

# Lecture 4

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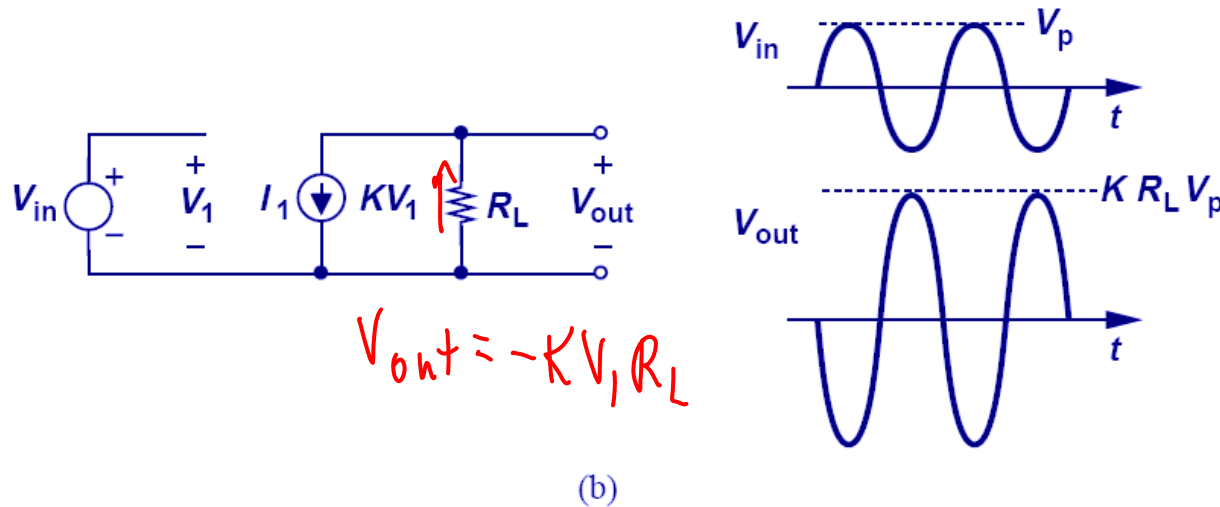
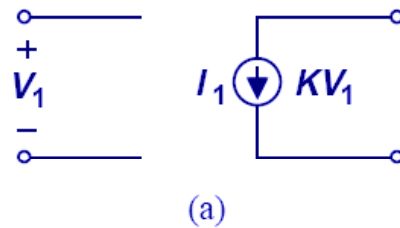
## OUTLINE

- Bipolar Junction Transistor (BJT)
  - General considerations
  - Structure
  - Operation in active mode
  - Large-signal model and  $I$ - $V$  characteristics

Reading: Chapter 4.1-4.4.2

# Voltage-Dependent Current Source

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

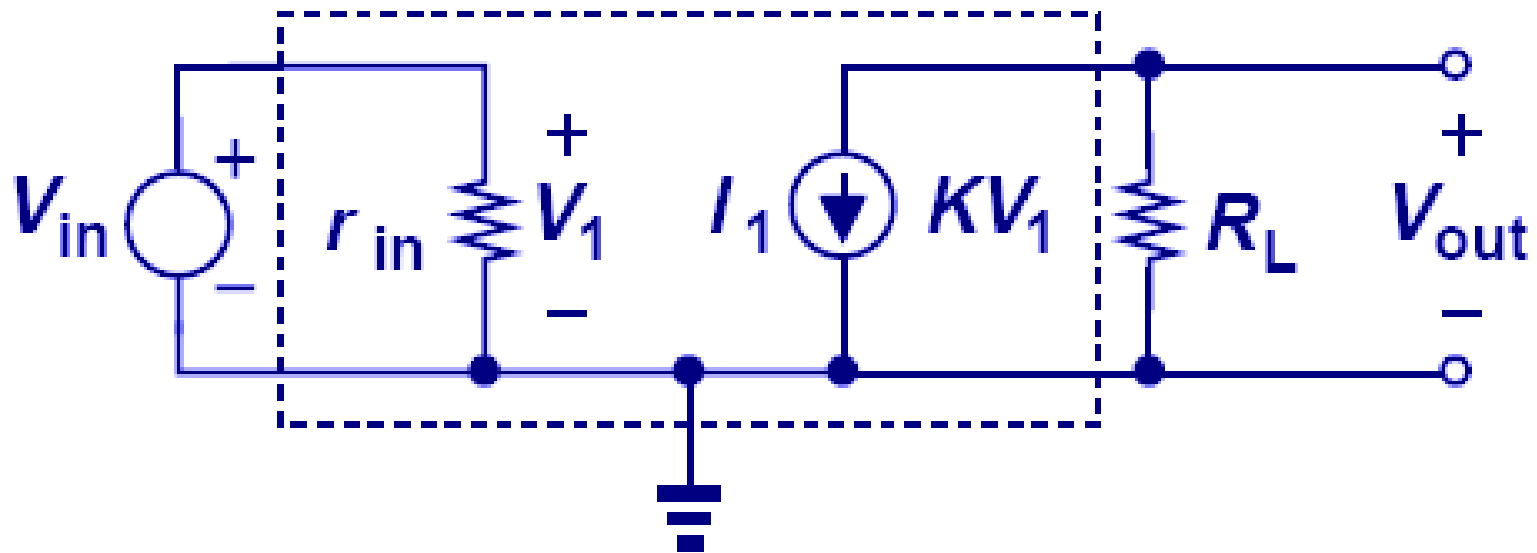


$$A_V \equiv \frac{V_{out}}{V_{in}} = -KR_L$$

# Voltage-Dependent Current Source with Input Resistance

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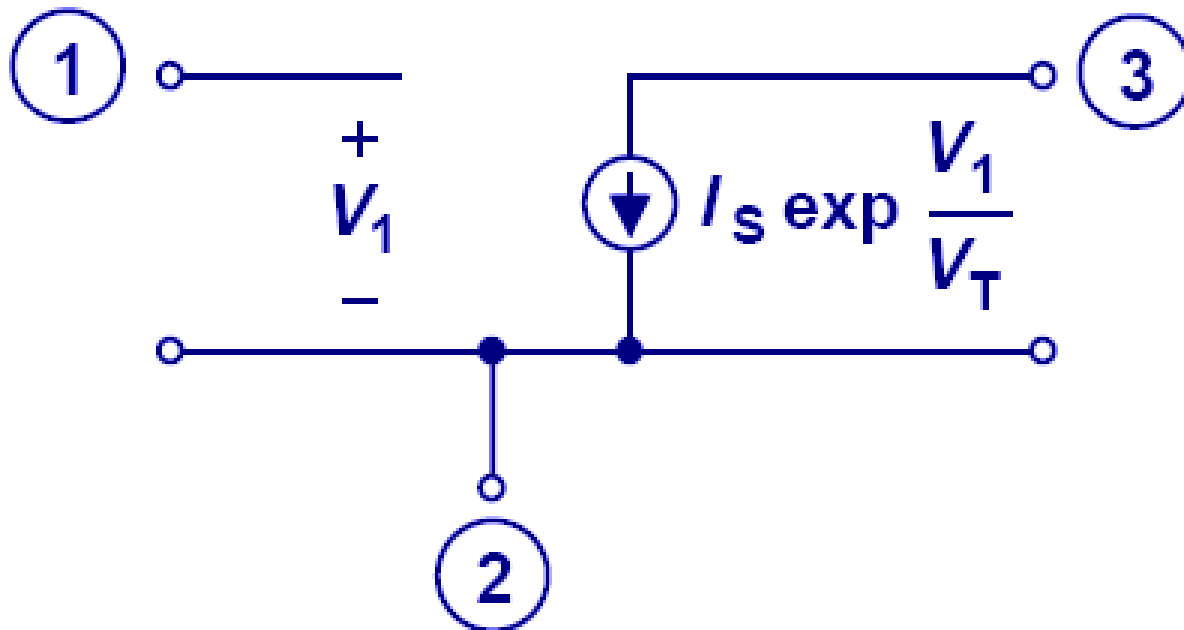
- The magnitude of amplification is independent of the input resistance  $r_{in}$ .



# Exponential Voltage-Dependent Current Source

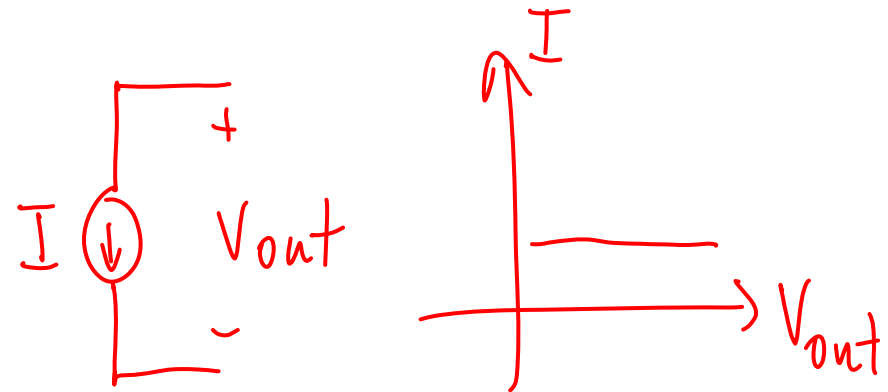
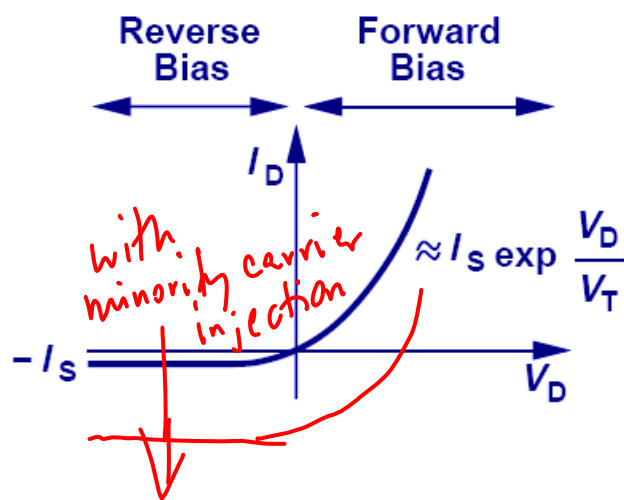
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- Ideally, a bipolar junction transistor (BJT) can be modeled as a three-terminal exponential voltage-dependent current source:



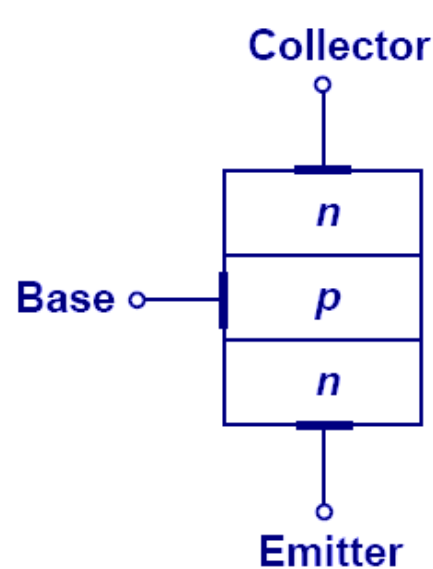
# Reverse-Biased PN Junction as a Current Source

- PN junction diode current is  $\sim$ independent of the reverse-bias voltage. It depends only on the rate at which minority carriers are introduced into the depletion region.  
 $\Rightarrow$  We can increase the reverse current by injecting minority carriers near to the depletion region.

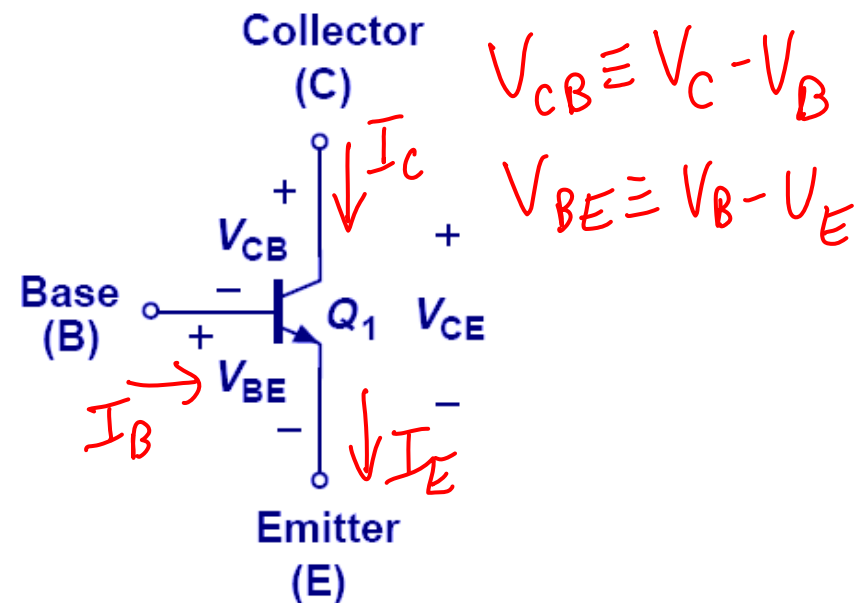


# BJT Structure and Circuit Symbol

- A bipolar junction transistor consists of 2 PN junctions that form a sandwich of three doped semiconductor regions. The outer two regions are doped the same type; the middle region is doped the opposite type.



(a)



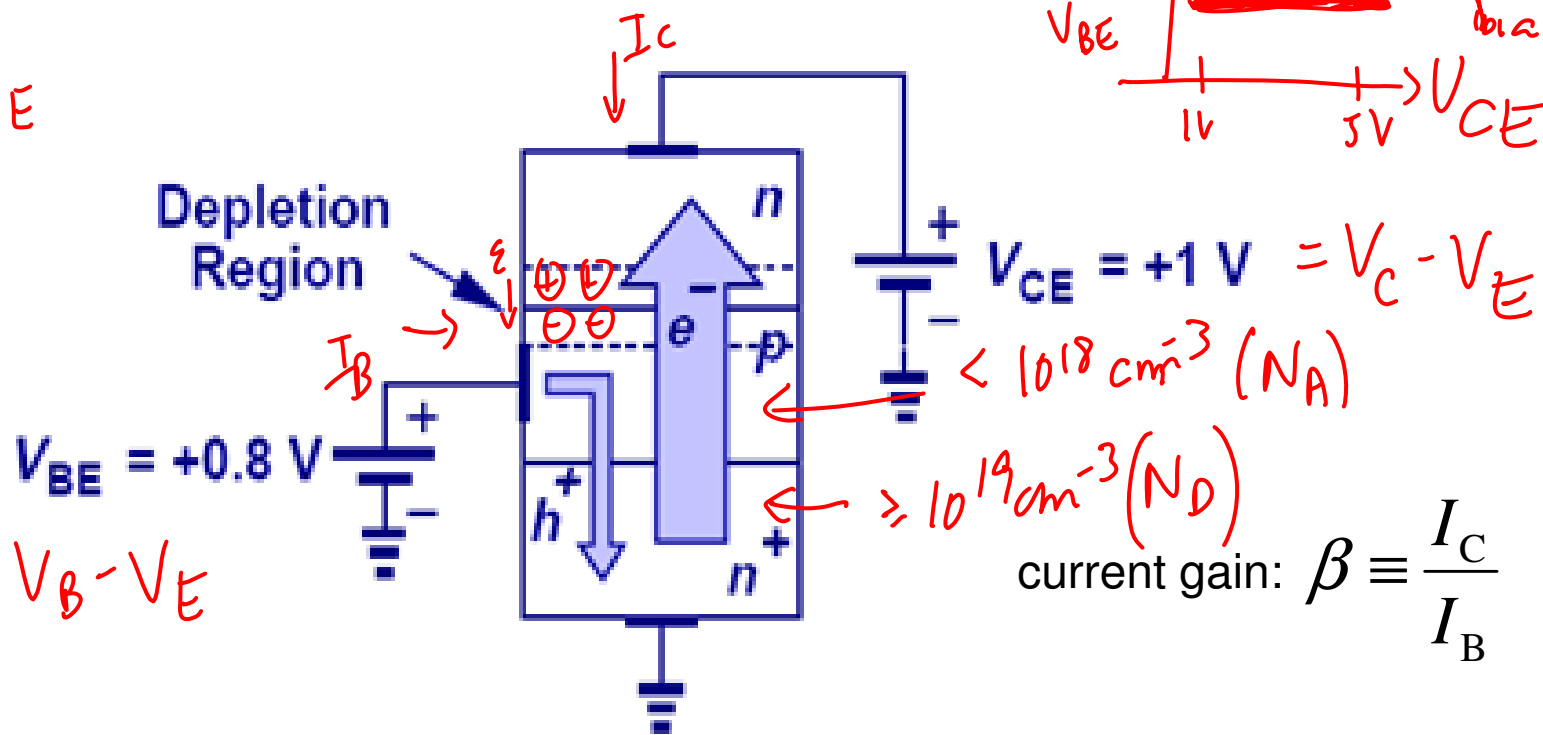
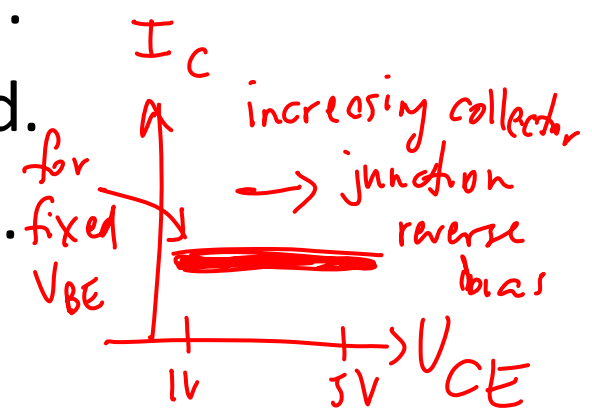
(b)

# NPN BJT Operation (Qualitative)

In the *forward active mode* of operation:

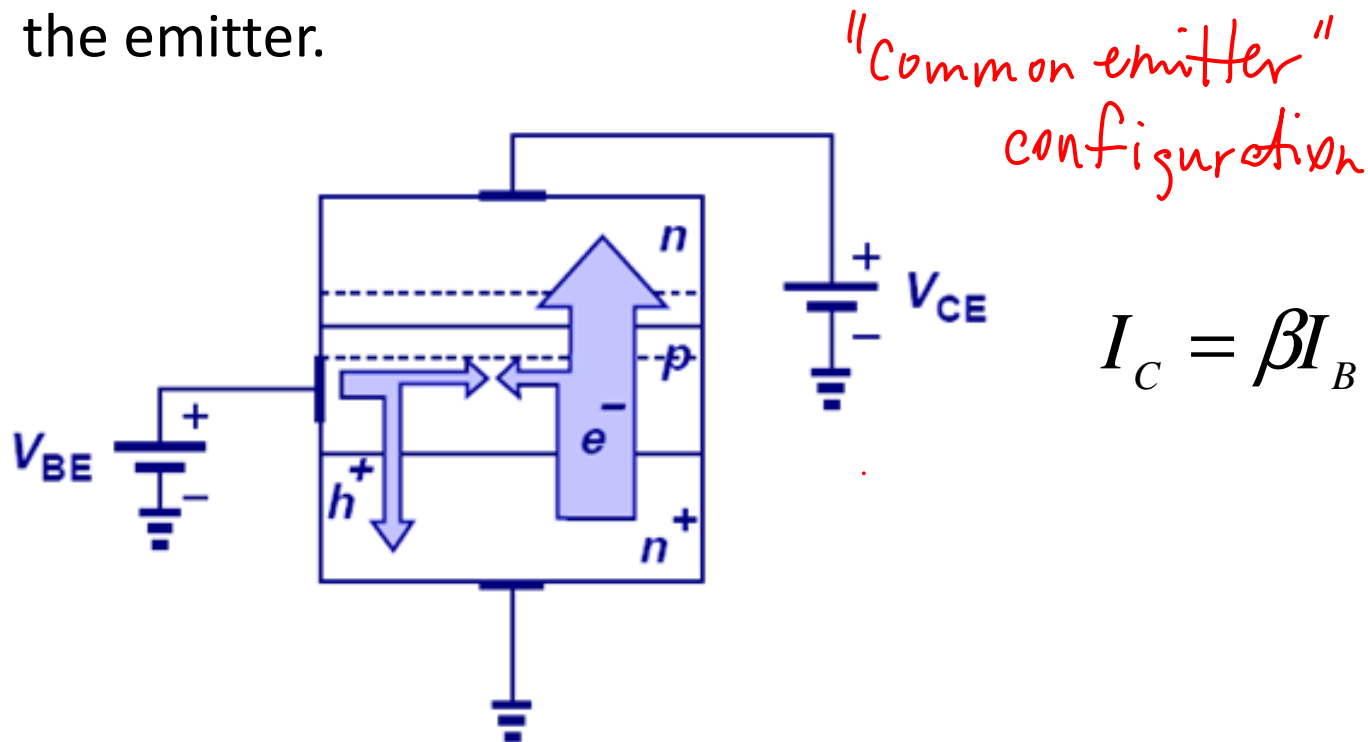
- The collector junction is reverse biased.
- The emitter junction is forward biased.

$V_{CE} > V_{BE}$   
 $\Rightarrow V_{CB} > 0$



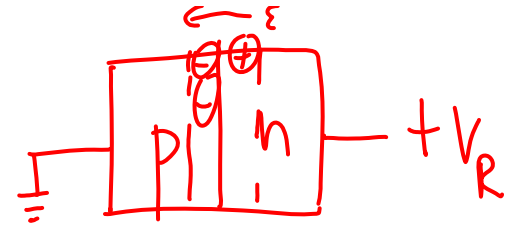
# Base Current

- The base current consists of two components:
  - 1) Injection of holes into the emitter, and
  - 2) Recombination of holes with electrons injected from the emitter.





# BJT Design



- Important features of a well-designed BJT (large  $\beta$ ):
  - Injected minority carriers do not recombine in the quasi-neutral base region.
    - Make quasi-neutral base width small compared to minority-carrier diffusion length  $L_B$  ←  $W_B \approx 0.1 \mu\text{m}$
  - Emitter current is comprised almost entirely of carriers injected into the base (rather than carriers injected into the emitter).
    - Dope emitter more heavily than the base

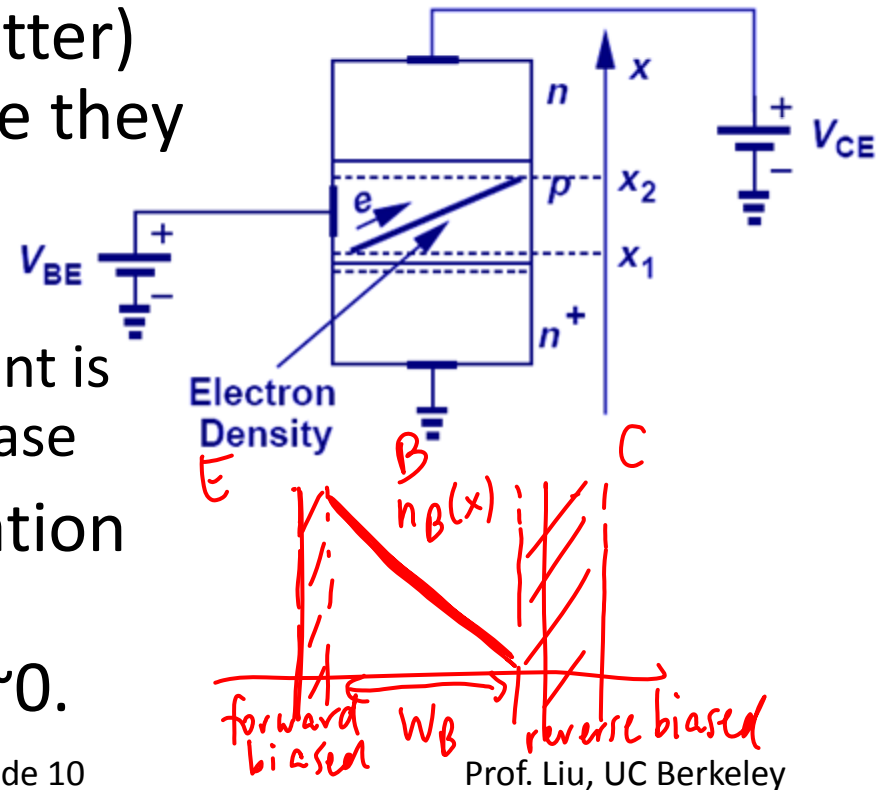
# Carrier Transport in the Base Region

- Since the width of the quasi-neutral base region ( $W_B = x_2 - x_1$ ) is much smaller than the minority-carrier diffusion length, very few of the carriers injected (from the emitter) into the base recombine before they reach the collector-junction depletion region.

→ Minority-carrier diffusion current is  $\sim$  constant in the quasi-neutral base

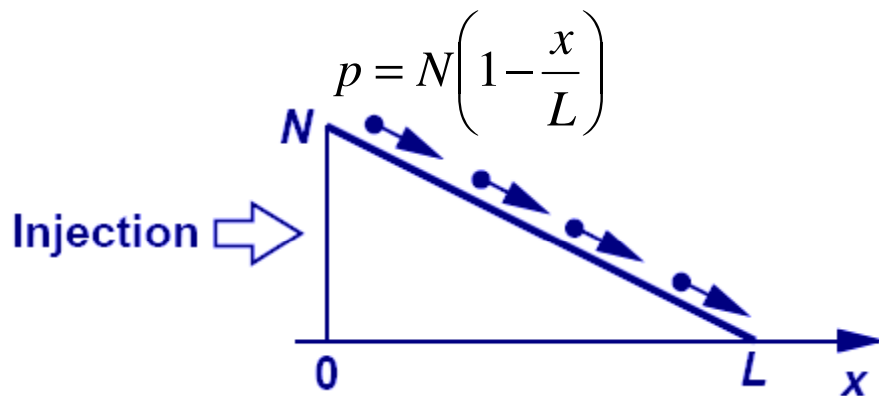
- The minority-carrier concentration at the edges of the collector-junction depletion region are  $\sim 0$ .

Minority carrier conc. @ edges of depletion region are changed by the factor  $e^{V_D/V_T}$



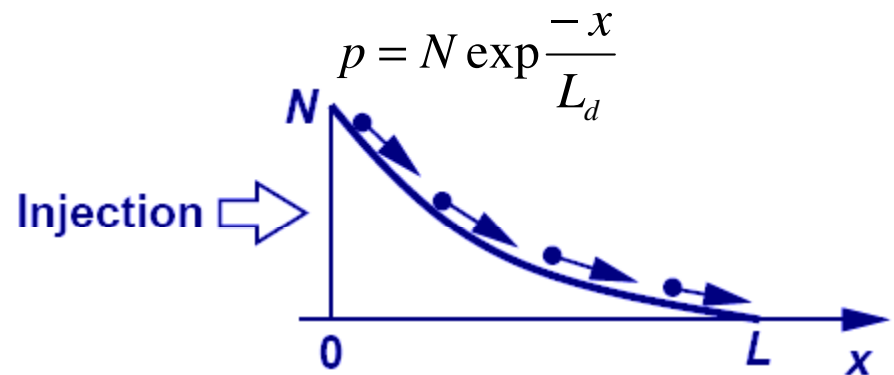
# Diffusion Example Redux

- Linear concentration profile  
→ constant diffusion current



$$J_{p,diff} = -qD_p \frac{dp}{dx}$$
$$= qD_p \frac{N}{L}$$

- Non-linear concentration profile  
→ varying diffusion current



$$J_{p,diff} = -qD_p \frac{dp}{dx}$$
$$= \frac{qD_p N}{L_d} \exp\left(-\frac{x}{L_d}\right)$$

# Collector Current

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$$I_C = \frac{A_E q D_n n_i^2}{N_B W_B} \left( \exp \frac{V_{BE}}{V_T} - 1 \right)$$

$$I_C \cong I_S \exp \frac{V_{BE}}{V_T} \quad \text{where} \quad I_S = \frac{A_E q D_n n_i^2}{N_B W_B}$$

- The equation above shows that the BJT is indeed a voltage-dependent current source; thus it can be used as an amplifier.

# Emitter Current

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- Applying Kirchhoff's Current Law to the BJT, we can easily find the emitter current.

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

$$I_C = \beta I_B \text{ in forward active mode}$$

# Summary of BJT Currents

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

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

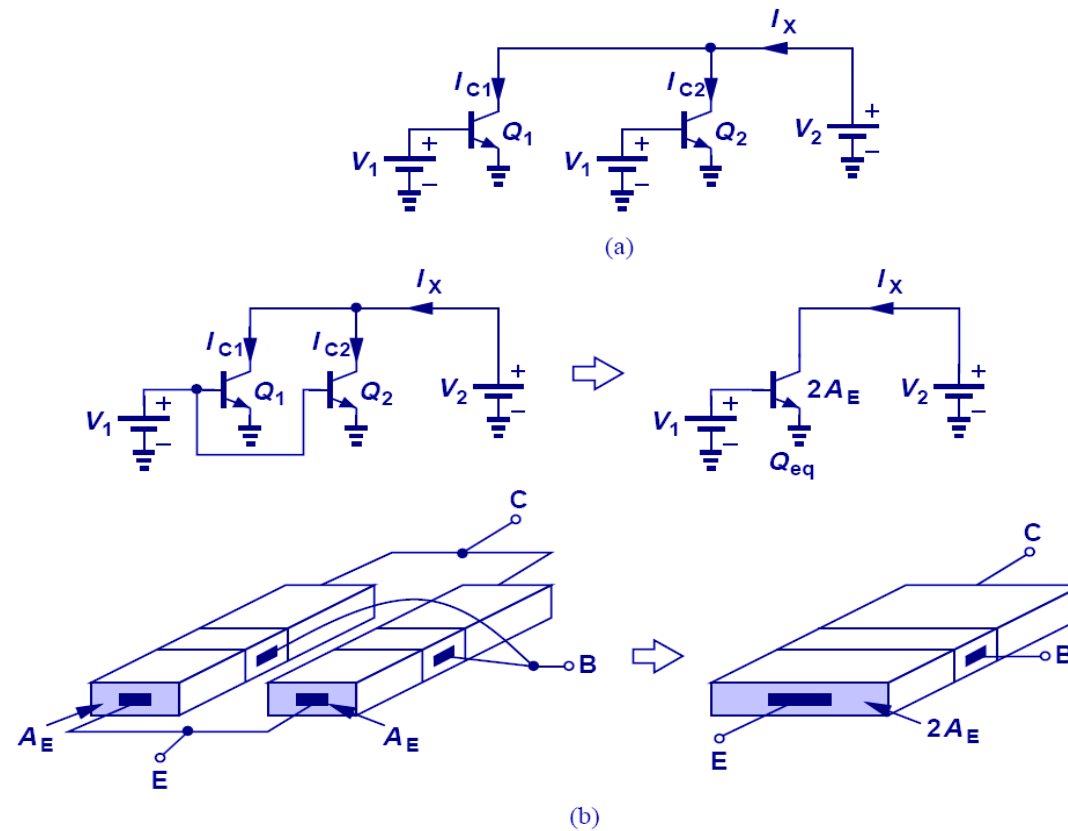
$$I_E = \frac{\beta + 1}{\beta} I_S \exp \frac{V_{BE}}{V_T}$$

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

"common base  
current gain"

# Parallel Combination of Transistors

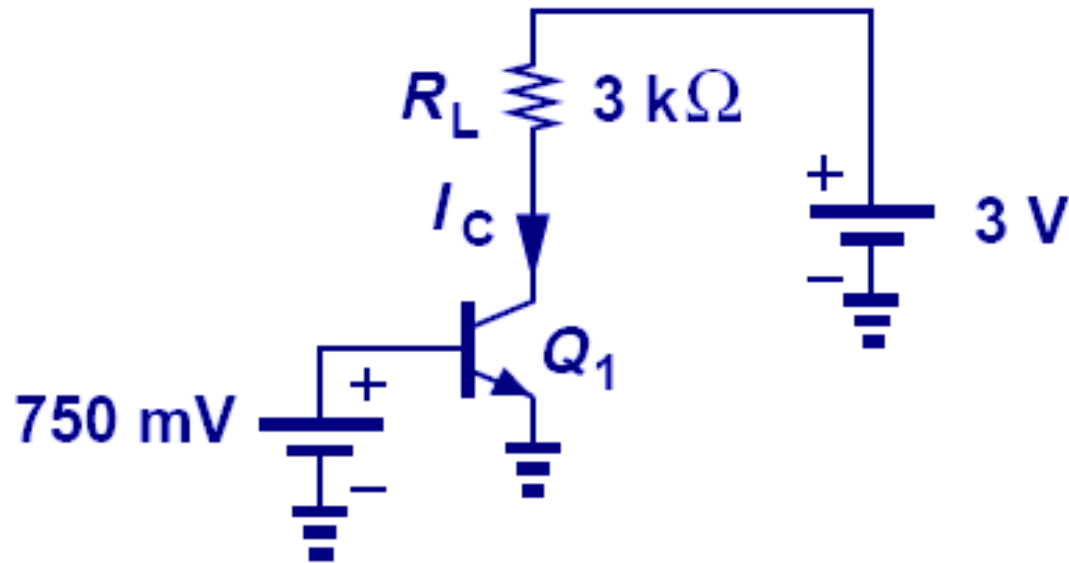
- When two transistors are connected in parallel and have the same terminal voltages, they can be considered as a single transistor with twice the emitter area.



# Simple BJT Amplifier Configuration

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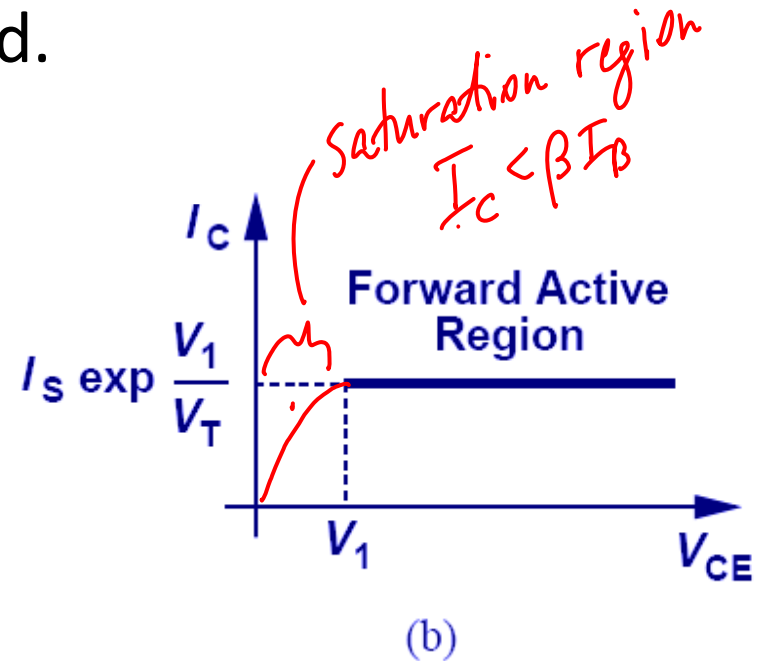
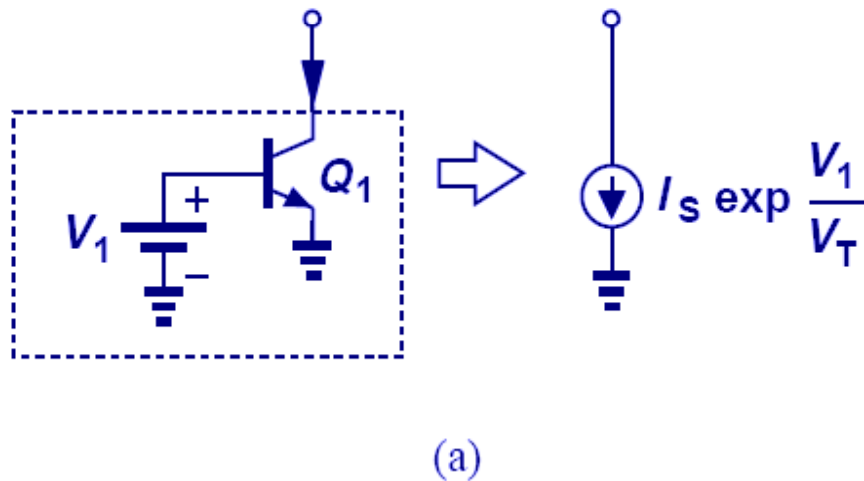
- Although the BJT converts an input voltage signal to an output current signal, an (amplified) output voltage signal can be obtained by connecting a “load” resistor (with resistance  $R_L$ ) at the output and allowing the controlled current to pass through it.





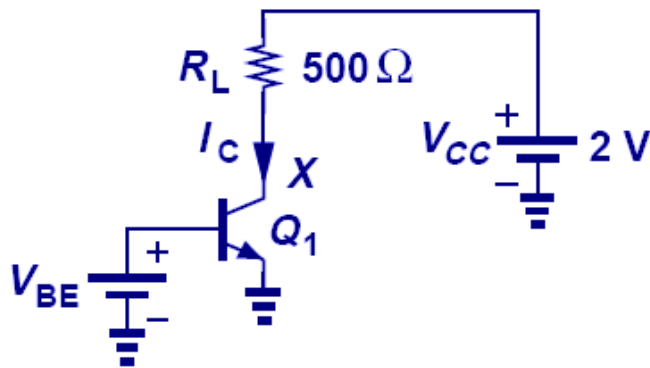
# BJT as a Constant Current Source

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

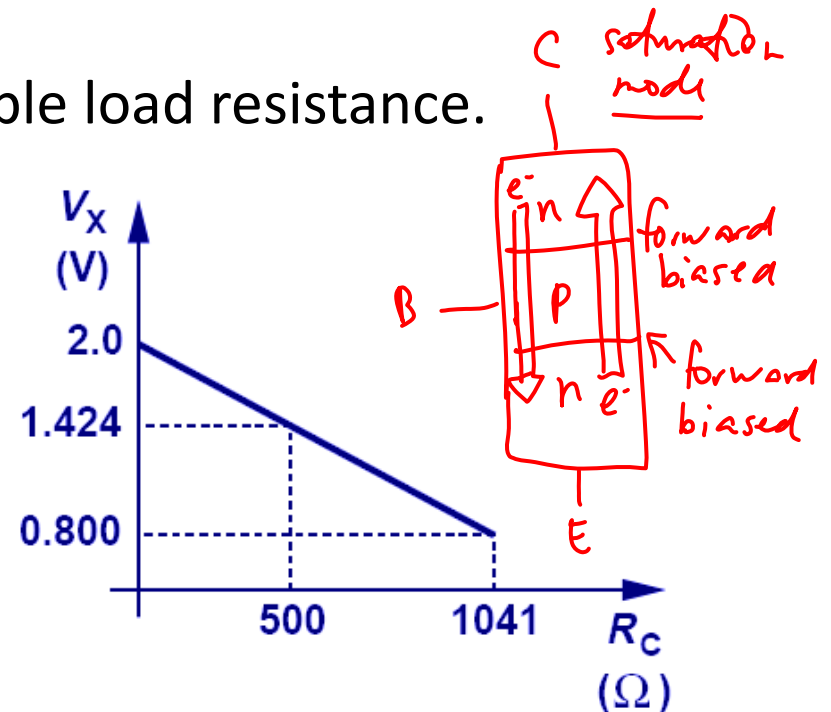


# Constraint on Load Resistance

- If  $R_L$  is too large, then  $V_X$  can drop to below  $\sim 0.8V$  so that the collector junction is forward biased. In this case, the BJT is no longer operating in the active mode, and so
 
$$I_C < \beta I_B$$
 → There exists a maximum tolerable load resistance.

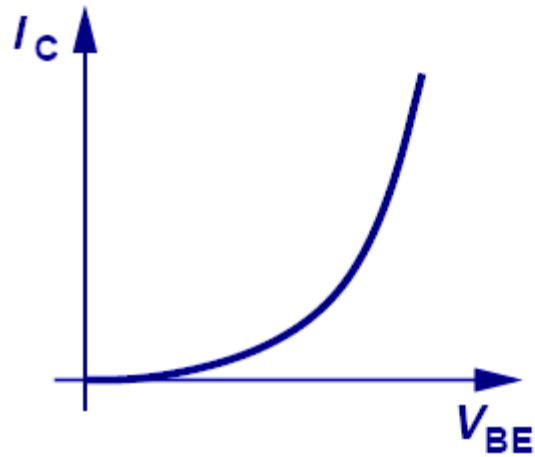
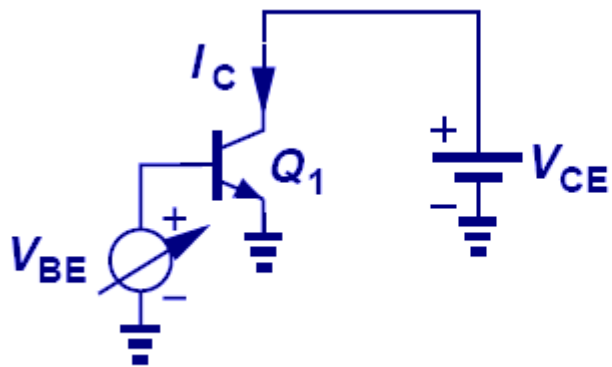


(a)

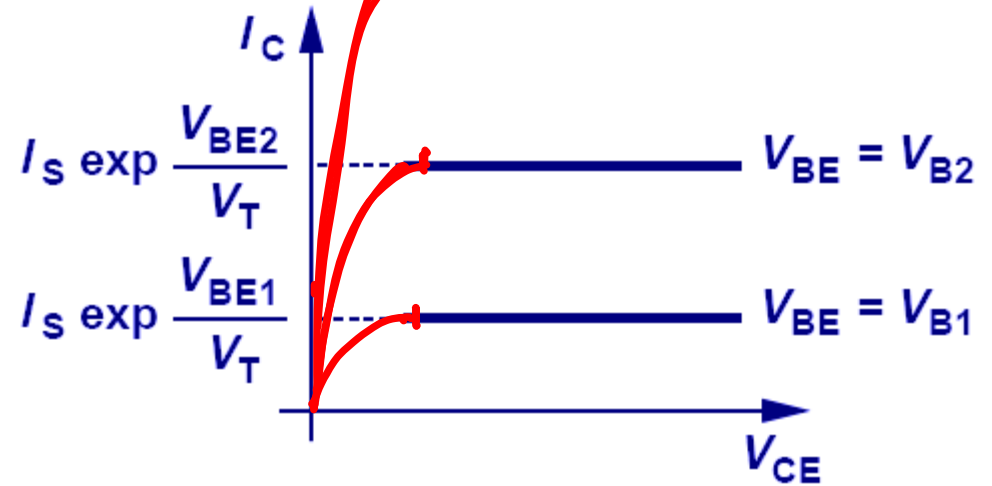
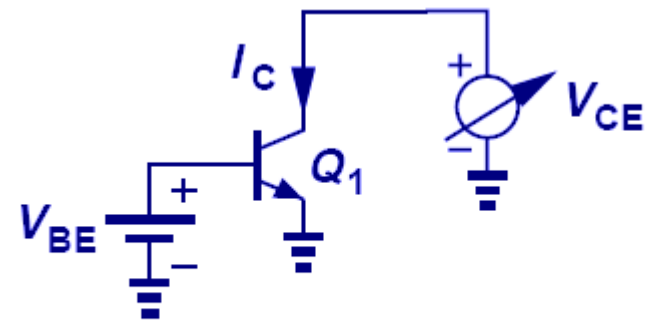


(b)

# BJT $I$ - $V$ Characteristics



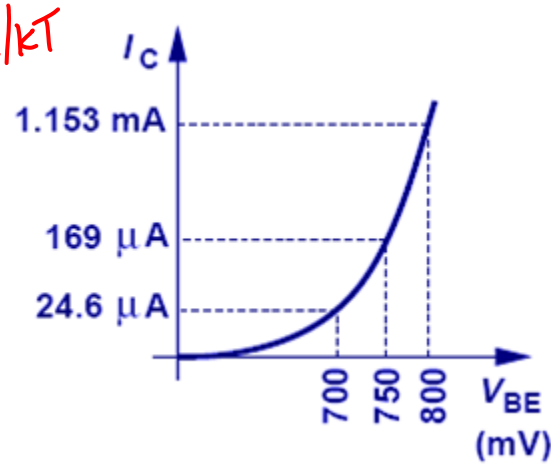
(a)



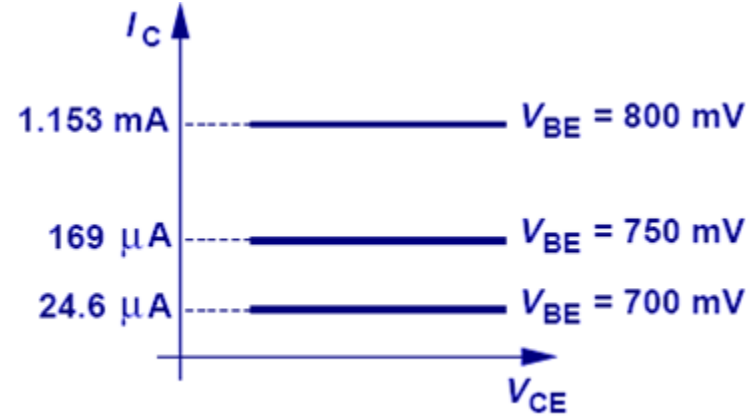
(b)

# Active Mode Example $I_s = 5 \times 10^{-17} \text{ A}, \beta = 100$

$I_c = I_s e^{qV_{BE}/kT}$

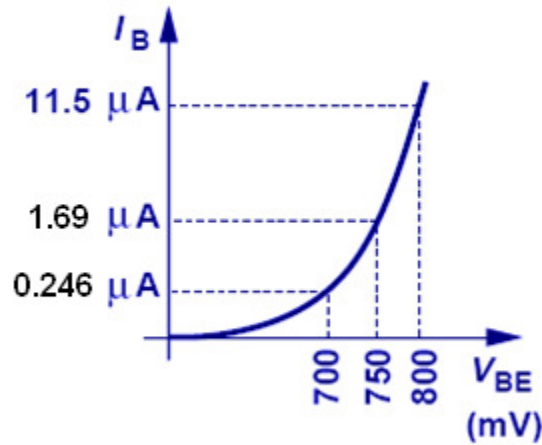


(a)

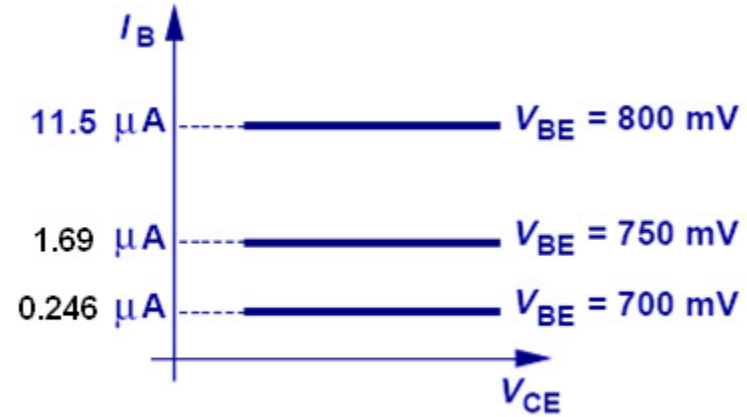


(b)

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



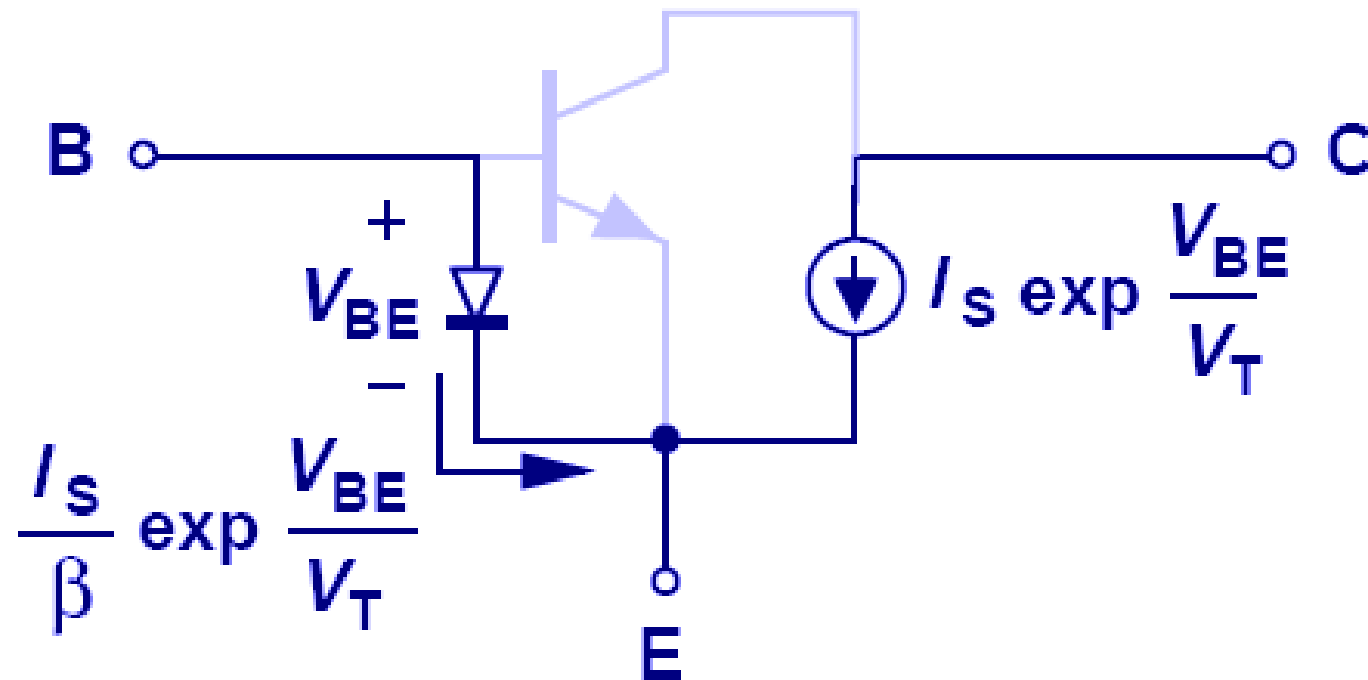
(c)



(d)

# BJT Large Signal Model

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



# BJT vs. Back-to-Back Diodes

- Figure (b) presents a wrong way of modeling the BJT.

