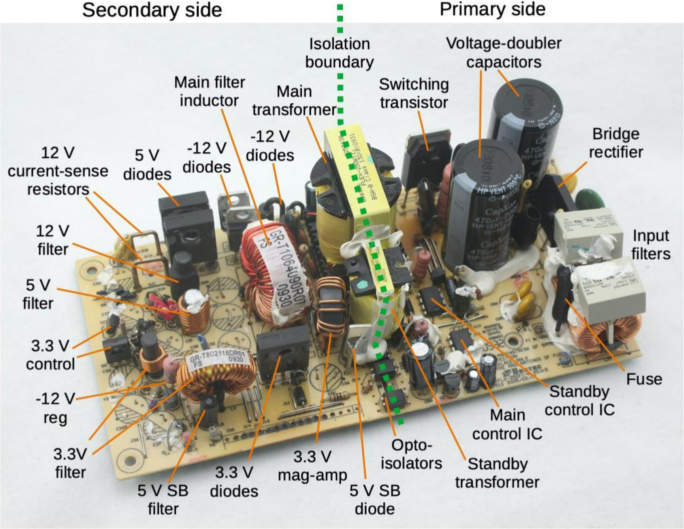

Bipolar Junction Transistors —BJTs

Kizito NKURIKIYEYEZU, Ph.D.

Introduction

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- Its current conduction process is due to both holes and electrons. That is why the name bipolar

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Simplified Structure

- A npn BJT (Fig. 1) consists of three semiconductor regions:

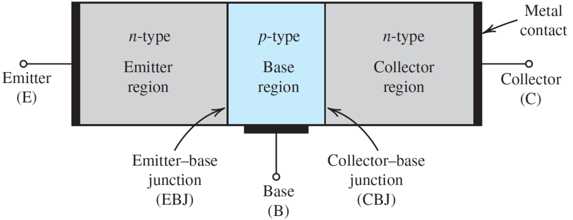
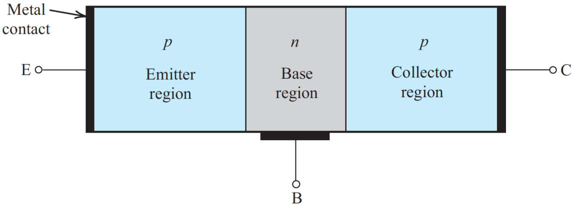


FIG 1. A simplified structure of the npn transistor



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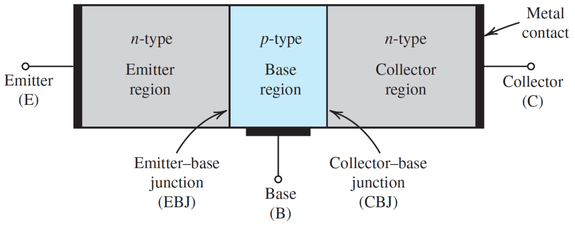

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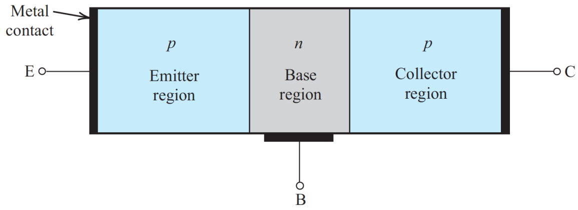

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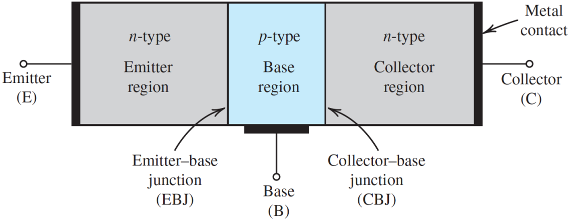

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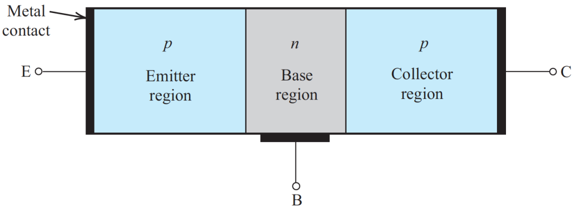

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- A npn BJT (Fig. 1) consists of three semiconductor regions:
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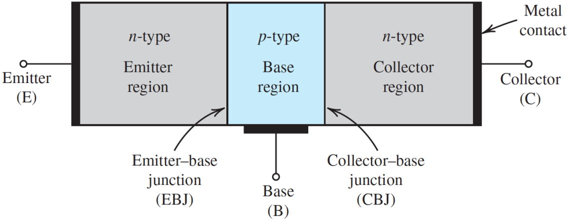
  - Collector (C)—n-type region



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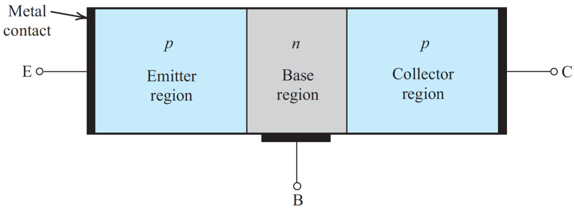

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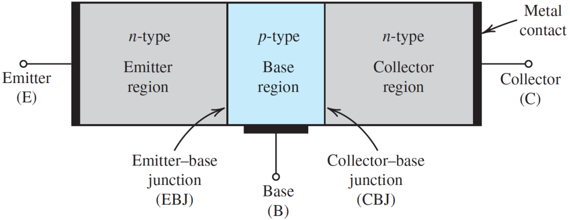
- The same regions exists for a pnp BJT (Fig. 2)—which has a has a p-type emitter, an n-type base, and a p-type collector



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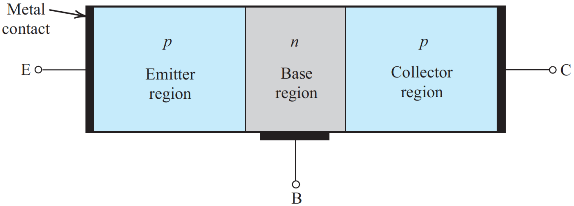

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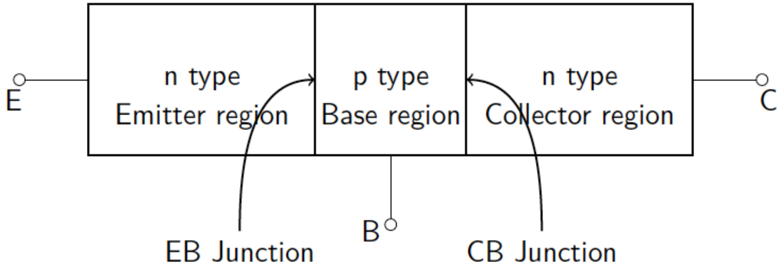


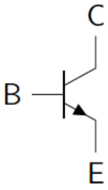
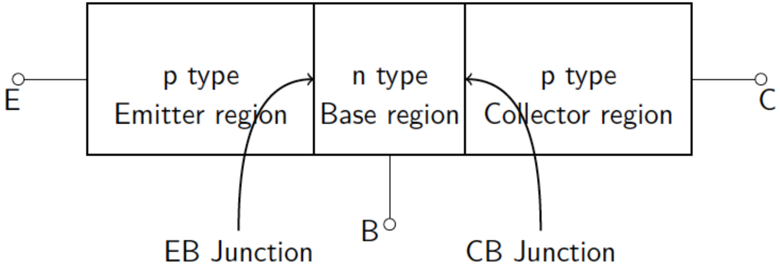


Figure : Symbol

FIG 3. Simplified structure of a npn BJT transistor

Simplified Structure



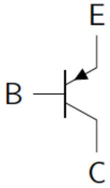


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FIG 4. Simplified structure of a pnp BJT transistor

Simplified Structure

- Transistor consists of two pn-junctions (Table 1)

TAB 1. BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

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- Transistor consists of two pn-junctions (Table 1)
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  - cutoff and saturation modes—used for switching.

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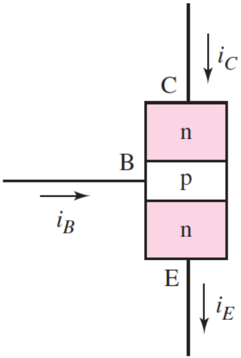
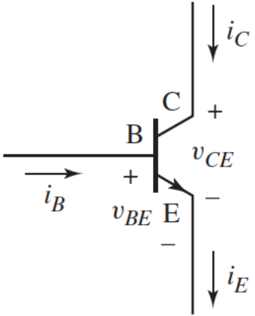
Circuit Symbols and Conventions



(a) simple block diagram



(b) circuit symbol

FIG 5. npn bipolar transistor

Note that the arrow is on the emitter terminal and indicates the direction of emitter current —which is also the forward direction of the base–emitter junction. In this case, I_C flows out of emitter terminal for the npn device

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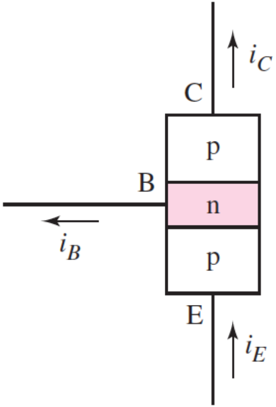

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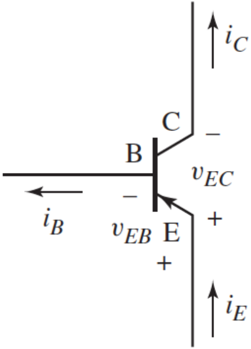

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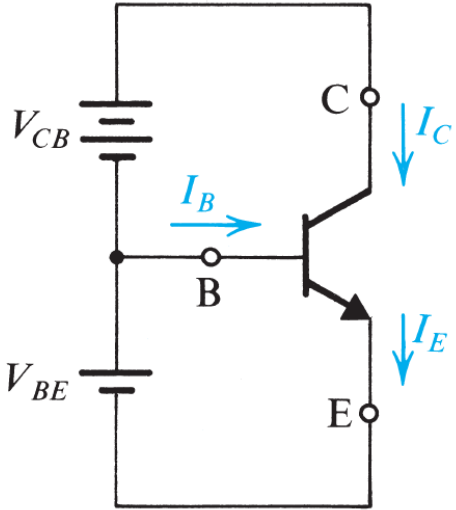

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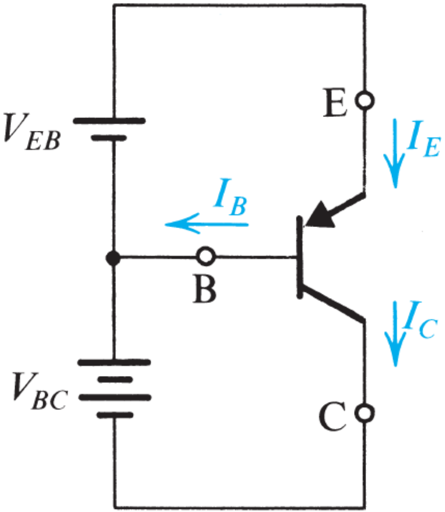

(b) pnp

FIG 7. Voltage polarities and current flow in transistors operating in the active mode.

Active Mode

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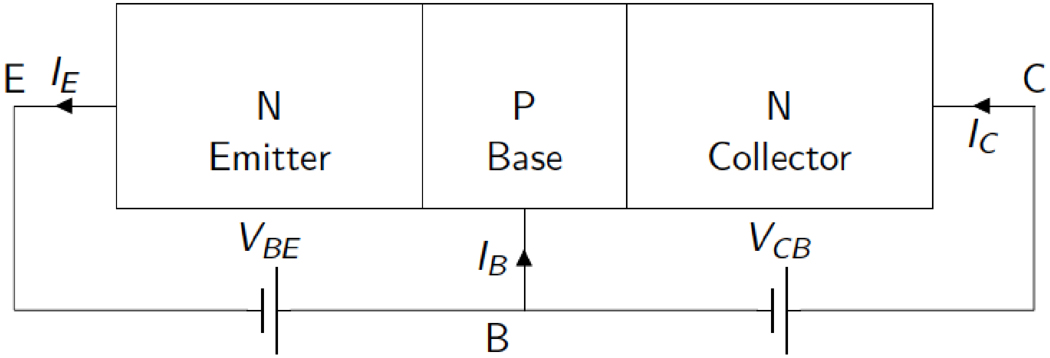

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- Collector current i_C (Equation (1))

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- Base current i_B (Equation (2))

$$\begin{aligned} i_B &= \frac{i_C}{\beta} \\ &= \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T} \end{aligned} \tag{2}$$

Where β is the common-emitter current gain. For modern npn transistors, β is in the range 50 to 200, but it can be as high as 1000 for special devices.

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- Finally, we can express β in terms of α, that is:

$$\beta = \frac{\alpha}{1-\alpha} \tag{5}$$

Equation (5) highlights an important fact: small changes in α correspond to very large changes in β

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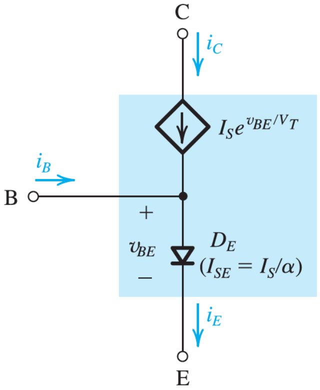
- The base current i_B is a factor $1/\beta$ of the collector current, and the emitter current is equal to the sum of the collector and base currents
- Since i_B is much smaller than i_C (i.e., $\beta \ggg 1$), $I_E \approxeq i_B$. More precisely, the collector current is a fraction α of the emitter current, with α smaller than, but close to, unity.

Equivalent-Circuit Models

This first-order model of transistor operation in the active mode can be represented by the equivalent circuit shown in Fig. 8

- Here, diode D_E has a scale current $I_{SE} = {}^{I_S}/_{\alpha}$



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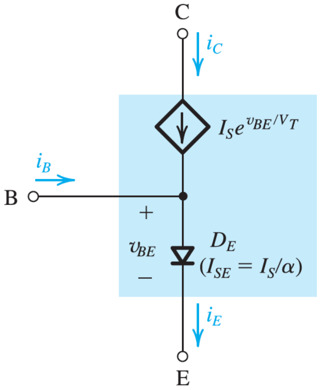

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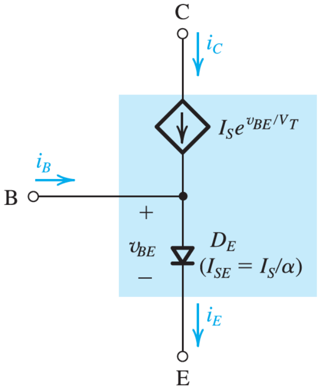

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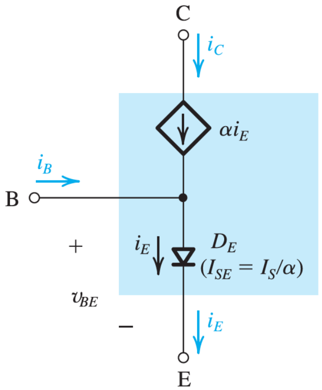

FIG 9. Model 2—A nonlinear current of the controlled source

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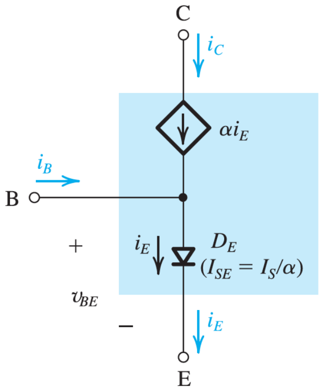

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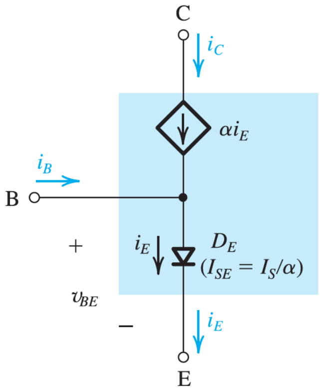
- This is the reason why α is called the common-base current gain.



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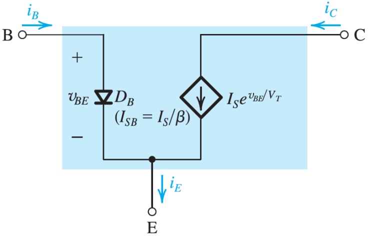

FIG 10. Model 3—A voltage-controlled current source

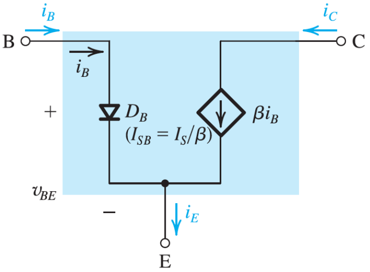

FIG 11. Model 4 —Current-controlled current-source

[3]These models apply for any positive value of v_{BE} and are referred to as large-signal models.

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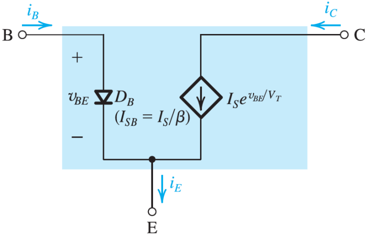
  - its current scale factor is I_S/β



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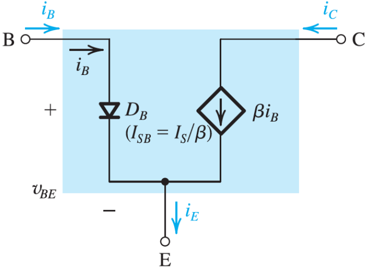

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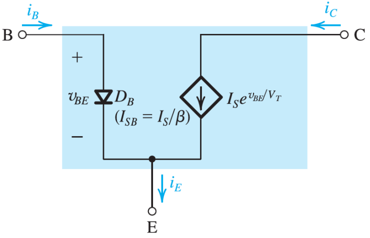

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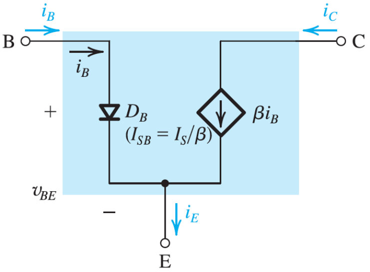

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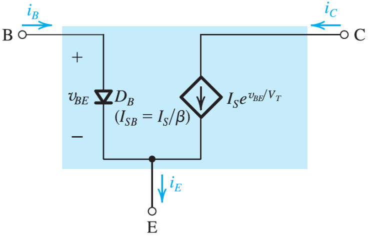

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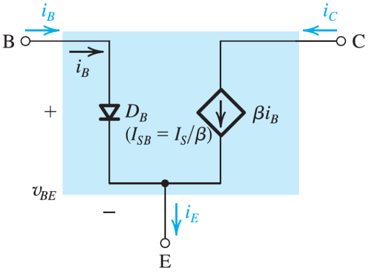

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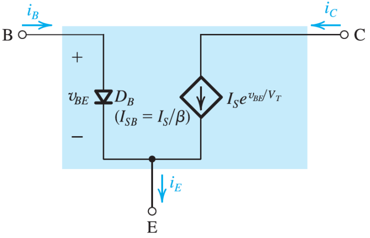

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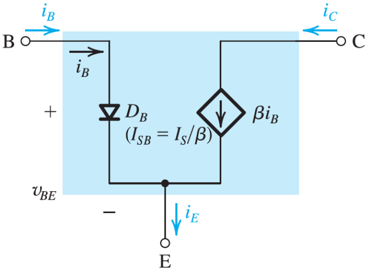

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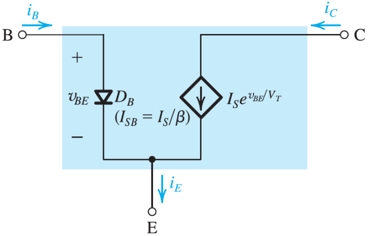
  - Consequential, β is called the common-emitter current gain.



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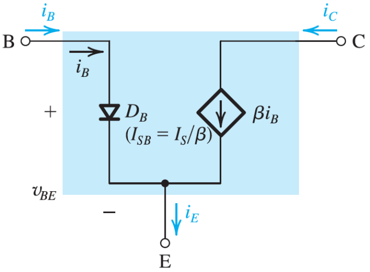

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Saturation Mode

Saturation mode

- For BJT to operate in active mode, CB Junction must be reverse biased.

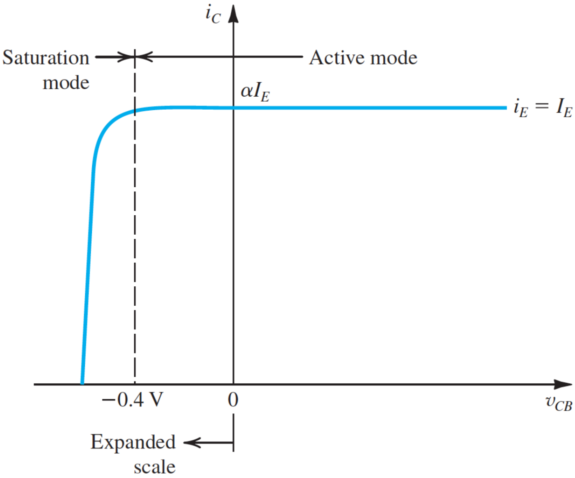

FIG 12. The i_C vs v_{CB} characteristic of an npn transistor fed with a constant emitter current I_E. The transistor enters the saturation mode of operation for $v_{CB} < -0.4\,V$, and the collector current diminishes.

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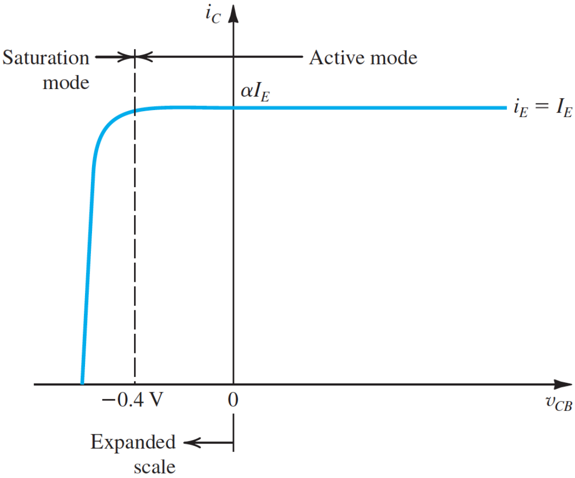

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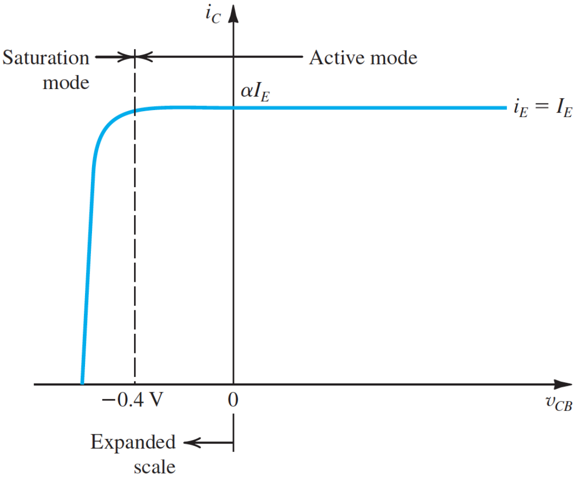

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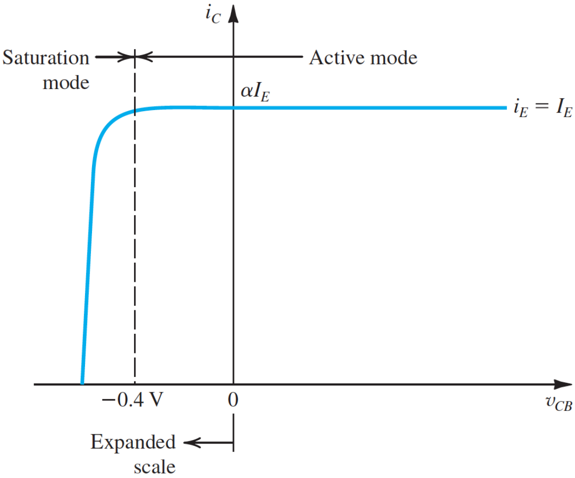
- However, for small values of forward-bias, a pn-junction does not operate effectively.
- As such, active mode operation of npn-transistor may be maintained for v_{CB} down to approximately $-0.4\,V$
- Only after this point will the diode begin to really conduct



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- The saturation mode of operation of the BJT is analogous to the triode region of operation of the MOSFET.
- On the other hand, the saturation region of operation of the MOSFET corresponds to the active mode of BJT operation.
- For a BJT, the saturation happens when the base current has increased well beyond the point that the emitter-base junction is forward biased; thus, the base current cannot increase the collector current. For a MOSFET, saturation happens when I_D does not increase with an increase in V_{DS}

Saturation mode

For a npn BJT, saturation occurs when Equation (6) is satisfied

$$v_E < v_B > v_C, \tag{6}$$

Such that both junctions are forward-biased

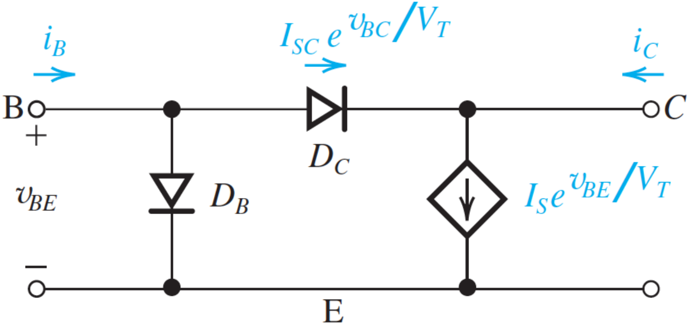

FIG 13. Equivalent circuit model of an npn transistor in saturation

The model is obtained by augmenting the model of Fig. 10 with a forward-conducting diode D_C. Note that the current through D_C increases i_B and reduces i_C.

Saturation mode

- Fig. 13 shows that the current i_{BC} will subtract from the controlled-source current, resulting in the reduced collector current i_C given by

$$i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T} \tag{7}$$

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  - The second term in Equation (7) will play an increasing role as v_{BC} exceeds 0.4 V or so, causing i_C to decrease and eventually reach zero.
- Fig. 13 also shows that, in saturation mode, the base current will increase

$$i_B = (I_S/\beta) e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T} \tag{8}$$

Saturation mode

- This relationship causes the value of β to change based on v_{BC}; i.e., v_{BC} "forces" to a value lower than the constant value of β in forward-active mode. The resulting new value of β is called forced β (Equation (9))

$$\beta_{forced} = \left.\frac{i_C}{i_B}\right|_{saturation} \leq \beta \tag{9}$$

- The value of β_{forced} allows to determine when the BJT is in saturation mode:
  - Is the *CBJ* forward-biased by more than $0.4\,V$?
  - Is the ratio $\frac{I_C}{I_B} < \beta$?
- From Fig. 13, it is clear that the collector-to-emitter voltage v_{CE} of a saturated transistor is given by Equation (10). Typically, $V_{CEsat} \approxeq 0.1\,V$ to $0.3\,V$.

$$V_{CEsat} = V_{BE} - V_{BC} \tag{10}$$

Where

  - $V_{CEsat} = 0.3\,V$ indicates that the transistor is at the edge of saturation
  - $V_{CEsat} \leq 0.2\,V$ indicates that the transistor is deep in the saturation region

BJT i_C vs v_{BE} curve

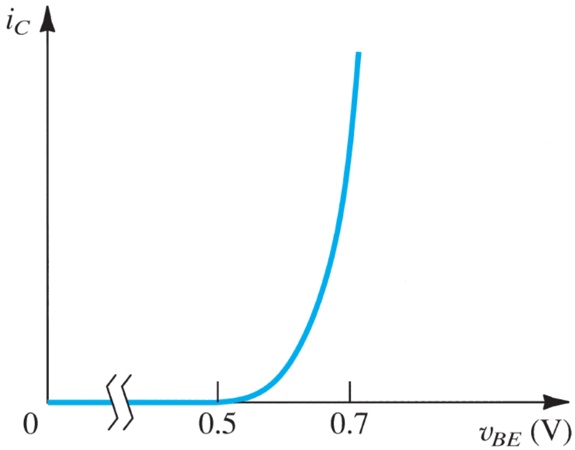


FIG 14. The i_C vs v_{BE} characteristic for an npn transistor

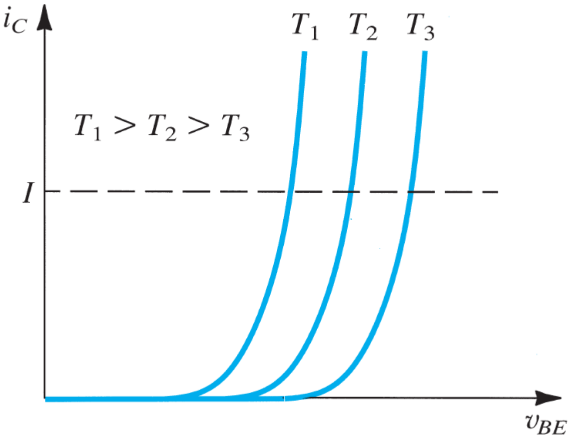


FIG 15. Effect of temperature on the i_C vs v_{BE} characteristic. At a constant emitter current (broken line), v_{BE} changes by $-2\,\text{mV}\,^\circ\text{C}^{-1}$

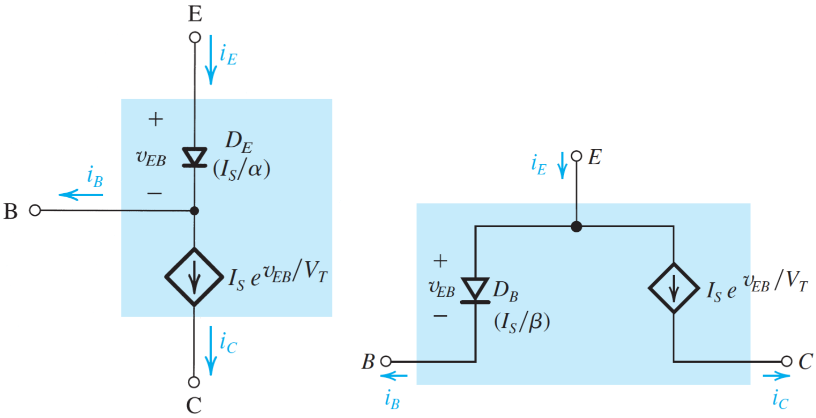
The pnp transistor

TAB 2. Difference between npn and pnp transistors

npn transistor	pnp transistor
two layers of N material and sandwiched with one layer of P material.	two layers of P material with a sandwiched layer of N material
current flows from the collector to the Emitter	current flows from the emitter to the collector.
a positive voltage is given to the collector terminal to produce a current flow	a positive voltage is given to the emitter terminal to produce current flow
When the base current increases, then the transistor turns ON and it conducts fully from the collector to emitter.	When the current exists at the base terminal of the transistor, then the transistor shuts OFF
When the base current decreases, the transistor turns ON less and until the current is so low, the transistor no longer conducts across the collector to emitter, and shuts OFF.	When there is not current at the base terminal of the PNP transistor, then the transistor turns ON.

The pnp Transistor

The pnp transistor operates in a manner similar to that of the npn device

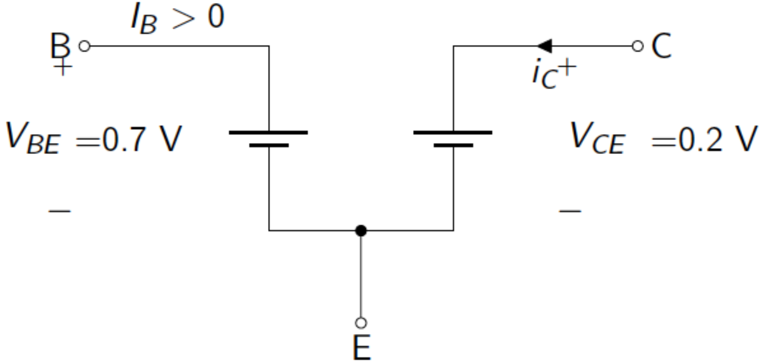


(a) Model 1 **(b)** Model 2

FIG 16. Two large-signal models for the pnp transistor operating in the active mode.

Saturation model summary

The saturation-mode BJT can be modeled as

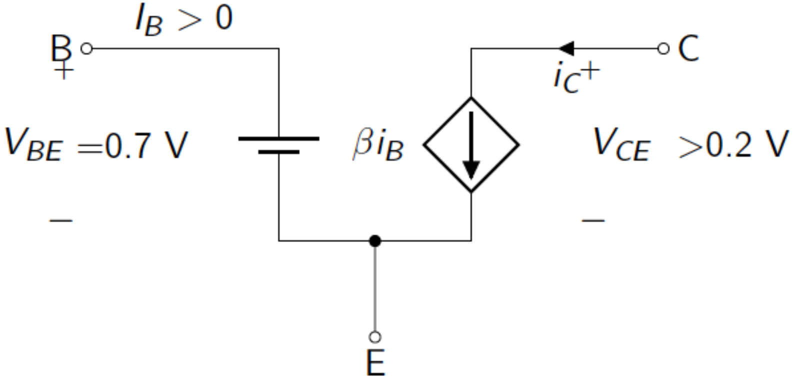


with:

- EBJ —Forward biased
- —CBJ —Forward biased

Active model summary

The active-mode BJT can be modeled as



with:

- EBJ —Forward biased
- CBJ—Reverse biased

Summary of the BJT Current–Voltage Relationships in the Active Mode

$$i_C = I_S e^{v_{BE}/V_T}$$

$$i_B = \frac{i_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta+1}$$

$$i_C = \beta i_B \qquad i_E = (\beta+1) i_B$$

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

$$V_T = \text{thermal voltage} = \frac{kT}{q} \simeq 25 \text{ mV at room temperature}$$

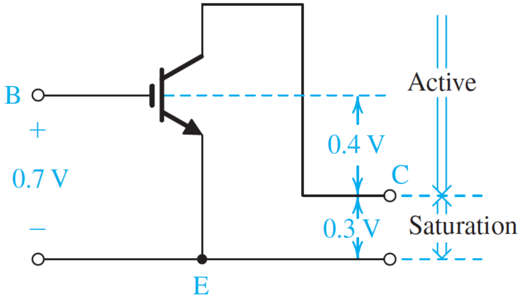
TAB 3. Summary of the bipolar current–voltage relationships in the active region

npn	pnp
$i_C = I_S e^{v_{BE}/V_T}$	$i_C = I_S e^{v_{EB}/V_T}$
$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$	$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$
$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$	$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$

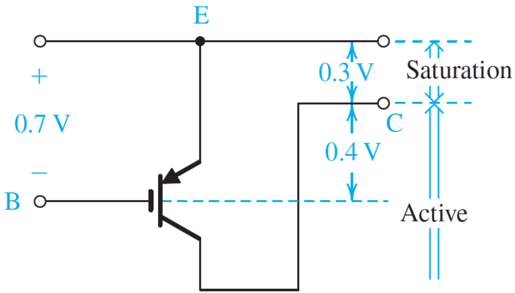
For both transistors

$i_E = i_C + i_B$	$i_C = \beta i_B$
$i_E = (1+\beta) i_B$	$i_C = \alpha i_E = \left(\frac{\beta}{1+\beta}\right) i_E$
$\alpha = \frac{\beta}{1+\beta}$	$\beta = \frac{\alpha}{1-\alpha}$

Summary of modes of operations



(a) npn



(b) pnp

FIG 17. Graphical representation of the conditions for operating the BJT in the active mode and in the saturation mode.

The end