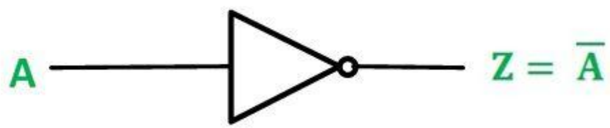
XMUT204 Electronic Design

Lecture 3a – Intro to Transistors (Construction and Operation)

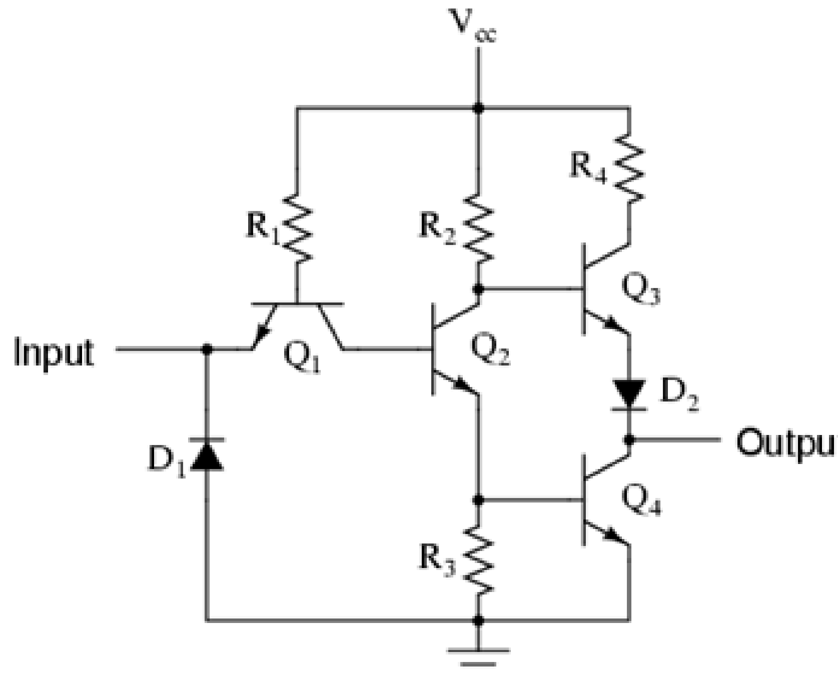
Overview

1. Transistors.
2. Invention of Transistor.
3. Basic Transistor Type.
4. Transistor Operation.
5. The Basic BJT Circuit and Notation.
6. The I-V Characteristic Curves.
7. Transistor Load Line.
8. “Constant” β_{DC}.
9. Maximum Transistor Power.

1. A Logic Gate Studies in XMUT202 – What is Inside?



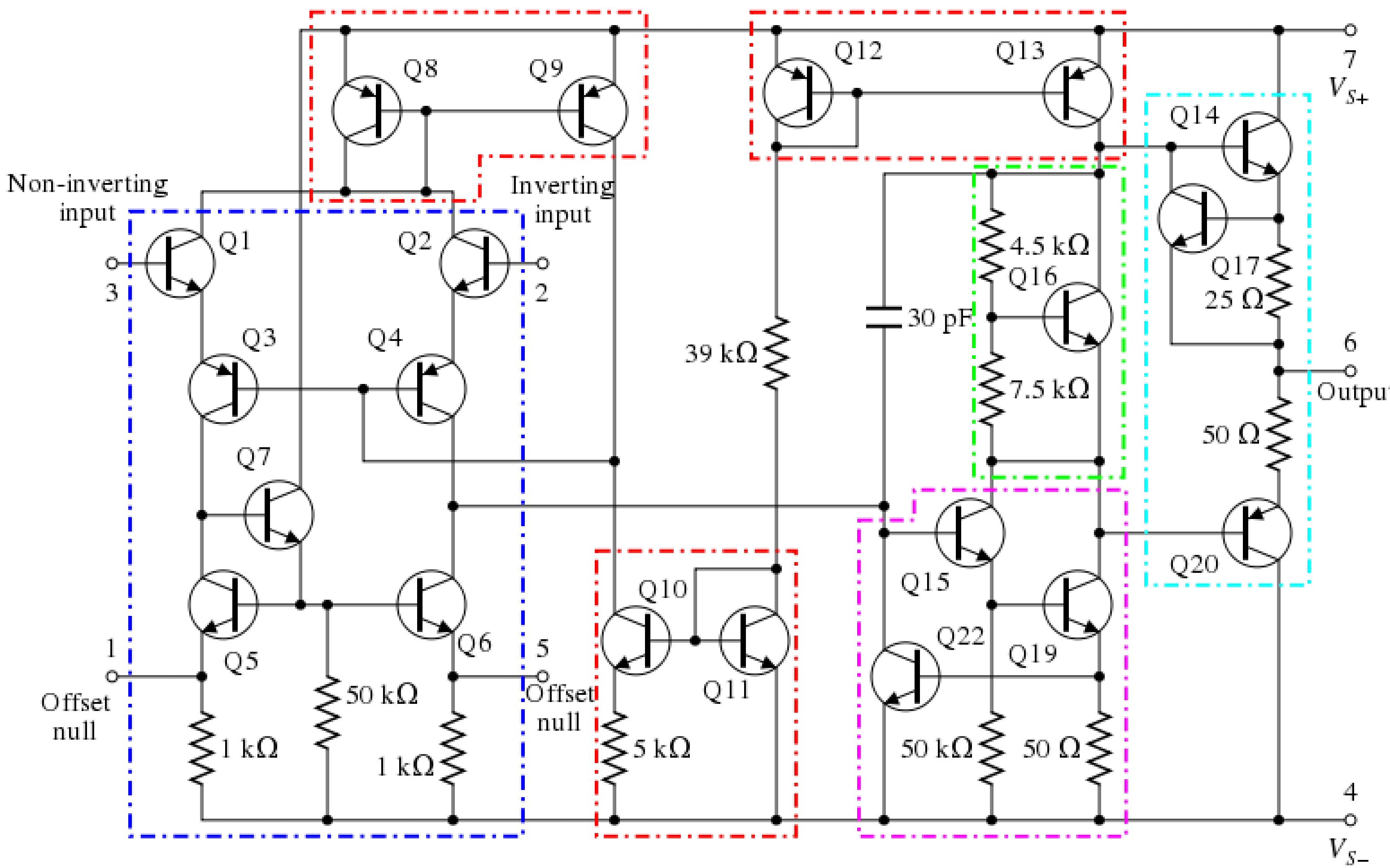
Input	Output
0	1
1	0



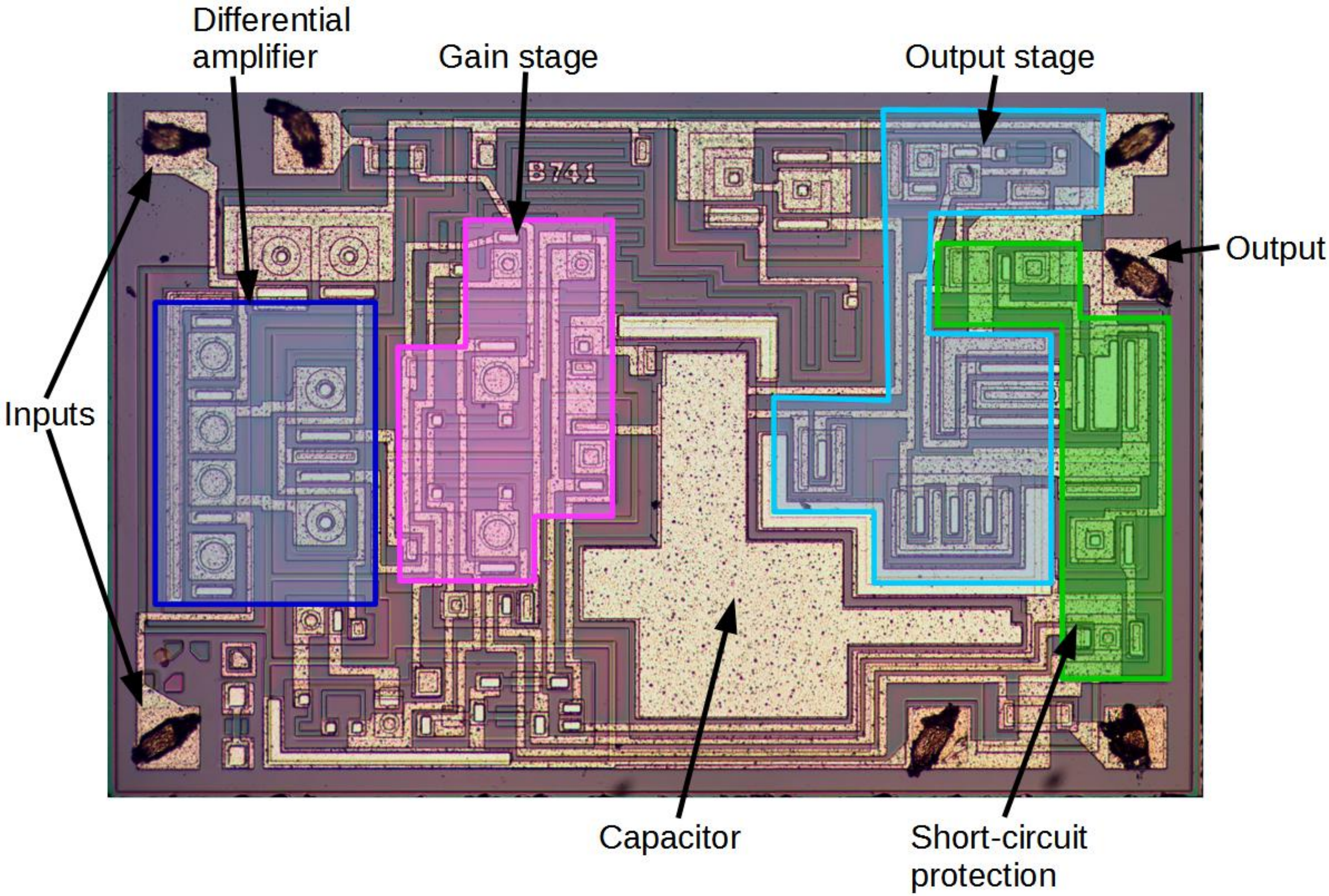
- The circuit above is a practical inverter (NOT) circuit.
- Transistors form the key element of nearly all integrated circuits ranging from amplifiers to logic gates to processors or memory ICs.

1. Operational Amplifier (Op-amps) in XMUT203 – What's Inside?

- What is actually in an op-amp? (e.g. 741) -> XMUT303.



- Semiconductor die view of the 741 op amp.



1. Transistors

- Early op-amps were built from discrete components – vacuum tubes at first, then transistors and ICs.

- Since about the mid-1960;s op-amps have been manufactured as integrated circuits (IC) with transistors and resistors all on the same silicon chip.
- The underlying physics of how an op-amp works remains based on the behaviour of transistors, principally now MOSFET's (Metal Oxide Semiconducting Field Effect Transistors), but also BJT's (Bipolar Junction Transistors).

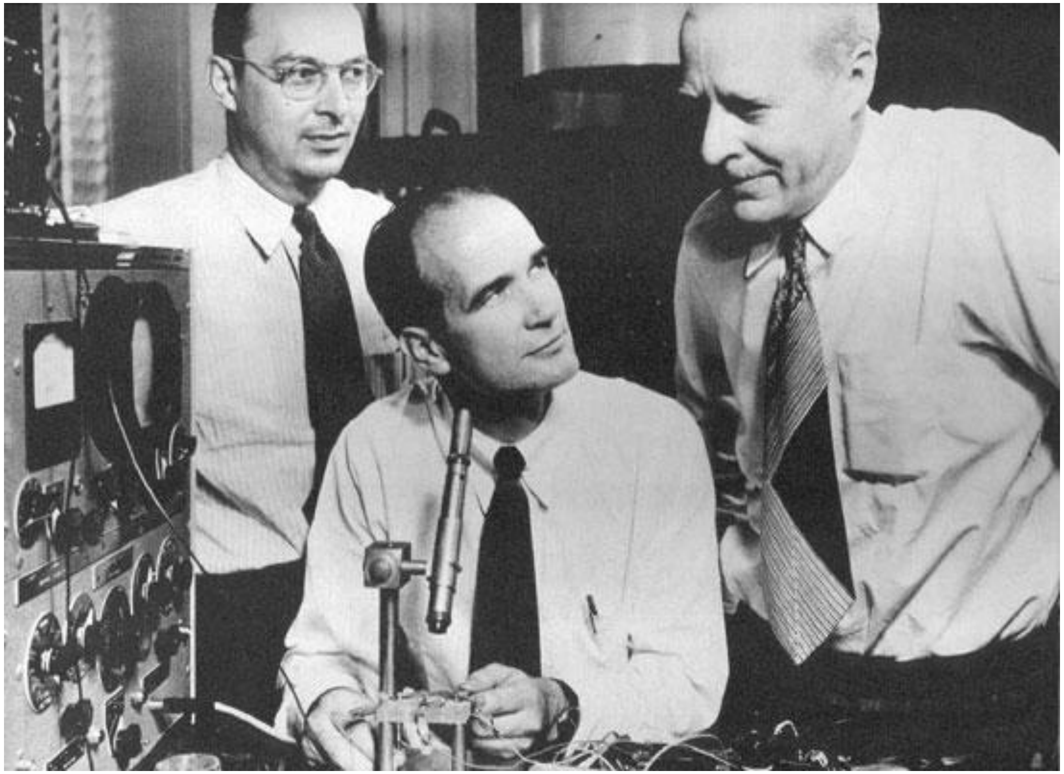
1. Transistors (cont.)

- Transistors are *three terminal* devices with a basic principle of operation that *the current that flows between two of the terminals can be controlled by the current or voltage in the third terminal*.
- They are important as **they are "active" components** $\Rightarrow$ **what happens can be controlled** rather than simply being a passive circuit element such as a resistor or a capacitor.
- Transistor as extensively used as both amplifiers and logic elements.

2. Invention of the Transistor

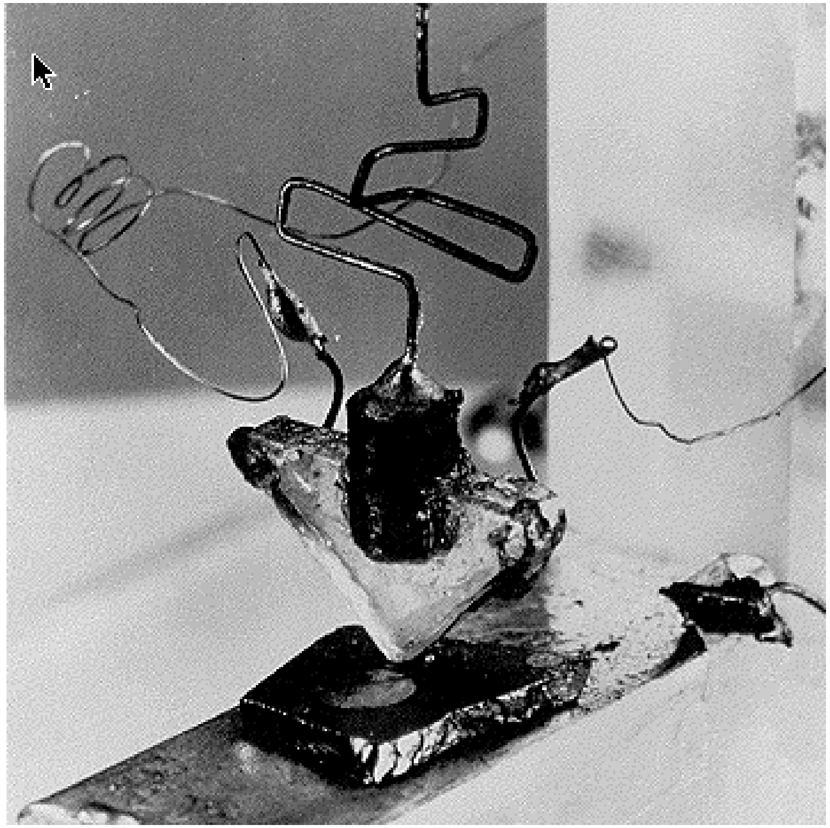
1. Who are the three guys in the picture?
2. When/where did this take place?
3. What did each of the three do later?
4. How did their transistor work?

2. Invention of the Transistor (cont.)



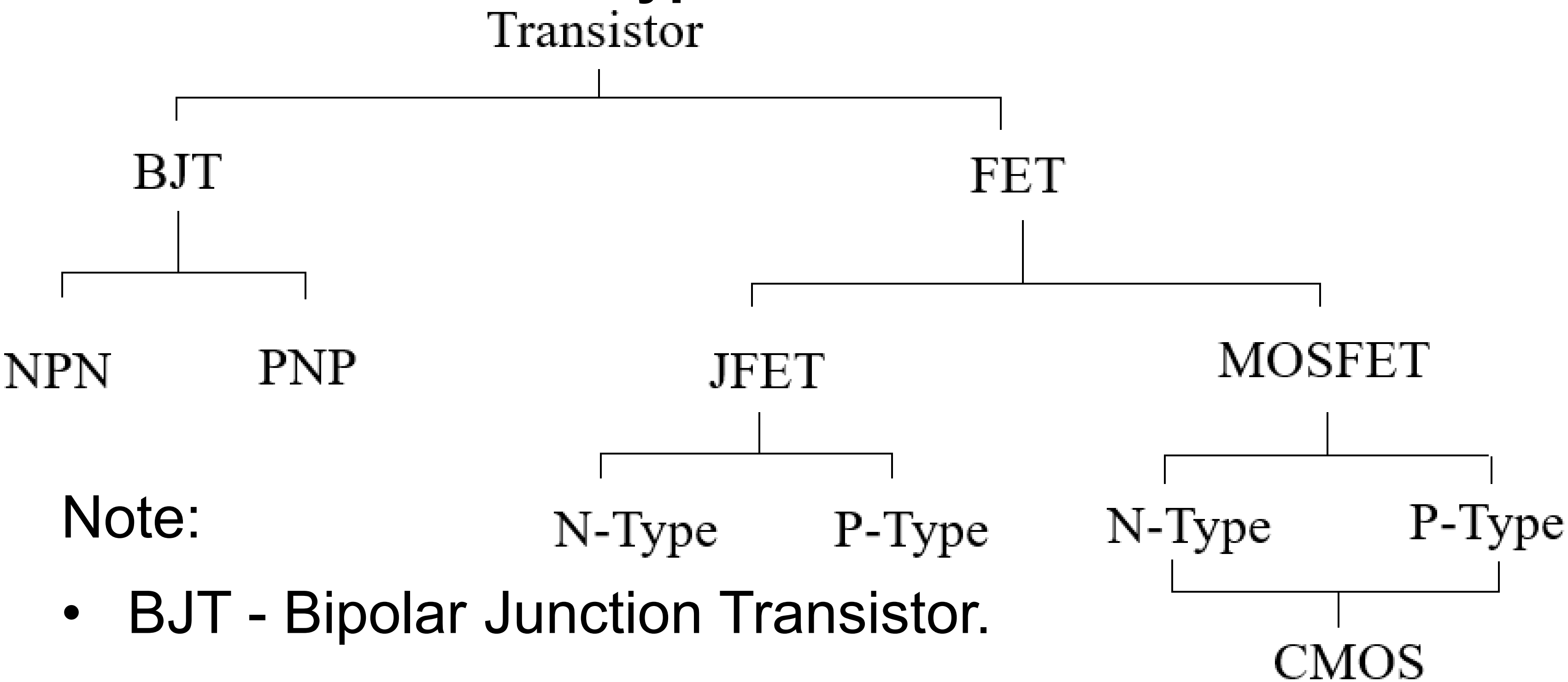
1. L-to-R: John Bardeen, William Shockley, Walter Brattain.
2. Bell Labs, USA, 1947.
3. Nobel Prize 1956.
4. Point contact transistor.

2. Invention of the Transistor (cont.)



- The first transistor – a point contact transistor (i.e. positive charge in the base causes electrons to rush from the emitter to the collector).
- This point contact transistor proved to be very difficult to manufacture in quantity and very unreliable.
- It was soon replaced by the planar junction transistor (BJT) in early 1950's.
- MOSFET technology developed during 1970's to facilitate large scale integration.

3. Basic Transistor Types

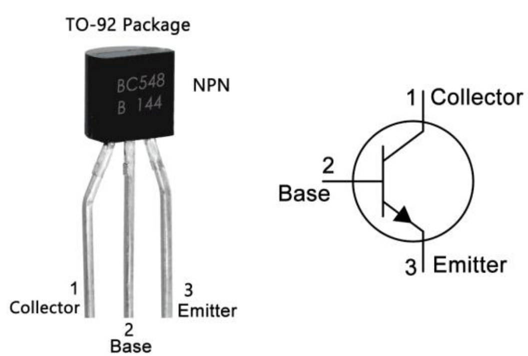


Note:

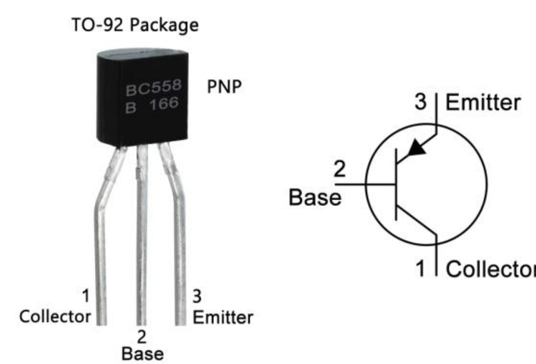
- BJT - Bipolar Junction Transistor.
- FET - Field Effect Transistor:
  - JFET - Junction Field Effect Transistor.
  - MOSFET - Metal Oxide Semiconductor Field Effect Transistor.
- CMOS - Complementary Metal Oxide Semiconductor.

3. Bipolar Junction Transistor (BJT)

- A BJT is made up of three doped semiconductor regions placed adjacent to each other:
  - Emitter - E.
  - Base – B - the central connection (filling in the sandwich).
  - Collector – C.
- Illustrated below are **NPN** and **PNP transistors**.



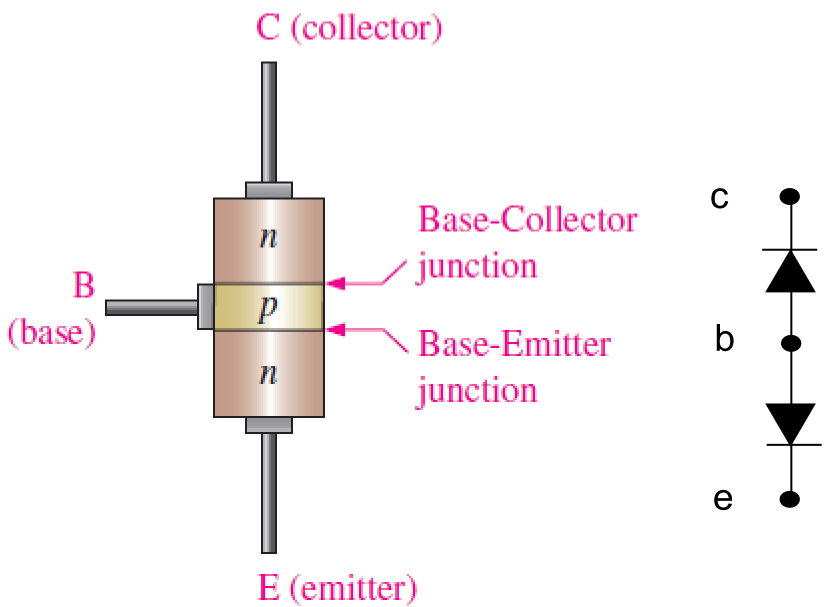
A NPN transistor and circuit symbol

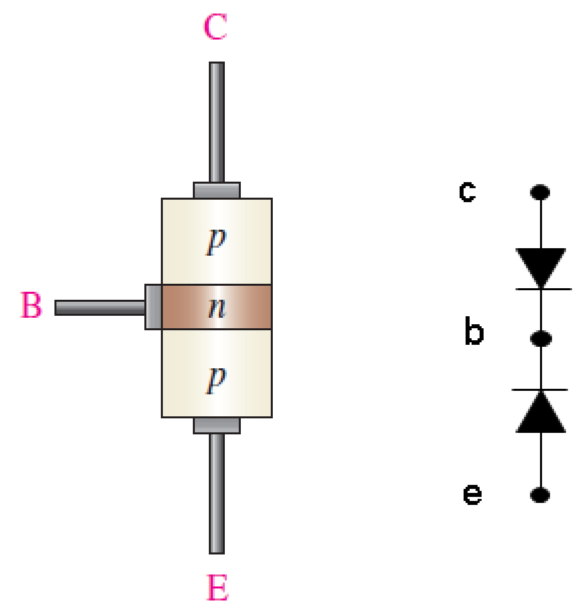


A PNP transistor and circuit symbol

3. Bipolar Junction Transistor (BJT) (cont.)

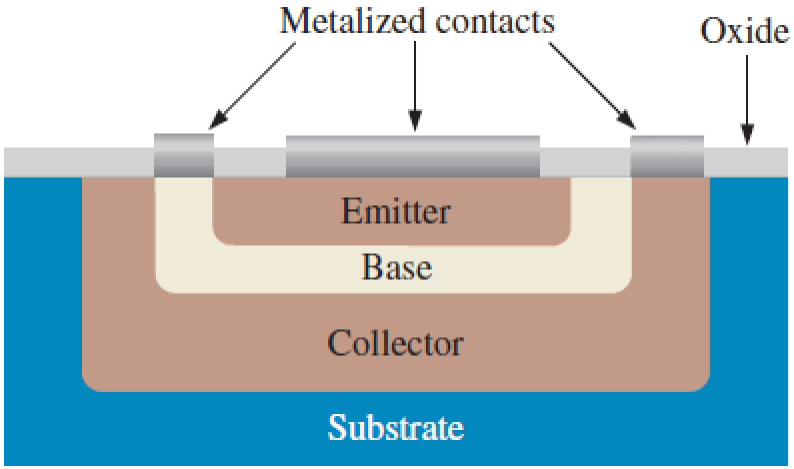
- **NPN** transistor (left-hand side) and **PNP** transistor (right-hand side) circuit symbols.
- These arrangements are essentially two PN diodes in series "back-to-back“.





3. Bipolar Junction Transistor (BJT) (cont.)

- The following diagram shows a typical planar BJT device structure.



Emitter region: Relatively thick, high doping level

Base region: Very thin with very low doping

Collector region: Relatively thick, medium doping level

- The presence of two p-n junctions means that four modes of operation are possible depending on bias configuration of each junction.

3. Bipolar Junction Transistor (BJT) (cont.)

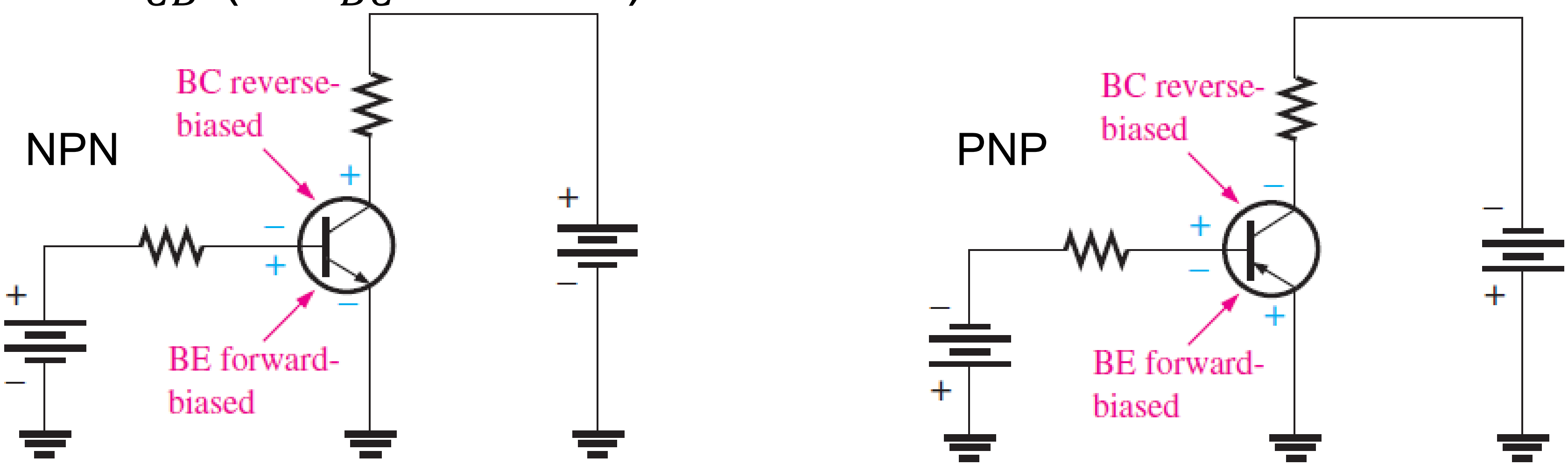
- However, *the design of the transistor is such that operation is totally different from two back to back diodes* – achieved by the following design:
  - The base (central region) is very thin, typically a few micron thick. Effectively we thus have two interacting pn junctions.
  - The device is not electrically symmetrical – use very different doping concentrations in B, E and C to create electrical non-symmetry. Typical doping levels in the regions $E - B - C$ = 10^{18} – 10^{15} – 10^{16} cm^{-3}.
  - Term “bipolar” indicates that both electrons and holes participate in the transistor operation.

4. Transistor Operation

Typical bias conditions called the **forward active mode** for both NPN and PNP transistors are shown below. We will concentrate on NPN in our discussion.

Note that:

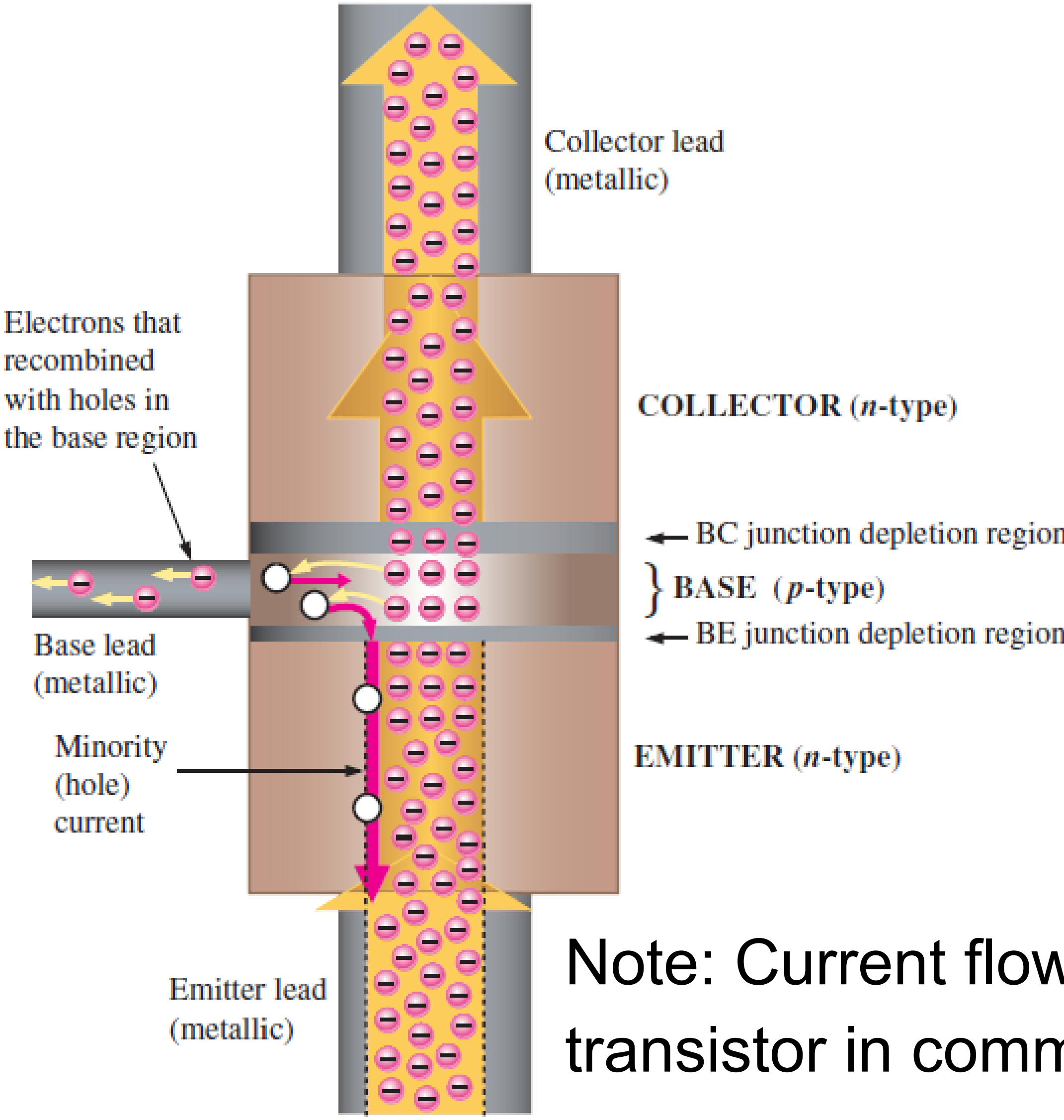
1. The BE junction is forward biased by the voltage V_{BE} (or V_{EB} for PNP).
2. The BC junction is reversed biased by the voltage V_{CB} (or V_{BC} for PNP).



4. Transistor Operation (cont.)

- Base-Emitter (BE) junction is in forward bias, electrons from the emitter side (majority carriers) will flow over the PN junction and become minority carriers in the base (P-side).
- The Base-Collector (BC) junction is in reverse bias and will thus have a wide depletion region. The electrons injected over the BE junction into the narrow base region are then easily caught in the electric field of the BC depletion region, and this field will sweep them into the collector region as a drift current.
- Base region made thin to minimise electron-hole recombination in this region and the put injected electrons close to the BC depletion region.

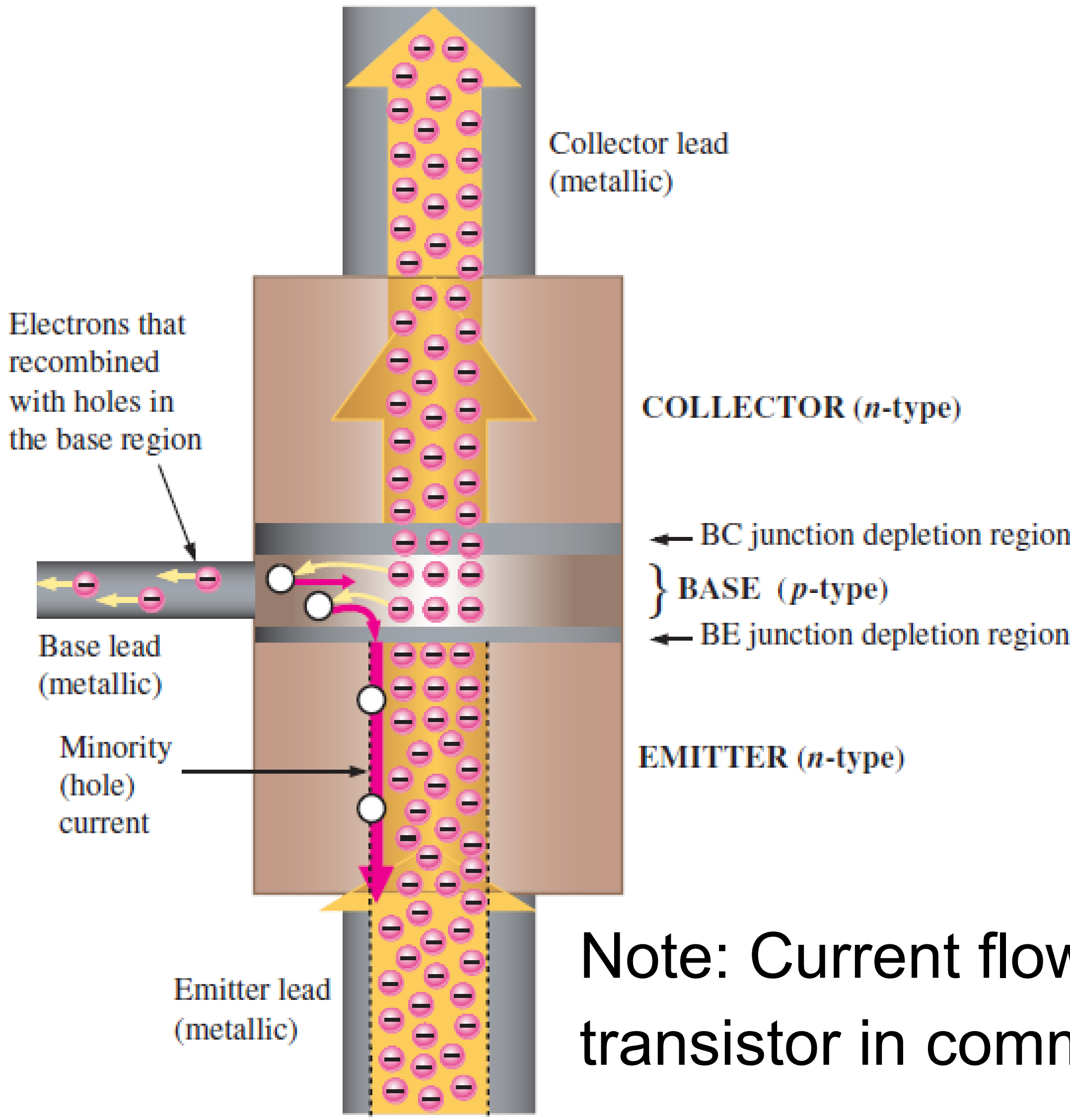
4. Transistor Operation (cont.)



- I_E: emitter current – consists of electrons from emitter flowing over BE junction into base where they are now minority carriers.
- This is a diffusion current as is normal in diode operation.

Note: Current flow (electron flow) in the NPN transistor in common emitter configuration.

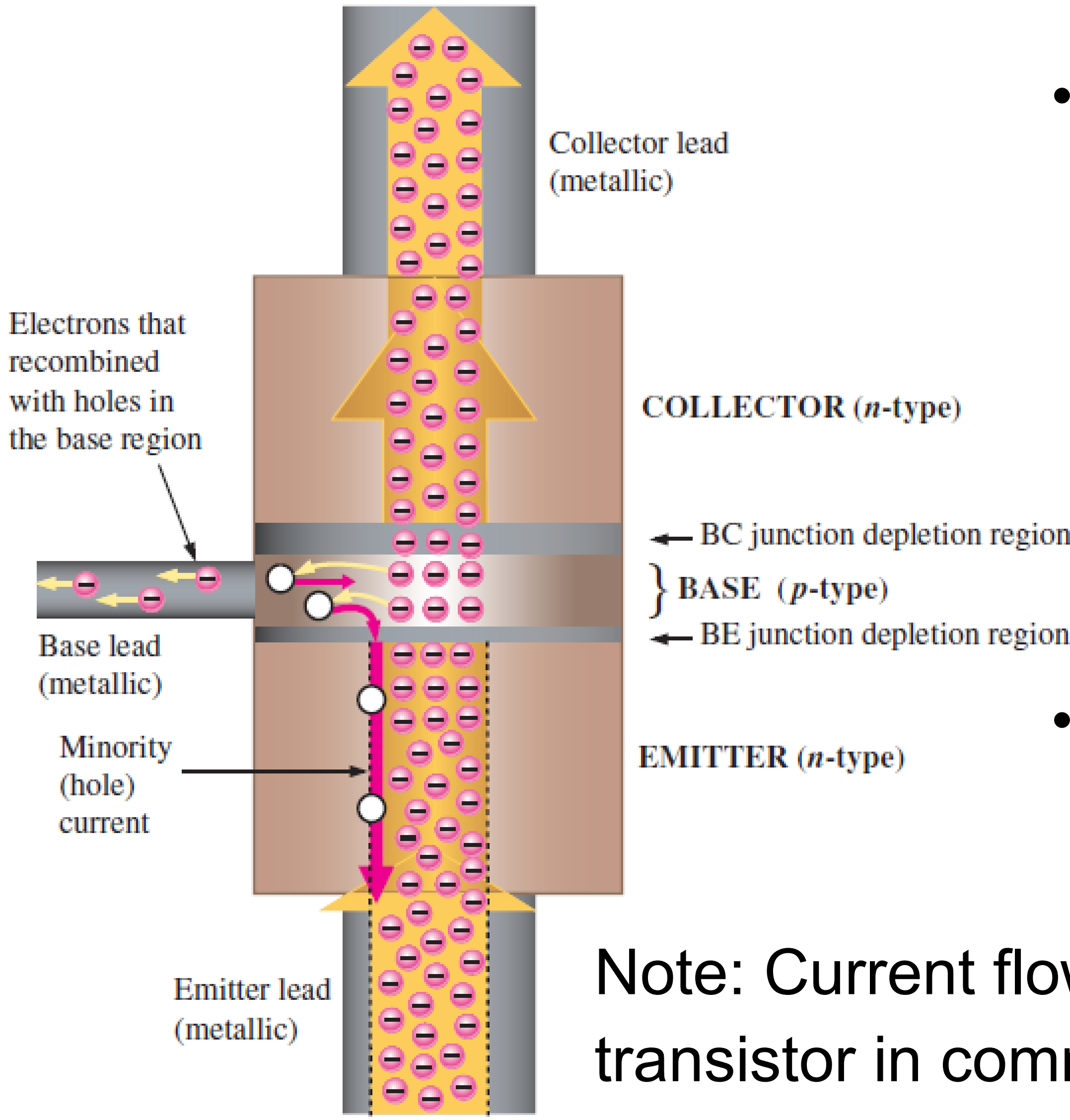
4. Transistor Operation (cont.)



- I_B: base current – a small number of the electrons arriving in the base will combine with holes in the base region.
- This will thus effectively flow into the base.

Note: Current flow (electron flow) in the NPN transistor in common emitter configuration.

4. Transistor Operation (cont.)



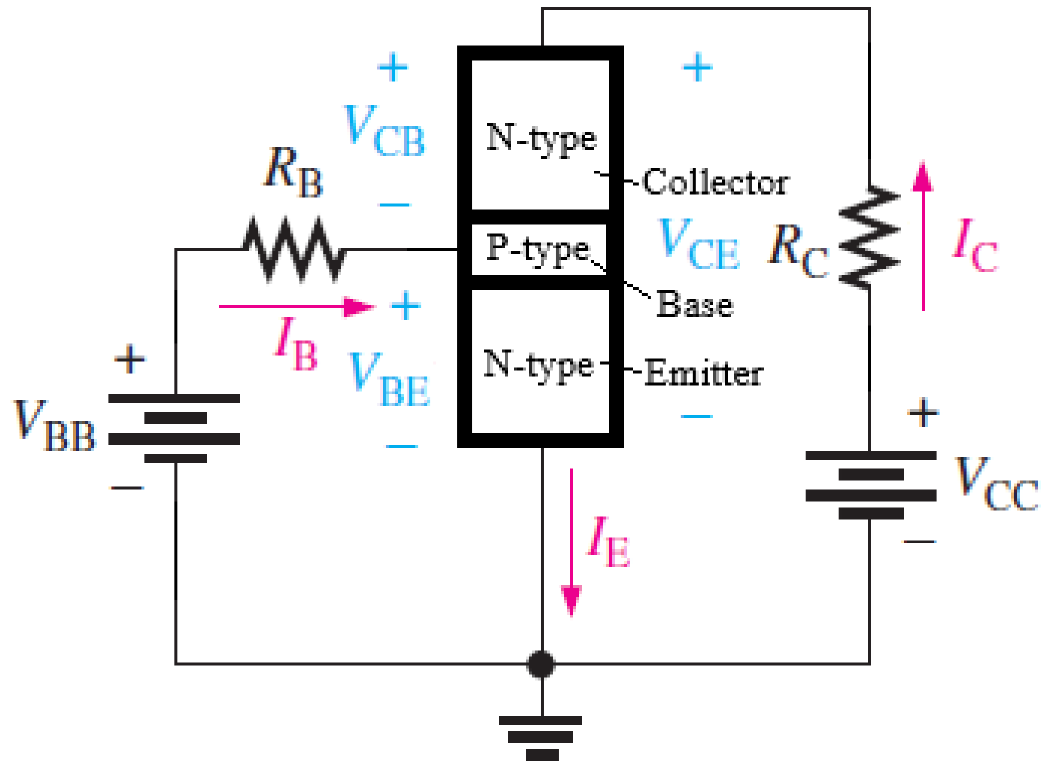
- I_C: collector current – most of the electrons arriving from the emitter will be caught in the depletion region from the base-collector junction (reverse biased).
- This will be swept into the collector.

Note: Current flow (electron flow) in the NPN transistor in common emitter configuration.

4. Transistor Operation (cont.)

- Conventional current representation of flow in the external circuit.
- By taking the transistor as a single node and using Kirchhoff's current law we can write:

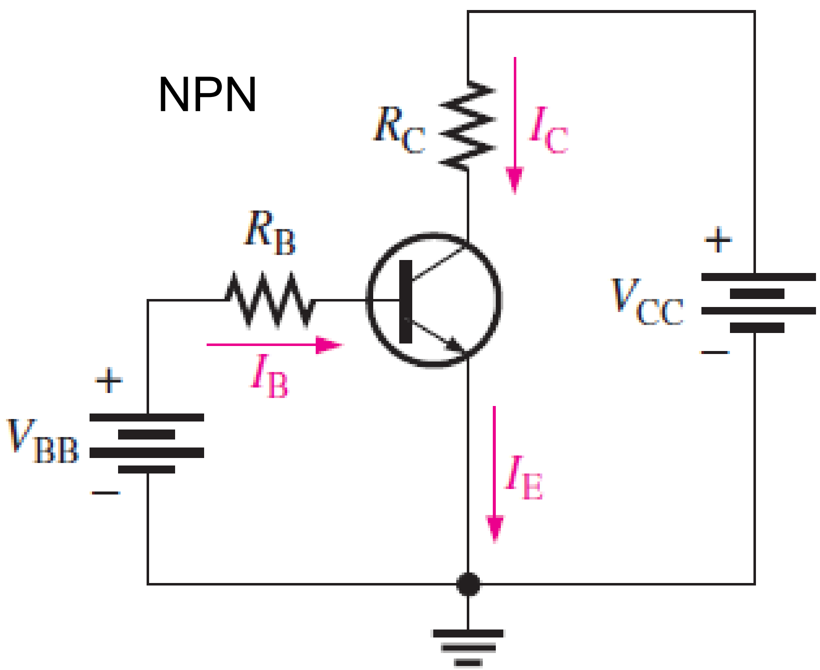
$$I_E = I_C + I_B$$

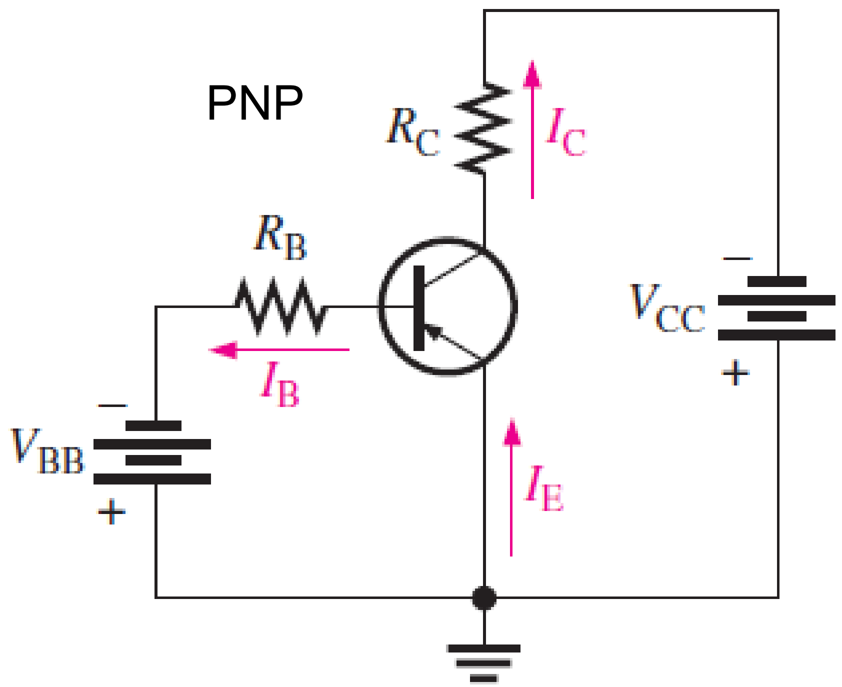


Note: Current flow (electron flow) in the NPN transistor in common emitter configuration.

4. Transistor Operation (cont.)

- Conventional (positive) current directions for in NPN and PNP transistors.
- Both the circuits are in a so-called common–emitter configuration.





4. Transistor Operation (cont.)

- From what we had previously said about transistor operation it is also clear that:
  - $I_C \sim I_E$ – collector current is nearly equal to the emitter current.
  - I_B is very much smaller than I_E or I_C.
- We now define two factors that describe the relationships between these currents:
  - The DC current gain of the transistor is defined as:

    $\beta_{DC} = I_C/I_B$ (typical values 100 - 400)
  - The DC alpha value is defined as the ratio:

    $\alpha_{DC} = I_C/I_E$ (typical values 0.95 - 0.99)

4. Transistor Operation (cont.)

When the transistor is in forward active mode, we have:

- BE junction forward biased and the BC junction reverse biased.

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

- Treat the transistor as a single node to get:

$$I_E = I_C + I_B$$

- Thus

$$I_E = (1 + \beta_{DC}) I_B$$

- Or we can write:

$$I_C = \left(\frac{\beta_{DC}}{1 + \beta_{DC}} \right) I_E$$

4. Transistor Operation (cont.)

- But, we had $I_C = \alpha_{DC} I_E$, so:

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

- Or, we can write:

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

- Remember α_{DC} is just smaller than 1 (~ 0.99) and β_{DC} is ~ 100.

4. Transistor Operation (cont.)

- The factor α_{DC} thus describes the relationship between the collector and emitter currents and is typically just smaller than 1.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

- The collector current is thus controlled by the BE voltage, e.g. the current at one terminal (the collector) is controlled by the voltage across two other terminals, hence transistor action.
- To a first approximation, the collector current is independent of the magnitude of the reverse biased BC voltage.

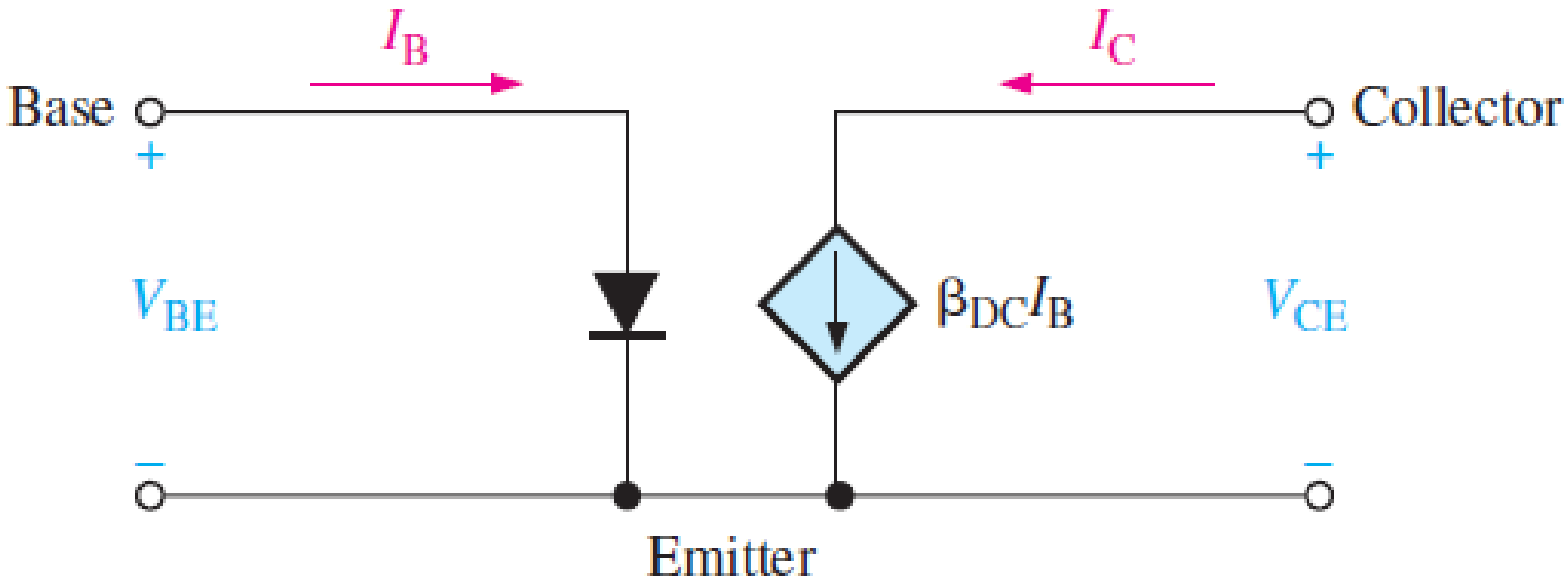
4. Transistor Operation (cont.)

- **Base current:** The base current consists of two components (for an NPN transistor):
  a. As the BE junction is forward biased, holes from the base will flow across the junction into the emitter (drift current).
  b. Holes will disappear in the base due to recombination with injected electrons – these holes will be replenished by the positive base terminal.
- Both the above current components are proportional to the exponential function of the BE voltage so that:

$$I_B \propto I_S e^{(V_{BE}/V_T)}$$

4. Transistor Operation (cont.)

- **The transistor model:** We can then model a BJT transistor as in figure below:

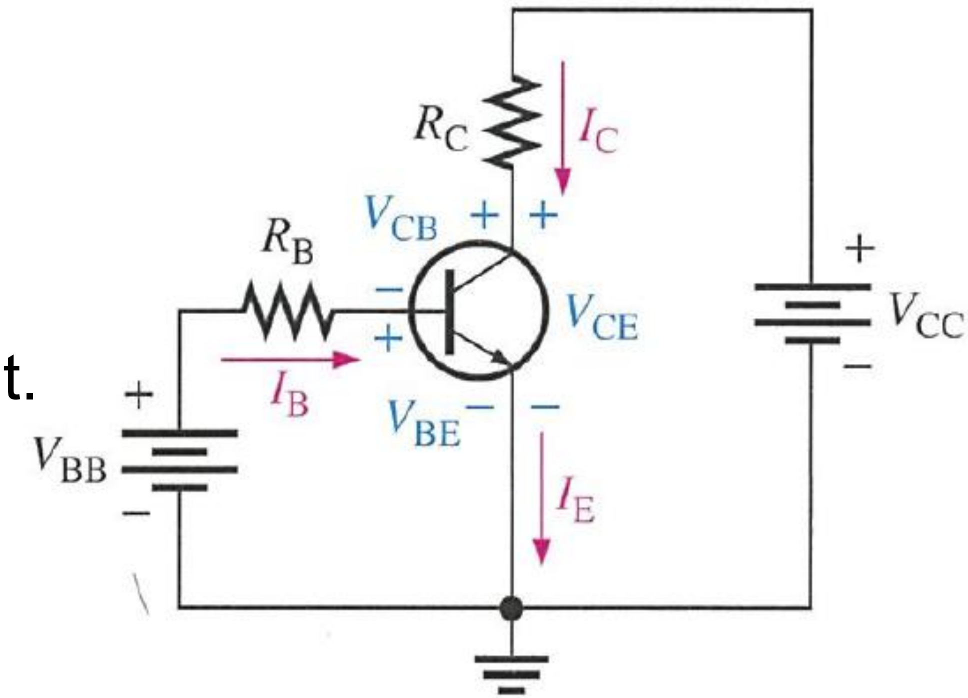


- **Input:** Current input I_B with current determined by forward bias on the BE junction.
- **Output:** Dependent constant current source (I_C) that drives a collector current of a magnitude $\beta_{DC} I_B$.

5. The Basic BJT Circuit and Notation

Currents:

- I_B = DC base current.
- I_E = DC emitter current.
- I_C = DC collector current.



Voltages:

- 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.

5. The Basic BJT Circuit and Notation (cont.)

- When BE junction is correctly forward biased, it will act as normal diode so that:

$$V_{BE} \approx 0.7\text{ V}$$

- The voltage across R_B is then:

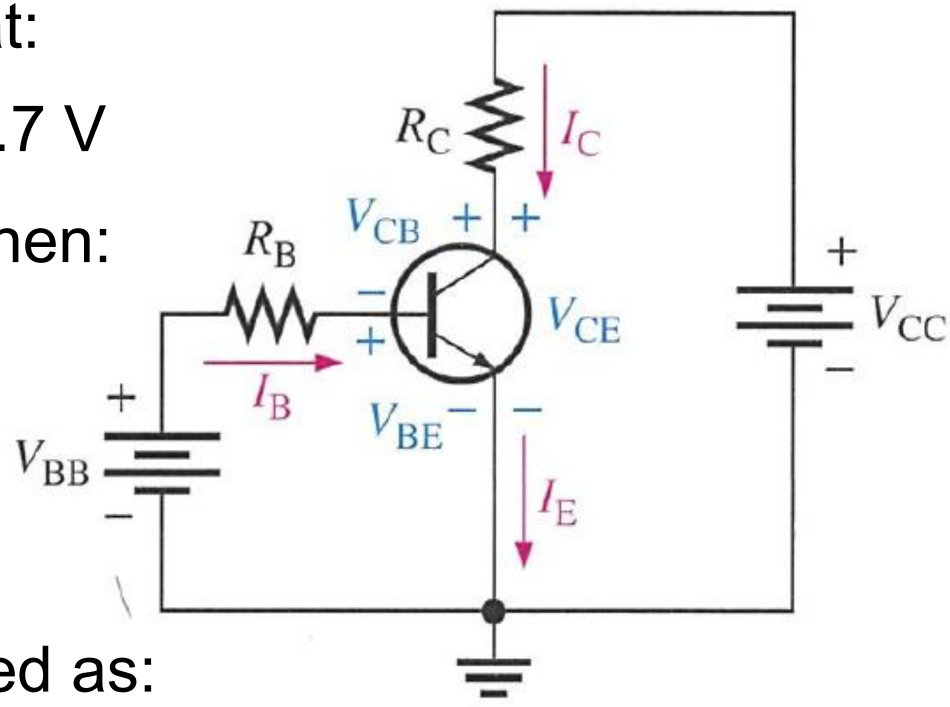
$$V_{R_B} = V_{BB} - V_{BE}$$

- and

$$V_{R_B} = I_B R_B$$

- So that I_B can be expressed as:

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



5. The Basic BJT Circuit and Notation (cont.)

- The voltage at the collector with respect to emitter is:

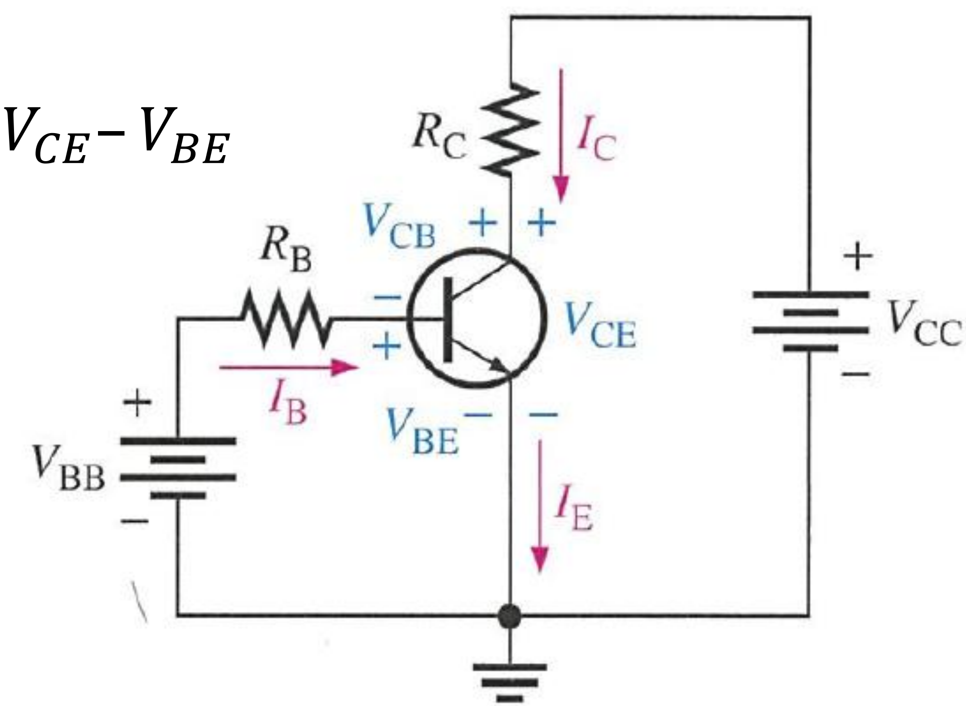
$$V_{CE} = V_{CC} - I_C R_C$$

- The voltage over the reverse biased CB junction is then:

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

- We should also keep in mind that:

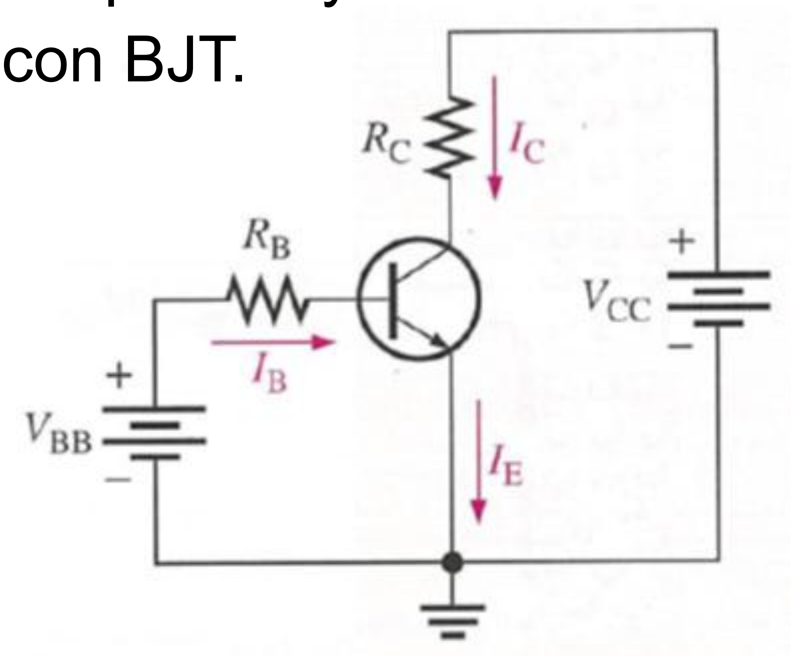
$$I_C = \beta_{DC} I_B$$



Example 1 – Circuit Parameters of BJT Circuit

A correctly forward-biased BJT transistor as shown below is being measured and evaluated in the laboratory.

The BJT is set up with biasing voltages V_{BB} = 1 V and V_{CC} = 12 V. The values of resistors of R_B and R_C are 10 kΩ and 1 kΩ respectively and the transistor being evaluated is a Silicon BJT.



Parameter	Value
I_B	30 μA
I_C	3 mA
I_E	3.03 mA
V_{R_B}	0.3 V
V_{R_C}	3 V

The given table shows the results of measurement of the circuit.

a. Determine the DC gain (β_{DC}) of the transistor.

[2 marks]

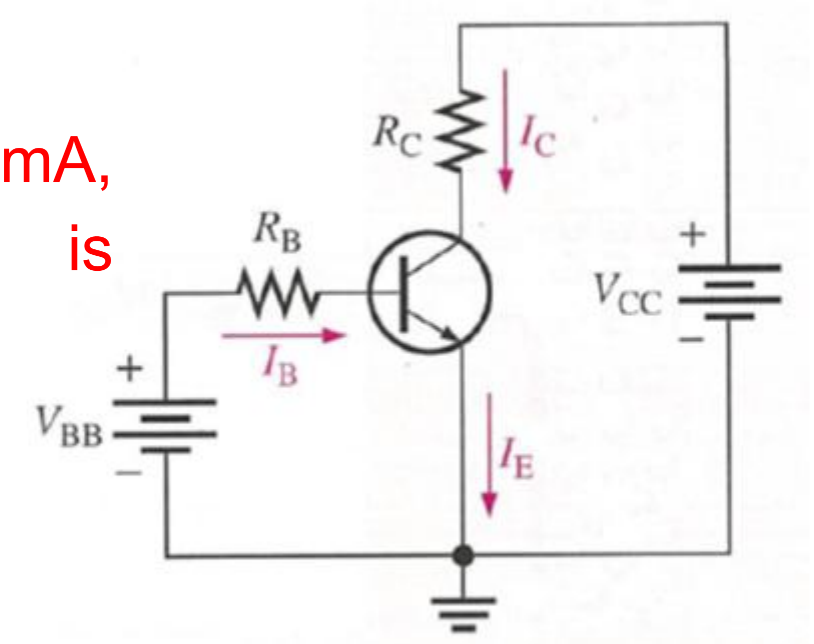
b. Calculate the current I_E. [2 marks]

c. Calculate the voltage V_{CE}. [2 marks]

d. Compared with the value obtained from measurement, determine whether the calculated values of I_E and V_{CE} are correct. [2 marks]

Answer

a. If I_B = 30 μA and I_C = 3 mA, then the value of β_{DC} is calculated from:



$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3\text{ mA}}{30\text{ μA}} = 100$$

b. The current that flows in the emitter is calculated from:

$$I_E = (\beta_{DC} + 1)I_B = (100 + 1)(30\text{ μA}) = 3.03\text{ mA}$$

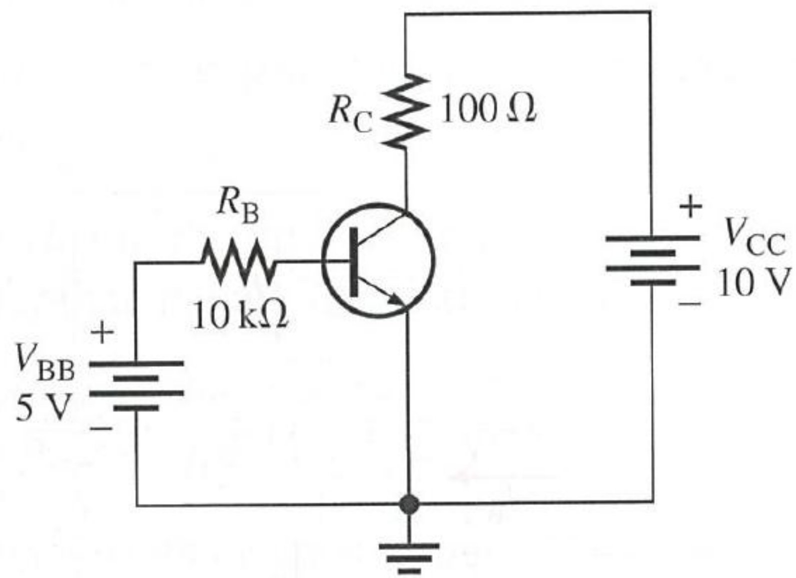
c. The voltage at the collector with respect to emitter is:

$$V_{CE} = V_{CC} - I_C R_C = 12\text{ V} - (3\text{ mA})(1\text{ kΩ}) = 9\text{ V}$$

d. The results of the measurements match the calculated values.

Example 2 – Circuit Parameters of BJT Circuit

Calculate the currents and voltages in the circuit below. Given that β_{DC} = 150.



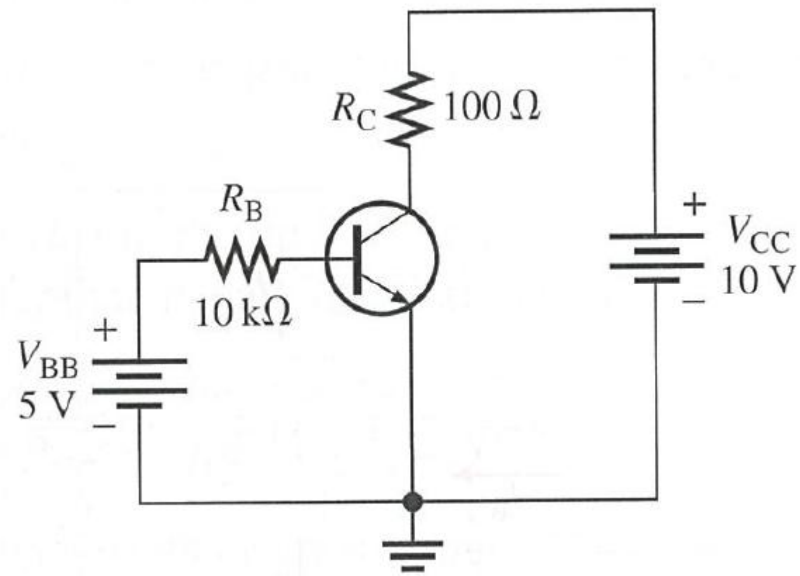
Hints: Use KVL to determine the currents first, then calculate the voltages.

Answer

- Calculate base current (I_B):

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

$$= \frac{5 - 0.7}{10\text{k}} = 0.43 \text{ mA}$$



- Current at collector (I_C):

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

$$= (150)(0.43 \text{ mA}) = 64.5 \text{ mA}$$

- Current at emitter (I_E):

$$I_E = I_C + I_B$$

$$= 64.5 \text{ mA} + 0.43 \text{ mA} = 64.93 \text{ mA}$$

- Calculate voltage at the base (V_B):

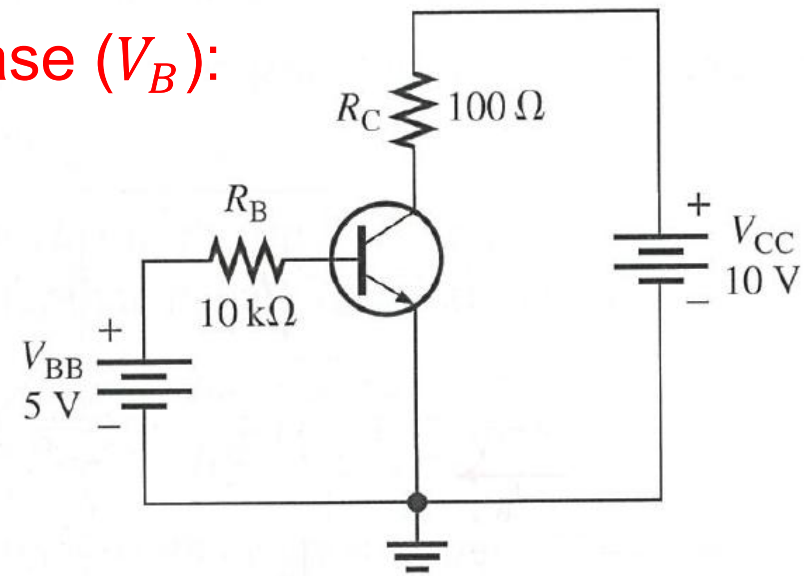
$$V_B = (V_{BB} - V_{BE})$$
$$= 5 - 0.7 = 4.3 \text{ V}$$

- Voltage at collector (V_C):

$$V_C = I_C R_C$$
$$= (\beta_{DC} I_B) R_C$$
$$= (150)(0.43 \text{ mA})(100 \ \Omega) = 6.45 \text{ V}$$

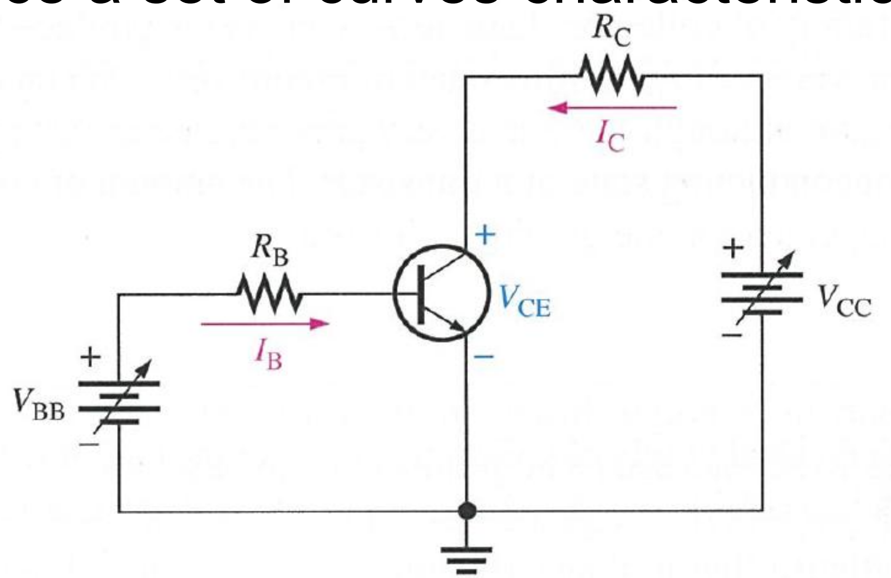
- Voltage at collector-emitter junction (V_{CE}):

$$V_{CE} = V_{CC} - V_C$$
$$= 10 - 6.45 = 3.55 \text{ V}$$



6. The I-V Characteristic Curves of a BJT

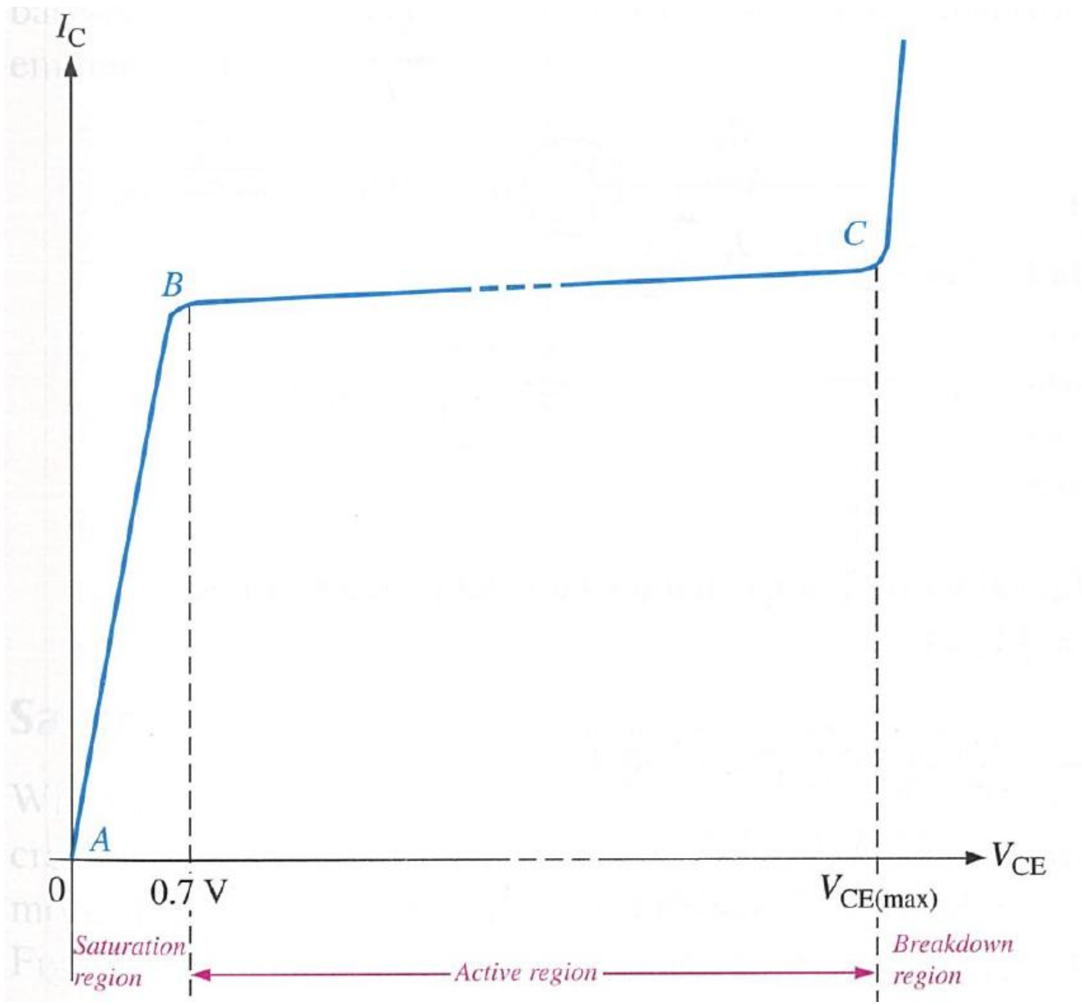
- The collector current I_C is typically plotted as a function of the voltage across CE junction (V_{CE}) while keeping the base current I_B constant.
- This will produce a set of curves characteristic of the transistor.



- In circuit above, set V_{BB} to achieve a desired I_B value, then vary V_{CC} from zero to achieve different values V_{CE} and thus of I_C. Plot I_C vs V_{CE}. Repeat for different value of I_B.

6. The I-V Characteristic Curves of a BJT (cont.)

- Curve of I_C vs V_{CE} for one specific value of I_B, assuming the BE junction is correctly forward biased.

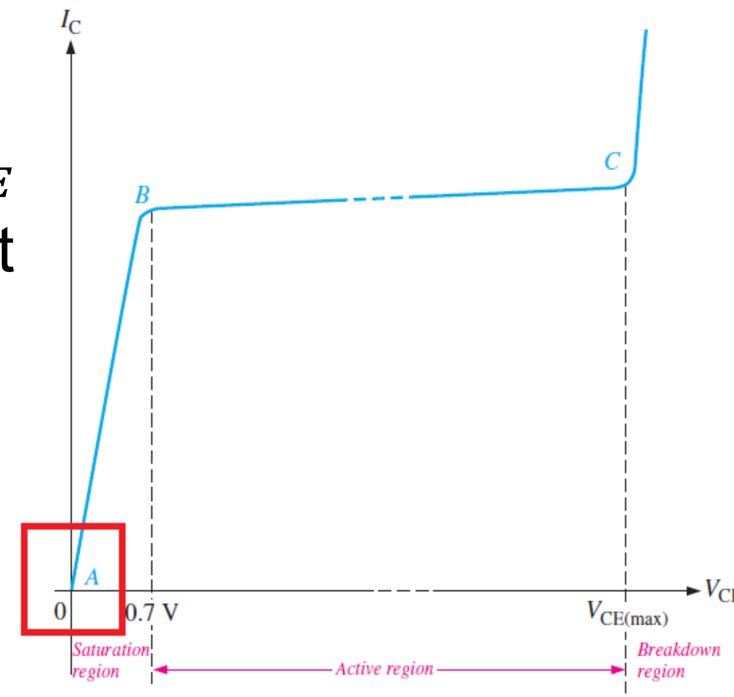


6. The I-V Characteristic Curves of a BJT (count.)

- For the BE junction in forward bias and some value of I_B, we will obtain a curve as shown on the previous slide.

- With V_{CC} = 0, we will also have V_{CE} = 0. As a result, the base will be at ~ 0.7 V while collector is at 0 V.

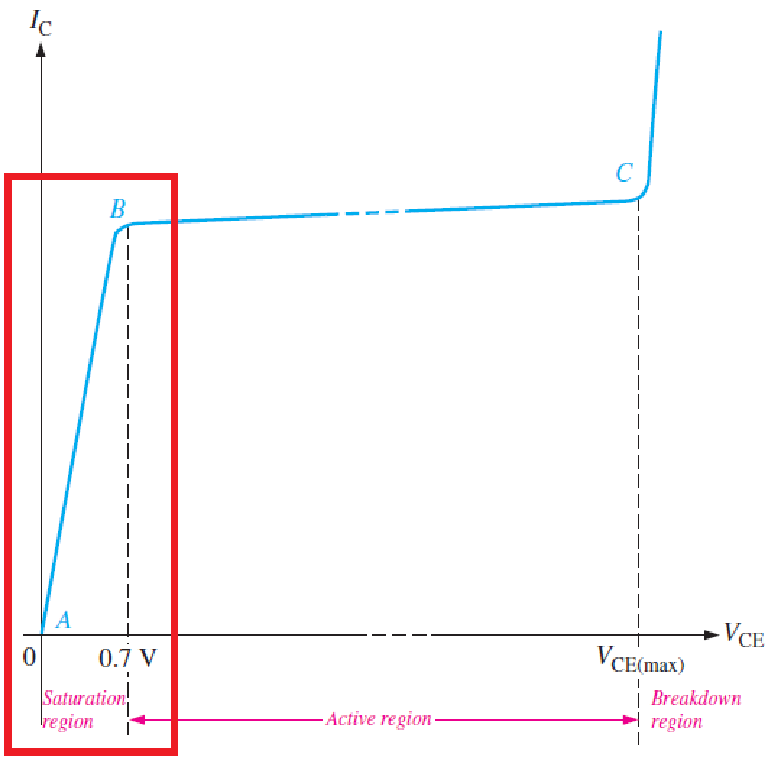
- So, that CB junction will be effectively forward biased (since V_{CB} < 0 V).



- Base current will flow over the base-emitter junction as this is low resistance path (high doping in emitter) and the collector current will be zero. **Point A on graph.**

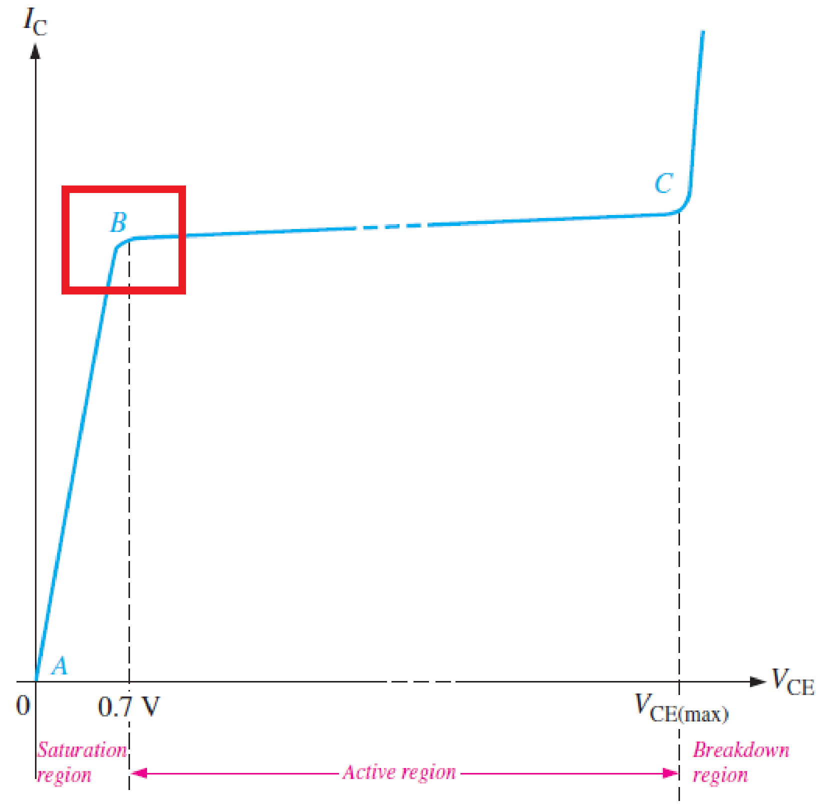
6. The I-V Characteristic Curves of a BJT (count.)

- As V_{CC} increases, V_{CE} will increase, thus decreasing the forward bias.
- As long as V_{CE} < 0.7 V, the CB junction will still be forward biased and the current I_C will rapidly increase.
- This is known as the **saturation region**, along the line AB in the graph.



6. The I-V Characteristic Curves of a BJT (count.)

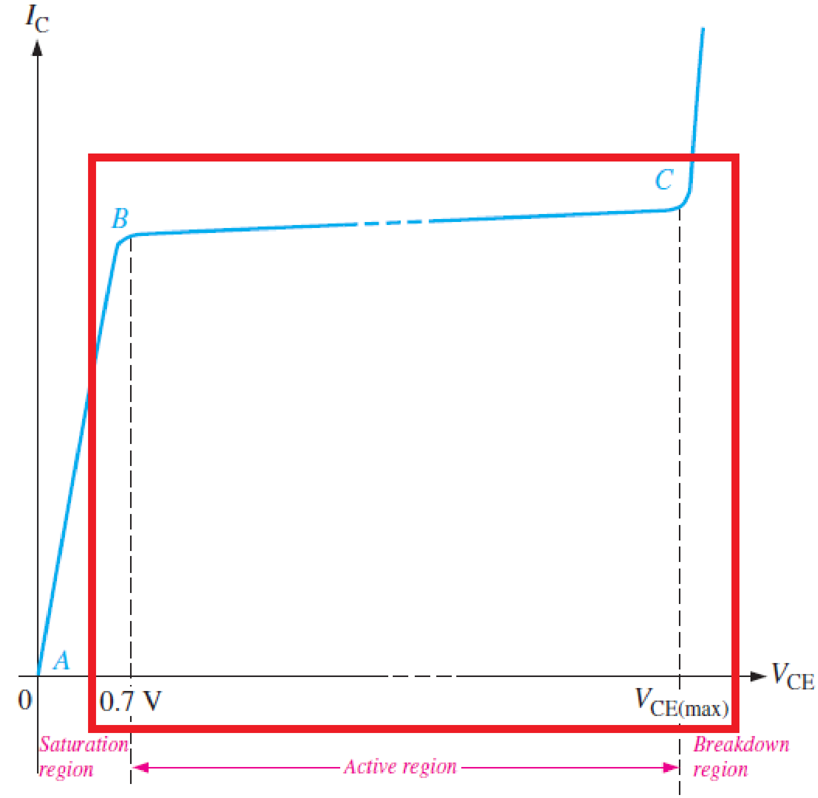
- In saturation the value of I_C goes from 0 to a maximum **(Point B on graph)** when the CB junction becomes reverse biased.
- I_C should remain constant from this point.



- When V_{CE} = 0.7 V, we will have V_{CB} = 0 V and the CB junction will transition from forward bias to reverse bias.
- The current I_C has now saturated (**Point B on graph**).

6. The I-V Characteristic Curves of a BJT (count.)

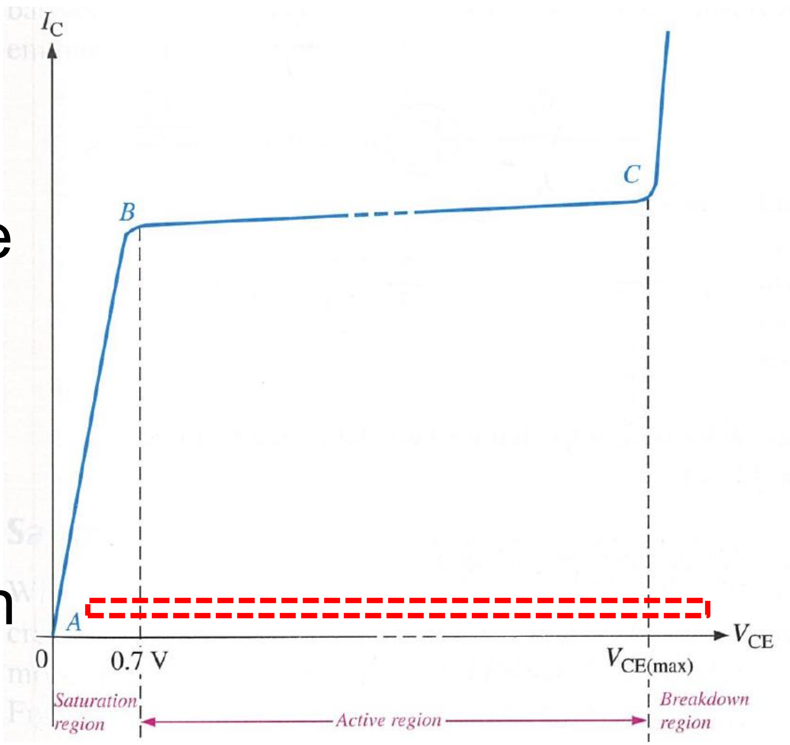
- With further increase of V_{CC} and thus V_{CE} the CB junction becomes reverse biased.
- The current I_C and remains essentially constant despite the fact that the reverse bias keeps on increasing as V_{CC} and thus V_{CE} increases.



- This is known as the **active or linear region (line $\boldsymbol{BC}$ on graph).**
- The value of I_C is now only determined by $I_C = \beta_{DC} I_B$ and should thus remain constant for a constant value of I_B.

6. The I-V Characteristic Curves of a BJT (count.)

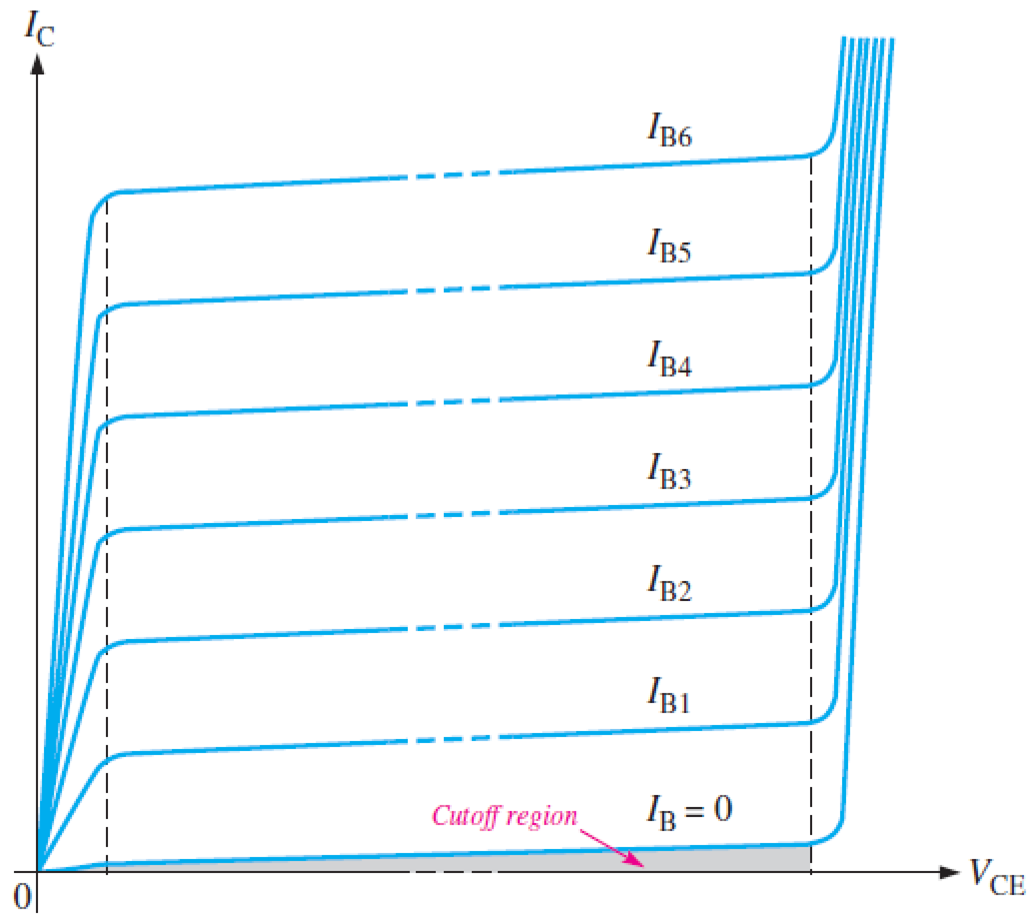
- In practice, we have a slight slope in I_C due to the increasing width of the depletion region due to reduced recombination in the base.
- The value of β_{DC} is then not absolutely constant in this region but depends weakly on V_{CE}



- Note on this graph that when the BE junction is not in forward bias (V_{BE} < 0.7 V), we will have I_B = 0. However, we will still have a very small collector current leakage flow.
- This is known as the **cut-off region** of the transistor and is the non-conducting state of the transistor.

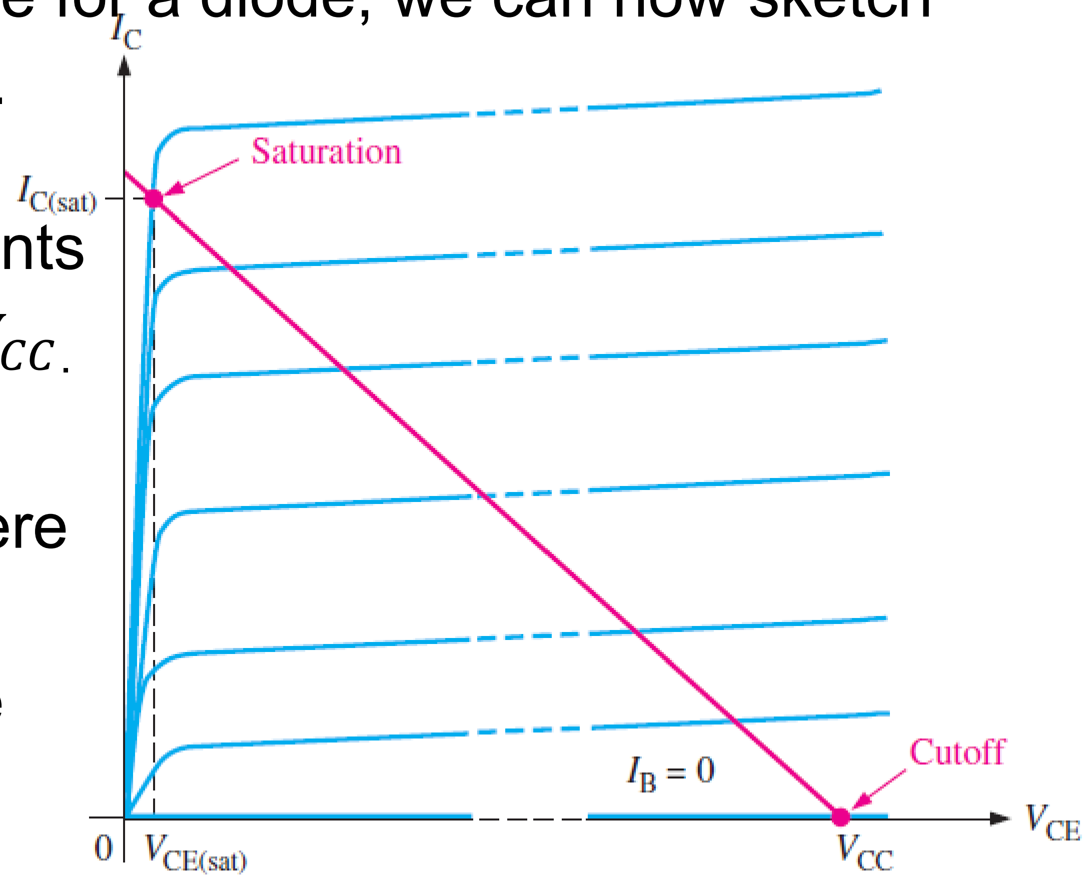
6. The I-V Characteristic Curves of a BJT (count.)

- If we follow the above process for different values of I_B, we will get a similarly shaped curve for each value of I_B, but with the value of I_C determined by $I_C = \beta_{DC} I_B$.
- Graph shown below is plotted for several values of I_B.



7. Transistor Load Line

- Just as we have done for a diode, we can now sketch a transistor load line.

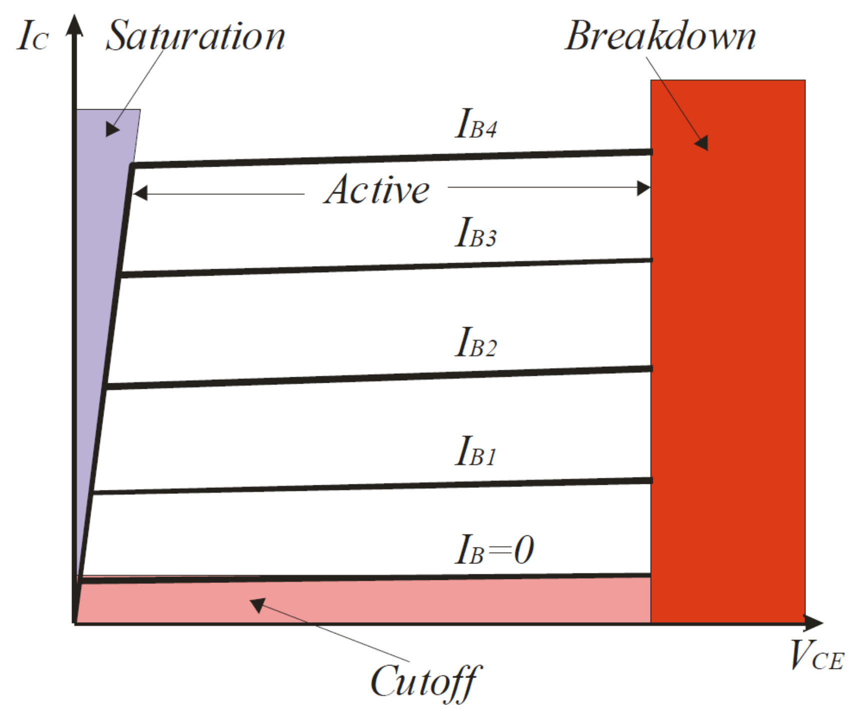


- Cut-off point represents I_C = 0 – thus $V_{CE} = V_{CC}$.
- Saturation point represents point where $I_C \approx I_C$ (sat) and CB junction has become reverse biased.
- Region between saturation and cut off is called the active (linear) region of operation.

7. Summary of Regions of Operation:

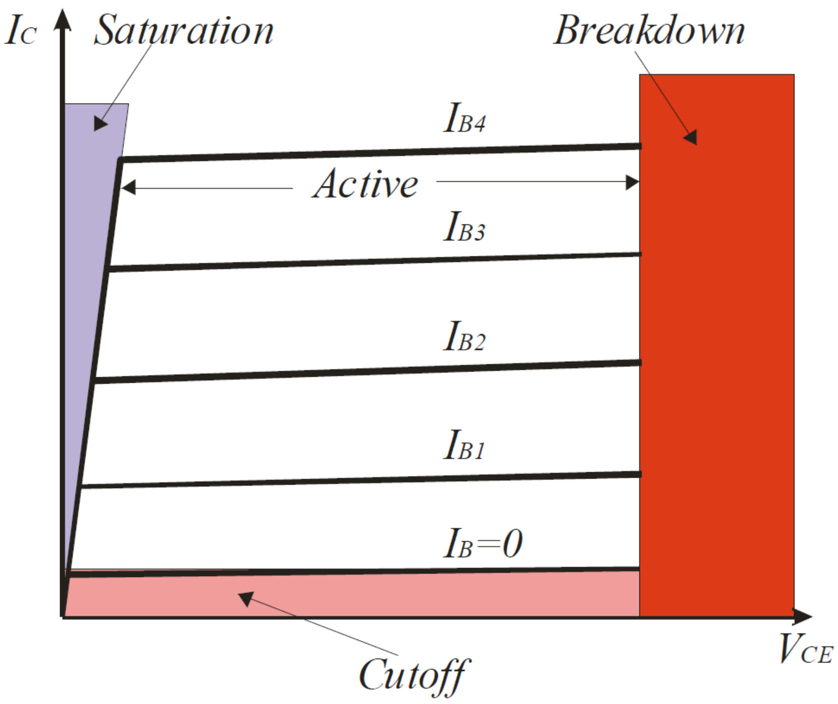
- Cut-off region – BJT is OFF.
- Saturation region – Voltage across BJT is maximum.
- Active region – Current gain/transfer is linear.
- Breakdown region – Destructive operation of BJT.

Region	**BE Junction**	**BC Junction**
Cut off	Reverse	Reverse
Saturation	Forward	Forward
Active (linear)	Forward	Reverse



7. Take Home Message:

- The mode of operation (i.e. cut off, saturation or active) will be determined by the external bias circuit i.e. the power supplies and (biasing) resistors.
- We thus need to bias transistor correctly to have it operating in the desired region.
- Much more on this in a later section.

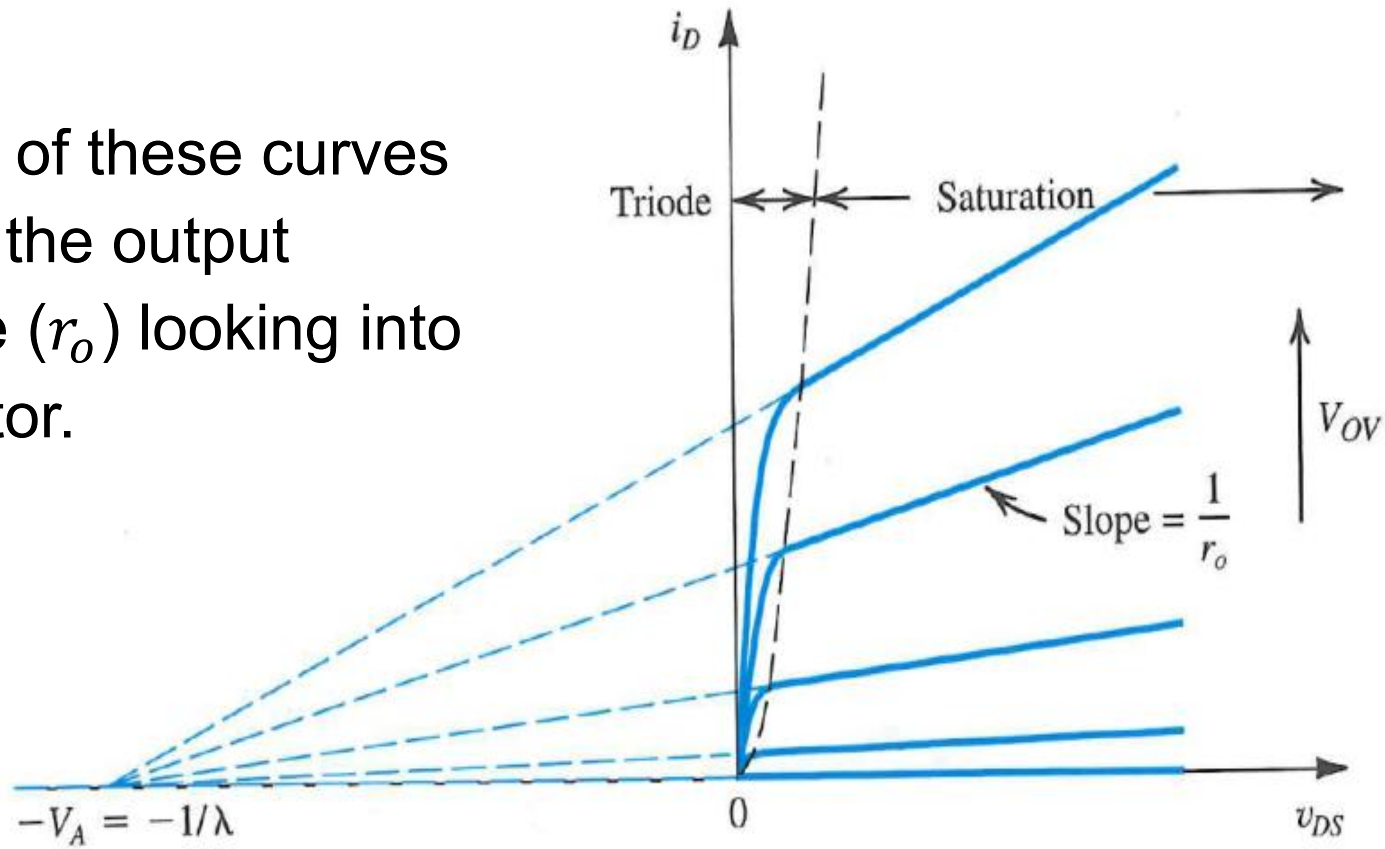


7. Why the Finite Slope in These Curves?

- For a constant value V_{BE}, an increase in V_{CE} will lead to an increase in the potential difference between B and C.
- This means an effective increase in the reverse bias voltage on the B-C junction, leading to an increase in the space-charge region at the junction and a thinner neutral region in the base.
- This causes an increase in the gradient of minority carrier electrons in the base and an increase in the current.

7. Why the Finite Slope in These Curves? (cont.)

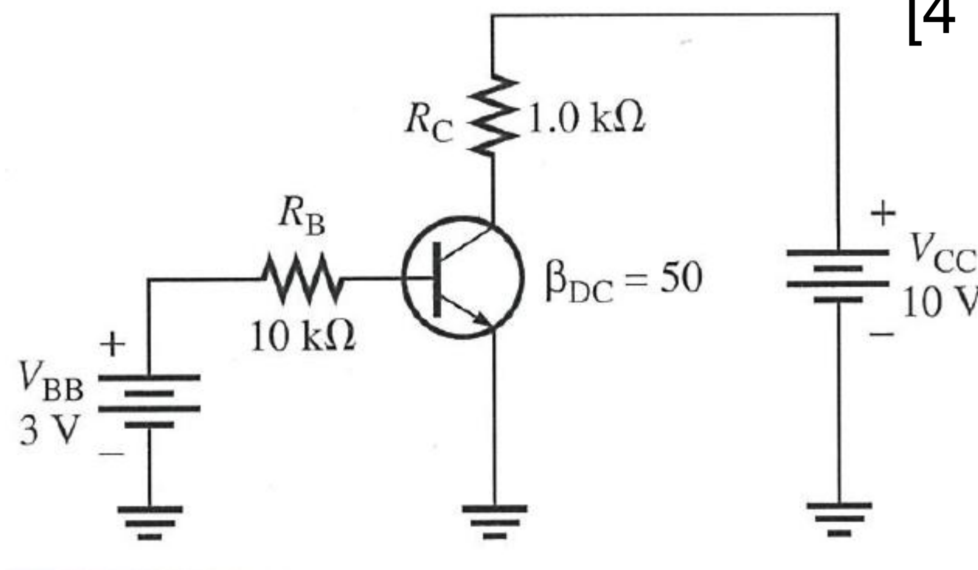
- The curves all tend to a point – V_A on the voltage axis - known as the **Early voltage**.
- It is a variation in the effective width of the base in a BJT due to a variation in the applied base-to-collector voltage).
- The slope of these curves represent the output resistance (r_o) looking into the collector.



Example 3 - BJT Characteristics

In the circuit below, we measure a value of V_{CE} = 0.2 V. Show whether this circuit is in saturation condition or not?

[4 marks]



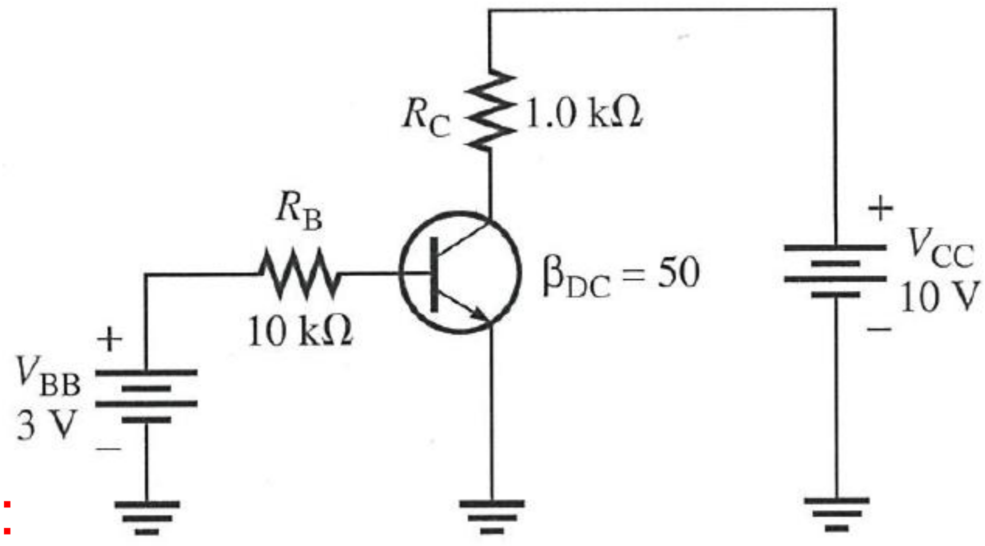
Hint: If V_{BE} is 0.7 V, then work out V_C from I_B for the given condition of the transistor.

Answer

- Calculate base current (I_B):

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

$$= \frac{3 - 0.7}{10\text{k}} = 0.23 \text{ mA}$$



- Voltage at collector (V_C):

$$V_C = I_C R_C$$

$$V_C = \beta I_B R_C = (50)(0.23\text{mA})(1\text{k}\Omega) = 11.5 \text{ V}$$

- Since V_C is bigger than V_{CC}, as a result the transistor is saturated.

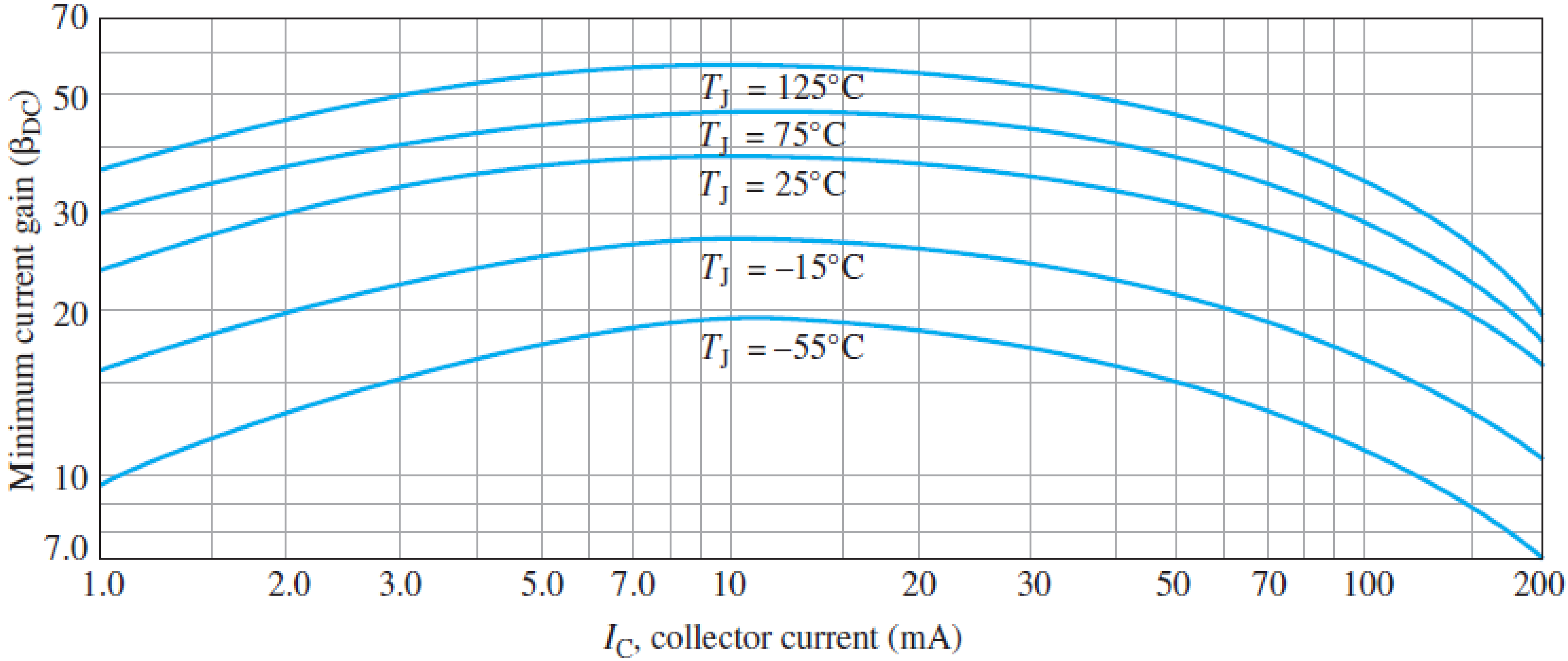
8. Note on the “Constant” $\boldsymbol{\beta_{DC}}$

- Often assume that the value of β_{DC} is constant.
- However, it is a weak function of the collector current (e.g. a slope in I_C).
- Actually, it only increases to a point after which it will decrease again.
- β_{DC} is also a function of the transistor temperature.
- As the temperature increases, the value of β_{DC} also goes up.

Thus, a bad idea to do the design of a transistor circuit based on a specific (supplied) value of $\boldsymbol{\beta_{DC}}$.

8. Note on the "Constant" β_{DC} (cont.)

- Datasheets of transistors would normally specify a minimum value of β_{DC} at a certain value of I_C.

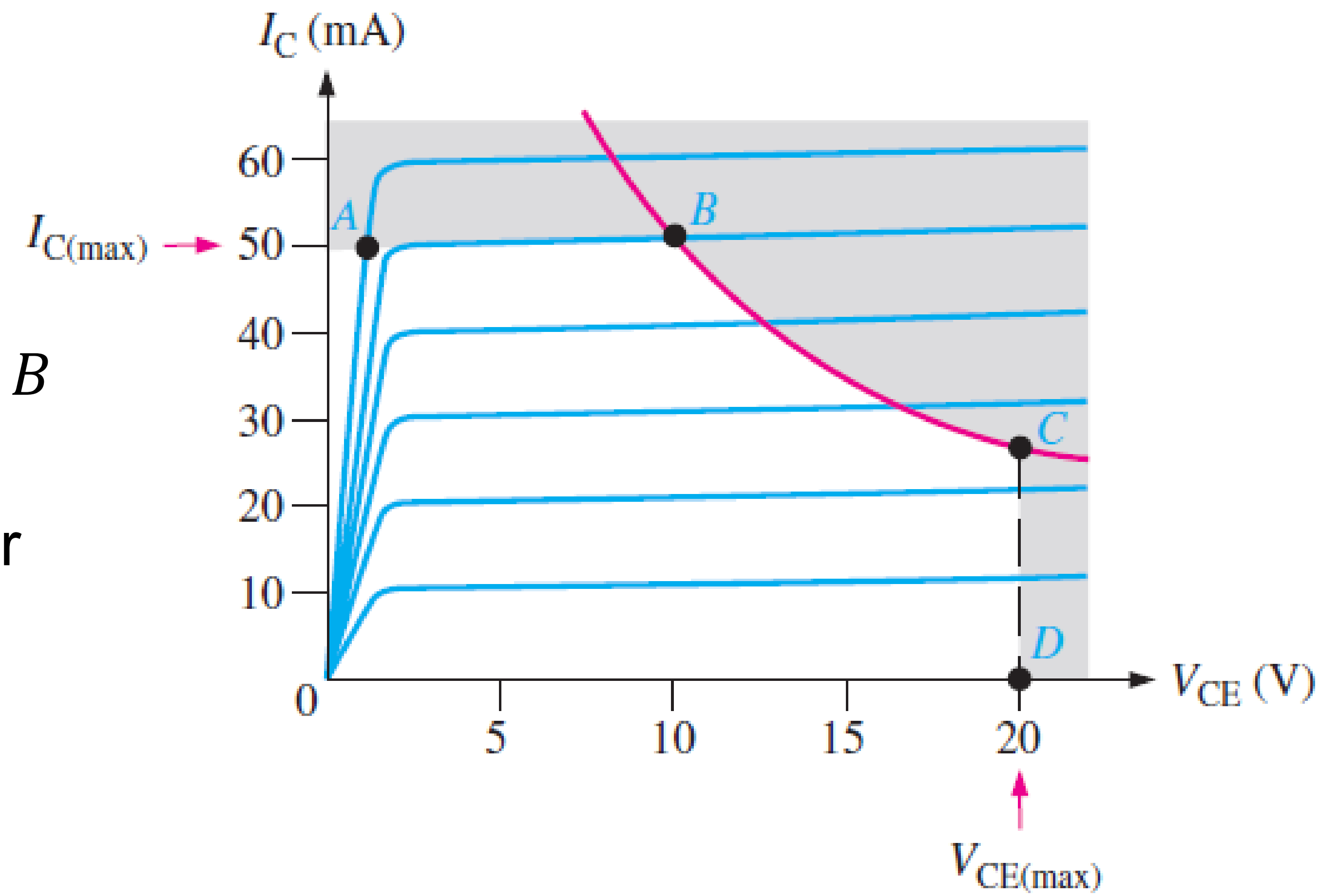


9. Maximum Transistor Ratings

- Like all devices transistors have maximum ratings beyond which they cannot reliably operate i.e. typically the voltages and currents over the different junctions.

Note:

Both points B and C give same power dissipation.



9. Maximum Transistor Ratings (cont.)

- The power rating is specified as the product of I_C and V_{CE}:

$$P(\max) = I_C V_{CE}$$

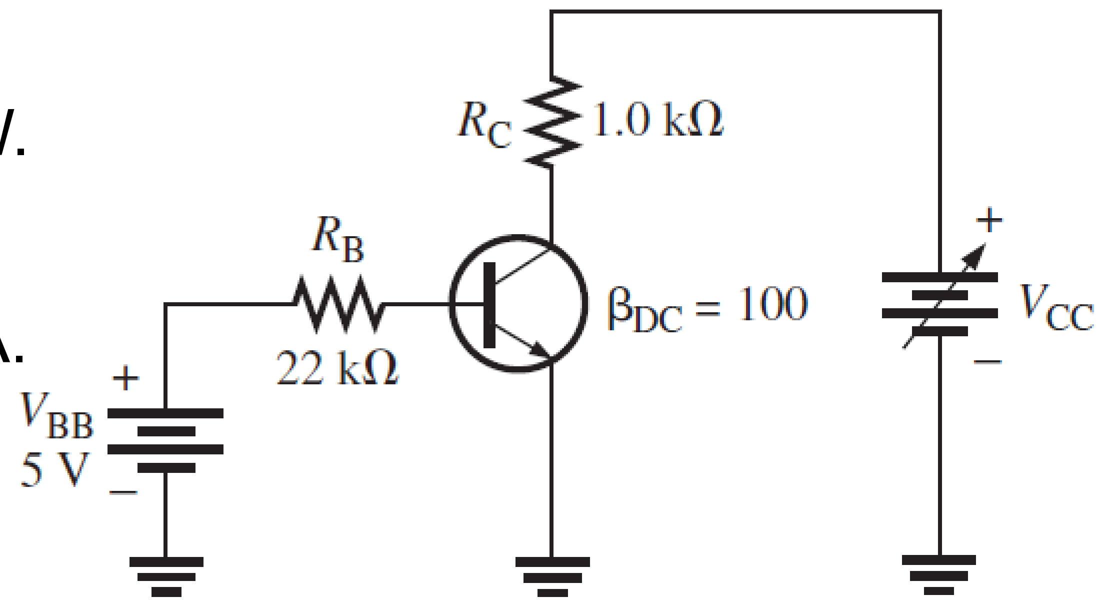
- Thus, we cannot maximise I_C and V_{CE} at the same time. We can get a maximum power dissipation curve.

$P_D(\max)$(mW)	V_{CE} (V)	I_C (mA)
500	5	100
500	10	50
500	15	33
500	20	25

Example 4 – Device Ratings of BJT

The transistor in this circuit has the following maximum ratings:

- $P(\text{max})$ = 800 mW.
- $V_{CE}(\text{max})$ = 15 V.
- $I_C(\text{max})$ = 100 mA.



a. Calculate the maximum value to which you can adjust V_{CE} without exceeding maximum ratings. Hint: Determine V_{CE} from maximum power dissipated.

[4 marks]

b. Calculate I_C and determine if this is less than maximum rating. [2 marks]

c. Calculate the maximum value to which you can adjust V_{CC} without exceeding maximum rating. Calculate the power dissipation of the BJT at this condition [6 marks]

d. Describe the V_{CE} when the V_{BB} is reduced to zero. Would any of the ratings is being exceeded?

[4 marks]

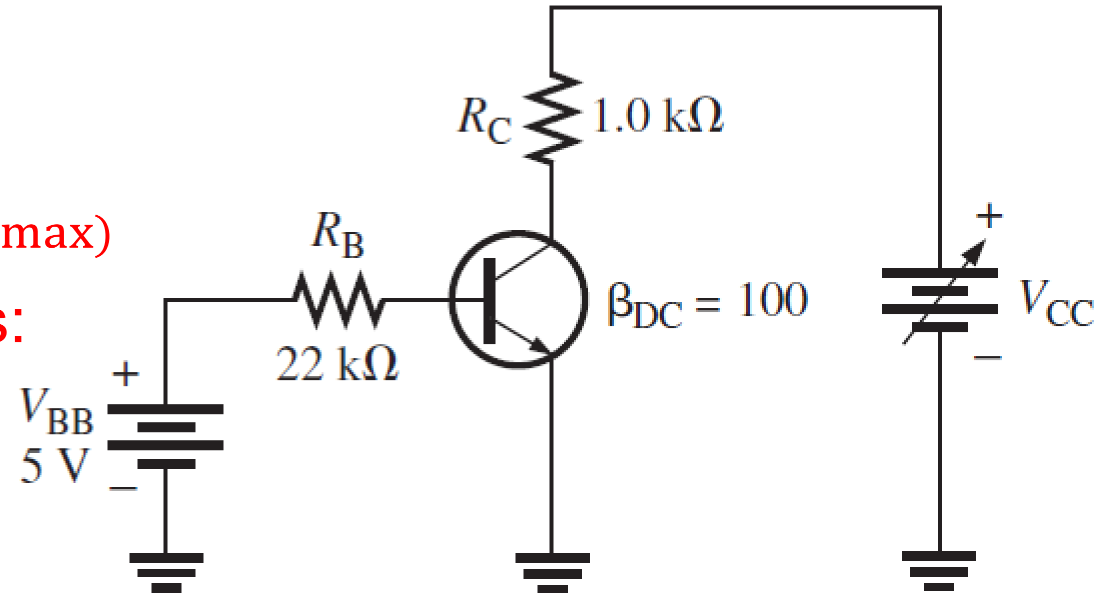
Answer

a. Knowing that:

$$P_{\max} = V_{CE(\max)} I_{C(\max)}$$

Thus, the $V_{CE}(\max)$ is:

$$V_{CE(\max)} = \frac{P_{\max}}{I_{C(\max)}}$$

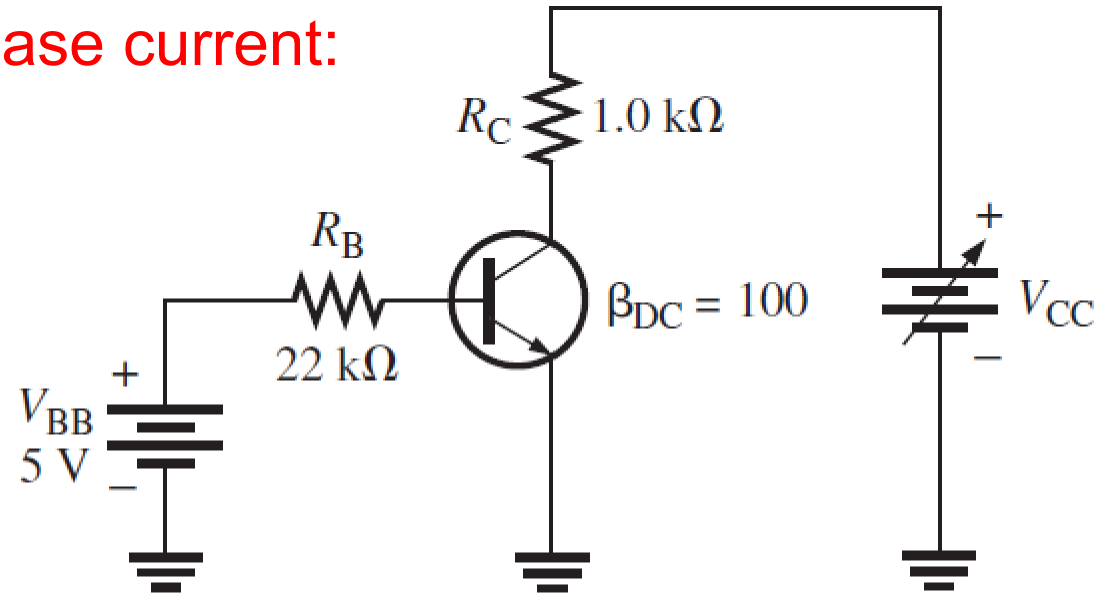


Based on the maximum transistor power dissipation, the maximum V_{CE} is:

$$V_{CE(\max)} = \frac{(800\text{ mW})}{(100\text{ mA})} = 8\text{ V}$$

Although from datasheet $V_{CE}(\max)$ = 15 V, the V_{CE} of the should be kept below 8 V.

b. First, calculate the base current:



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

$$= \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega}$$

$$= 0.195\text{ mA}$$

For the transistor in active (linear) mode, I_C is then:

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

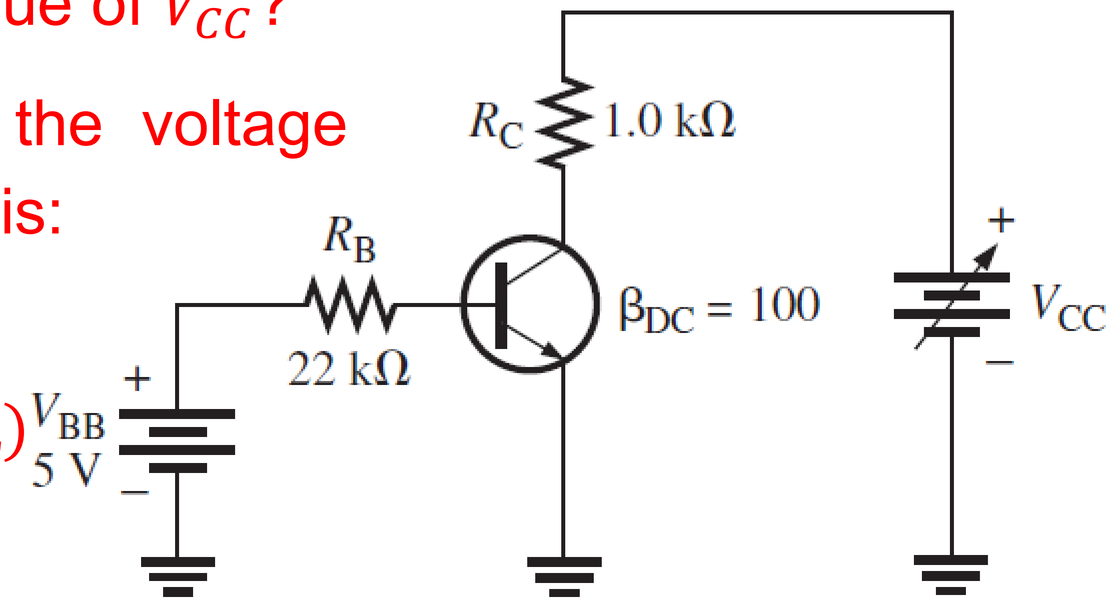
$$= (100)(0.195) = 19.5\text{ mA}$$

This is significantly smaller than $I_C(\text{max})$, so maximum rating for I_C not exceeded.

c. What is maximum value of V_{CC}?

For I_C = 19.5 mA, the voltage drop over resistor R_C is:

$$V_{R_C} = I_C R_C$$
$$= (19.5\ \text{mA})(1\ \text{k}\Omega)$$
$$= 19.5\ \text{V}$$



For a maximum value of $V_{CE}(\max)$ = 15 V, the maximum value of V_{CC} is then:

$$V_{CC}(\max) = V_{CE}(\max) + V_{R_C}$$
$$= 15\ \text{V} + 19.5\ \text{V} = 34.5\ \text{V}$$

The power dissipation of the transistor is then:

$$P = I_C V_{CE} = (19.5\ \mathrm{mA})(15\ \mathrm{V}) = 292.5\ \mathrm{mW}$$

This is within limits of transistor ($P(\max)$ = 800 mW).

d. Keep in mind what will happen if V_{BB} is reduced to zero Volts. Thus, the BE junction is not forward biased and the BE junction is an open circuit.

The I_C is then zero, but the voltage V_{CC} is now in total be dropped over V_{CE}.

Thus, V_{CE} = 34.5 V and the transistor ratings will be exceeded, even though no power is dissipated in the transistor (I_C = 0).