and collector are of *p*-type.

BJT Symbol



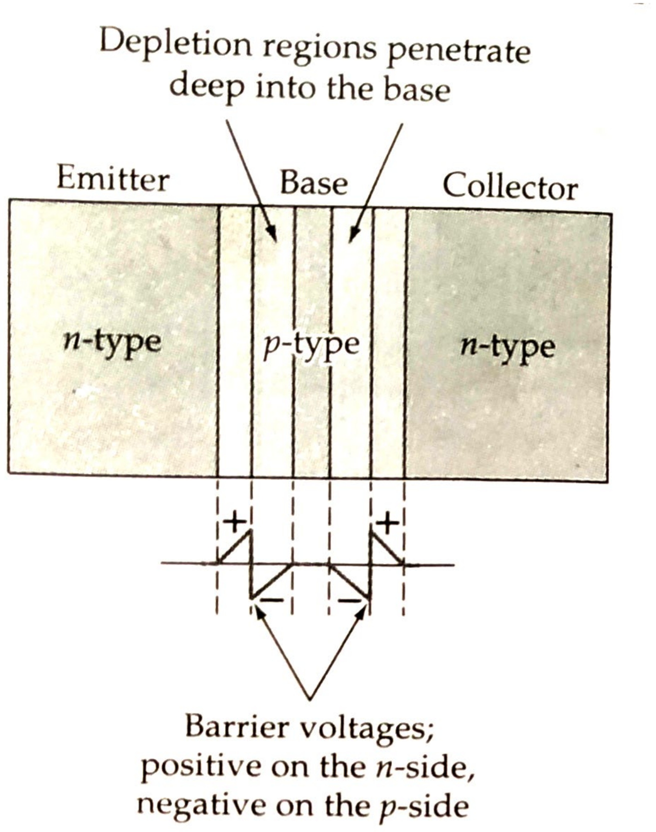
(a) *npn* transistor



(b) *pnp* transistor

BJT Operation

npn Transistor Operation



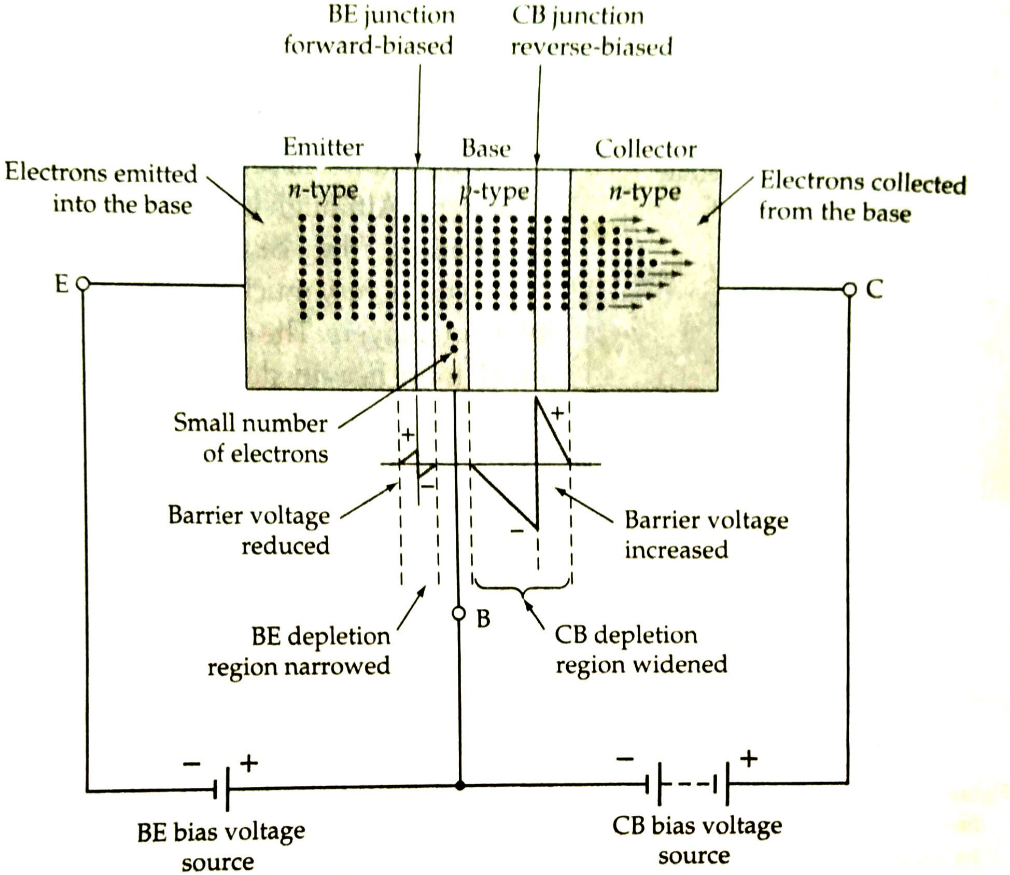
Unbiased npn Transistor

npn Transistor Operation

- The center layer (base) is very much narrower than the outer layers (emitter and collector).
- The outer layers are also much more heavily doped than the base, so that the depletion regions penetrate deep into the base.
  - As a result, the distance between the two depletion regions is very short.
- The barrier voltages are positive on the emitter and collector and negative on the base.

npn Transistor Operation

Note:
Base-Emitter **Junction is forward biased**
Collector-Base **Junction is reverse biased**



Biased npn Transistor

npn Transistor Operation

- For normal operation, the base-emitter (BE) junction is forward biased and the collector-base (CB) junction is reverse biased.
- The forward bias of the BE junction reduces the barrier voltage and causes electrons to flow from the *n*-type emitter to the *p*-type base.
- The electrons are *emitted* into the base region.
  - Hence the name *emitter.*

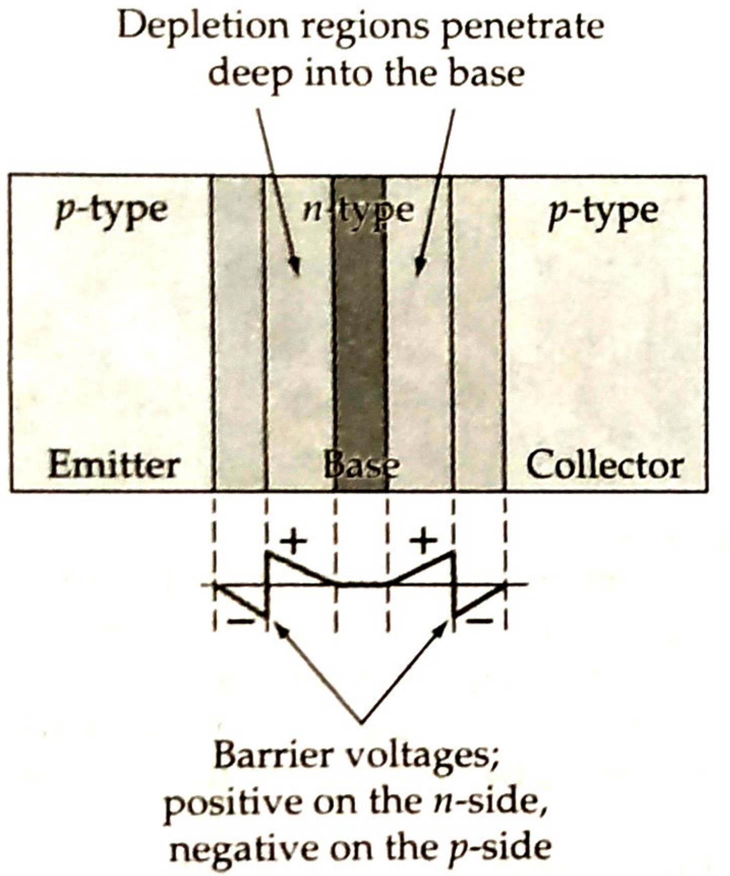
npn Transistor Operation

- The reverse bias at the CB junction cause the CB depletion region to penetrate deeper into the base.
- The electrons crossing from the emitter to the base arrive quite close to the large barrier voltage at the CB depletion region.
- Since electrons are negatively charged, they are drawn across the CB junction by this bias voltage.
- Electrons are said to be *collected* in this region.
  - Hence the name *collector*.

npn Transistor Operation

- A small percentage of the charge carriers entering the base from the emitter do not reach the collector, but flow out through the base.
- However, this number is very small because the path from the BE junction to the CB depletion region is much shorter than that to the base terminal.

pnp Transistor Operation



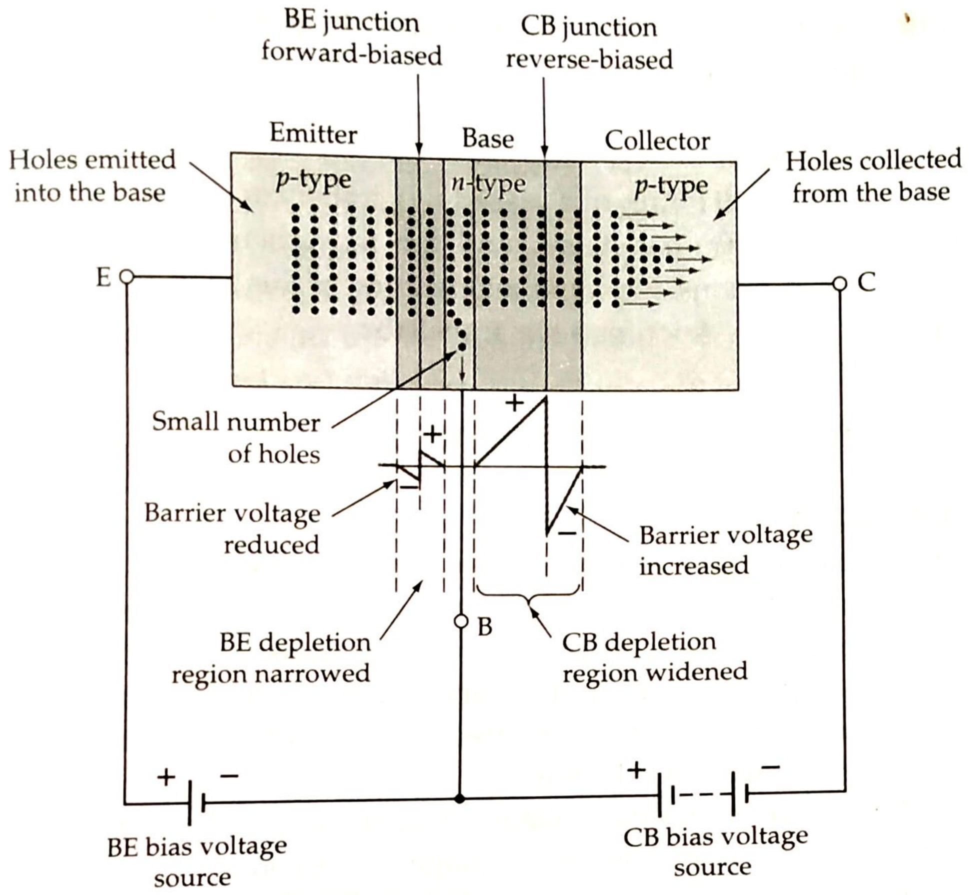
Unbiased pnp Transistor

pnp Transistor Operation

- The barrier voltages are positive on the base and negative on the emitter and collector.
- The collector and emitter are heavily doped, so that the BE and CB depletion regions penetrate deep into the lightly doped base.

pnp Transistor Operation

Note:
***Base-Emitter* Junction is forward biased**
***Collector-Base* Junction is reverse biased**



Biased pnp Transistor

pnp Transistor Operation

- For normal operation, the base-emitter (BE) junction is forward biased and the collector-base (CB) junction is reverse biased.
- Holes are emitted from the *p*-type emitter across the forward-biased BE junction into the base.
- In the *n*-type base, the holes find few electrons to absorb.
- Some of the holes flow out via the base terminal, but most are drawn across to the collector by the positive-negative electric field at the reverse biased CB junction.

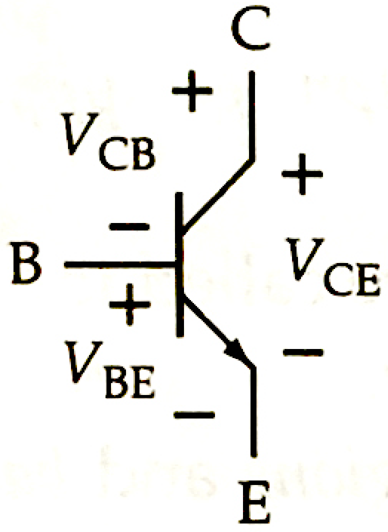
Bipolar Devices

- Although one type of charge carrier is in the majority in a *pnp* or *npn* transistor, two types of charge carriers (holes and electrons) are involved in the current flow.
- Hence these devices are called *Bipolar Junction Transistors (BJTs).*

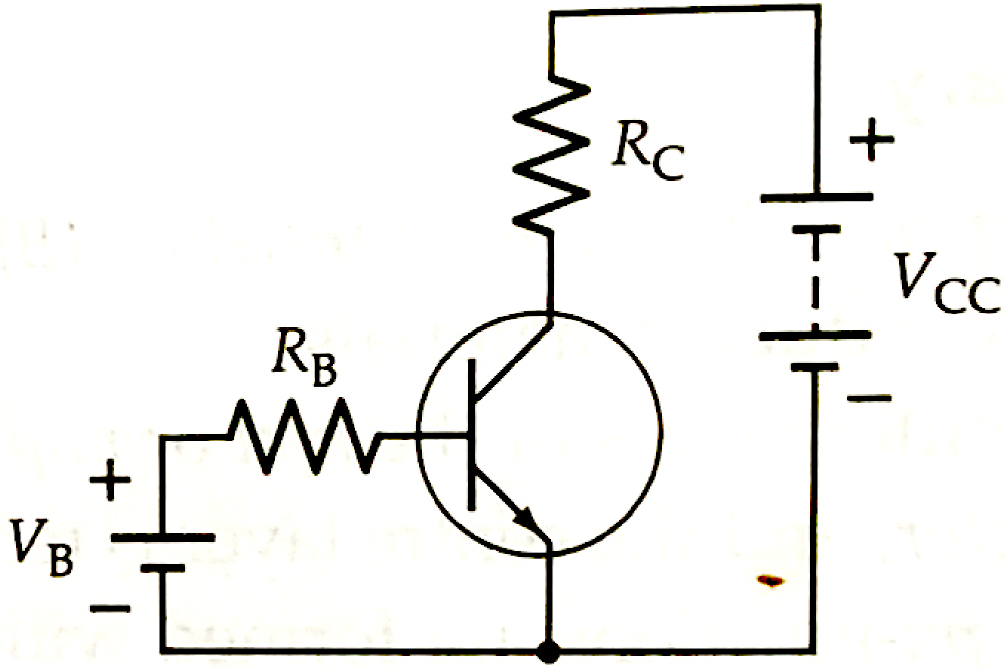
BJT Voltages and Currents

Terminal Voltages

V_{BE} → ***Base-Emitter*** **Voltage**
V_{CB} → ***Collector-Base*** **Voltage**
V_{CE} → ***Collector-Emitter*** **Voltage**



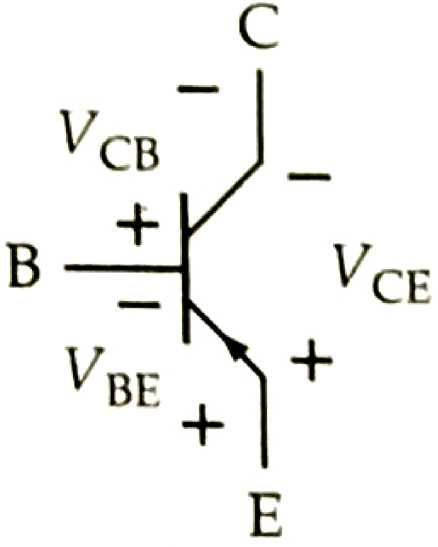
(a) *npn* terminal voltage polarities



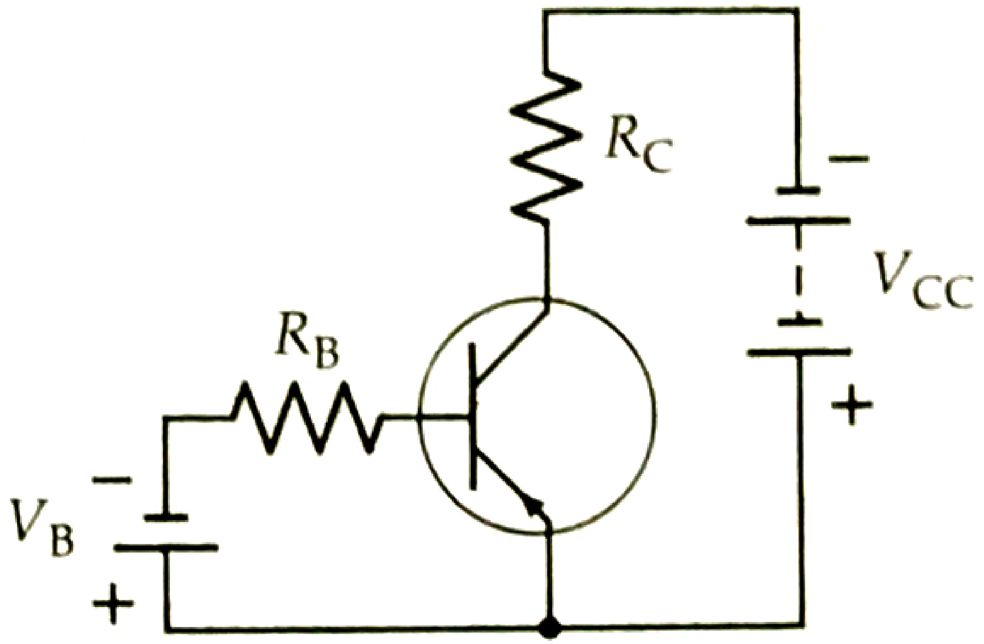
(b) Voltage source connections

Terminal Voltages

V_{BE} → ***Base-Emitter*** **Voltage**
V_{CB} → ***Collector-Base*** **Voltage**
V_{CE} → ***Collector-Emitter*** **Voltage**



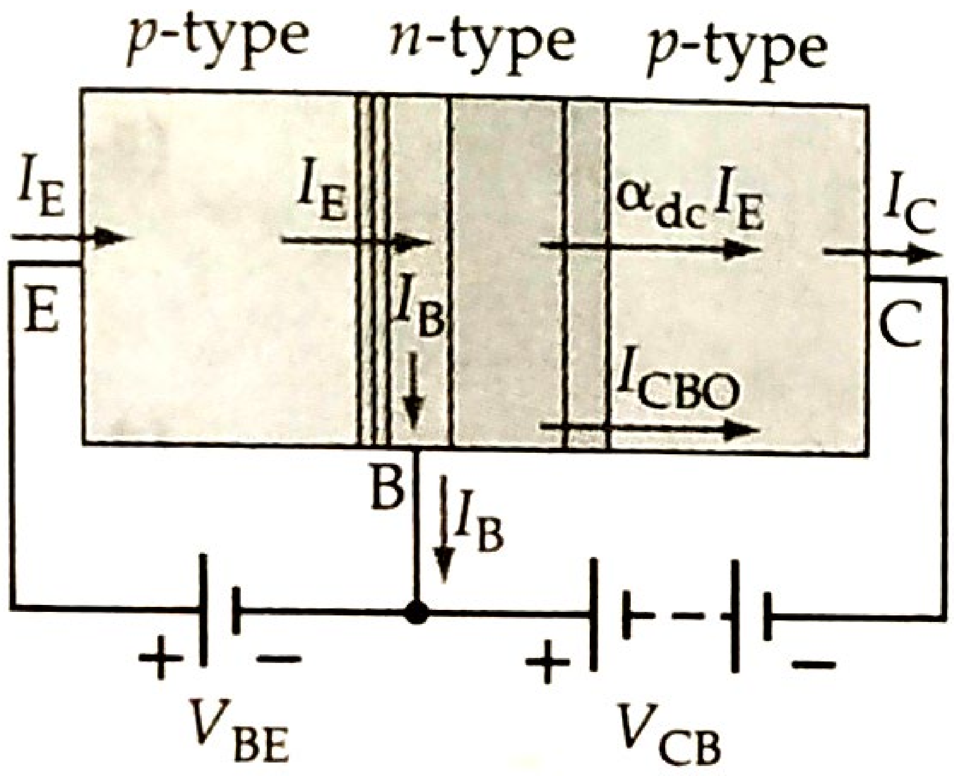
(a) *pnp* terminal voltage polarities



(b) Voltage source connections

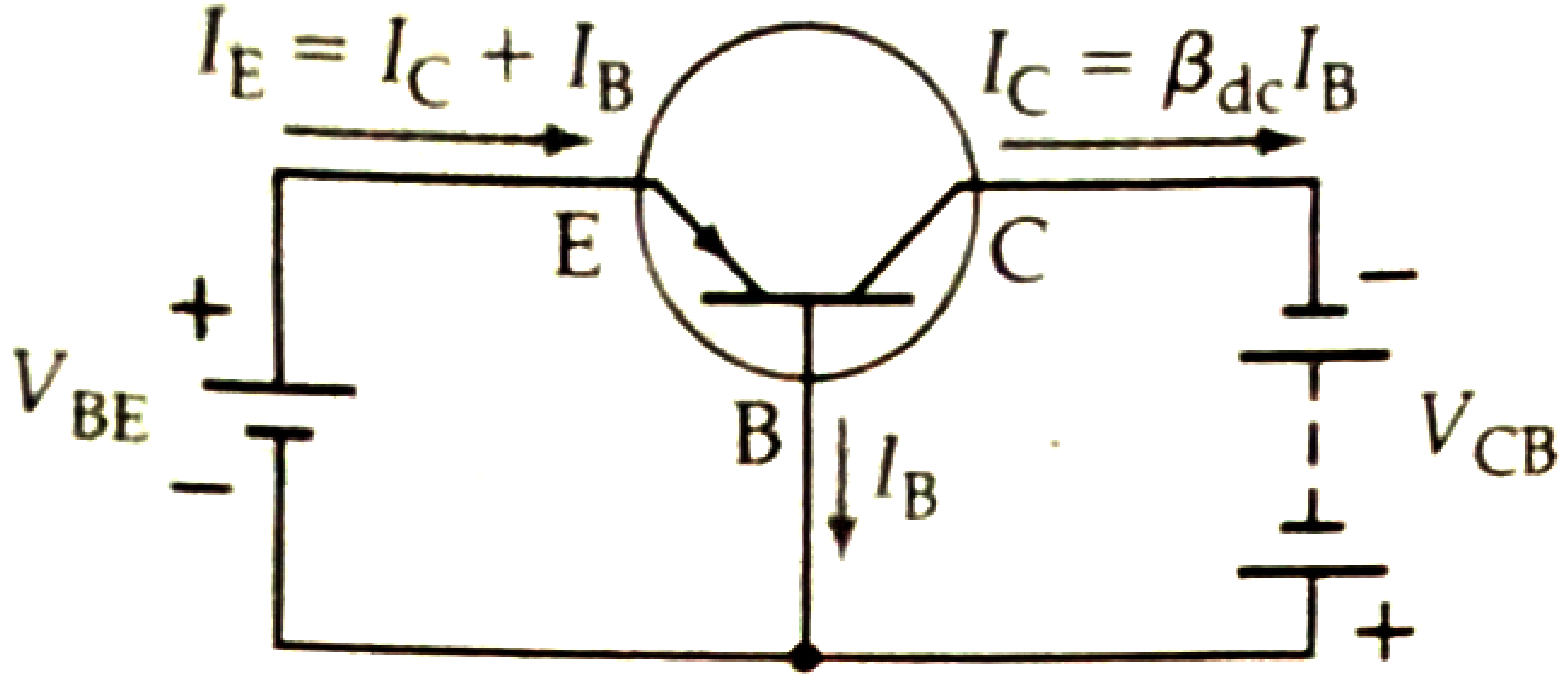
Transistor Currents

I_B → ***Base*** **Current**
I_C → ***Collector*** **Current**
I_E → ***Emitter*** **Current**



Currents in a pnp Transistor

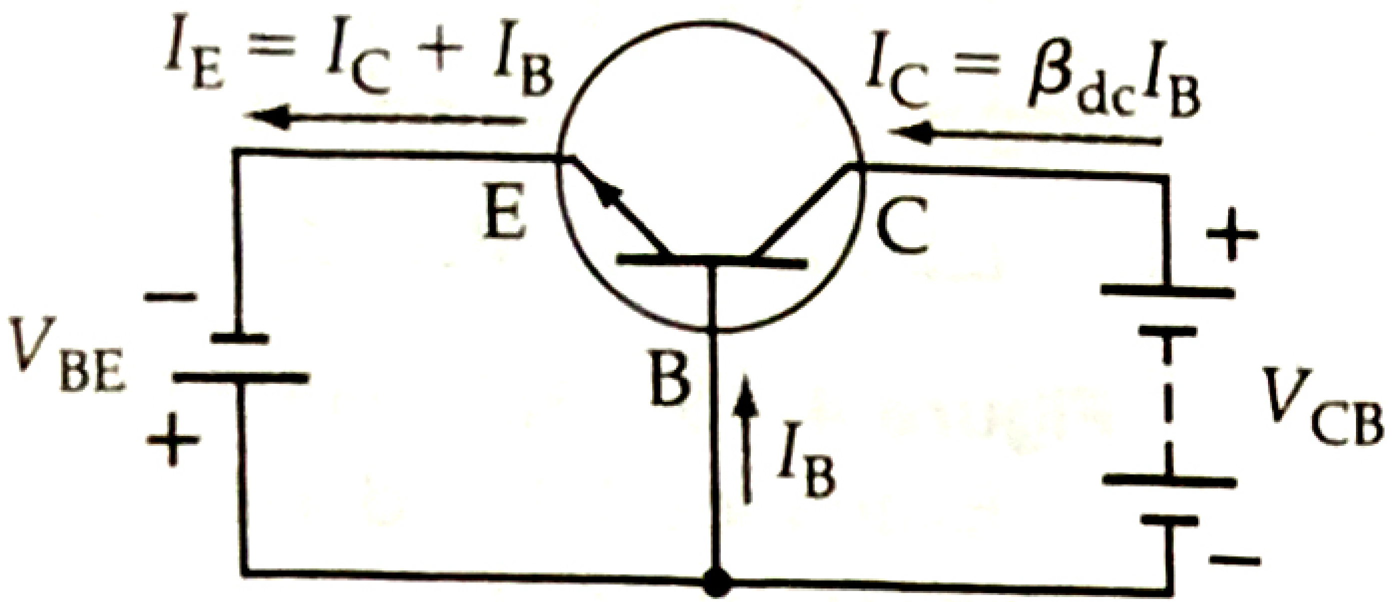
Transistor Currents



Currents in a pnp Transistor

Transistor Currents

I_B → ***Base*** **Current**
I_C → ***Collector*** **Current**
I_E → ***Emitter*** **Current**



Currents in an npn Transistor

Transistor Currents

- In *pnp* transistor, current I_E flows into the transistor, while currents I_C and I_B are flowing out.
- In *npn* transistor, current I_E flows out of the transistor, while currents I_C and I_B are flowing in.
- Hence,

$$I_E = I_C + I_B$$

- Almost all of I_E crosses to the collector and only a small portion flows out of the base.
- Also, there is a small leakage current I_{CBO} due to minority charge carriers.

Transistor Currents

- Hence we can write,

$$I_C = \alpha_{dc} I_E + I_{CBO}$$

where α_{dc} is called *emitter-to-collector current gain*, also called *common base dc current gain*. Typically its value ranges from 0.96 to 0.995.

- Since I_{CBO} is very small, it can be ignored. Hence,

$$I_C \cong \alpha_{dc} I_E$$

Transistor Currents

$$I_C = \alpha_{dc}(I_C + I_B)$$

$$I_C = \alpha_{dc}I_C + \alpha_{dc}I_B$$

$$I_C - \alpha_{dc}I_C = \alpha_{dc}I_B$$

$$I_C(1 - \alpha_{dc}) = \alpha_{dc}I_B$$

$$I_C = \frac{\alpha_{dc}}{1 - \alpha_{dc}}I_B$$

$$\frac{I_C}{I_B} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

Transistor Currents

- But $\frac{I_C}{I_B}$ is base-to-collector current gain β_{dc}.

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

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

- β_{dc} is also called common emitter dc current gain. Typically, its value ranges from 25 to 300. β_{dc} is also indicated as h_{FE}.

$$\alpha_{dc} = \frac{\beta_{dc}}{1 + \beta_{dc}}$$

BJT Amplification

Current Amplification

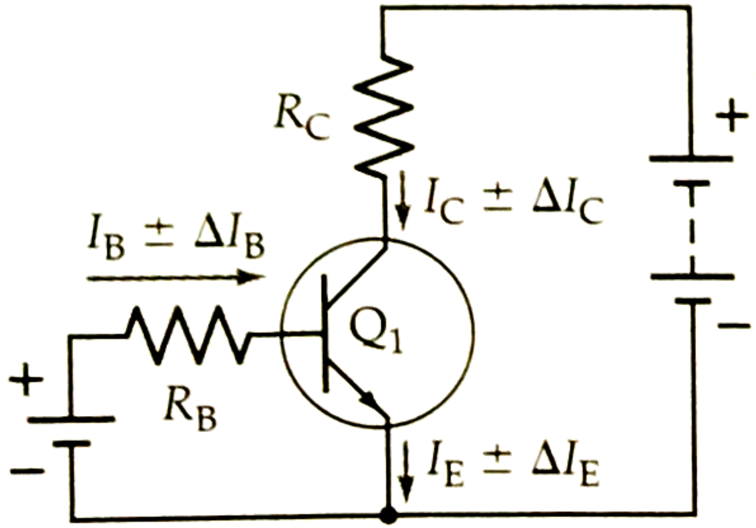
- A small change in the base current (ΔI_B) produces a large change in collector current (ΔI_C) and also a large change in emitter current (ΔI_E).
  - Thus, transistor can be used for current amplification.
- The current gain can be stated in terms of current level changes.

$$\beta_{dc} = \frac{\Delta I_C}{\Delta I_B}$$

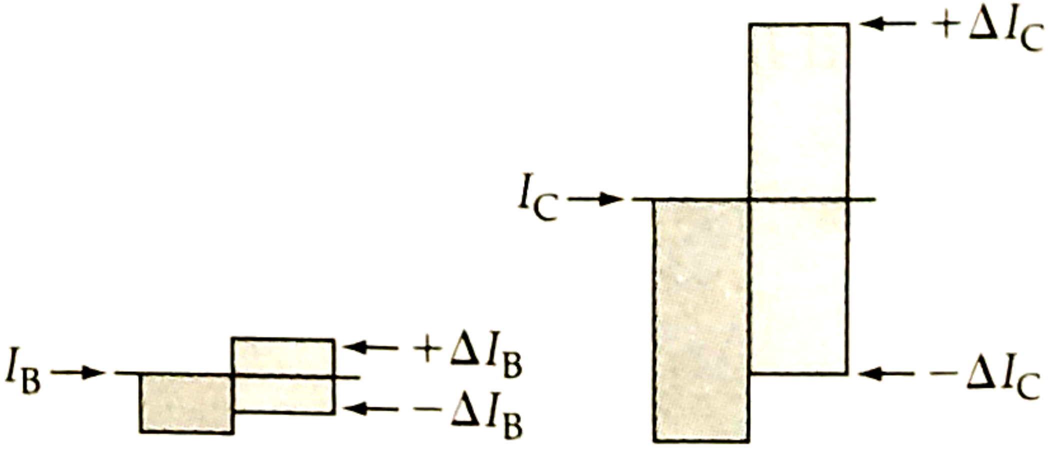
- The increasing and decreasing levels of currents may be defined as alternating quantities.
  - I_b is ac base current, I_c is ac collector and I_e is ac emitter current.

Current Amplification

$$\beta_{dc} = \frac{\Delta I_C}{\Delta I_B}$$



(a) Current levels and current changes



(b) Base and collector currents

Current Amplification

- The alternating current gain from base to collector may now be stated as

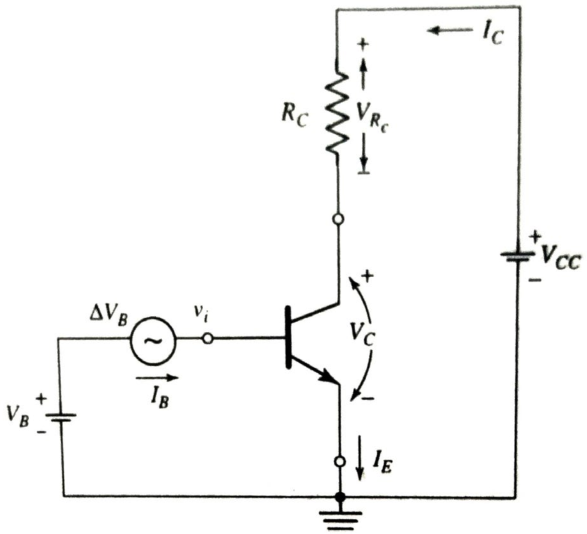
$$\beta_{ac} = \frac{I_c}{I_b}$$

- The ac current gain β_{ac} is also indicated as h_{fe}.

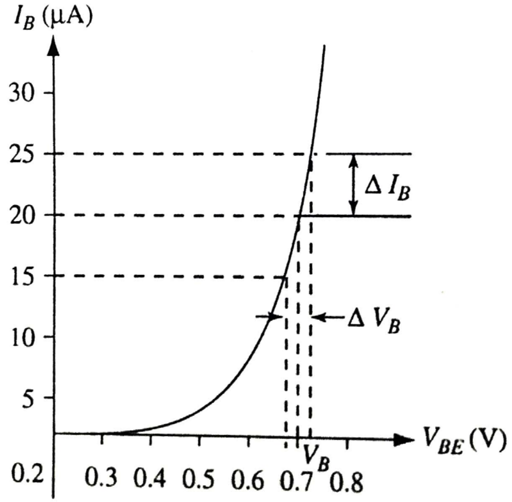
Voltage Amplification

- A change in input voltage V_B produces a change in input current I_B.
- This results in larger changes in I_C and output voltage V_C.
- The changes in output voltage are much larger than the changes in input voltage.
- Thus, transistor can be used for voltage amplification.

Voltage Amplification



(a) Transistor circuit with base bias and signal generator



(b) V_{BE} changes produce I_B changes

Figure 4-17 BJT voltage amplification. Increasing and decreasing the (input) V_B voltage ($\pm\Delta V_B$) produces I_B changes. This results in larger I_C changes and (output) V_C variations ($\pm\Delta V_C$) that are larger than the input voltage changes.

Voltage Amplification

- We know that,

$$I_C = \beta_{dc} I_B$$

- From the circuit,

$$V_{CC} = V_C + I_C R_1$$

$$V_C = V_{CC} - I_C R_1$$

- If input voltage changes by ΔV_B, it causes a change in input current by ΔI_B, which results in larger changes in out put current by ΔI_C.
-

Voltage Amplification

- Then,

$$\Delta I_C = \beta_{dc} \Delta I_B$$

- Now this change ΔI_C causes a change in the voltage drop across R_1 and thus produces a variation in collector voltage, given by,

$$\Delta V_C = \Delta I_C R_1$$

- The base voltage change ΔV_B is the ac input and collector voltage change ΔV_C is ac output.
- Since the output is larger than the input, it is a voltage amplifier and the circuit has a voltage gain.

Voltage Amplification

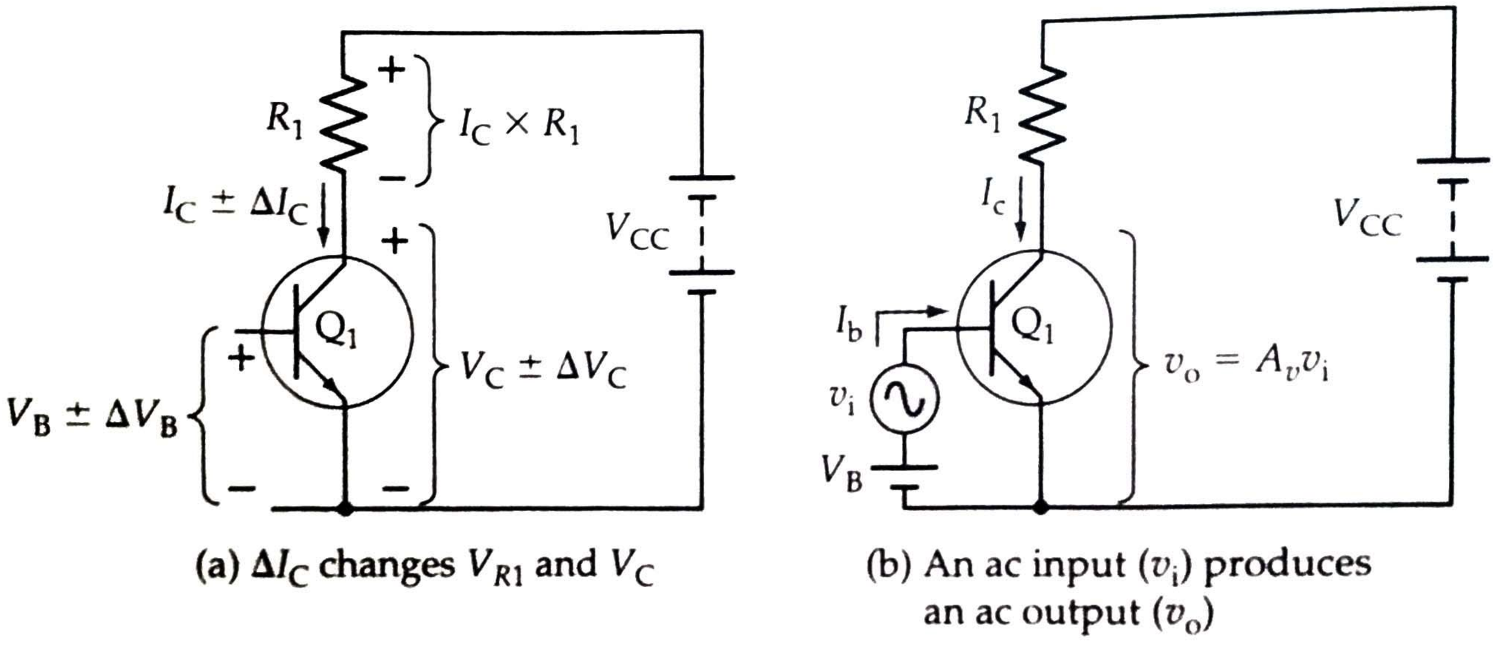


Figure 4-18 I_C changes produce changes in the voltage drop across the collector resistor (R_1), which result in V_C changes. This means that an ac input voltage (v_i) produces an amplifier output voltage ($v_o = A_v v_i$).

Voltage Amplification

- The voltage gain is the ratio of the output voltage to the input voltage, given by,

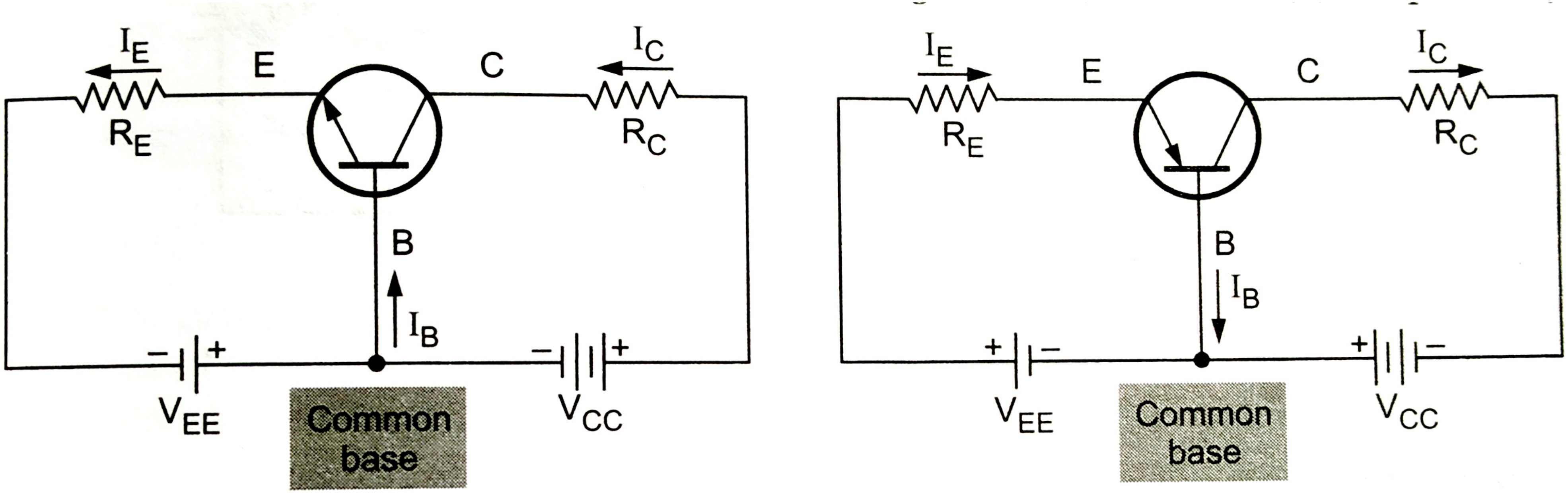
$$A_v = \frac{\Delta V_C}{\Delta V_B}$$

- The increasing and decreasing voltage levels can be defined as ac quantities.
- The ac signal voltage v_i produces the ac base current I_b, and this generates the ac collector current I_c, which produces the ac output voltage v_o.
- The equation for ac voltage gain is

$$A_v = \frac{v_o}{v_i}$$

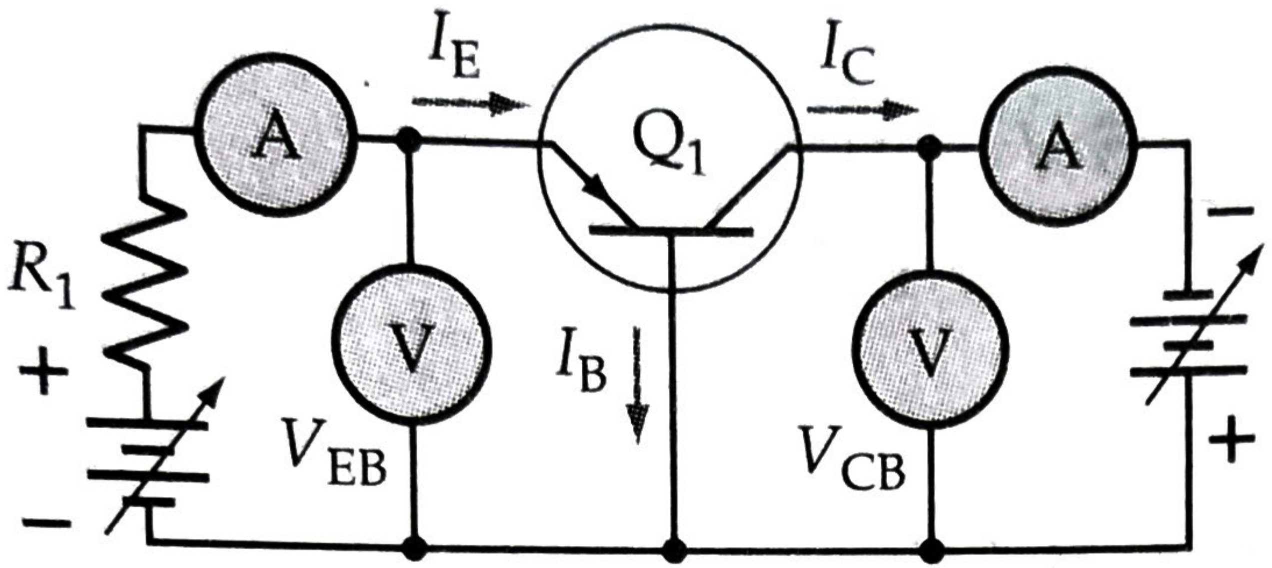
Common Base Characteristics

Common Base Circuit



(a) npn transistor (b) pnp transistor

Common Base Circuit



Common-Base Input Characteristics

- To investigate the input characteristics, the output voltage V_{CB} is kept constant and the input voltage V_{EB} is set at several convenient levels.
- At each input voltage, the corresponding input current I_E is recorded.
- A graph is then plotted for V_{EB} vs I_E.
- This is repeated for other values of V_{CB}.

Common-Base Input Characteristics

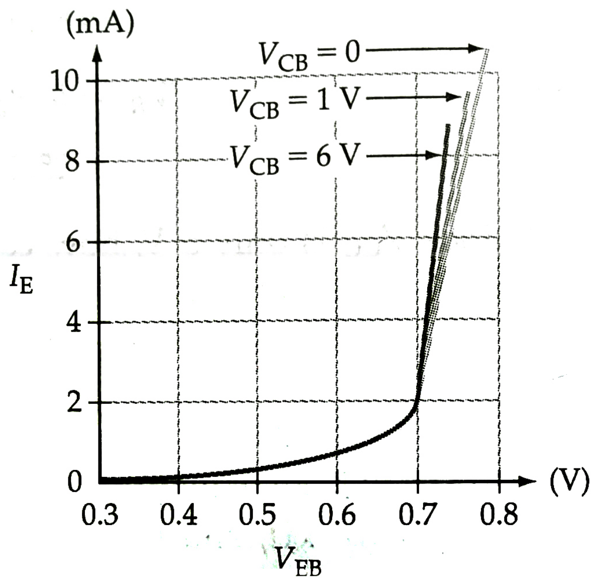


Figure 4-23 The common-base input characteristics for a BJT are (input) emitter current I_E plotted versus (input) base-emitter voltage V_{EB}. The characteristics are similar to those of a forward biased *pn*-junction.

Common-Base Input Characteristics

- Since the emitter-base junction is forward biased, the characteristics are those of a forward-biased *pn*-junction.
- Also, for a given input voltage V_{EB}, more input current flows when higher levels of collector-base voltage V_{CB} are used.
- This is because larger collector-base (reverse bias) voltages causes the depletion region at the collector-base junction to penetrate deeper into the base, thus shortening the distance and reducing the resistance between the emitter-base and collector-base depletion regions.

Common-Base Output Characteristics

- To investigate the output characteristics, the input current I_E is kept constant and the output voltage V_{CB} is set at several convenient levels.
- At each output voltage, the corresponding output current I_C is recorded.
- A graph is then plotted for V_{CB} vs I_C.
- This is repeated for other values of I_E.

Common-Base Output Characteristics

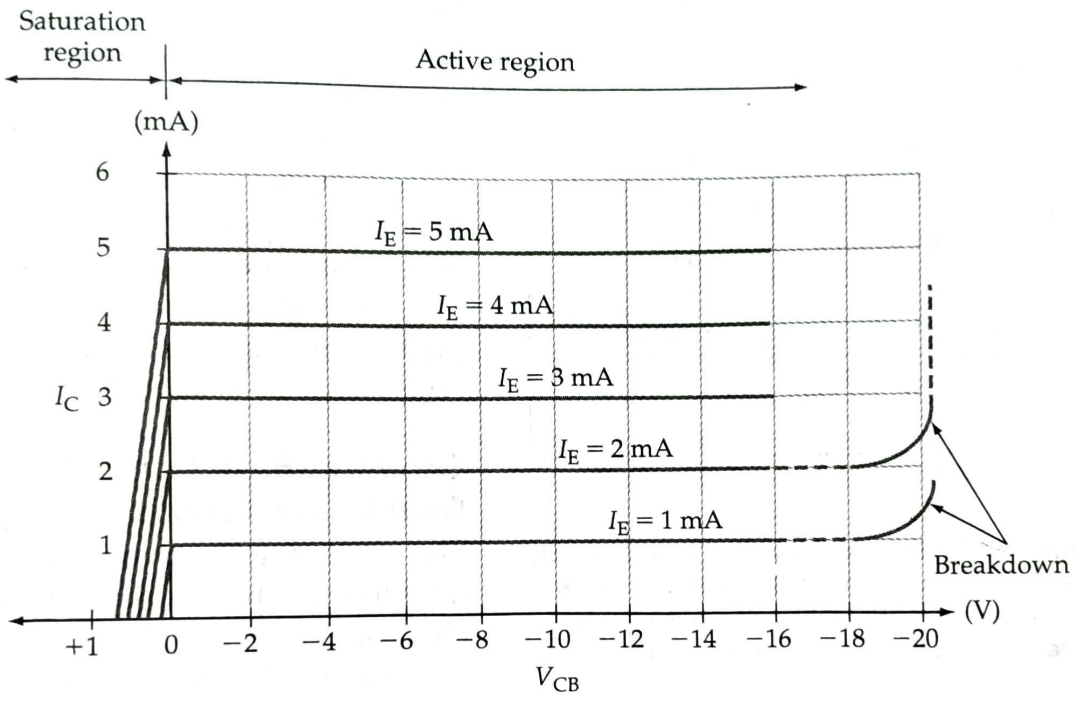


Figure 4-24 The common-base output characteristics (or collector characteristics) for a BJT are a graph of (output) collector current I_C plotted versus (output) collector-base voltage V_{CB} for various constant levels of (input) emitter current I_E. In the active region, I_C remains substantially constant for each level of I_E regardless of V_{CB}. In the saturation region, I_C is reduced to zero when V_{CB} is forward-biased.

Common-Base Output Characteristics

- The common-base output characteristics show that for each fixed level of I_E, I_C is almost equal to I_E, and I_C appears to remain constant when V_{CB} is increased.
- There is a very small increase in I_C with increasing V_{CB}. This is because the increase in V_{CB} expands the collector-base depletion region and thus shortens the distance between the two depletion regions.
- The slope on the output characteristics is also called *Early effect*.

Common-Base Output Characteristics

- When V_{CB} is reduced to zero, I_C still flows. This is because, even when the externally applied voltage is zero, there is still a barrier voltage existing at the collector-base junction, and this assists the flow of I_C.
- To stop the flow of charge carriers, the collector-base junction has to be forward-biased.
- The region of the graph for the forward-biased collector-base junction is known as the *saturation region*.
- The region in which the junction is reverse-biased is known as the *active region*.
  - This is the normal operating region for the transistor.

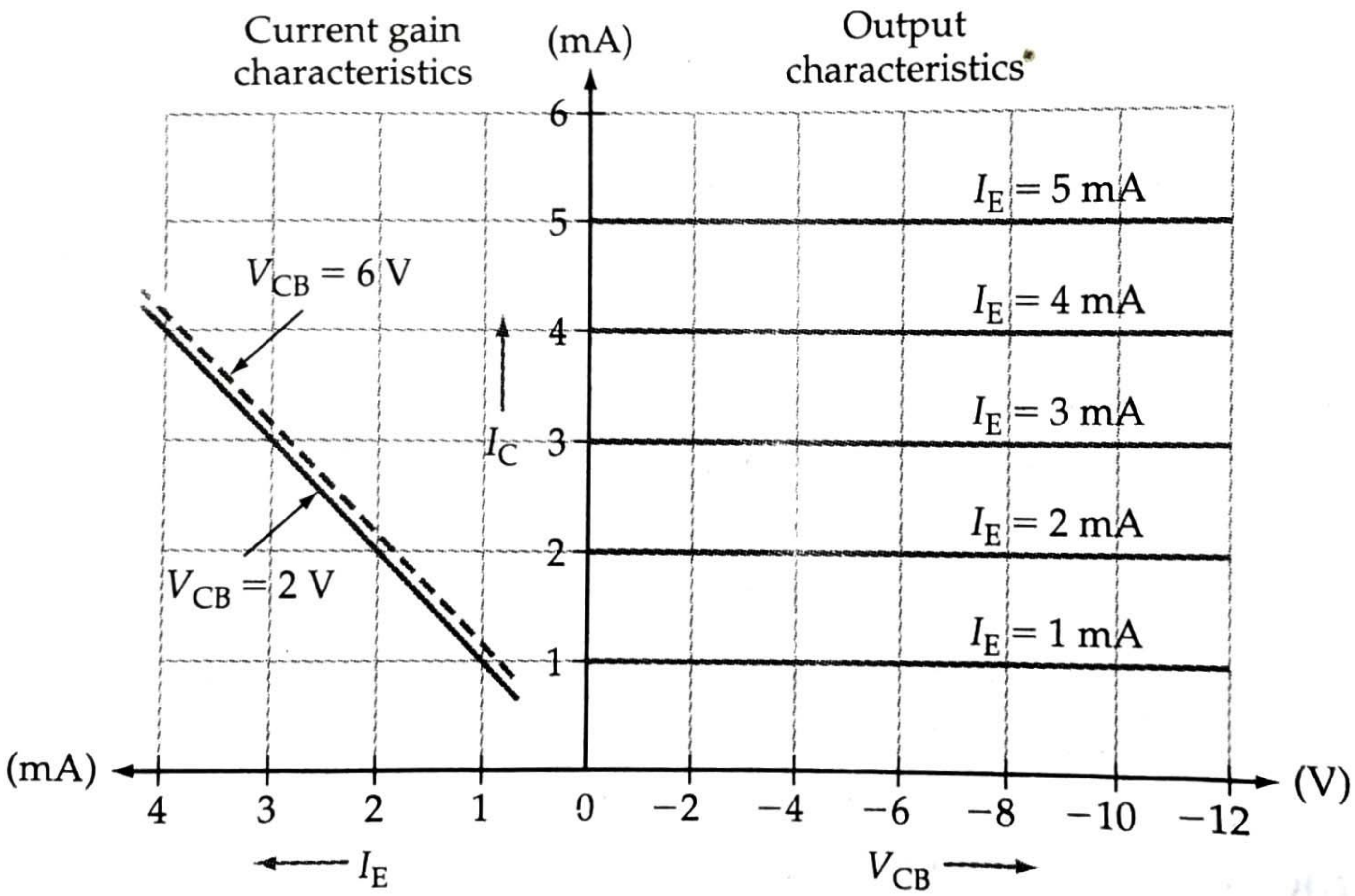
Common-Base Output Characteristics

- If an excessive reverse-bias voltage is applied to the collector-base junction, the device breakdown may occur.
- Breakdown can also result from the collector-base depletion region penetrating into the base until it makes contact with the emitter-base depletion region.
- This condition is known as *punch-through* or *reach-through*, and very large currents can flow when it occurs, destroying the device.

Common-Base Current Gain Characteristics

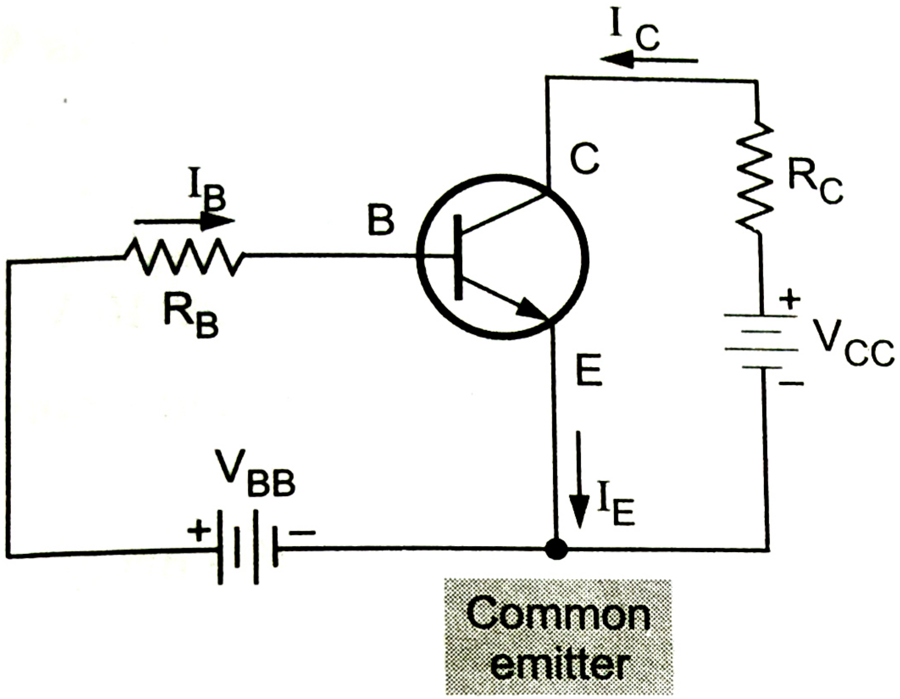
- To investigate the current gain characteristics, the output voltage V_{CB} is kept constant and the input current I_E is set at several convenient levels.
- At each input current, the corresponding output current I_C is recorded.
- A graph is then plotted for I_E vs I_C.
- This is repeated for other values of V_{CB}.
- The common-base current gain characteristics can be derived from the output characteristics as shown.

Common-Base Current Gain Characteristics

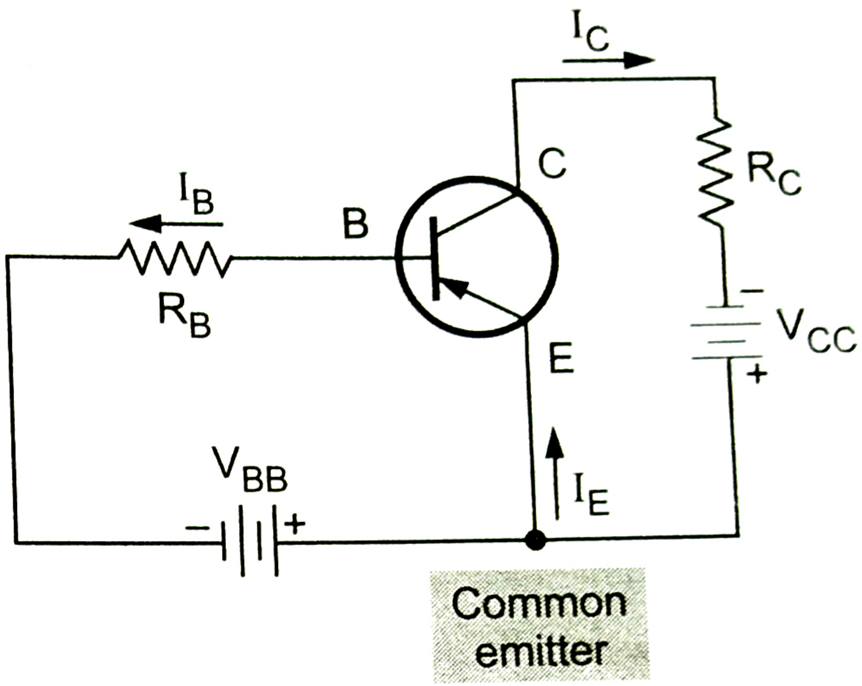


Common Emitter Characteristics

Common Emitter Configuration

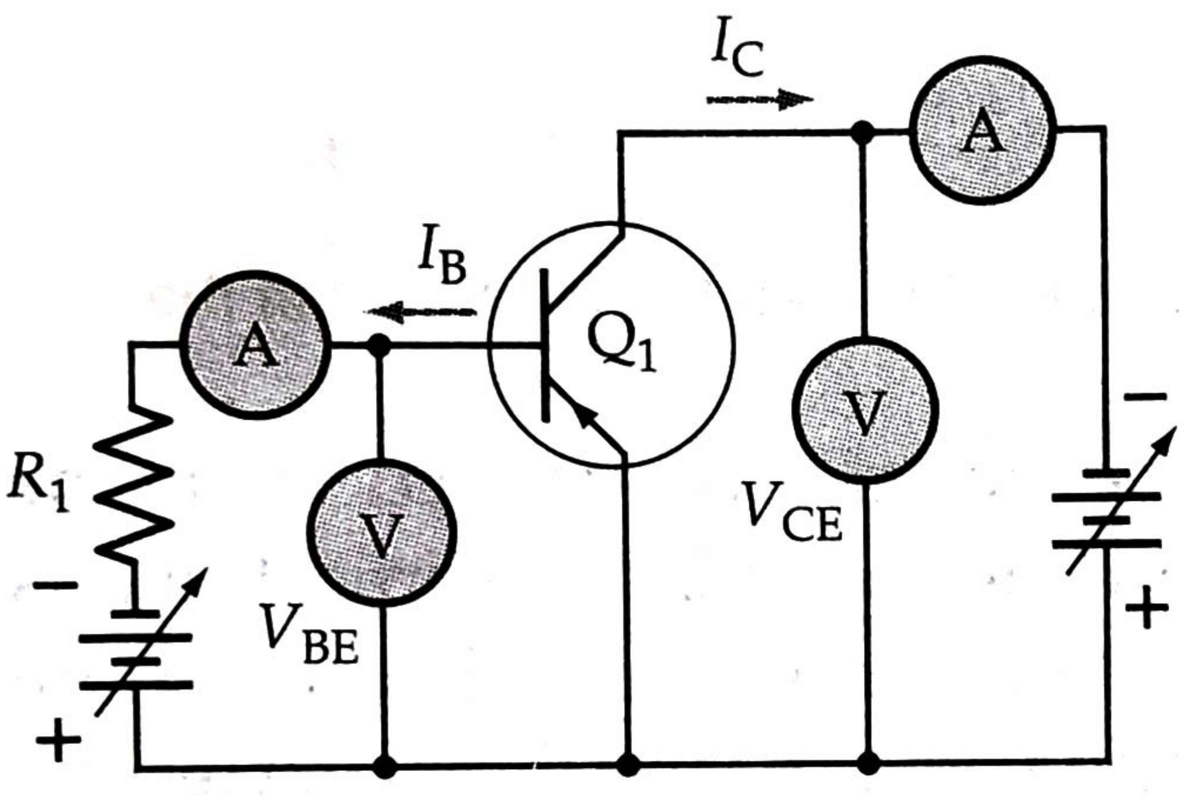


(a) npn transistor



(b) pnp transistor

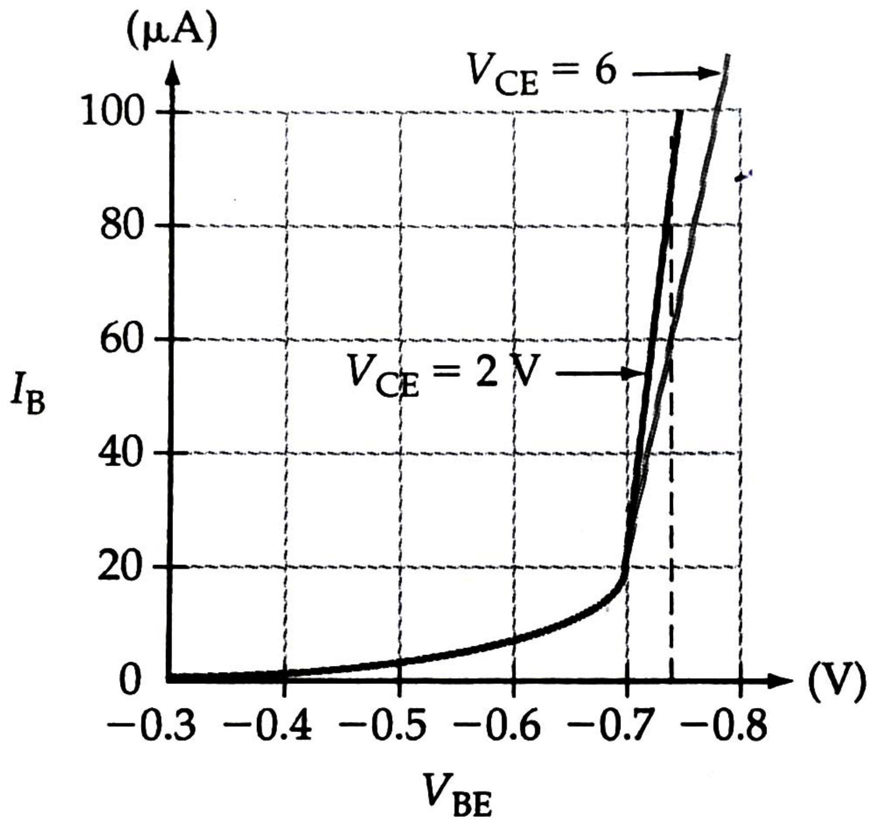
Common Emitter Circuit



Common-Emitter Input Characteristics

- To investigate the input characteristics, the output voltage V_{CE} is kept constant and the input voltage V_{BE} is set at several convenient levels.
- At each input voltage, the corresponding input current I_B is recorded.
- A graph is then plotted for V_{BE} vs I_B.
- This is repeated for other values of V_{CE}.

Common-Emitter Input Characteristics



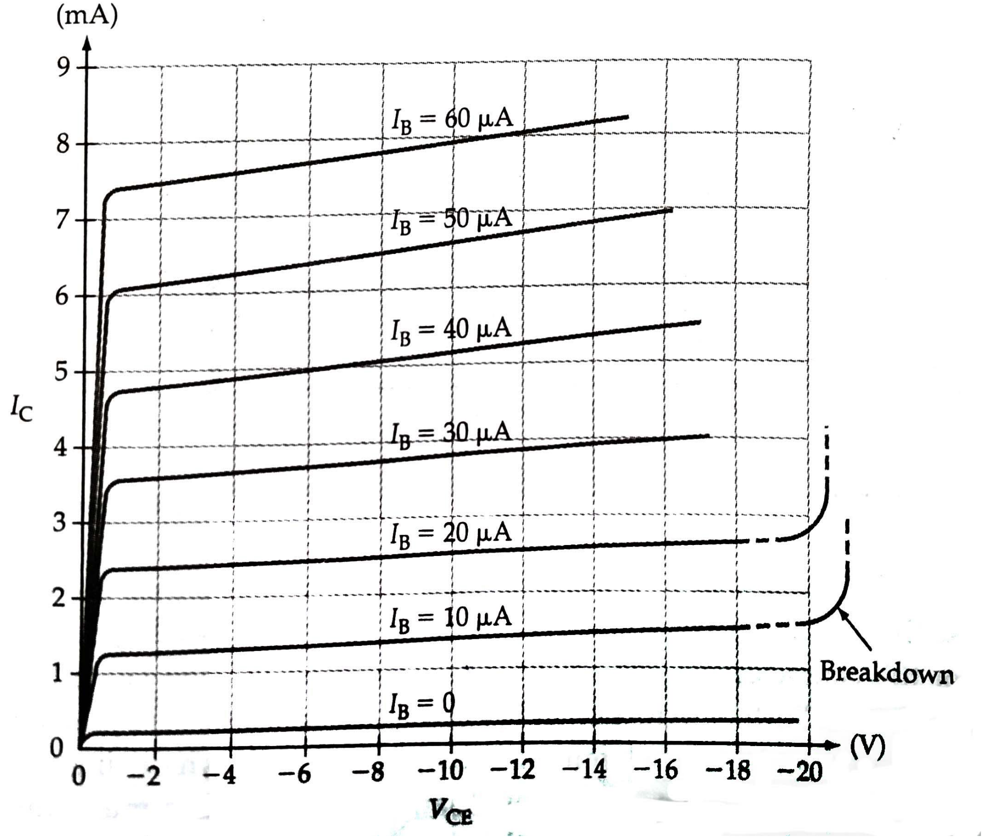
Common-Emitter Input Characteristics

- Since the base-emitter junction is forward biased, the characteristics are those of a forward-biased *pn*-junction.
- Also, for a given input voltage V_{BE}, I_B is reduced when higher levels of V_{CE} are used.
- This is because the higher V_{CE} produces greater depletion region penetration into the base, reducing the distance between the collector-base and emitter-base depletion regions.
- Consequently, the current I_C increases, whereas I_B reduces.

Common-Emitter Output Characteristics

- To investigate the output characteristics, the input current I_B is kept constant and the output voltage V_{CE} is set at several convenient levels.
- At each output voltage, the corresponding output current I_C is recorded.
- A graph is then plotted for V_{CE} vs I_C.
- This is repeated for other values of I_B.

Common-Emitter Output Characteristics



Common-Emitter Output Characteristics

- Since I_E is not held constant, when V_{CE} is increased, the distance between the depletion regions is shortened, drawing more current into the collector.
- So I_C increases when V_{CE} increases.
- The slope on the output characteristics is also called *Early effect*.
- When the characteristics are extended to the left of the current axis, they will meet at a point called Early voltage (V_A).

Common-Emitter Output Characteristics

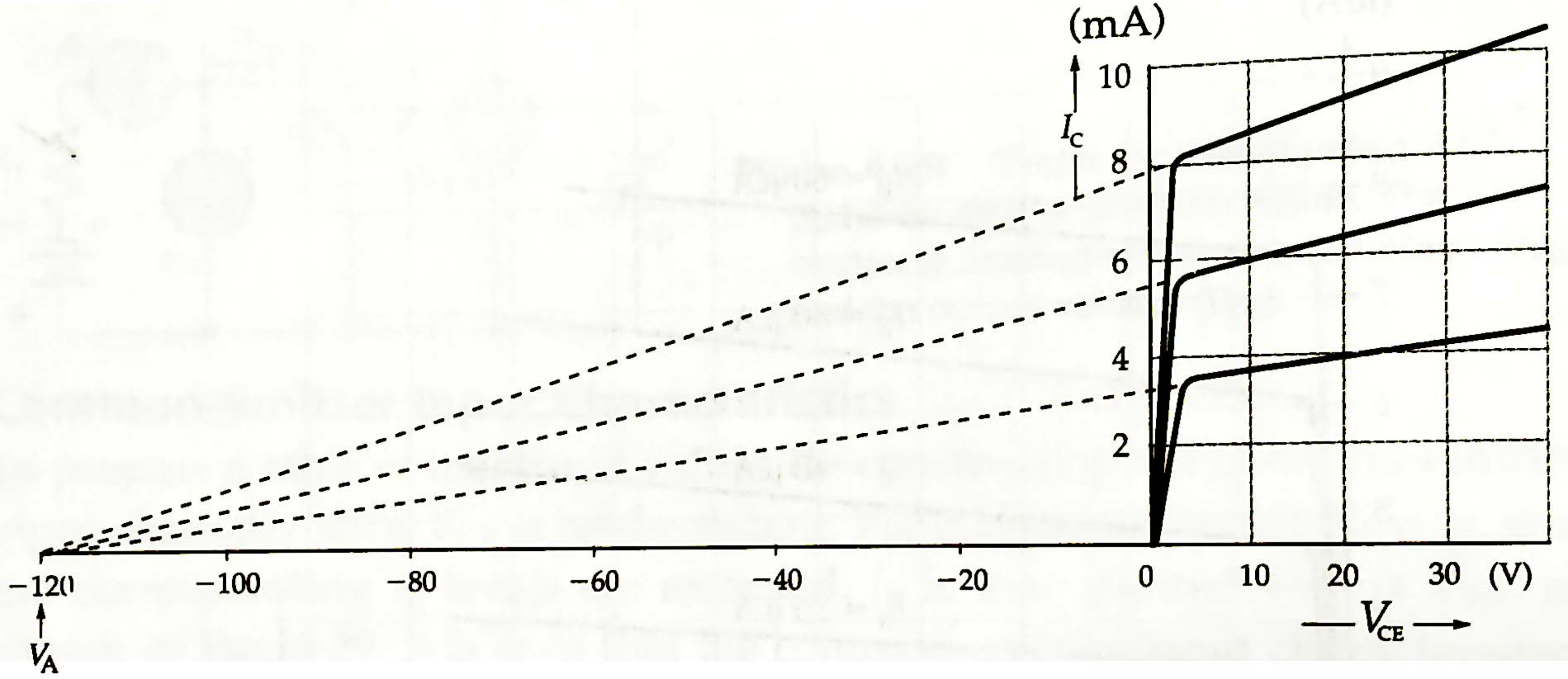
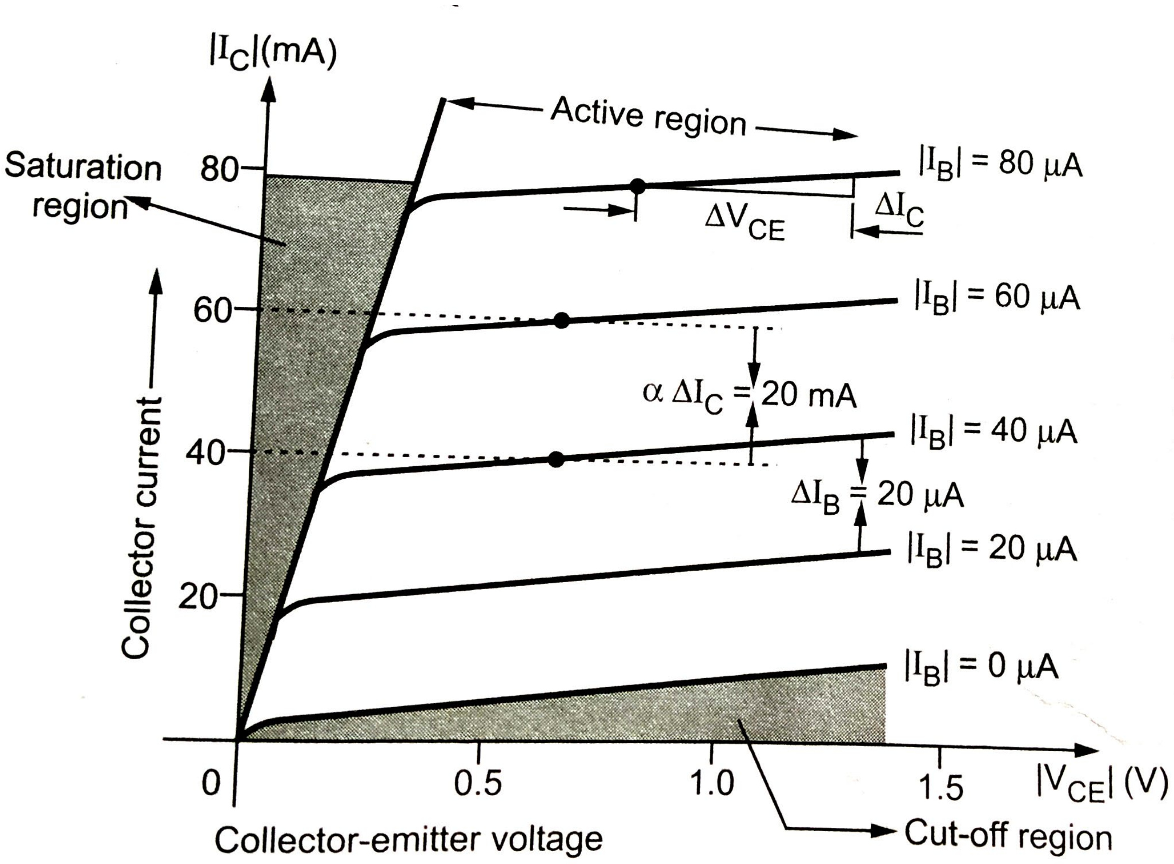


Figure 4-31 Extended common-emitter output characteristics intersect the horizontal axis at a point known as the *Early voltage*.

Common-Emitter Output Characteristics

- I_C reduces to zero when V_{CE} becomes zero.
  - This is because, V_{CE} is the sum of V_{CB} and V_{BE}.
  - At the knee of the characteristic, V_{CB} is zero.
  - Further reduction in V_{CE} causes collector-base junction to be forward-biased, and this repels minority charge carriers, thus reducing I_C to zero.
- If an excessive reverse-bias voltage is applied to the collector-base junction, the device breakdown may occur and I_C increases rapidly.

Common-Emitter Output Characteristics



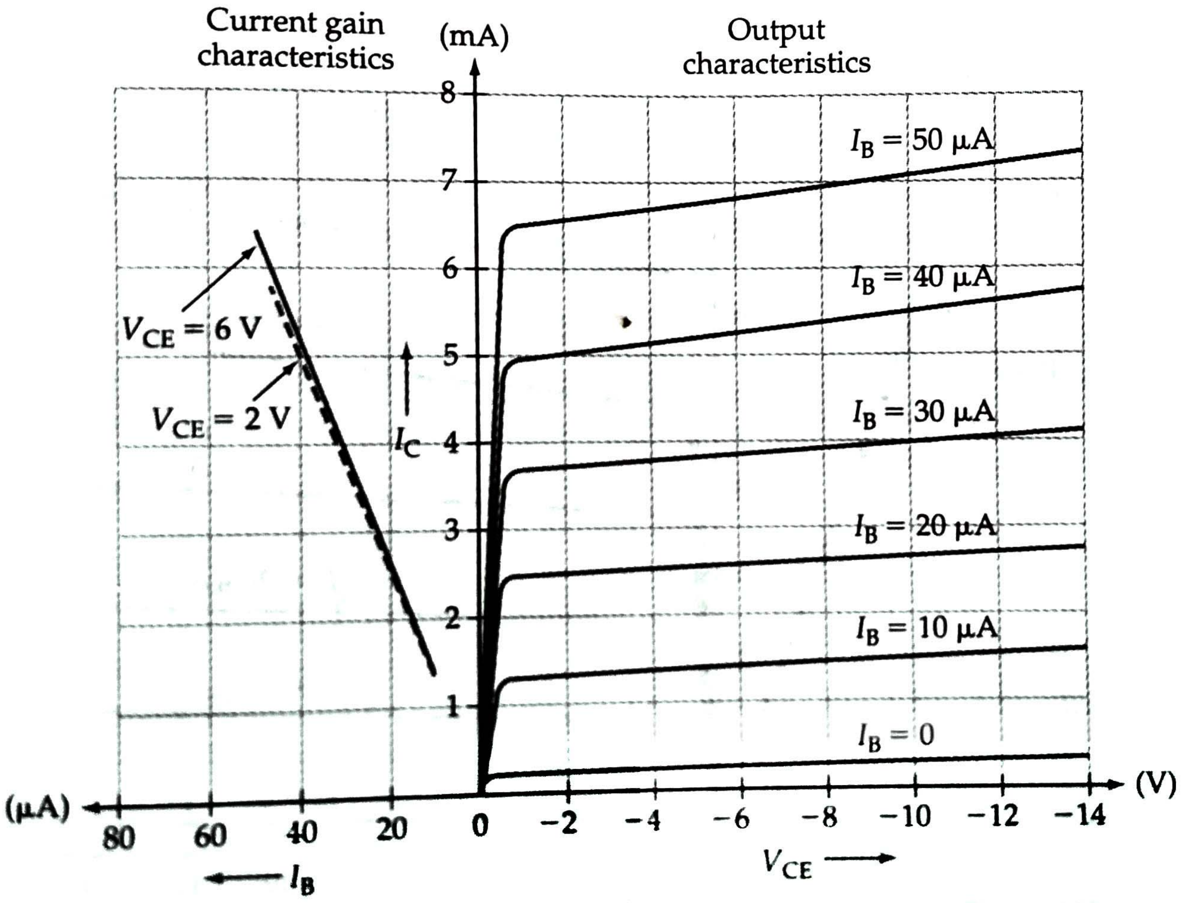
Common-Emitter Output Characteristics

- **Active region**:
  - Base-emitter junction is forward biased and collector-base junction is reverse biased.
  - BJT is used as Amplifier in this region.
- **Saturation region**:
  - Both base-emitter and collector-base junctions are forward biased.
  - BJT is used as Closed Switch in this region
- **Cut-off region**:
  - Both base-emitter and collector-base junctions are reverse biased.
  - BJT is used as Open Switch in this region

Common-Emitter Current Gain Characteristics

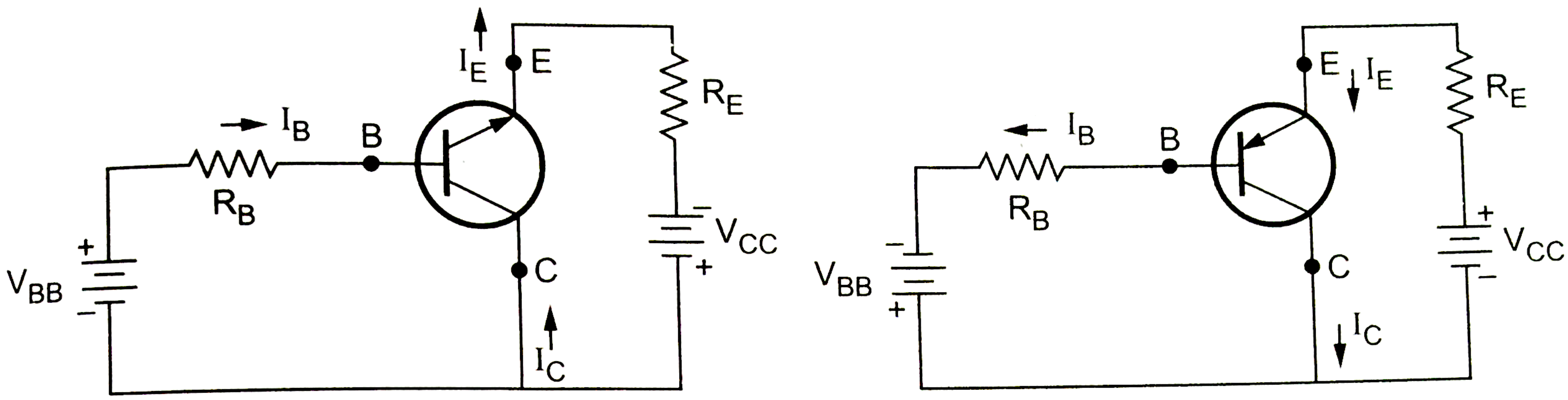
- To investigate the current gain characteristics, the output voltage V_{CE} is kept constant and the input current I_B is set at several convenient levels.
- At each input current, the corresponding output current I_C is recorded.
- A graph is then plotted for I_B vs I_C.
- This is repeated for other values of V_{CE}.
- The common-emitter current gain characteristics can be derived from the output characteristics as shown.

Common-Emitter Current Gain Characteristics



Common Collector Characteristics

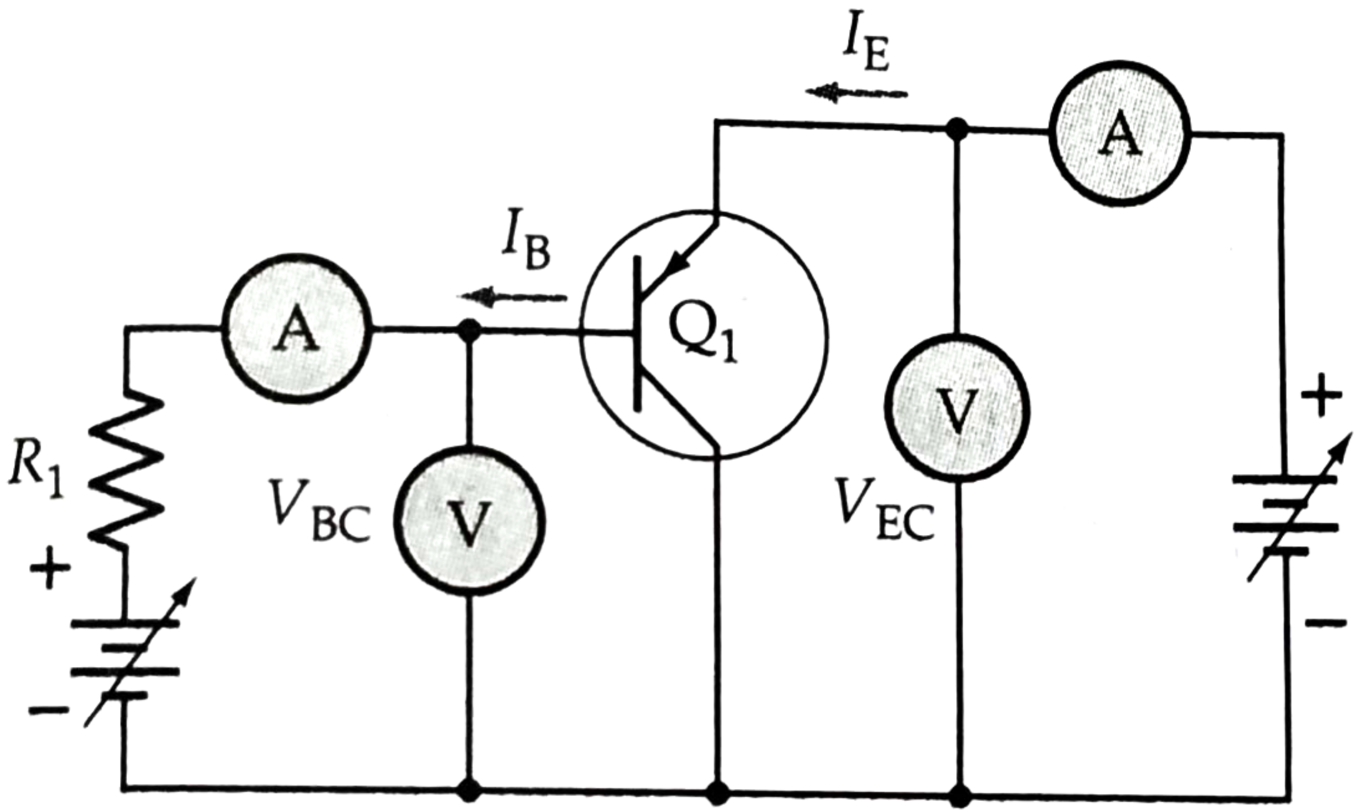
Common Collector Configuration



(a) npn

(b) pnp

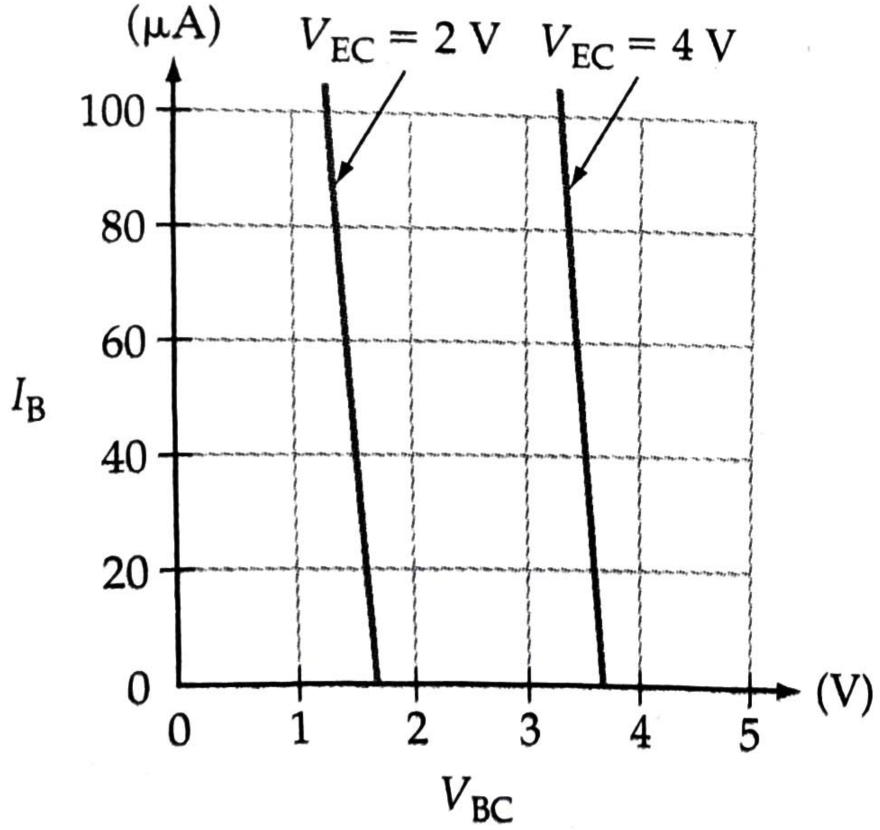
Common-Collector Circuit



Common-Collector Input Characteristics

- To investigate the input characteristics, the output voltage V_{EC} is kept constant and the input voltage V_{BC} is set at several convenient levels.
- At each input voltage, the corresponding input current I_B is recorded.
- A graph is then plotted for V_{BC} vs I_B.
- This is repeated for other values of V_{EC}.

Common-Collector Input Characteristics



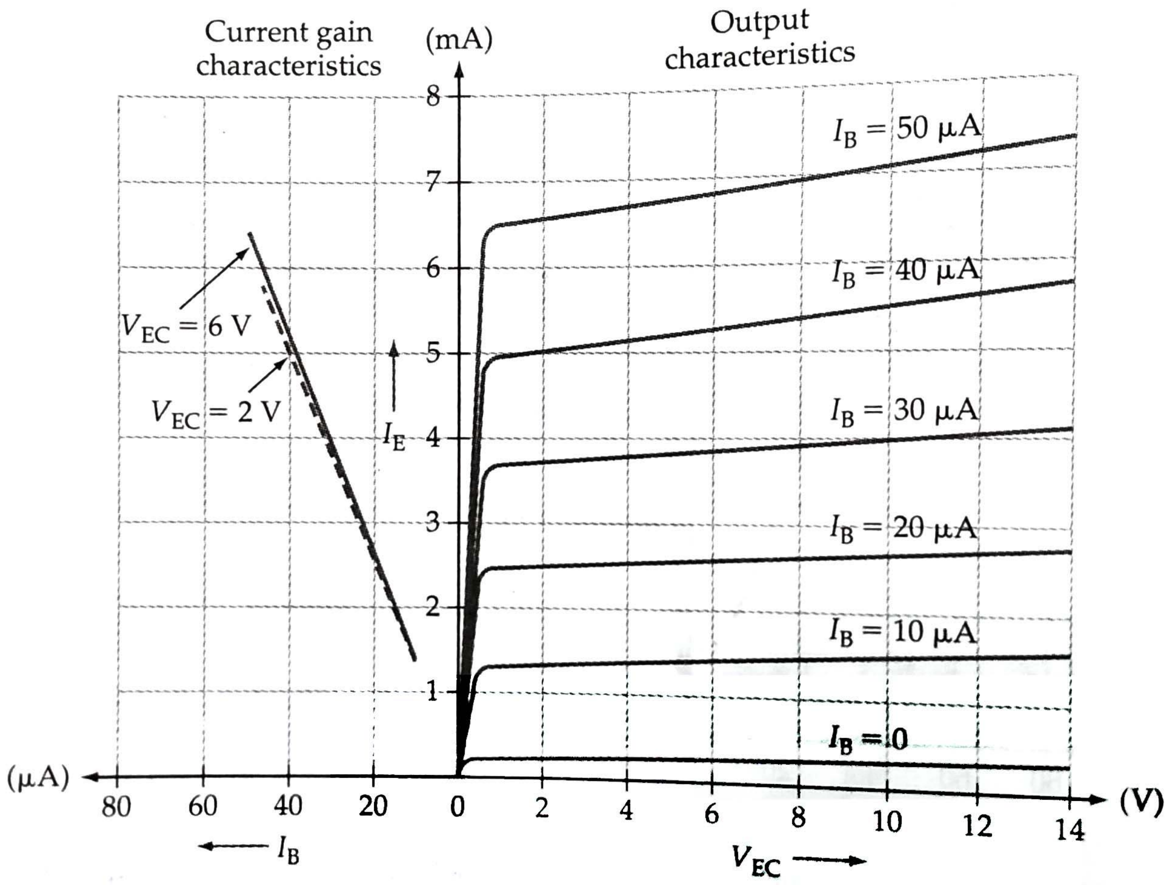
Common-Collector Input Characteristics

- The common-collector input characteristics are quite different from either common-base or common-emitter input characteristics.
- This is because the collector-base junction is reverse-biased and the input voltage V_{BC} is largely determined by the output voltage V_{EC}.
- We see that, $V_{EC} = V_{EB} + V_{BC}$
- Or $V_{EB} = V_{EC} - V_{BC}$
- Increasing the level of V_{BC} with V_{EC} held constant reduces V_{EB} and thus reduces I_B.

Common-Collector Output Characteristics

- To investigate the output characteristics, the input current I_B is kept constant and the output voltage V_{EC} is set at several convenient levels.
- At each output voltage, the corresponding output current I_E is recorded.
- A graph is then plotted for V_{EC} vs I_E.
- This is repeated for other values of I_B.

Common-Collector Output Characteristics



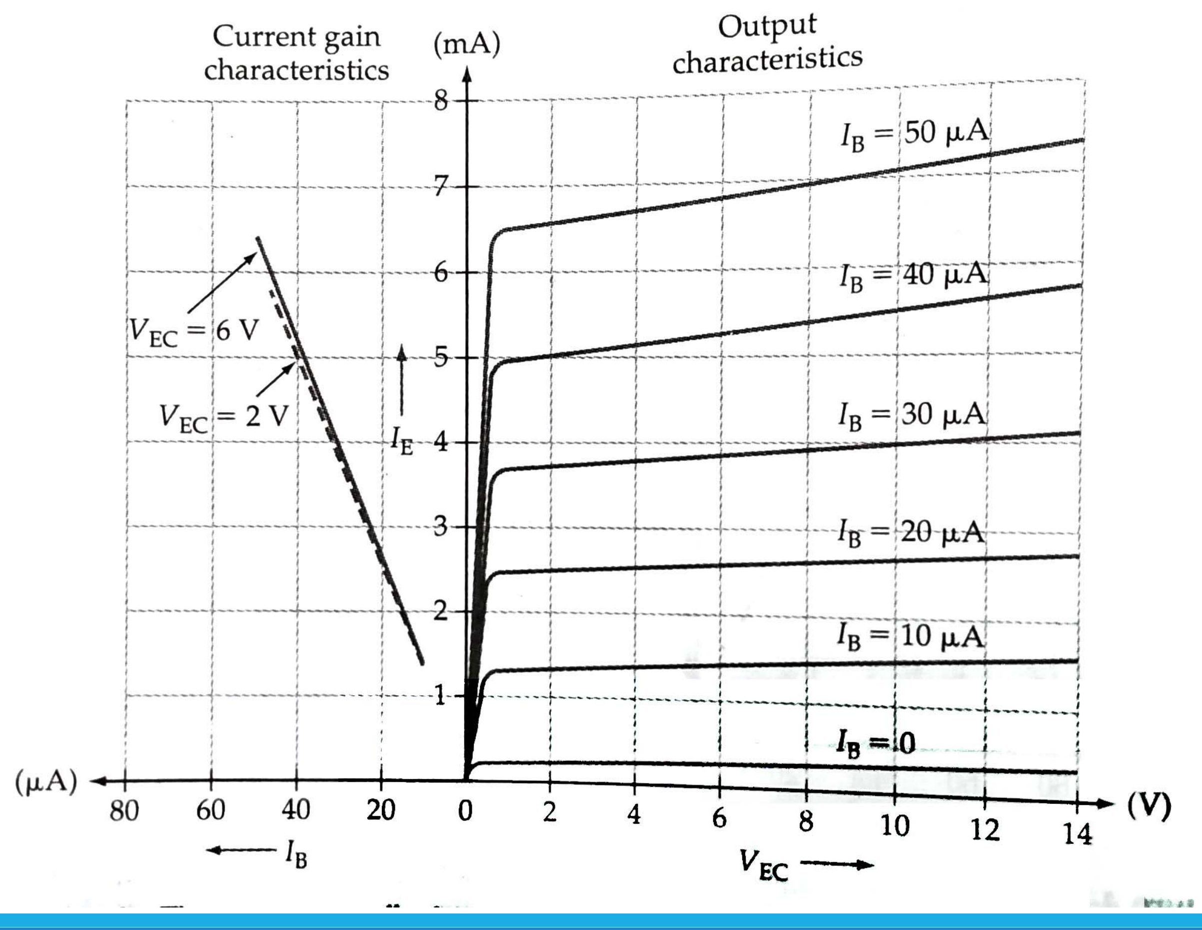
Common-Collector Output Characteristics

- Since I_E is approximately equal to I_C, common-collector output characteristics are practically identical to common-emitter output characteristics.
- When V_{EC} is increased, the distance between the depletion regions is shortened, drawing more current into the collector.
- So I_E increases when V_{EC} increases.

Common-Collector Current Gain Characteristics

- To investigate the current gain characteristics, the output voltage V_{EC} is kept constant and the input current I_B is set at several convenient levels.
- At each input current, the corresponding output current I_E is recorded.
- A graph is then plotted for I_B vs I_E.
- This is repeated for other values of V_{EC}.
- The common-emitter current gain characteristics can be derived from the output characteristics as shown.

Common-Collector Current Gain Characteristics



BJT Biasing

BJT Biasing

- Transistors used in amplifier circuits must be biased into an ON state with constant levels of collector, base and emitter currents and constant terminal voltages.
- Ideally the current and voltage levels in a bias circuit should remain absolutely constant.
- In practical circuits, these quantities are affected by the transistor current gain (h_{FE}) and by temperature changes.
- The best bias circuits are those which have greatest stability.
  - They hold the currents and voltages constant regardless of h_{FE} and temperature variations.
  - Voltage Divider Bias circuits are found to be the most stable bias circuits.

DC Load Line and Bias Point

DC Load Line

- The *dc load line* is a straight line drawn on the transistor output characteristics.
- For a common-emitter (CE) circuit, the load line is a graph of collector current I_C versus collector-emitter voltage V_{CE}, for a given value of collector resistance R_C and a given supply voltage V_{CC}.
- The dc load line shows all corresponding levels of I_C and V_{CE} that can exist in a particular circuit.

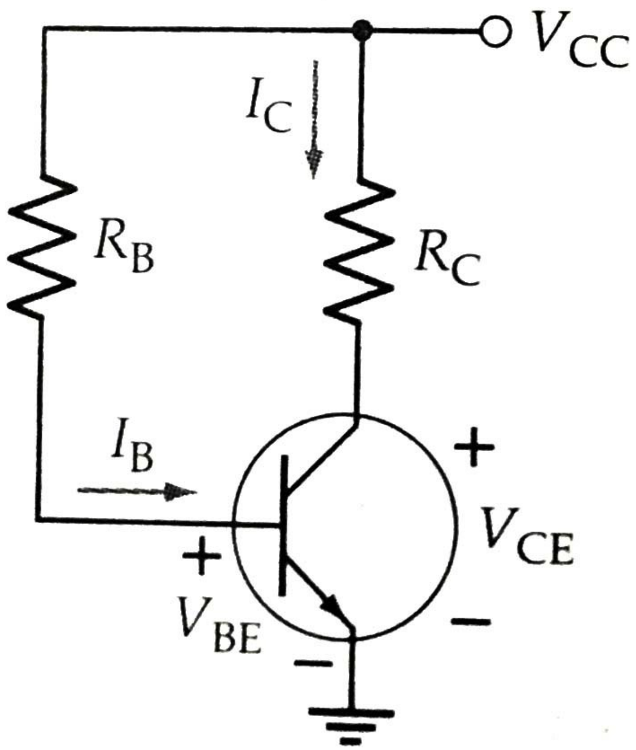
DC Load Line

- Consider the common-emitter circuit shown in the figure.
- It is called Base Bias circuit.
- Considering base-emitter loop,

$$V_{cc} = I_B R_B + V_{BE}$$

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

$$I_C = h_{FE} I_B$$



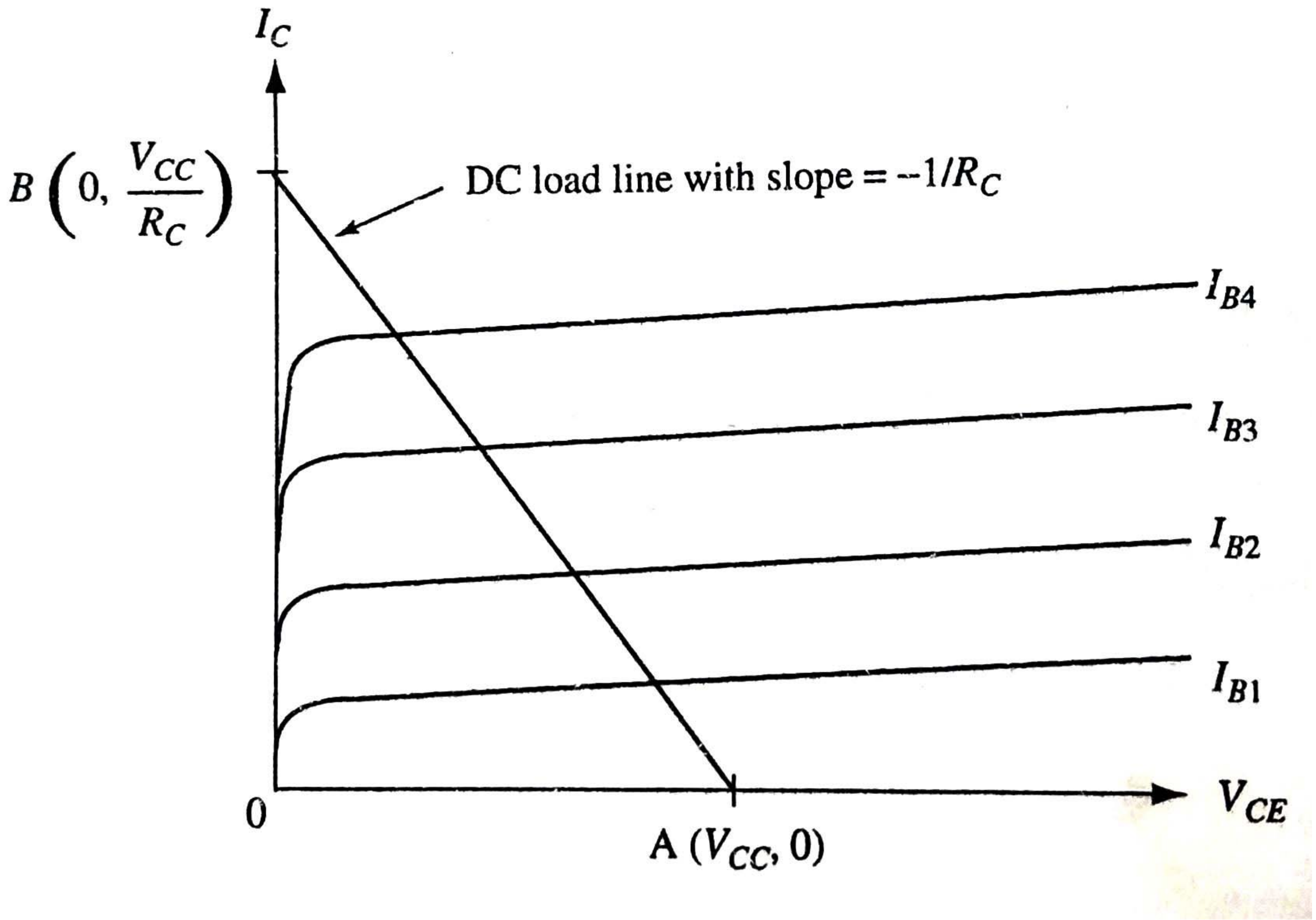
DC Load Line

- Considering collector-emitter loop,

$$V_{cc} = I_C R_C + V_{CE} \longrightarrow \quad (1)$$

- To get point A, put $I_C = 0$ in Eqn. (1) and to get point B, put $V_{CE} = 0$ in Eqn. (1)
- We get the points as $A(V_{cc}, 0)$ and $B\left(0, \frac{V_{CC}}{R_C}\right)$
- The straight line drawn through points A and B is the dc load line.

DC Load Line



I_C
$B\left(0, \frac{V_{CC}}{R_C}\right)$
DC load line with slope = −1/R_C
I_{B4}
I_{B3}
I_{B2}
I_{B1}
0
V_{CE}
A (V_{CC}, 0)

DC Bias Point

- The *dc bias point* identifies the transistor collector current I_C and collector-emitter voltage V_{CE} when there is no input signal at the base terminal.
- The dc bias point is also called *quiescent point (Q-point)* or *dc operating point.*
- It defines the dc conditions in the circuit.

DC Bias Point

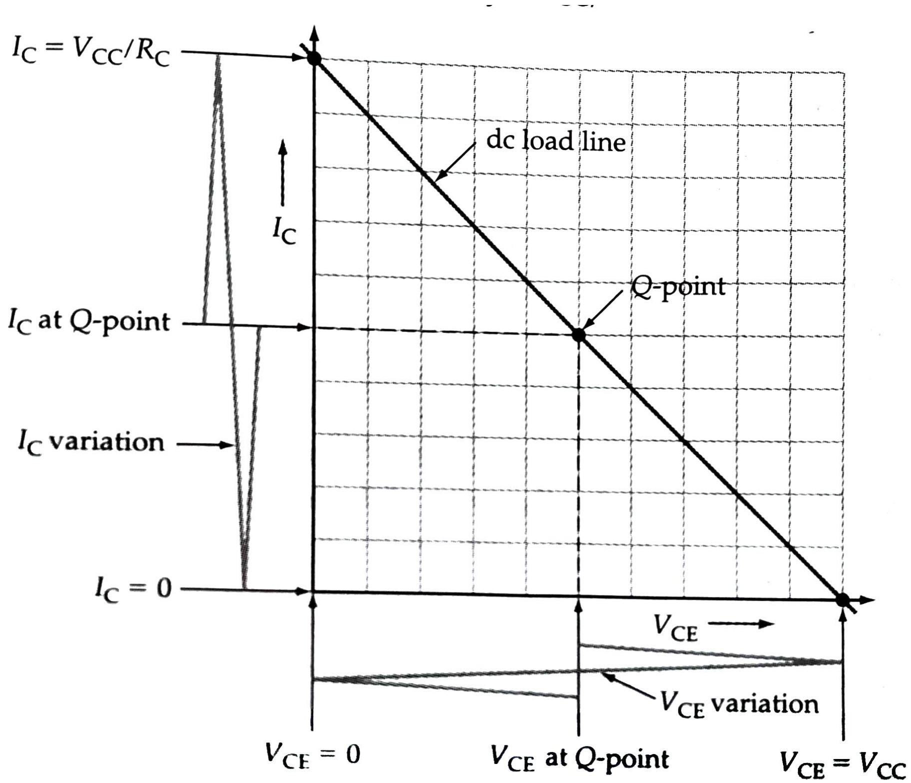


Figure 5-7 Transistor collector-emitter voltage (V_{CE}) ranges from approximately V_{CC} to zero when I_C goes from zero to V_{CC}/R_C.

DC Bias Point

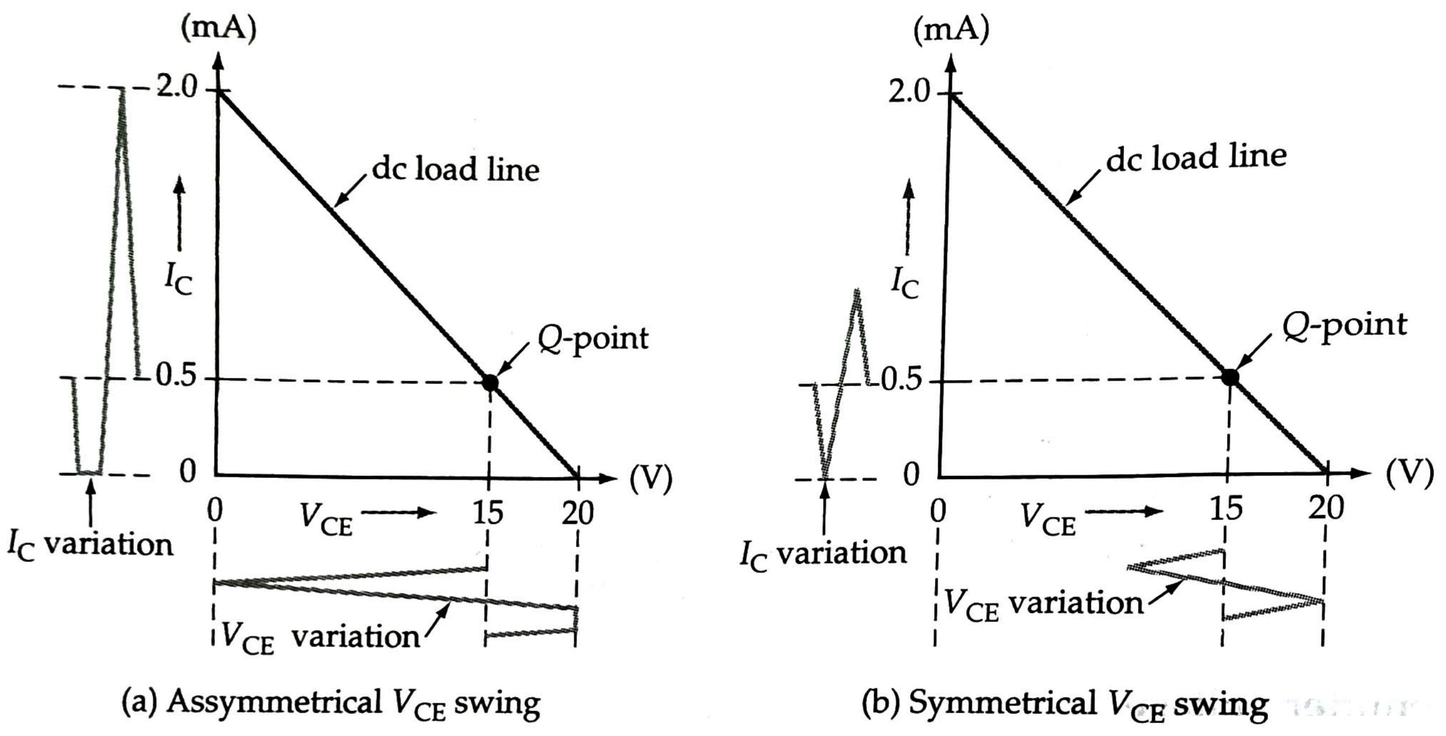


Figure 5-8 The *Q*-point does not have to be at the centre of the dc load line. But its position determines the maximum symmetrical collector-emitter voltage swing.

DC Bias Point

- With the Q-point at the centre of the load line, the maximum possible collector voltage swing is seen to be approximately $\pm V_{CC}/2$.
- Circuits used for large-signal amplifiers are designed to have the Q-point at the centre of the load line to give the maximum possible symmetrical output voltage swing.
- Small-signal amplifiers usually require an output voltage swing not greater than $\pm 1\ V$.
- So transistors in amplifiers do not all have to be biased at the centre of the dc load line.

References

- David A Bell, "*Electronic Devices and Circuits*", 5th Edition, Oxford University Press, 2016
- R. D. Sudhaker Samuel et al., "*Basic Electronics*", Sanguine Technical Publications, 2006