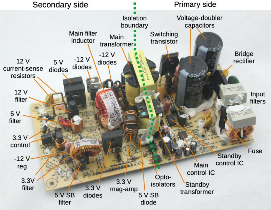

Bipolar Junction Transistors —BJTs

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Introduction

- This lecture examines another three-terminal device: the bipolar junction transistor (BJT)
  - The physical structure of the bipolar transistor and how it works.
  - How the voltage between two terminals of the transistor controls the current that flows through the third terminal, and the equations that describe these current-voltage relationships.
- The BJT was invented in 1948 at Bell Telephone Laboratories[1]
  - Ushered in a new era of solid-state circuits.
  - It was replaced by MOSFETas predominant transistor used in modern electronics.
- It is a three terminal device and has three semiconductor regions.
- It can be used in signal amplification and digital logic circuits as well

Simplified Structure

- A npn BJT (Fig. 1) consists of three semiconductor regions:
  - Emitter (E)—n-type region
  - Base (B)—p-type region. The base control the current through other terminals.
  - Collector (C)—n-type region
- The same regions exists for a pnp BJT (Fig. 2)—which has a has a p-type emitter, an n-type base, and a

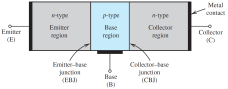


FIG 1. A simplified structure of the npn transistor

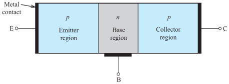
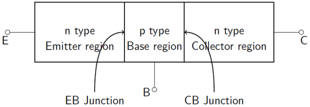


FIG 2. A simplified structure of the pnp transistor

Simplified Structure



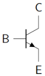
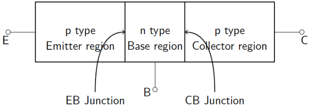


Figure : Symbol

FIG 3. Simplified structure of a npn BJT transistor

Simplified Structure



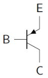


Figure : Symbol

FIG 4. Simplified structure of a pnp BJT transistor

Simplified Structure

- Transistor consists of two pn-junctions (Table 1)
  - Emitter-base junction (EBJ)
  - Collector-base junction (CBJ)
- Operating mode depends on biasing.
  - active mode—used for amplification
  - cutoff and saturation modes—used for switching.

TAB 1. BJT Modes of Operation

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

Circuit Symbols and Conventions

(a) simple block diagram **(b)** circuit symbol

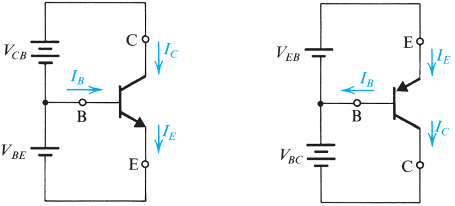
FIG 5. npn bipolar transistor
Note that the arrow is on the emitter terminal and indicates the direction of emitter current —which is also the forward direction of the base–emitter junction. In this case, I_C flows out of emitter terminal for the npn device

Circuit Symbols and Conventions

(a) simple block diagram **(b)** circuit symbol

FIG 6. pnp 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 into the emitter terminal for the pnp device

Circuit Symbols and Conventions



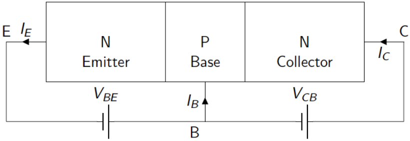
(a) npn **(b)** pnp

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

Active Mode

Active Mode —NPN Transistor

- Active mode is the "most important" region
- Two external voltage sources are required for biasing to achieve it.



Active mode current flow —NPN Transistor

- Collector current i_C (Equation (1))

$$i_C = I_s e^{v_{BE}/V_T} \tag{1}$$

where:

- I_s is the saturation current ($10^{-12}A < I_s < 10^{-18}A$) and is inversely proportional to W and directly proportional to area of EBJ. It is also referred to as scale current
- V_T is the thermal voltage. $V_T \approx 25mv$ at $25\,^\circ$C

- 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

Active mode current flow —NPN Transistor

- emitter current (i_E)—current which flows across EBJ and out of the emitter lead
- By Kirchoff's Current Law (KCL), all current which enters transistor must leave.

$$\begin{aligned} i_E &= i_C + i_B = i_C + \frac{i_C}{\beta} \\ &= i_C\frac{\beta+1}{\beta} \end{aligned} \quad (3)$$

Where $\alpha = \frac{\beta}{1+\beta}$ is called the common-base current gain

- Consequently, the emitter current i_C

$$i_E = \frac{I_S}{\alpha} e^{v_{BE}/V_T} \quad (4)$$

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

$$\beta = \frac{\alpha}{1-\alpha} \quad (5)$$

Summary

- The first-order BJT model assumes npn transistor in active mode
- Basic relationship is collector current i_C is related exponentially to forward-bias voltage v_{BE}.
- The current i_C remains independent of v_{CB} as long as this junction remains reverse biased (i.e., $v_{CB} \geq 0$)
- Thus, in the active mode, the collector terminal behaves as an ideal constant-current source where the value of the current is determined by v_{BE}.
- 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 $I_{SE} = I_S/\alpha$
- Thus, the diode provides a current i_E related to v_{BE} as shown in Equation (4)
- i_C is controlled by v_{BE} according to the exponential relationship in Equation (1)

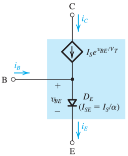


FIG 8. Model 1—A nonlinear voltage-controlled current source.

Equivalent-Circuit Models

The model Fig. 8 can be converted to the current-controlled current-source model shown in Fig. 9 by expressing the current of the controlled source as αi_E

- This is also a nonlinear model because of the exponential relationship of the current i_E through diode D_E and the voltage v_{BE}
- This model shows that if the transistor is used as a two-port network with the input port between E and B and the output port between C and B (i.e., with B as a common terminal), then the

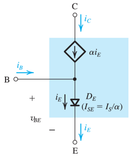


FIG 9. Model 2—A nonlinear current of the controlled source

Equivalent-Circuit Mod

- The model In Fig. 10, the diode D_B conducts the base current
  - its current scale factor is I_S/β
  - Its resulting in the i_B vs v_{BE} relationship given in Equation (2)
- The model in Fig. 11 expresses the collector current as βi_B
  - If the transistor is used as a two-port network with with the emitter E as the common terminal, then the current gain observed is equal to β.
  - Consequential, β is called the common-emitter current gain.

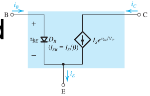


FIG 10. Model 3—A voltage-controlled current source

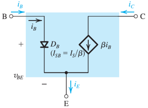


FIG 11. Model 4 —Current-controlled current-source

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

Saturation Mode

Saturation mode

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

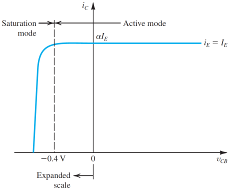


FIG 12. The i_C vs v_{CB} characteristic of an npn transistor fed with a constant emitter current I_E. The transistor enters the saturation mode of operation for $v_{CB} < -0.4\,V$, and the collector current diminishes.

Saturation mode —Important remarks

The concept of saturation means something completely different in a BJT and in a MOSFET.

- 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

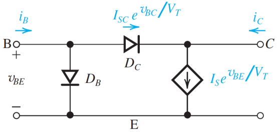


FIG 13. Equivalent circuit model of an npn transistor in saturation
The model is obtained by augmenting the model of Fig. 10 with a forward-conducting diode D_C.
Note that the current through D_C increases i_B and reduces i_C.

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

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

  where
  - I_{SC} is the saturation current for DC and is related to I_S by the ratio of the areas of the CBJ and the EBJ.
  - 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 $0.4V$?
  - 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, $V_{CEsat} \approxeq 0.1V$ to $0.3V$.

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

Where

BJT i_C vs v_{BE} curve

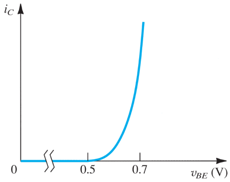


FIG 14. The i_C vs v_{BE} characteristic for an npn transistor

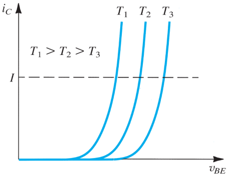


FIG 15. Effect of temperature on the i_C vs v_{BE} characteristic. At a constant emitter current (broken line), v_{BE} changes by $-2\,\mathrm{mV}\,^\circ\mathrm{C}^{-1}$

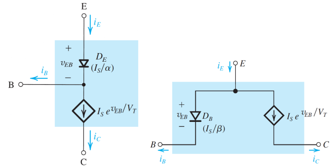
The pnp transistor

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

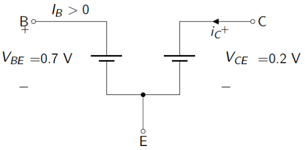


(a) Model 1 **(b)** Model 2

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

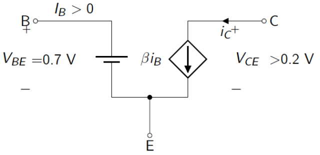


with:

- 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}.

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

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

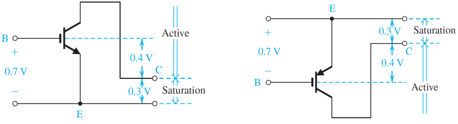
$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta+1}$$

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

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