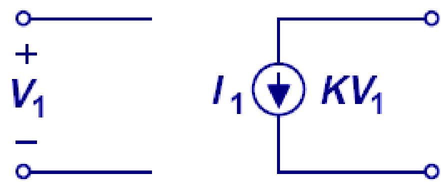
Chapter 4 Physics of Bipolar Transistors

Bipolar Transistor

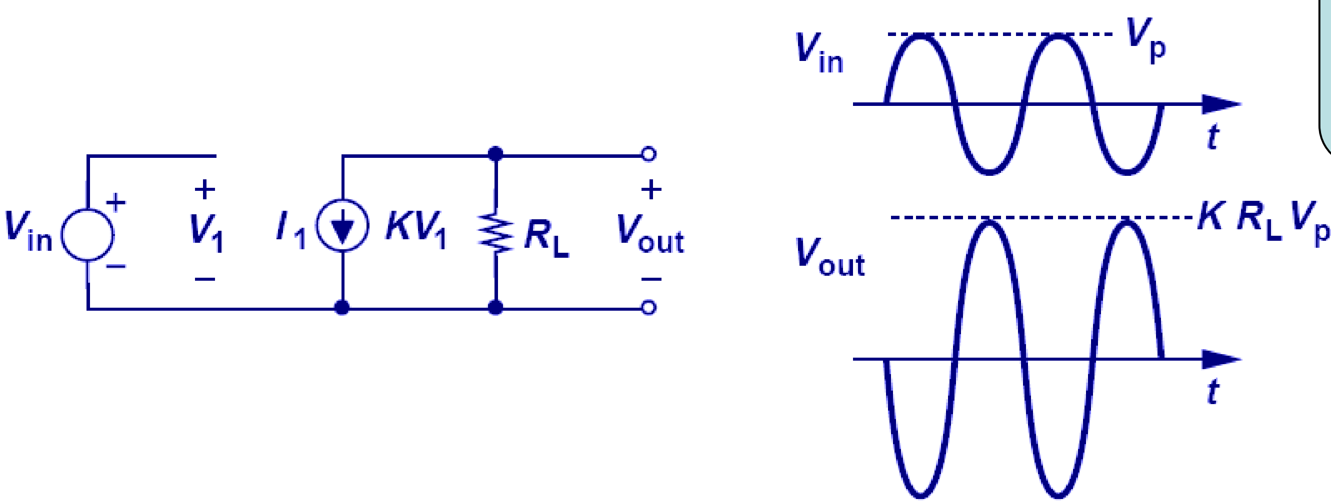
Voltage-Controlled Device as Amplifying Element ⇨ Structure of Bipolar Transistor ⇨ Operation of Bipolar Transistor ⇨ Large-Signal Model ⇨ Small-Signal Model

- **In the chapter, we will study the physics of bipolar transistor and derive large and small signal models.**

Voltage-Dependent Current Source



(a)

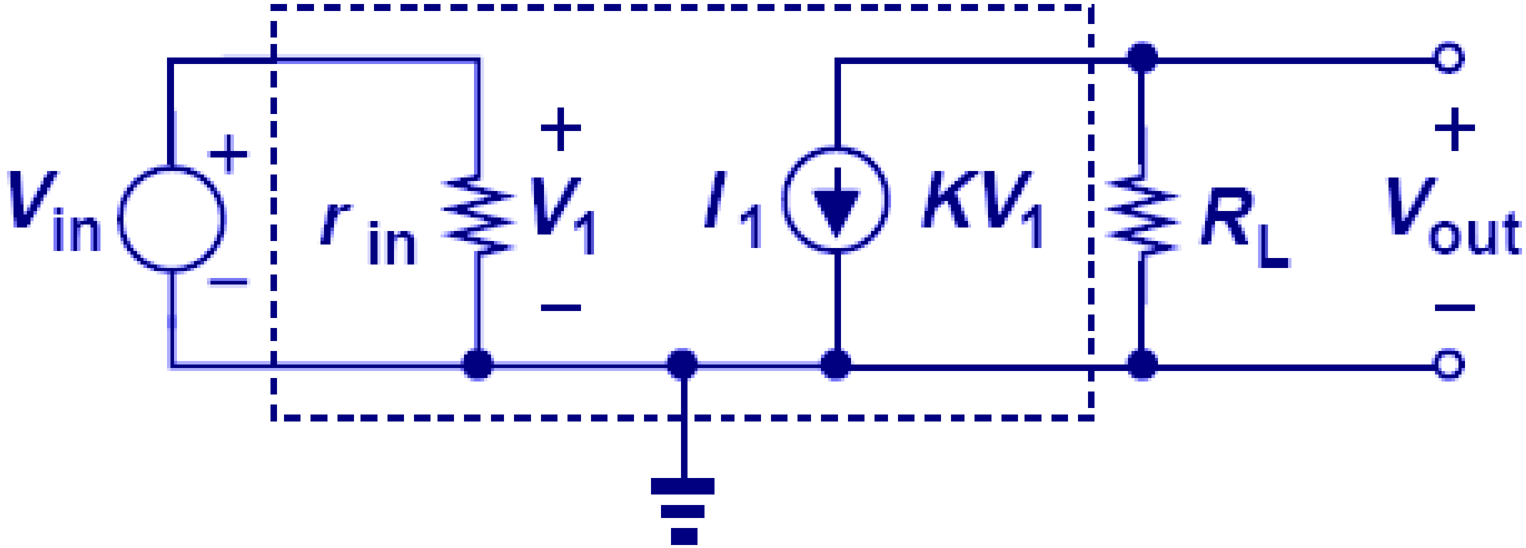


(b)

$$A_V = \frac{V_{out}}{V_{in}} = -KR_L$$

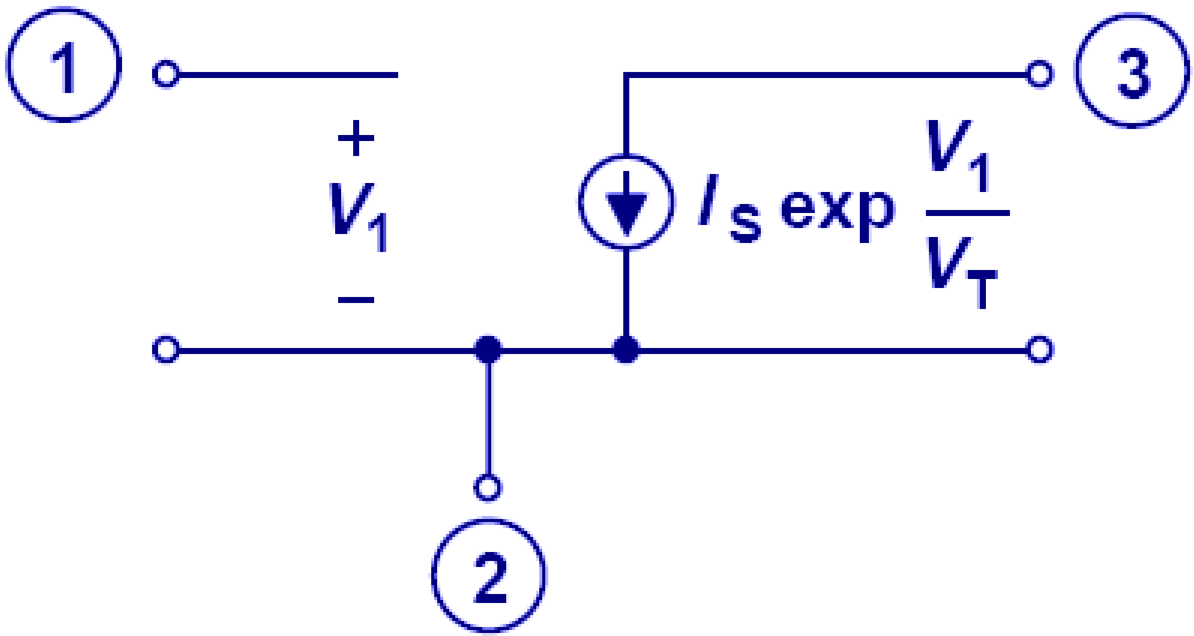
- A voltage-dependent current source can act as an amplifier.
- If KR_L is greater than 1, then the signal is amplified.

Voltage-Dependent Current Source with Input Resistance



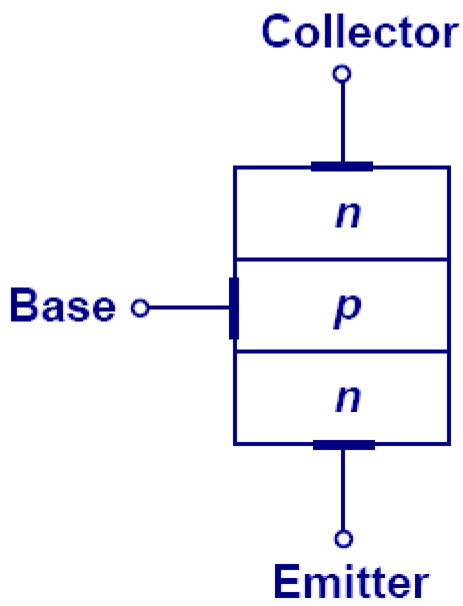
- Regardless of the input resistance, the magnitude of amplification remains unchanged.

Exponential Voltage-Dependent Current Source

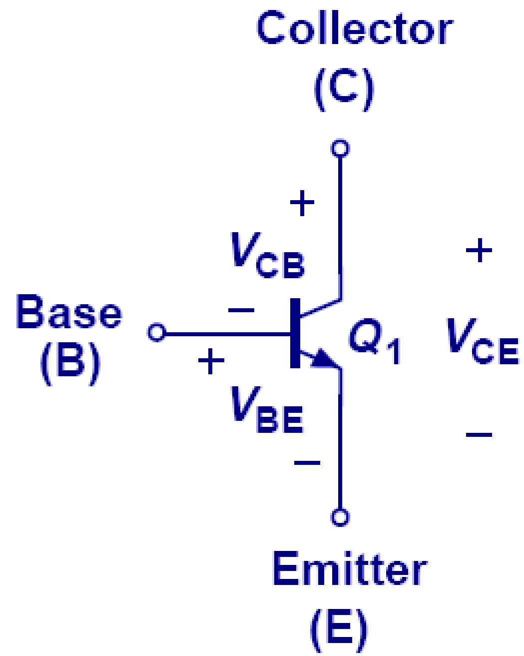


- **A three-terminal exponential voltage-dependent current source is shown above.**
- **Ideally, bipolar transistor can be modeled as such.**

Structure and Symbol of Bipolar Transistor



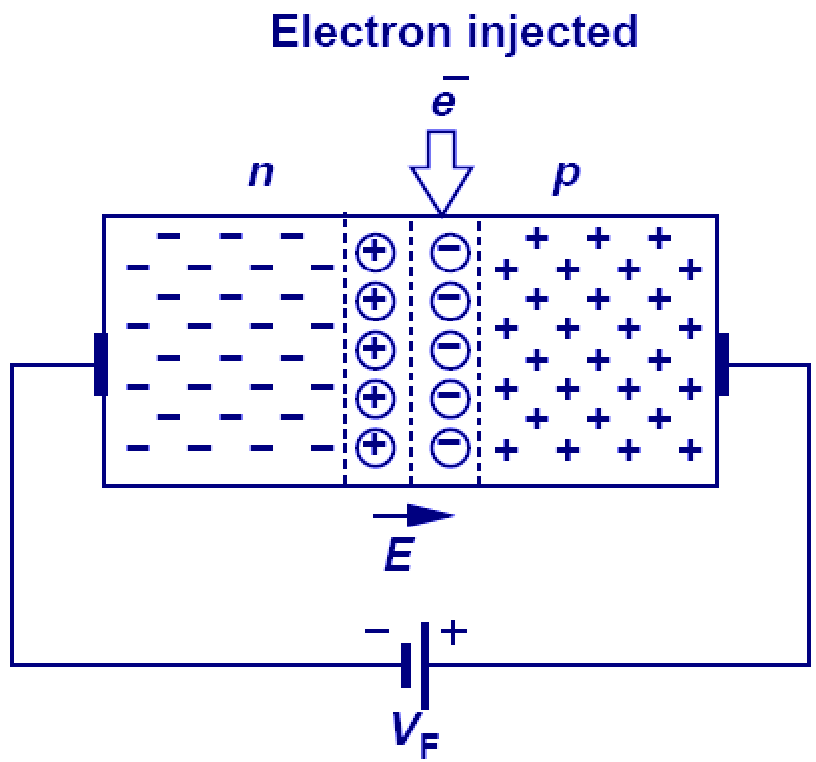
(a)



(b)

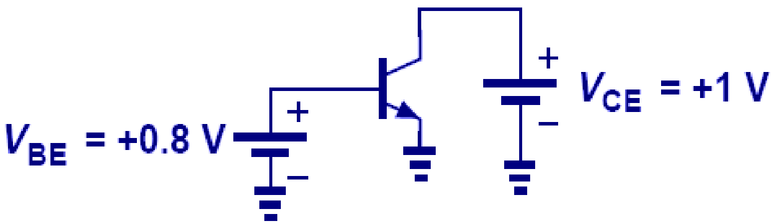
- Bipolar transistor can be thought of as a sandwich of three doped Si regions. The outer two regions are doped with the same polarity, while the middle region is doped with opposite polarity.

Injection of Carriers

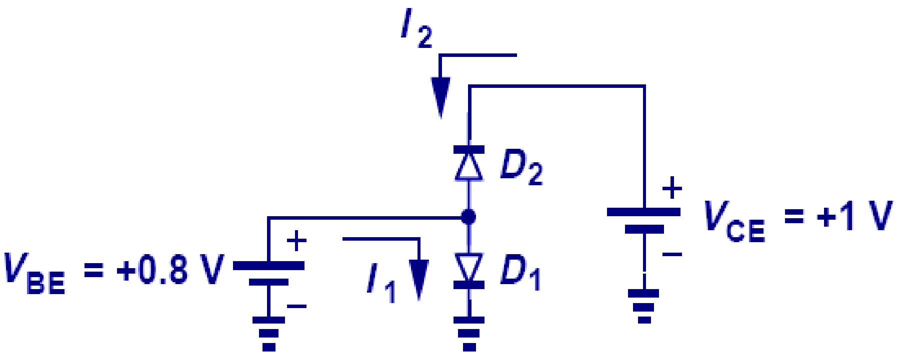


- Reverse biased PN junction creates a large electric field that sweeps any injected minority carriers to their majority region.
- This ability proves essential in the proper operation of a bipolar transistor.

Forward Active Region



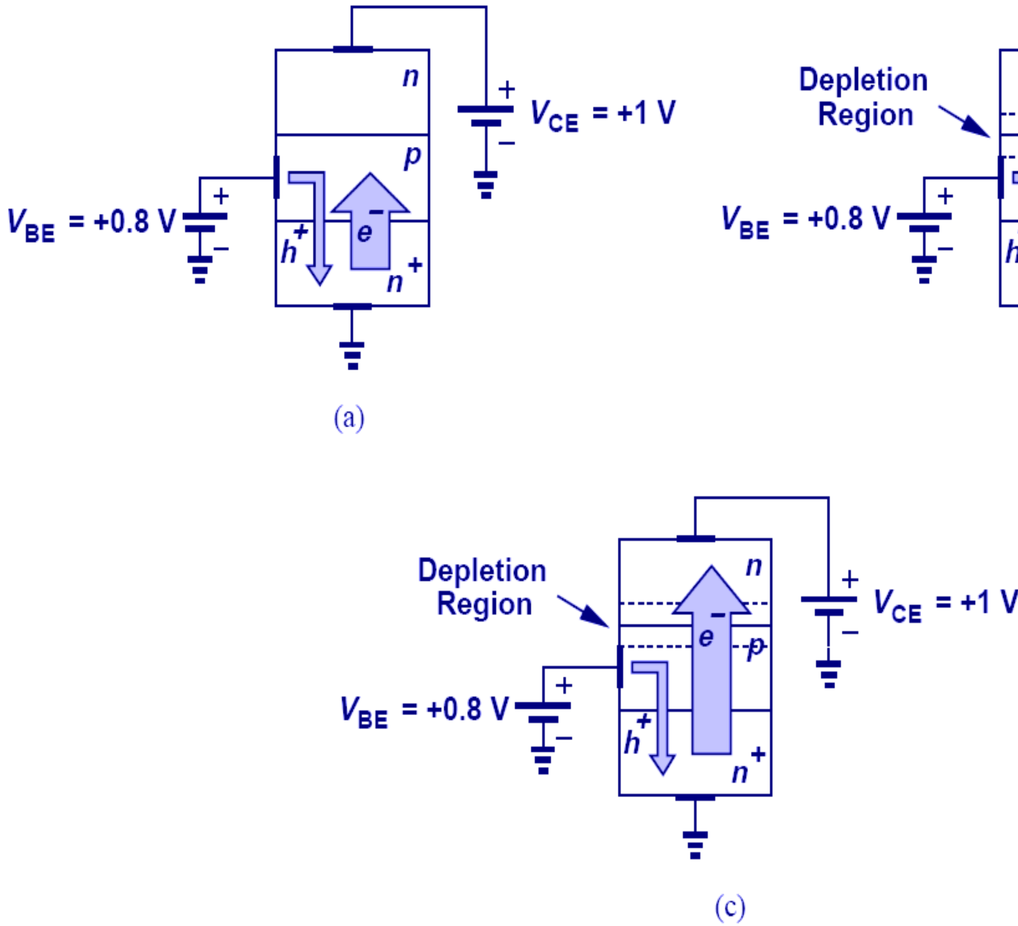
(a)



(b)

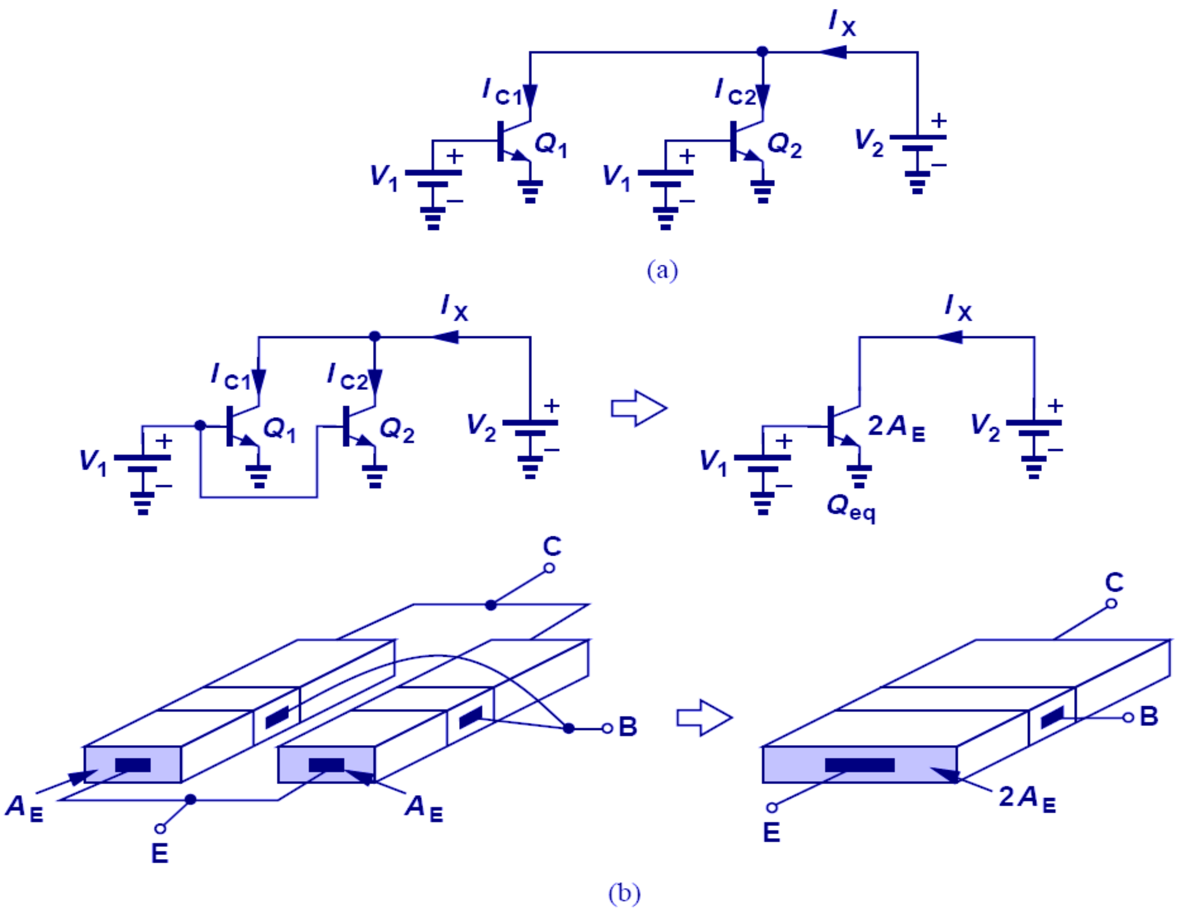
- **Forward active region: $V_{BE} > 0$, $V_{BC} < 0$.**
- **Figure b) presents a wrong way of modeling figure a).**

Accurate Bipolar Representation



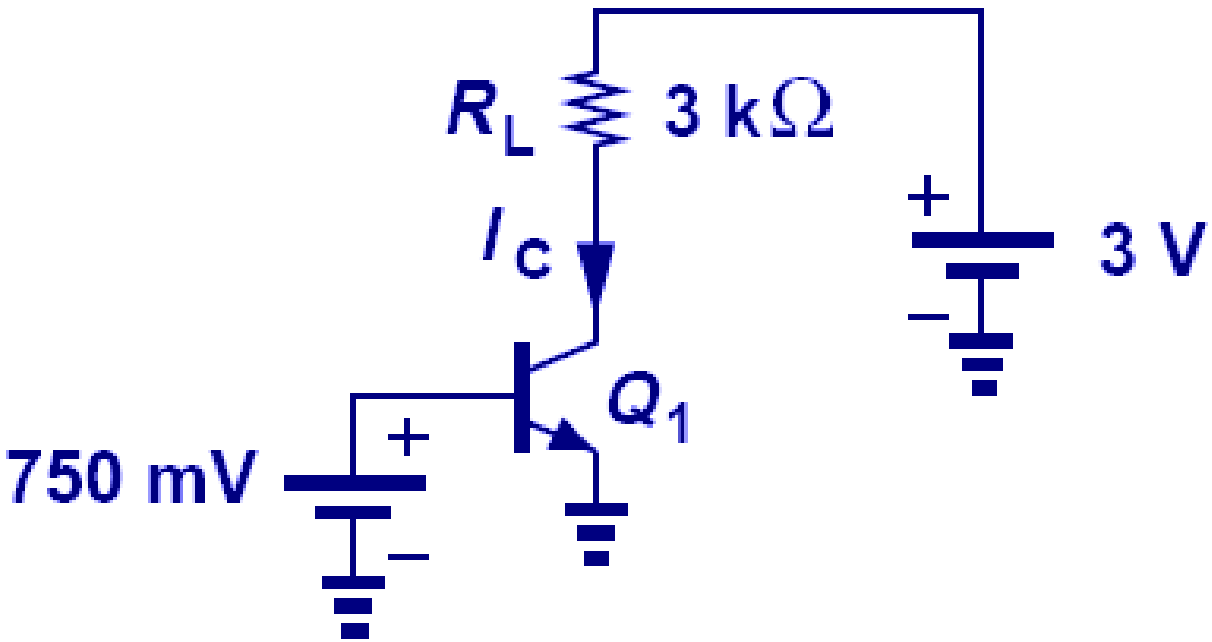
- **Collector also carries current due to carrier injection from base.**

Parallel Combination of Transistors



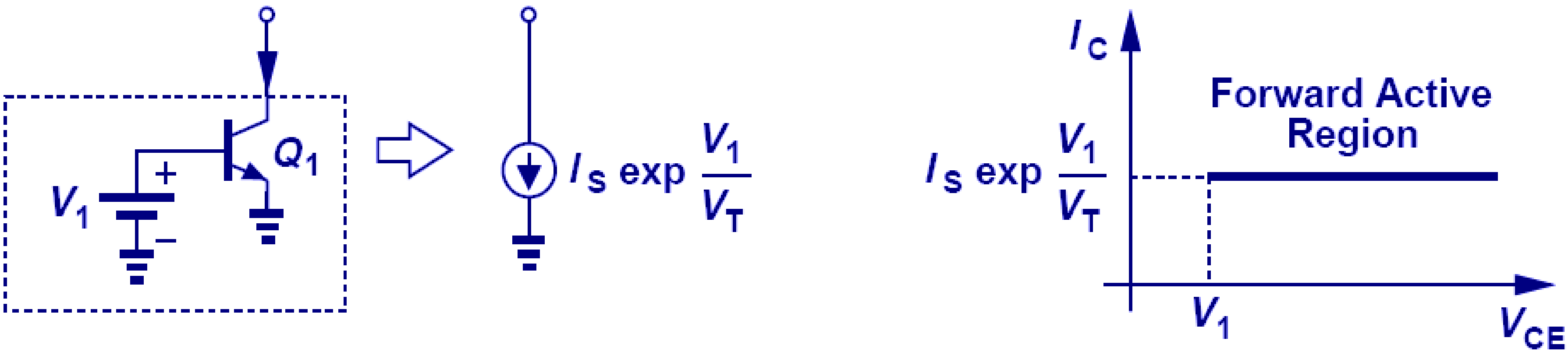
- **When two transistors are put in parallel and experience the same potential across all three terminals, they can be thought of as a single transistor with twice the emitter area.**

Simple Transistor Configuration



- Although a transistor is a voltage to current converter, output voltage can be obtained by inserting a load resistor at the output and allowing the controlled current to pass thru it.

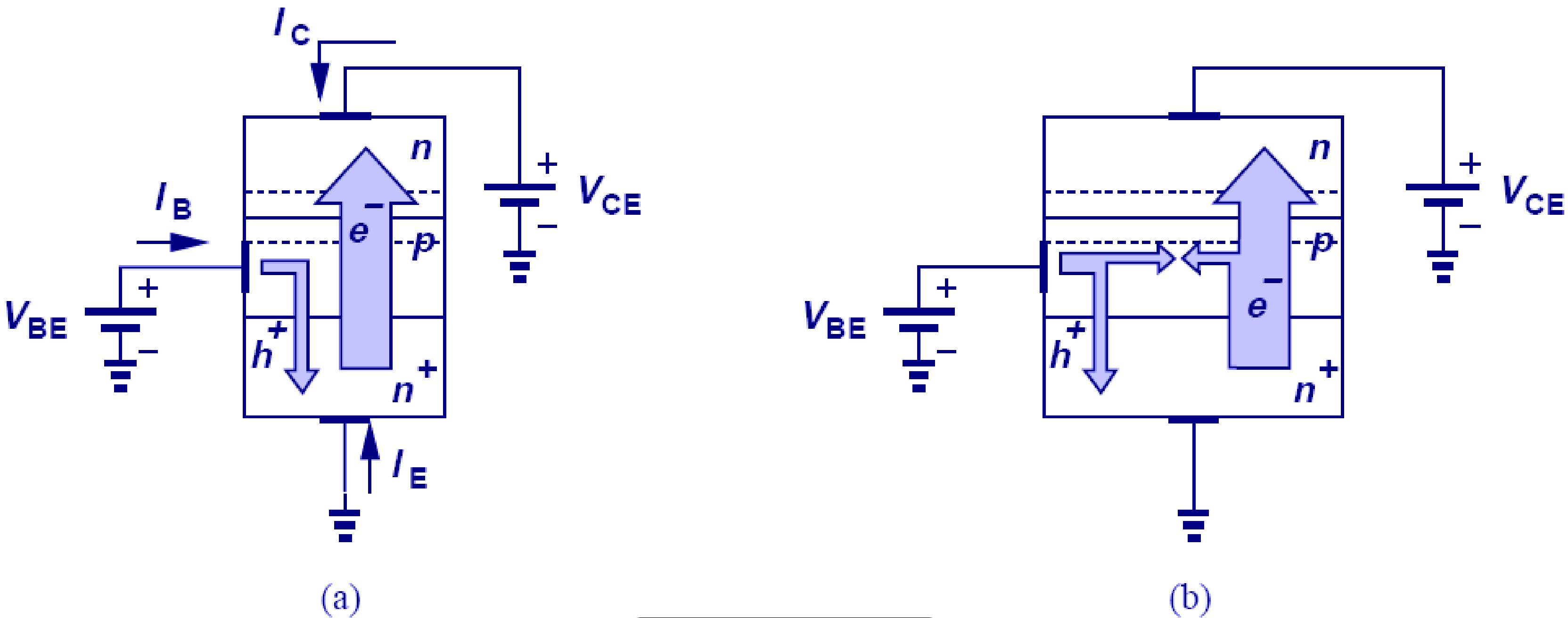
Constant Current Source



(a) (b)

- **Ideally, the collector current does not depend on the collector to emitter voltage. This property allows the transistor to behave as a constant current source when its base-emitter voltage is fixed.**

Base Current



$$I_C = \beta I_B$$

- Base current consists of two components: 1) Reverse injection of holes into the emitter and 2) recombination of holes with electrons coming from the emitter.

Emitter Current

$$I_E = I_C + I_B$$

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

$$\beta = \frac{I_C}{I_B}$$

- **Applying Kirchoff's current law to the transistor, we can easily find the emitter current.**

Summary of Currents

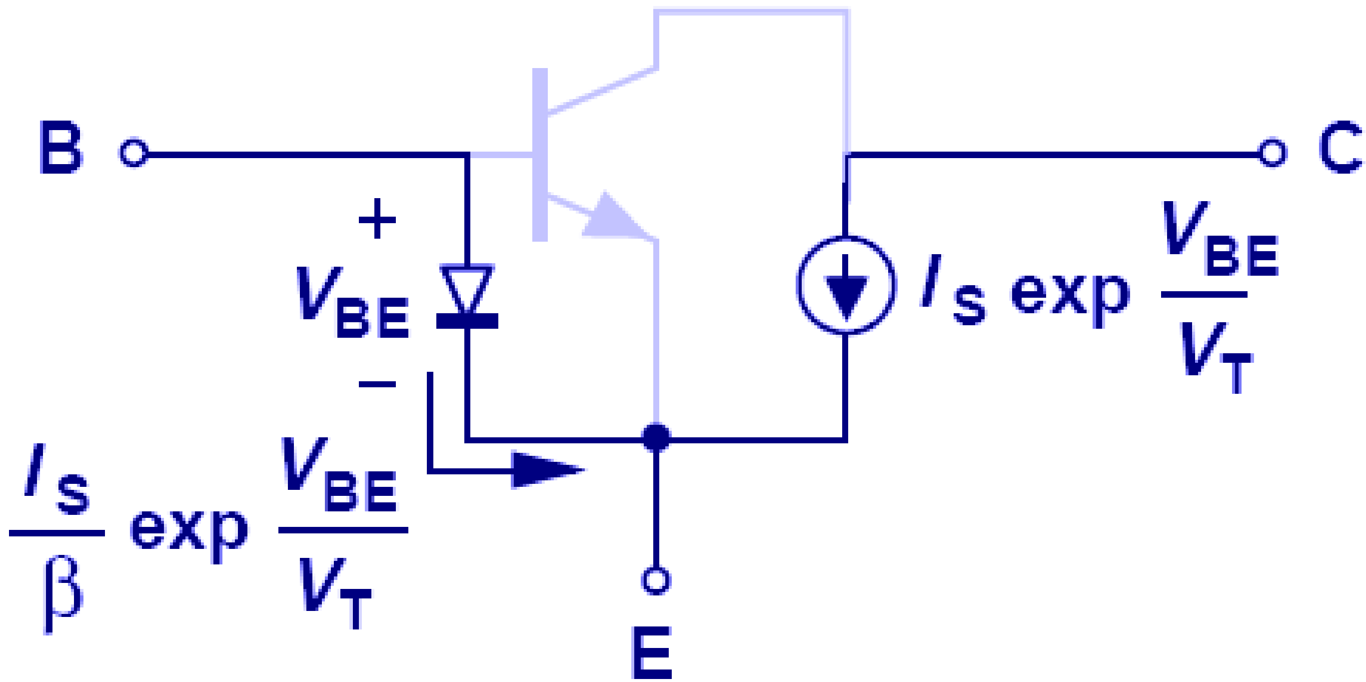
$$I_C = I_S \exp \frac{V_{BE}}{V_T}$$

$$I_B = \frac{1}{\beta} I_S \exp \frac{V_{BE}}{V_T}$$

$$I_E = \frac{\beta + 1}{\beta} I_S \exp \frac{V_{BE}}{V_T}$$

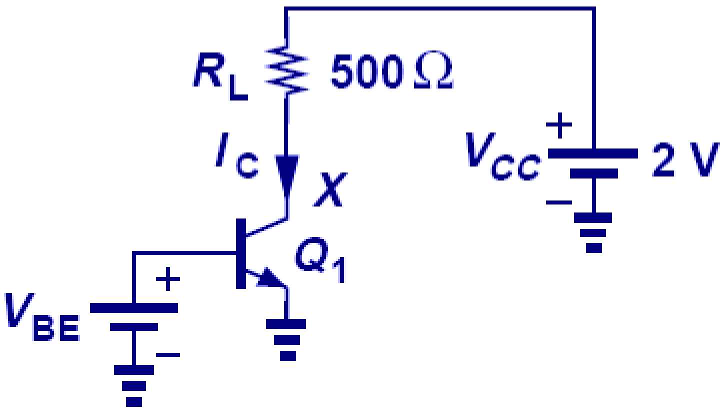
$$\frac{\beta}{\beta + 1} = \alpha$$

Bipolar Transistor Large Signal Model

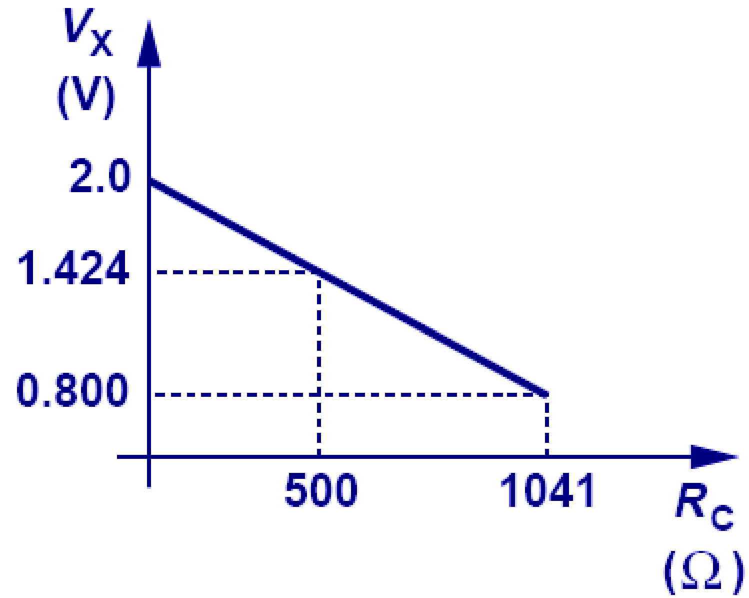


- A diode is placed between base and emitter and a voltage controlled current source is placed between the collector and emitter.

Example: Maximum R_L



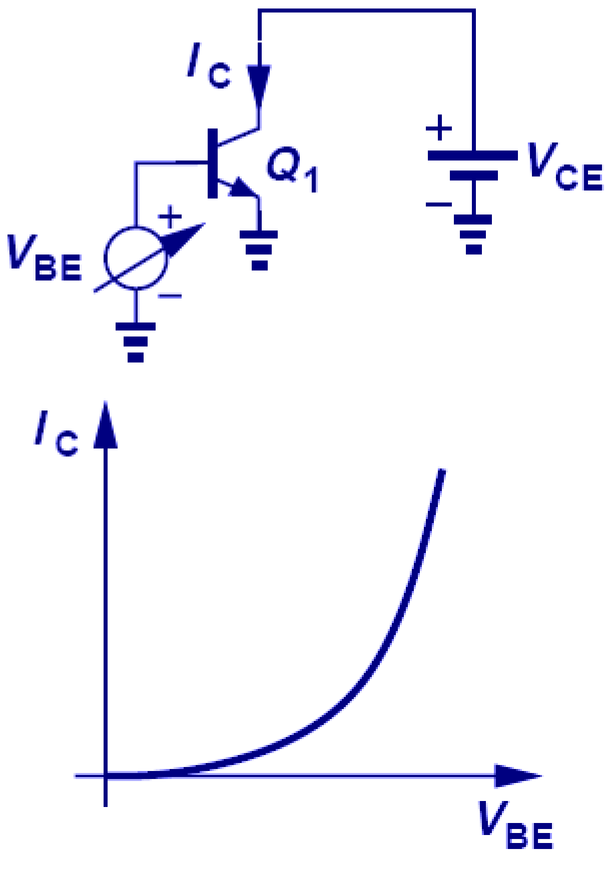
(a)



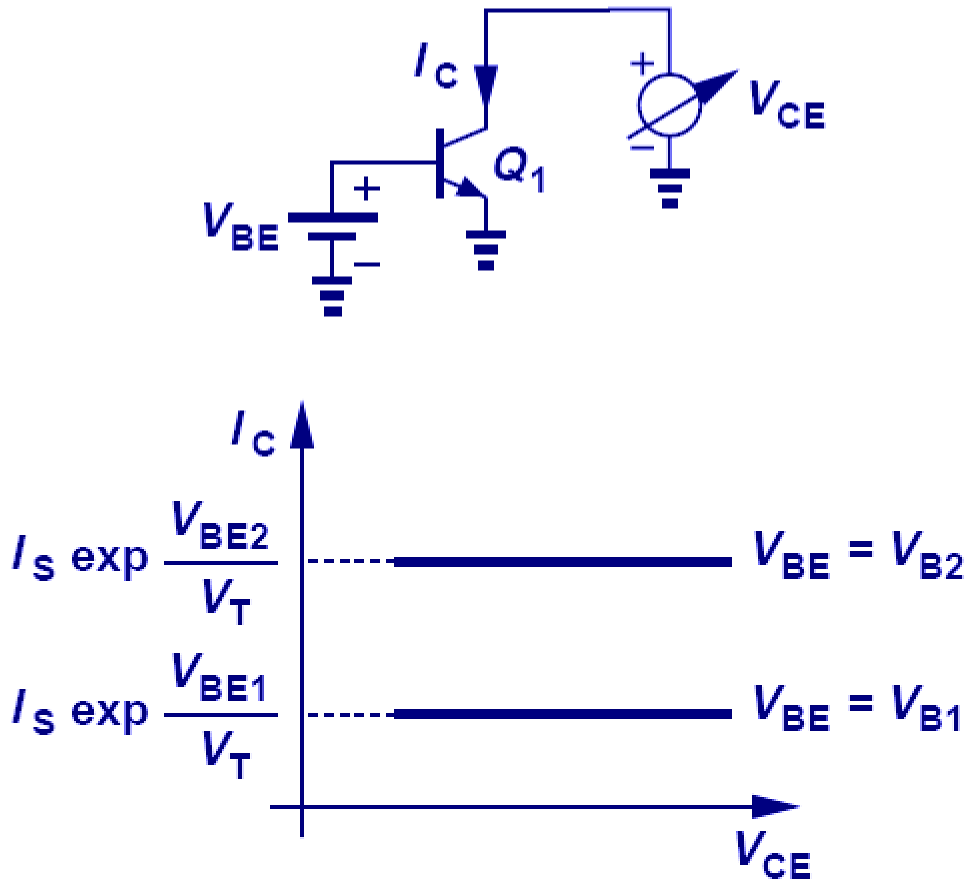
(b)

- As R_L increases, V_x drops and eventually forward biases the collector-base junction. This will force the transistor out of forward active region.
- Therefore, there exists a maximum tolerable collector resistance.

Characteristics of Bipolar Transistor

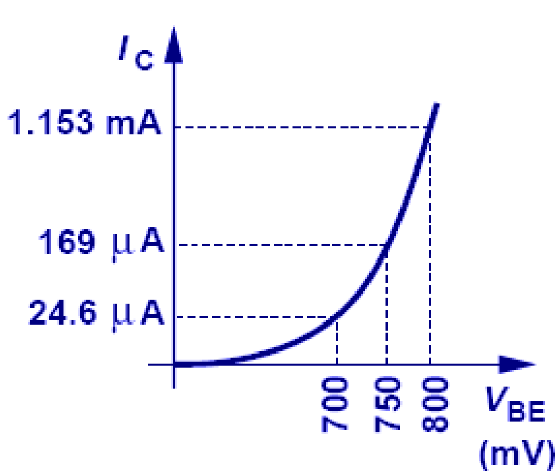


(a)

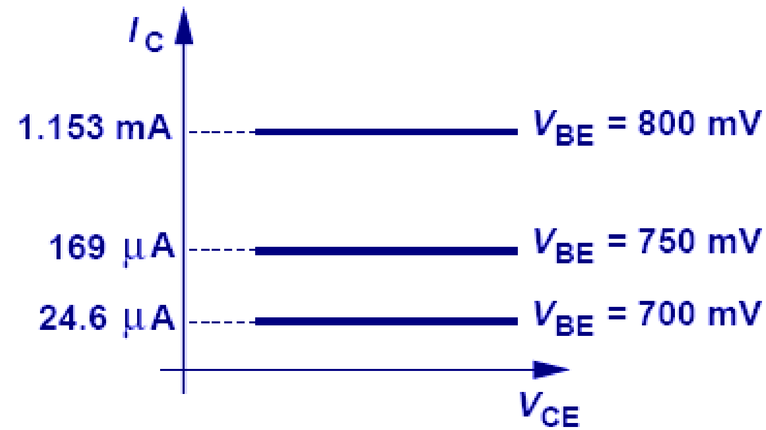


(b)

Example: IV Characteristics



(a)



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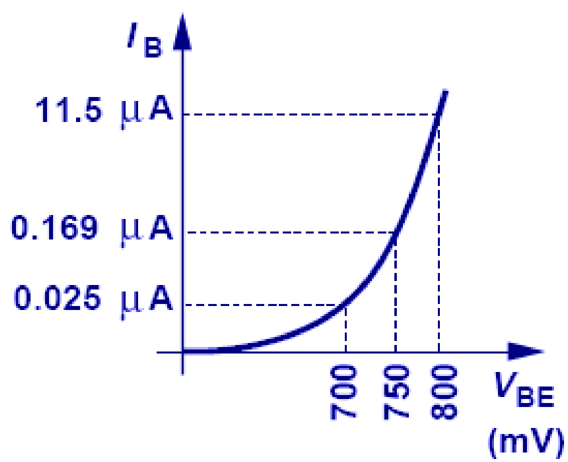

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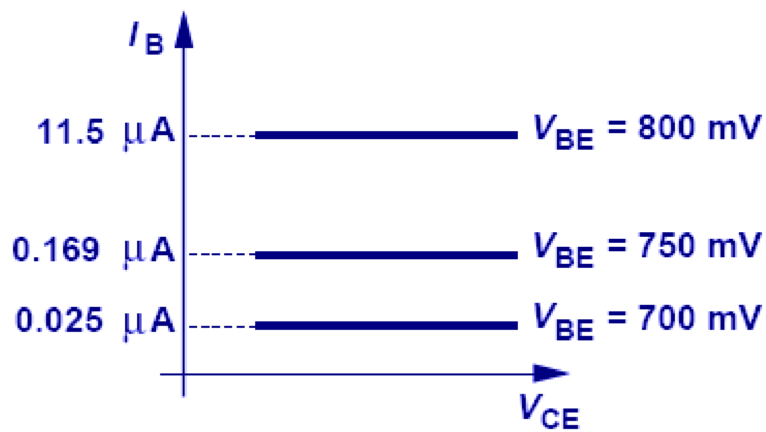
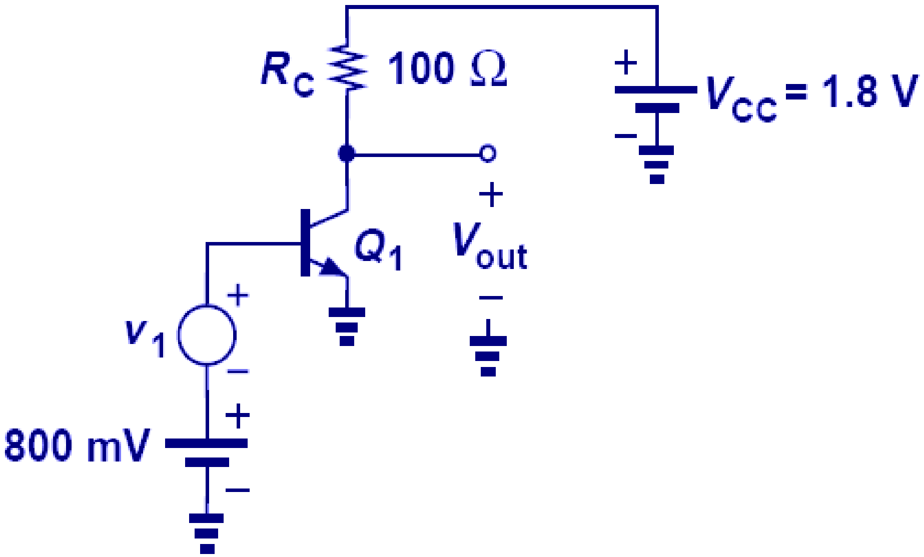
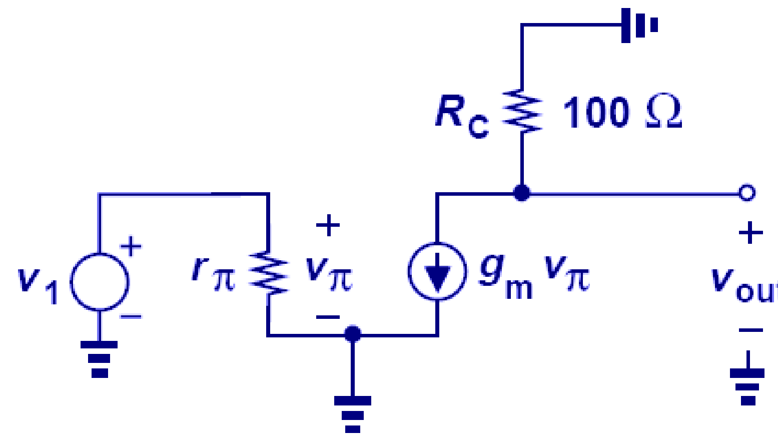


(d)

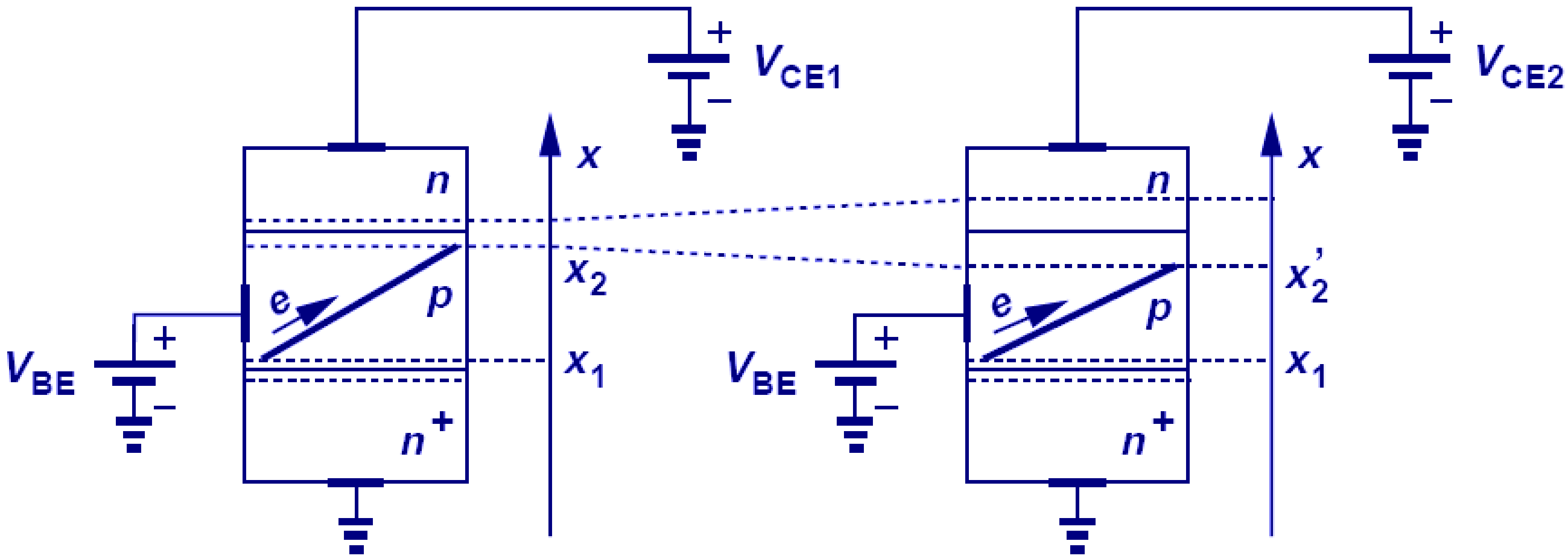
Small Signal Example II





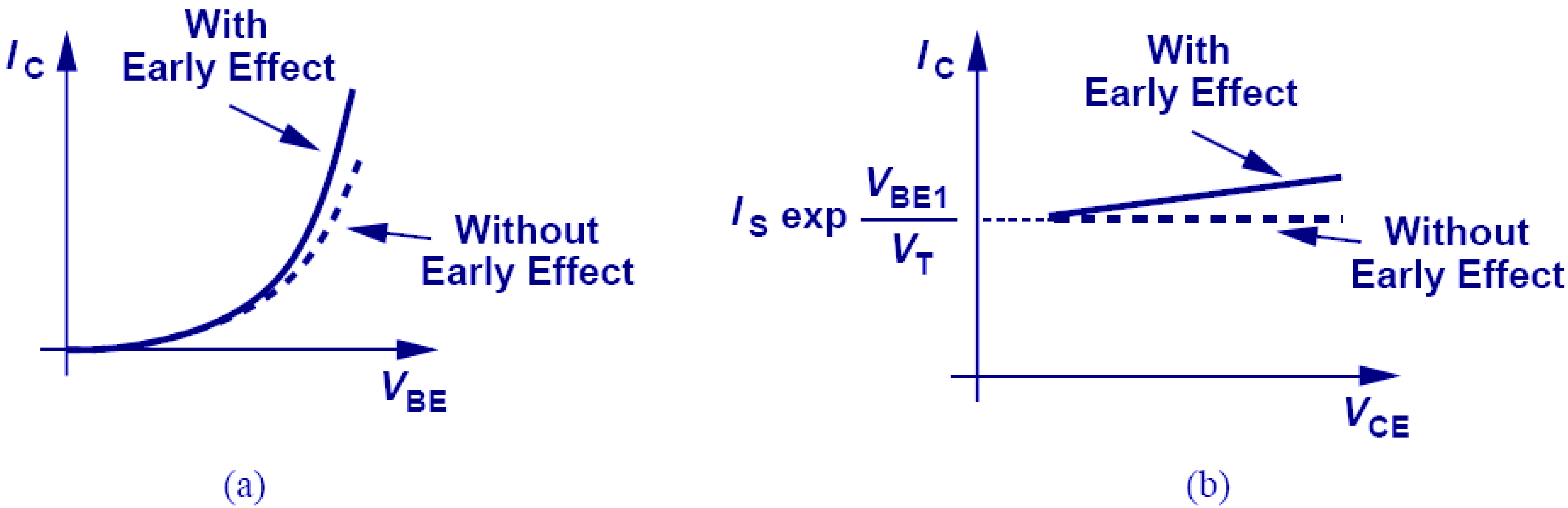
- In this example, a resistor is placed between the power supply and collector, therefore, providing an output voltage.

Early Effect



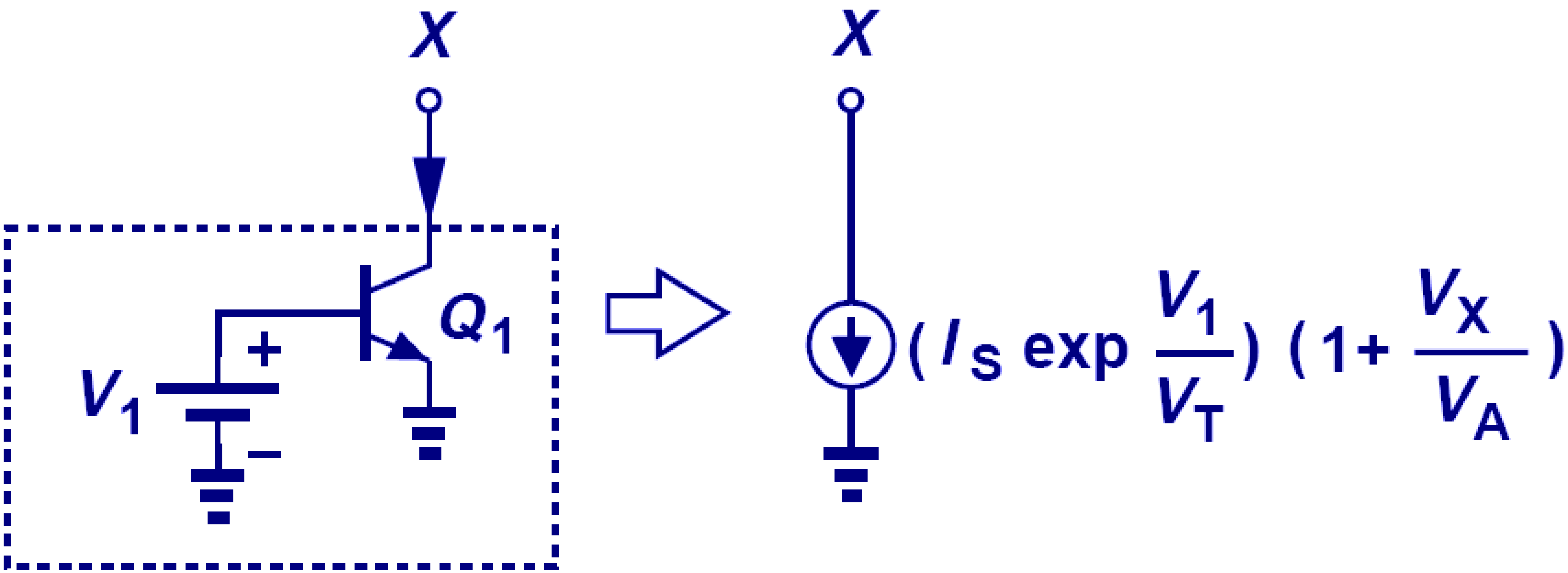
- The claim that collector current does not depend on V_{CE} is not accurate.
- As V_{CE} increases, the depletion region between base and collector increases. Therefore, the effective base width decreases, which leads to an increase in the collector current.

Early Effect Illustration

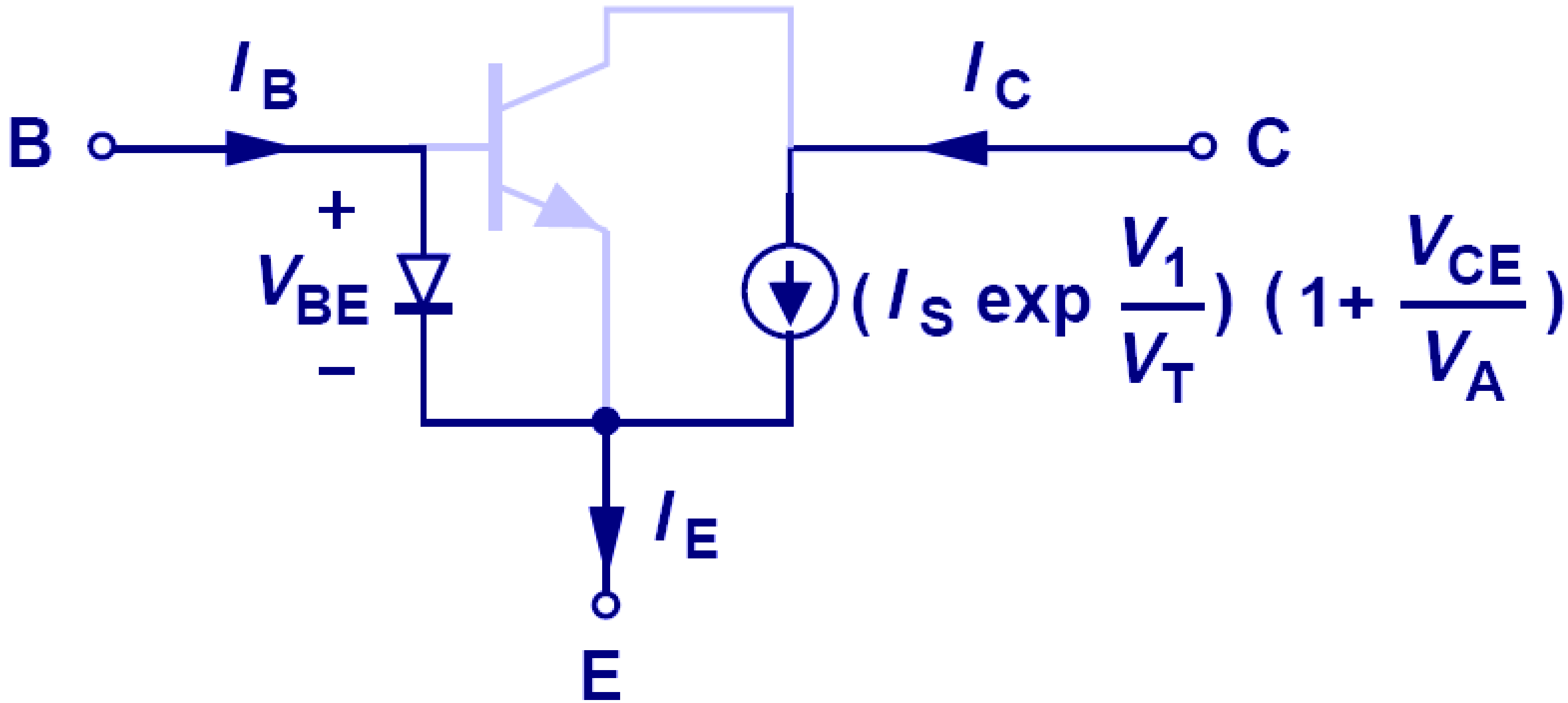


- With Early effect, collector current becomes larger than usual and a function of V_{CE}.

Early Effect Representation

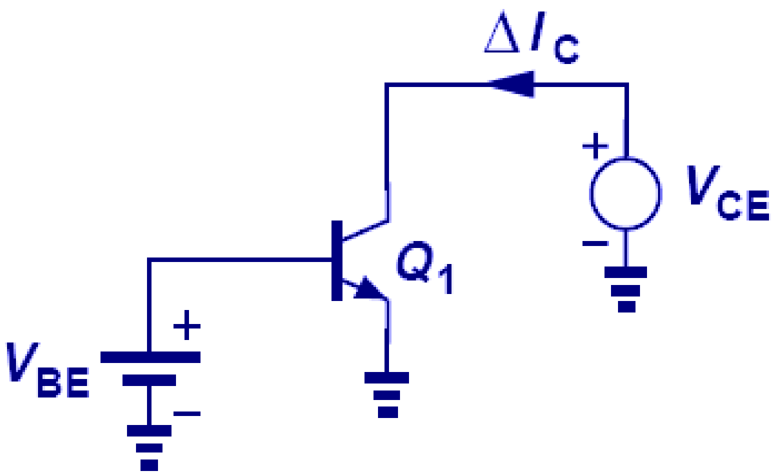


Early Effect and Large-Signal Model

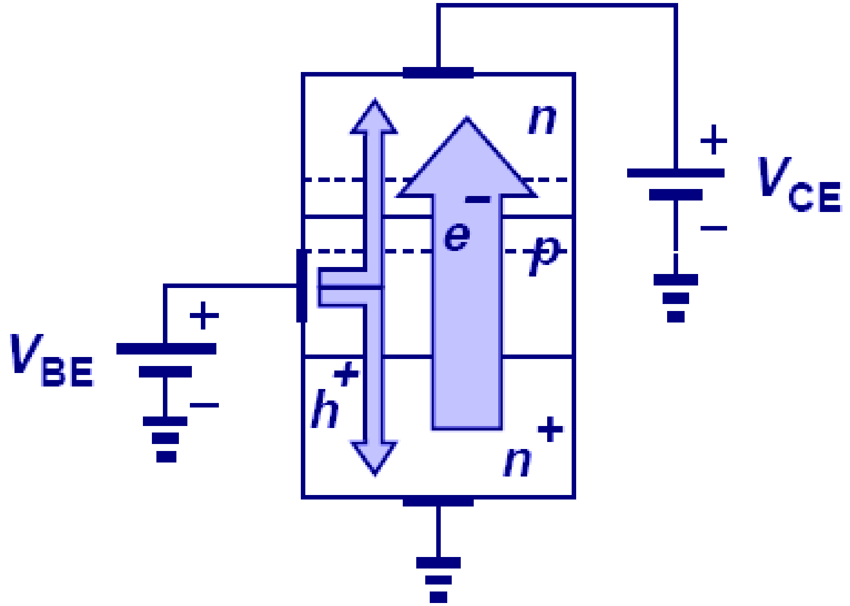


- Early effect can be accounted for in large-signal model by simply changing the collector current with a correction factor.
- In this mode, base current does not change.

Bipolar Transistor in Saturation



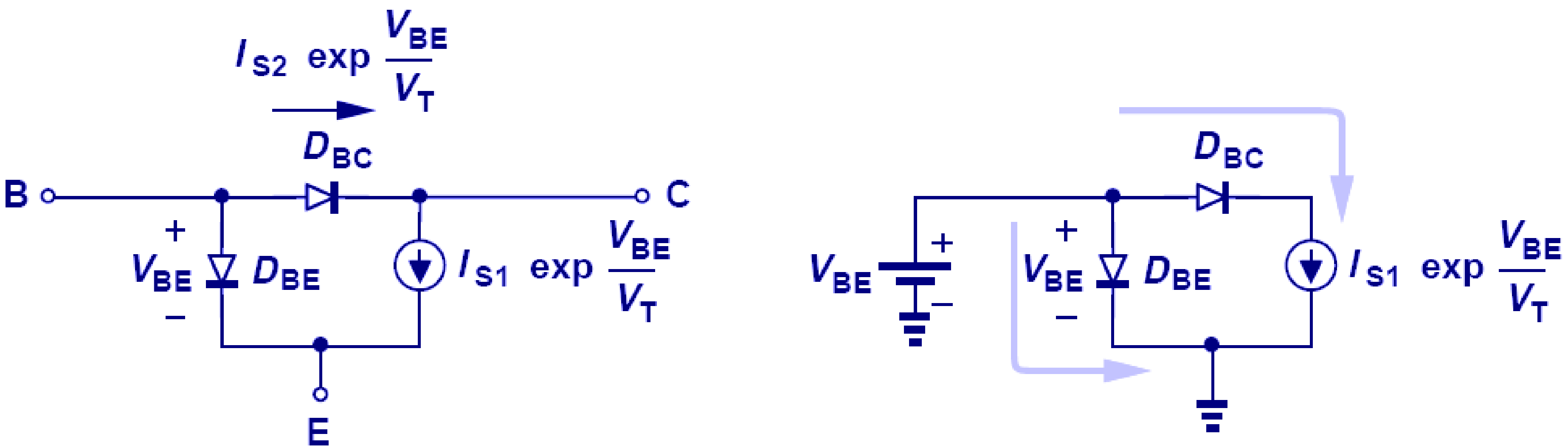
(a)



(b)

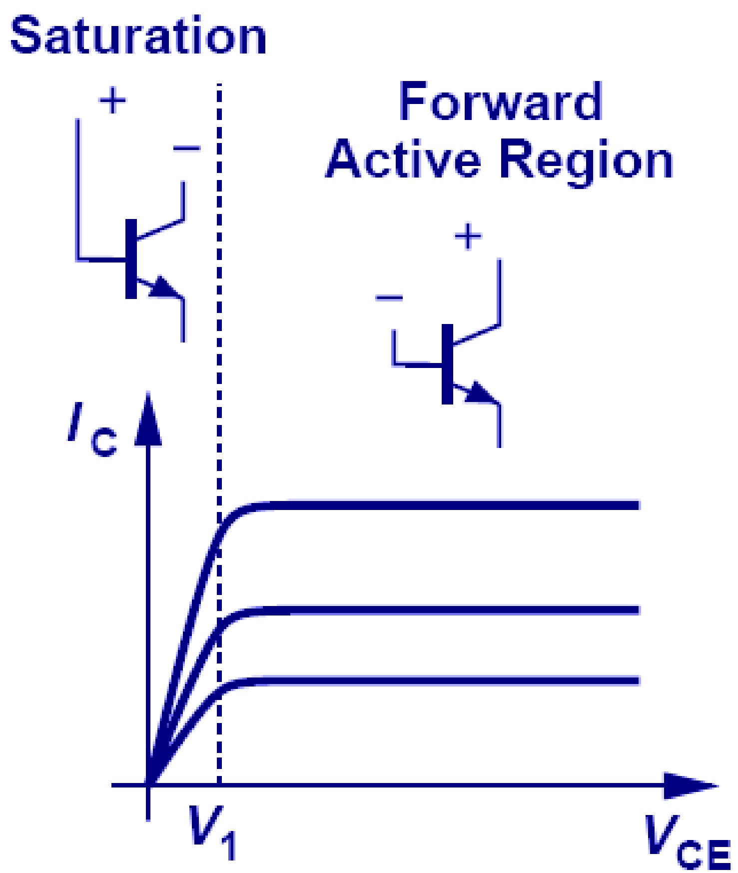
- When collector voltage drops below base voltage and forward biases the collector-base junction, base current increases and decreases the current gain factor, β.

Large-Signal Model for Saturation Region



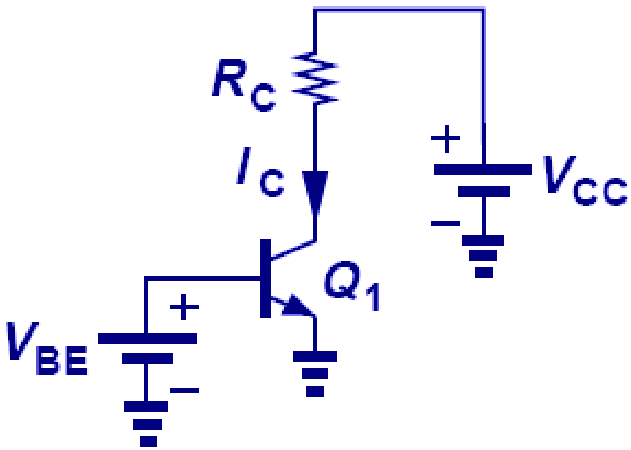
(a) (b)

Overall I/V Characteristics

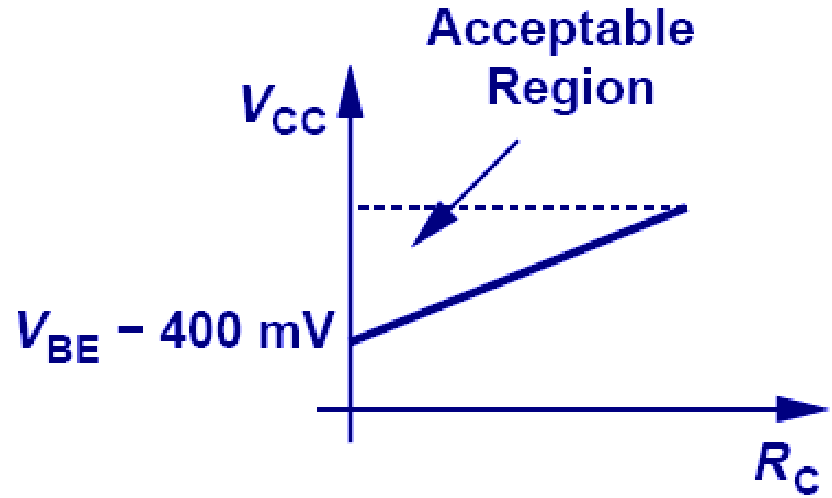


- The speed of the BJT also drops in saturation.

Example: Acceptable V_{CC} Region



(a)

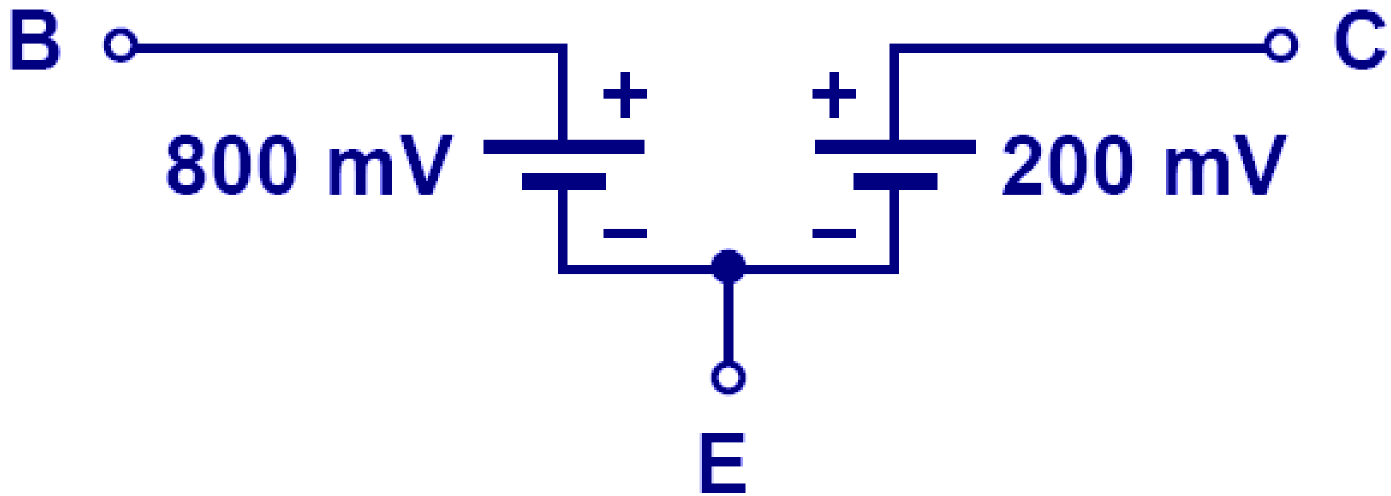


(b)

$$V_{CC} \geq I_C R_C + (V_{BE} - 400mV)$$

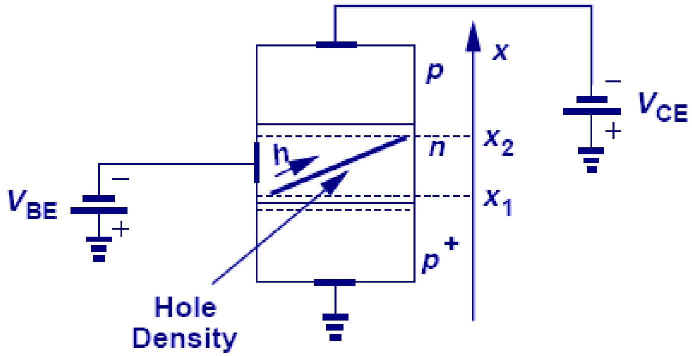
- In order to keep BJT at least in soft saturation region, the collector voltage must not fall below the base voltage by more than 400mV.
- A linear relationship can be derived for V_{CC} and R_C and an acceptable region can be chosen.

Deep Saturation

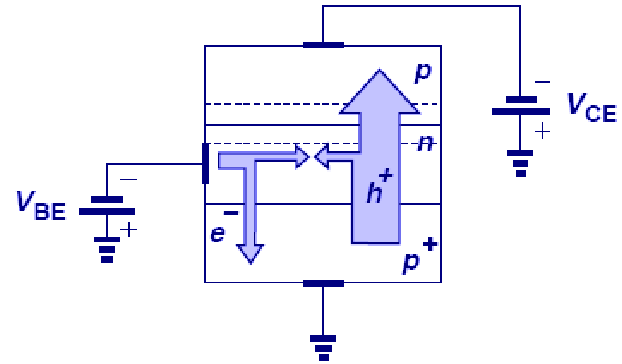


➢ **In deep saturation region, the transistor loses its voltage-controlled current capability and V_{CE} becomes constant.**

PNP Transistor



(a)



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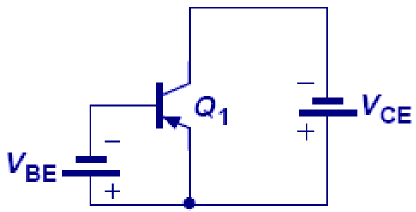

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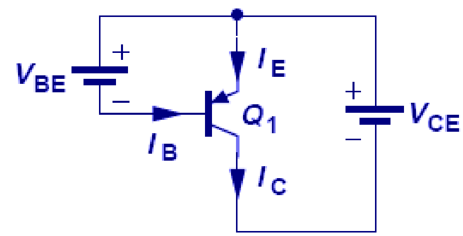
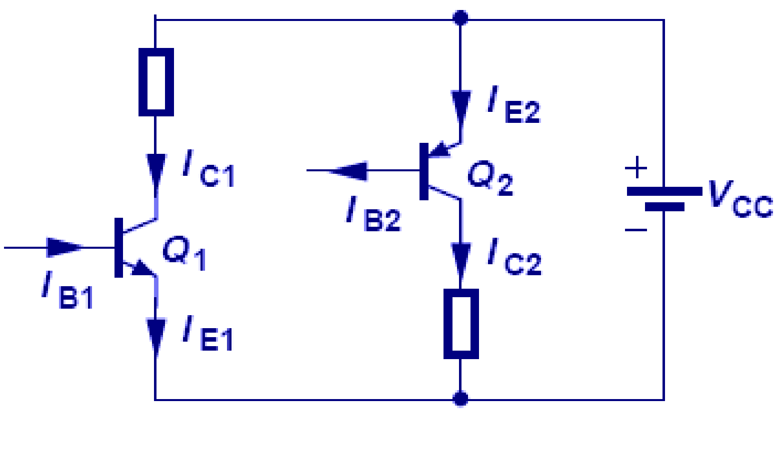


(d)

- **With the polarities of emitter, collector, and base reversed, a PNP transistor is formed.**
- **All the principles that applied to NPN's also apply to PNP's, with the exception that emitter is at a higher potential than base and base at a higher potential than collector.**

A Comparison between NPN and PNP Transistors



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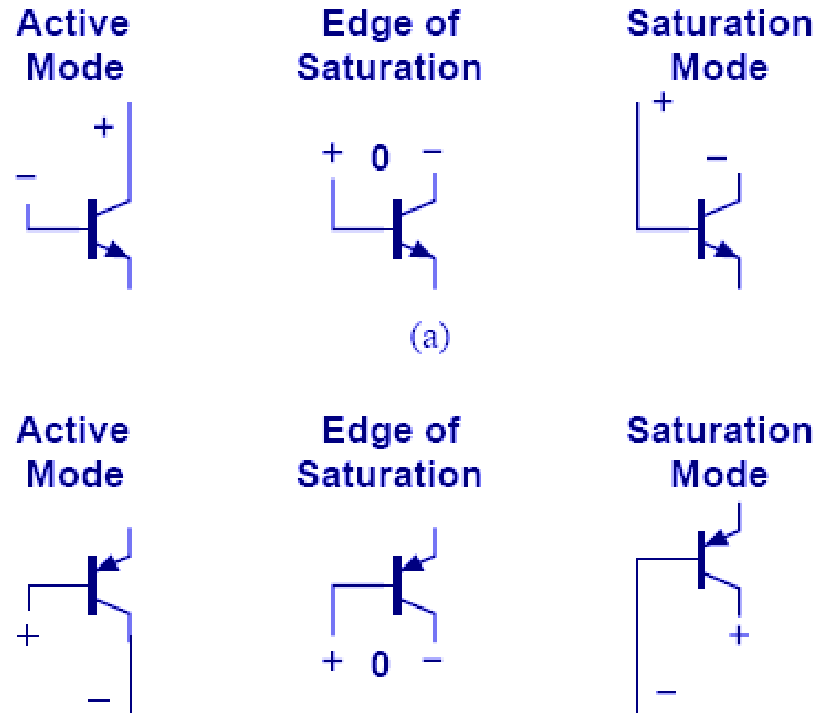


(a) (b)

- The figure above summarizes the direction of current flow and operation regions for both the NPN and PNP BJT's.

PNP Equations

Early Effect ⇒

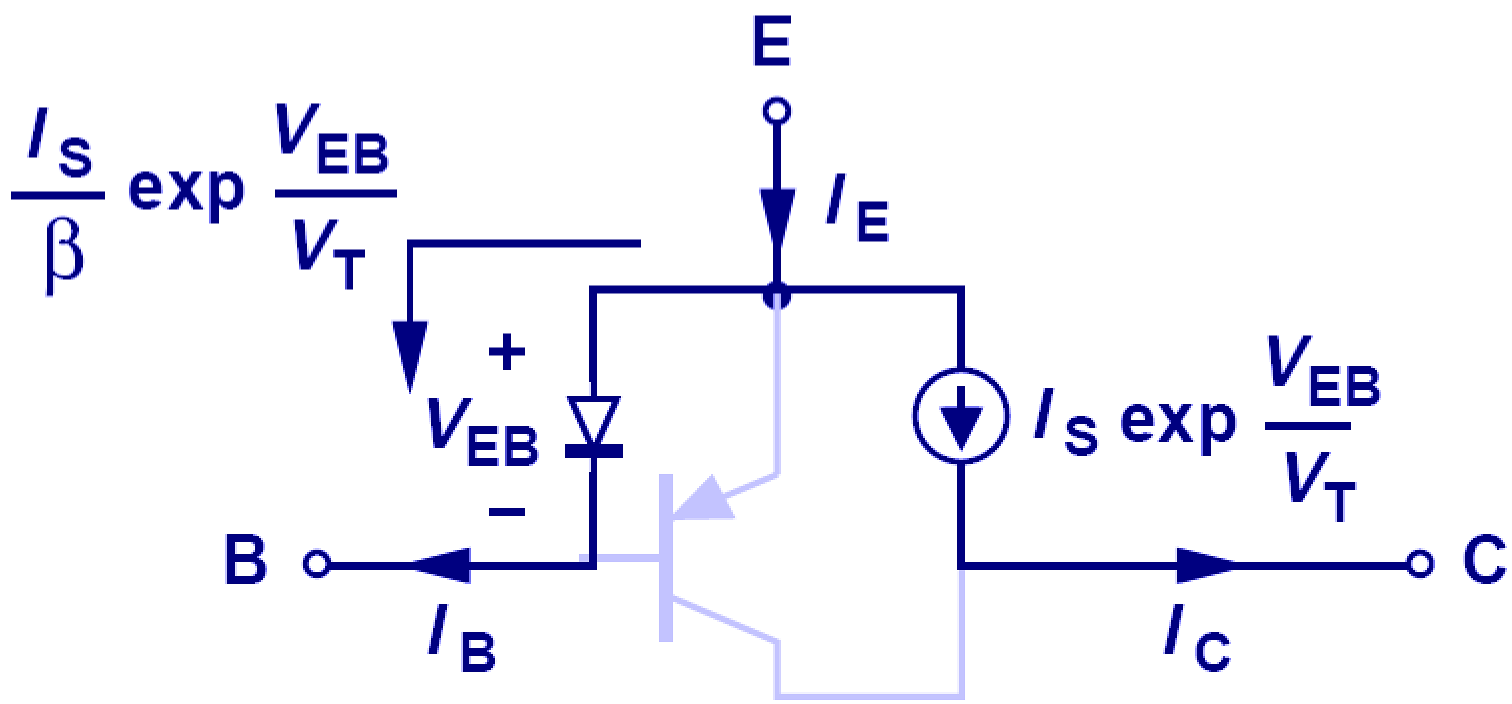
$$I_C = I_S \exp \frac{V_{EB}}{V_T}$$

$$I_B = \frac{I_S}{\beta} \exp \frac{V_{EB}}{V_T}$$

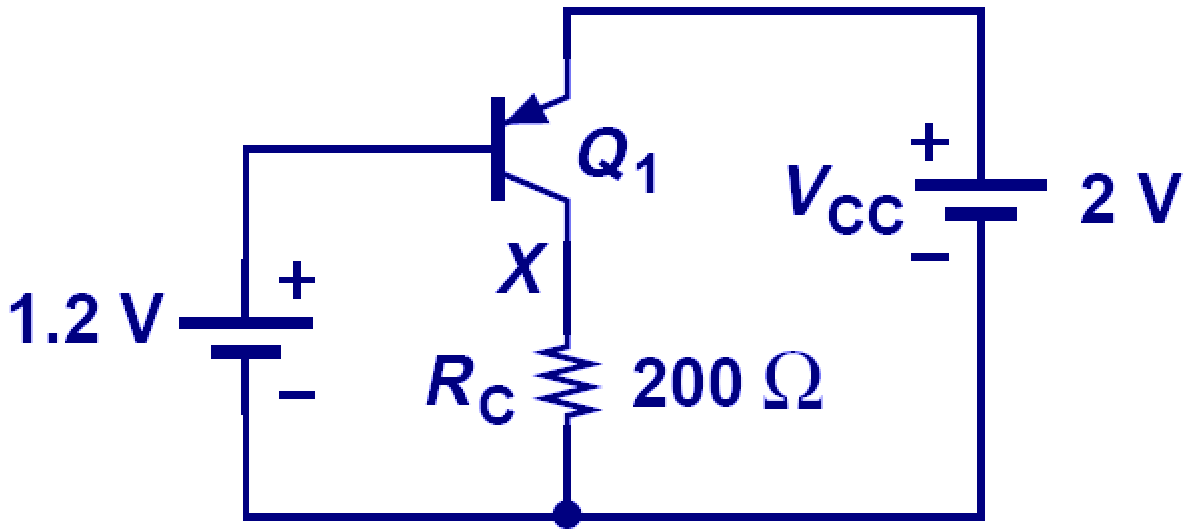
$$I_E = \frac{\beta + 1}{\beta} I_S \exp \frac{V_{EB}}{V_T}$$

$$I_C = \left(I_S \exp \frac{V_{EB}}{V_T} \right) \left(1 + \frac{V_{EC}}{V_A} \right)$$

Large Signal Model for PNP



PNP Biasing



- Note that the emitter is at a higher potential than both the base and collector.