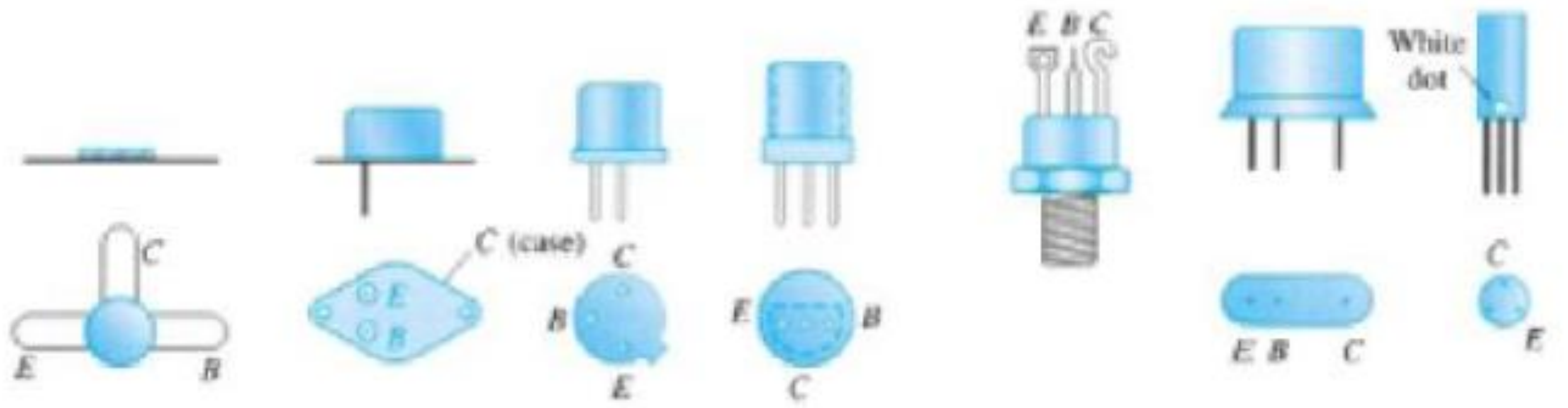


Bipolar Junction Transistors

Instructor

Nasser Ismail


2N4123

CASE 29-04, STYLE 1

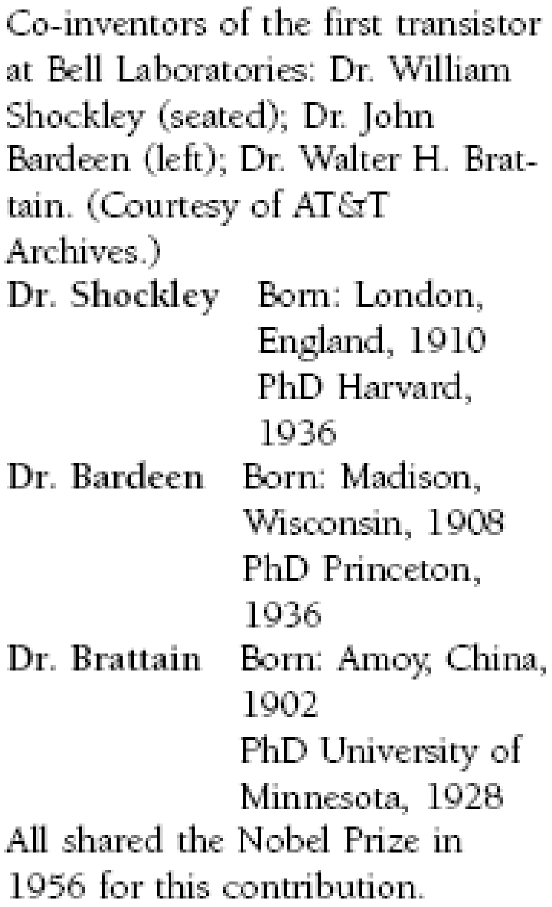
TO 92 (TO-226AA)

GENERAL PURPOSE

TRANSISTOR

NPN SILICON

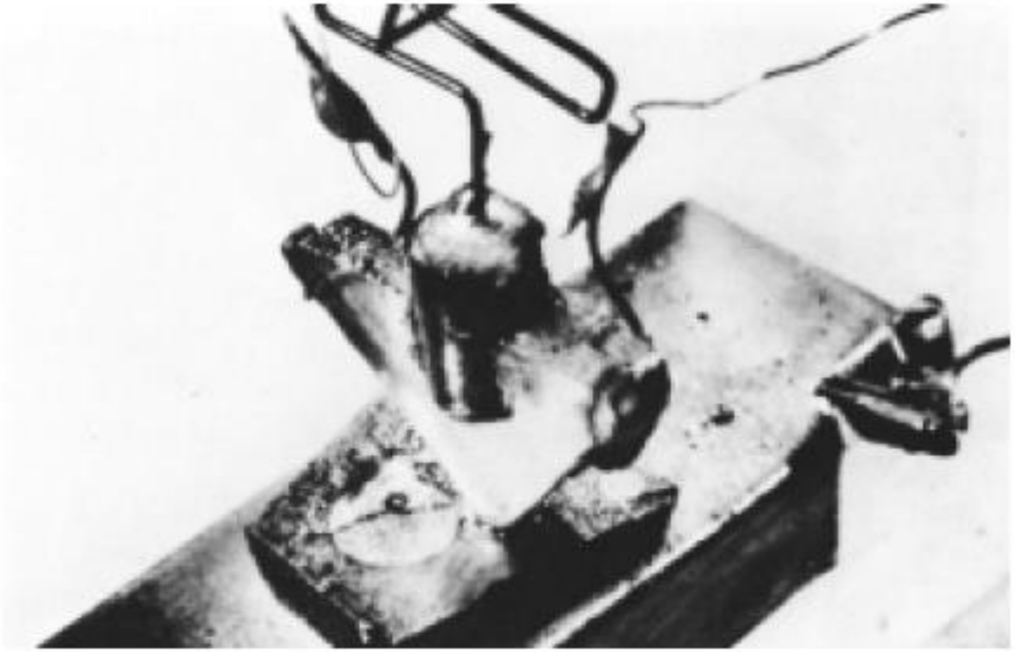
The First Transistor



Co-inventors of the first transistor at Bell Laboratories: Dr. William Shockley (seated); Dr. John Bardeen (left); Dr. Walter H. Brattain. (Courtesy of AT&T Archives.)

Dr. Shockley	Born: London, England, 1910 PhD Harvard, 1936
Dr. Bardeen	Born: Madison, Wisconsin, 1908 PhD Princeton, 1936
Dr. Brattain	Born: Amoy, China, 1902 PhD University of Minnesota, 1928

All shared the Nobel Prize in 1956 for this contribution.

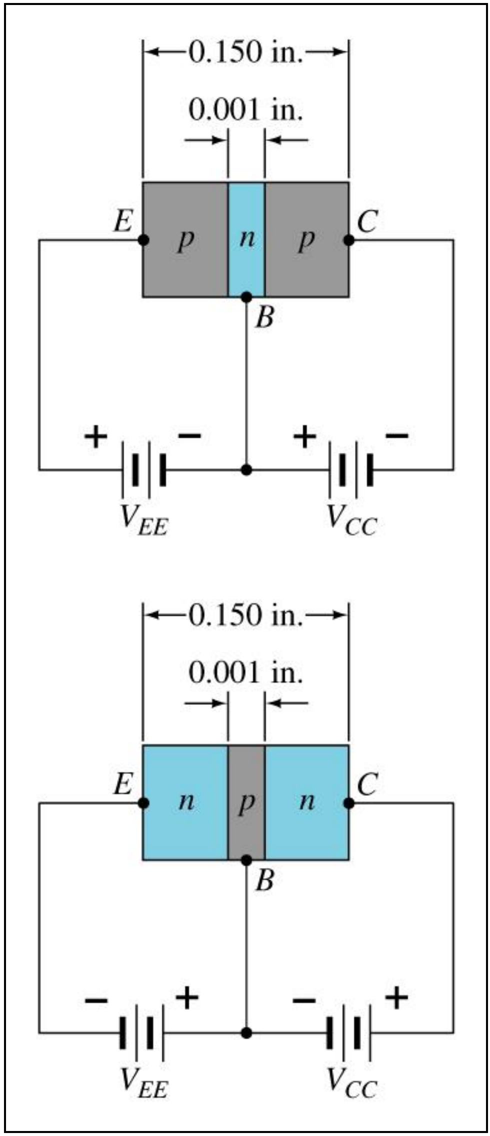


E

Figure 3.1 The first transistor. (Courtesy Bell Telephone Laboratories.)

Construction

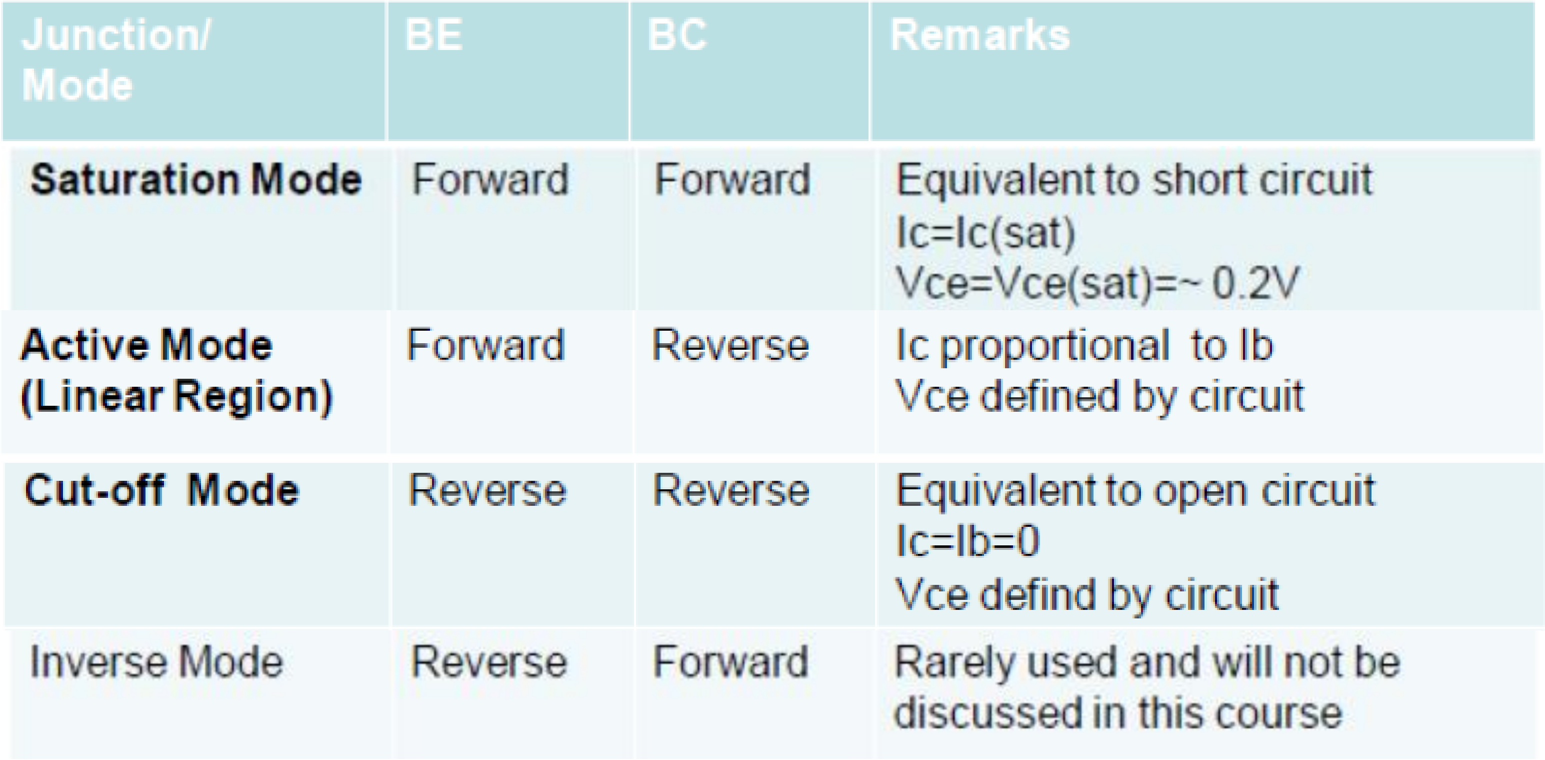
- 3-Layer Semiconductor device
- 2 p- layers and one n-layer or vise versa
- pnp or npn types
- Two pn junctions , each of them can be either forward or reverse biased
- This results in 4 possible modes of operation



pnp

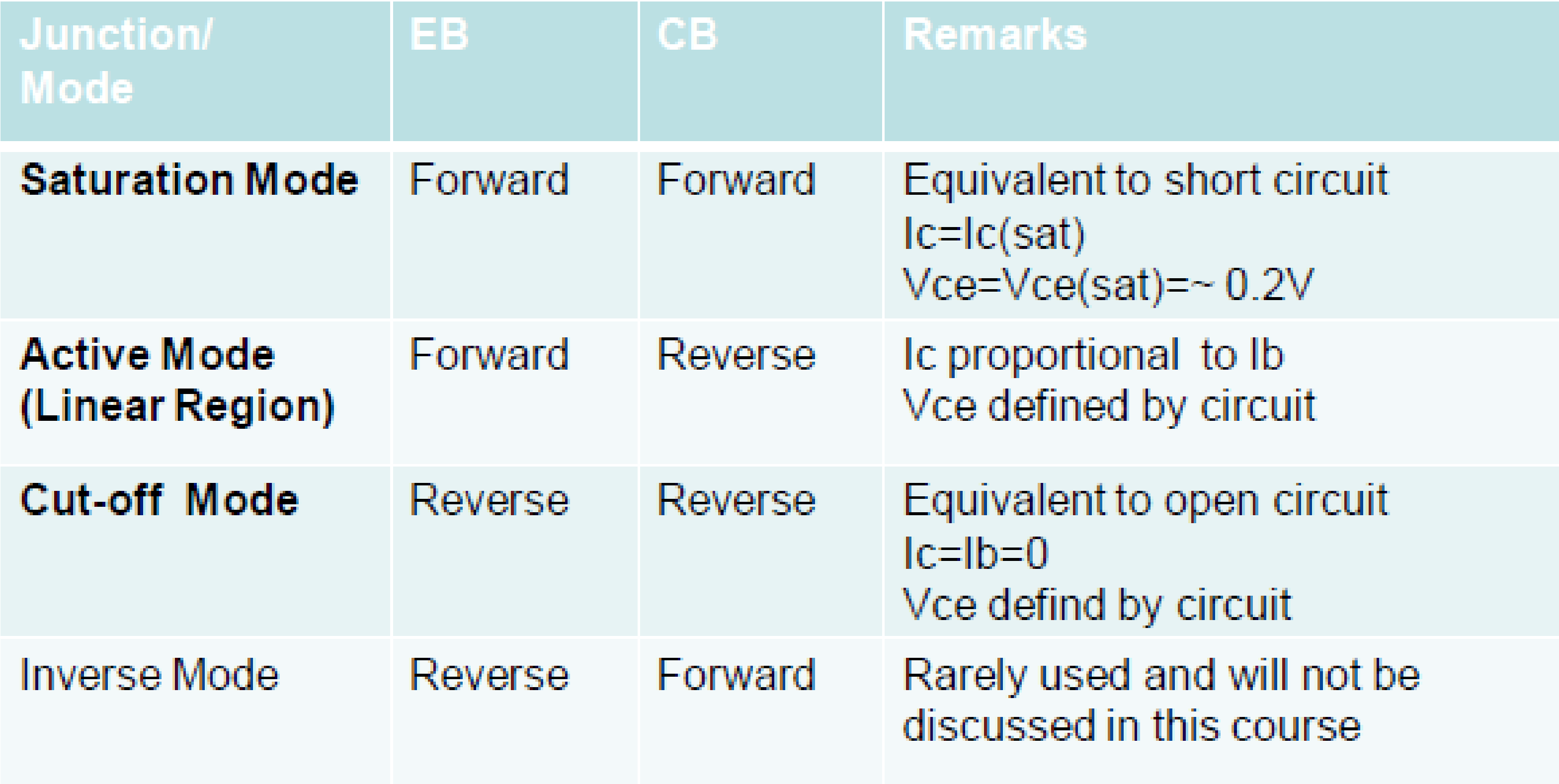
npn

npn transistor modes of operation



Junction/ Mode	BE	BC	Remarks
Saturation Mode	Forward	Forward	Equivalent to short circuit Ic=Ic(sat) Vce=Vce(sat)=~ 0.2V
Active Mode (Linear Region)	Forward	Reverse	Ic proportional to Ib Vce defined by circuit
Cut-off Mode	Reverse	Reverse	Equivalent to open circuit Ic=Ib=0 Vce defind by circuit
Inverse Mode	Reverse	Forward	Rarely used and will not be discussed in this course

pnp transistor modes of operation



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Saturation Mode	Forward	Forward	Equivalent to short circuit Ic=Ic(sat) Vce=Vce(sat)=~ 0.2V
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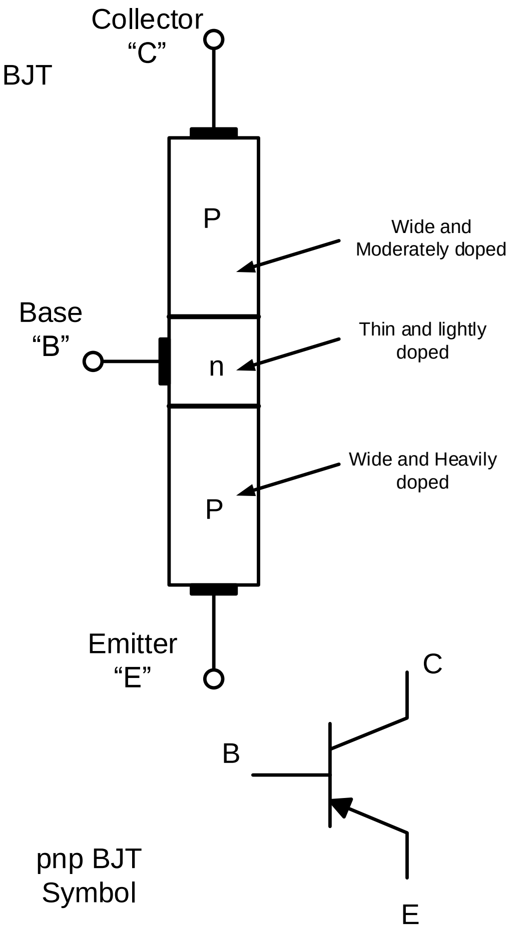
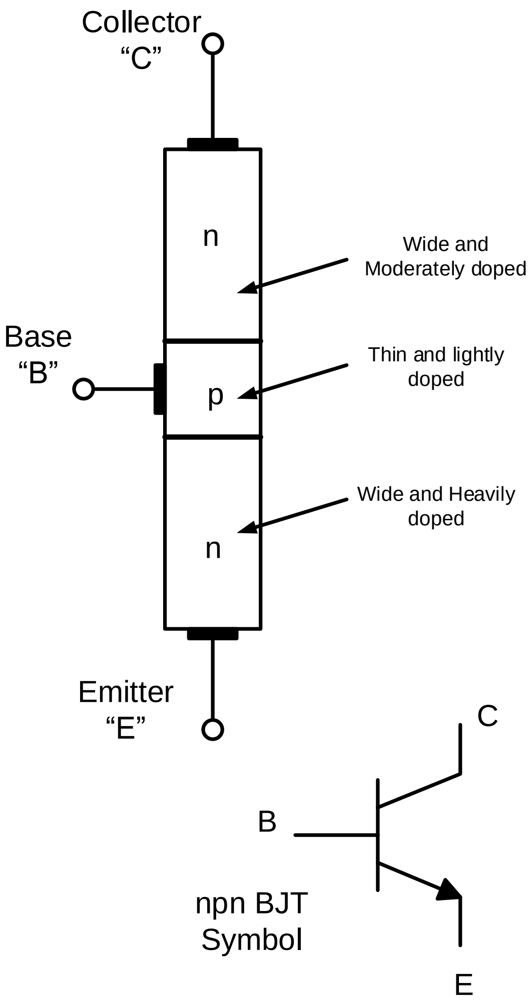
Cut-off Mode	Reverse	Reverse	Equivalent to open circuit Ic=Ib=0 Vce defind by circuit
Inverse Mode	Reverse	Forward	Rarely used and will not be discussed in this course

Construction and Symbol

pnp BJT

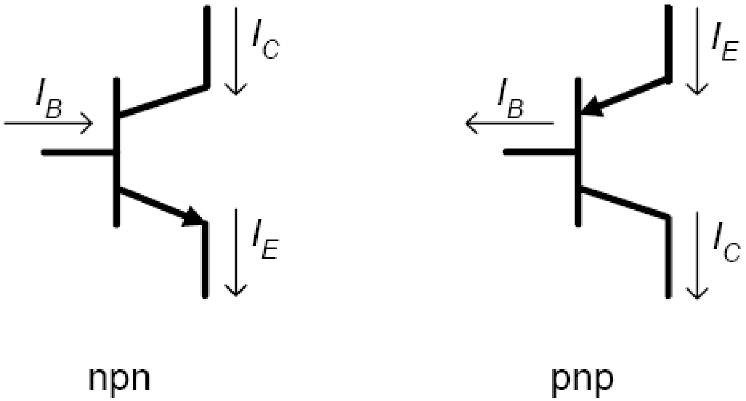


pnp BJT
Symbol



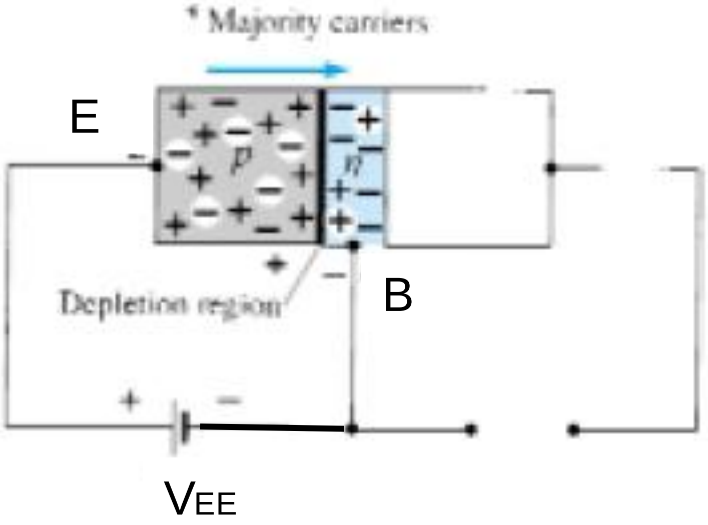
npn BJT
Symbol

- Current Directions



Transistor Operation in the Active Mode(pnp CB)

- EB is forward biased
- CB not biased
- This is similar to the forward biased diode
- The depletion region is reduced due to applied bias resulting in heavy flow of majority carriers (+) from p-layer to n-layer



Forward Biased EB Junction of a pnp transistor

Transistor Operation

5) Remove EB bias and apply reverse bias on CB junction resulting in widening of the depletion region

6) Recall that the flow of majority carriers is zero,resulting in only a minority-carrier flow

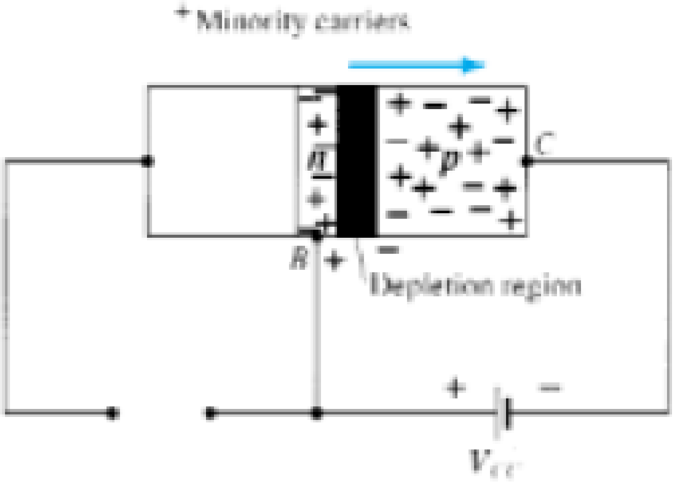
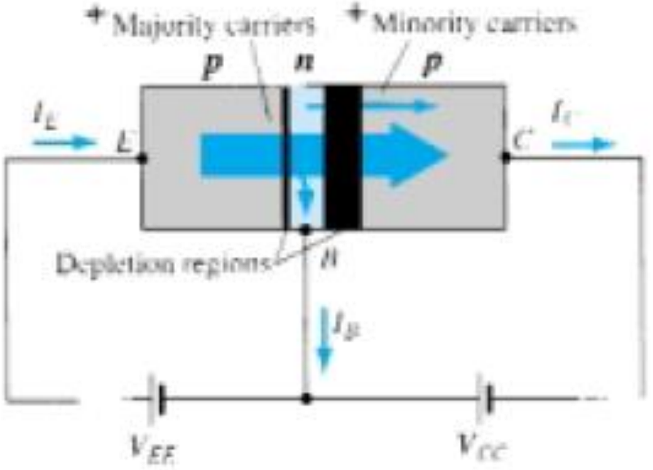


Figure 3.4 Reverse-biased junction of a *pnp* transistor.

Transistor Operation

- **If the two previous sources were applied with one junction FB and the other reverse biased**
- **a large number of majority carriers will diffuse across the forward-biased *p-n* junction into the *n*-type material.**
- **Since the base is very thin and has a low conductivity, a very small number of these carriers will take this path of high resistance to the base terminal**
- **The magnitude of the base current is typically on the order of microamperes as compared to milliamperes for the emitter and collector currents**



Transistor Operation

- The larger number of these majority carriers will diffuse across the reverse-biased junction into the *p*-type material connected to the collector terminal as indicated in Fig. 3.5.
- The reason for the relative ease with which the majority carriers can cross the reverse-biased junction is easily understood if we consider that for the reverse-biased diode **the injected majority carriers will appear as minority carriers in the *n*-layer.**
- In other words, there has been an *injection* of minority carriers into the *n*-type base region material.

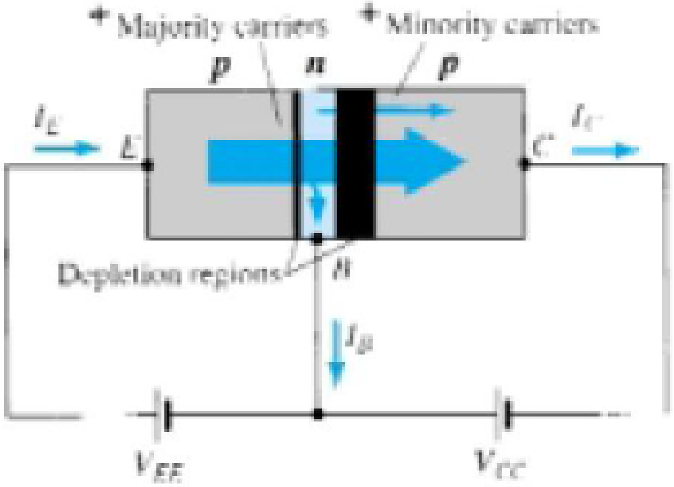
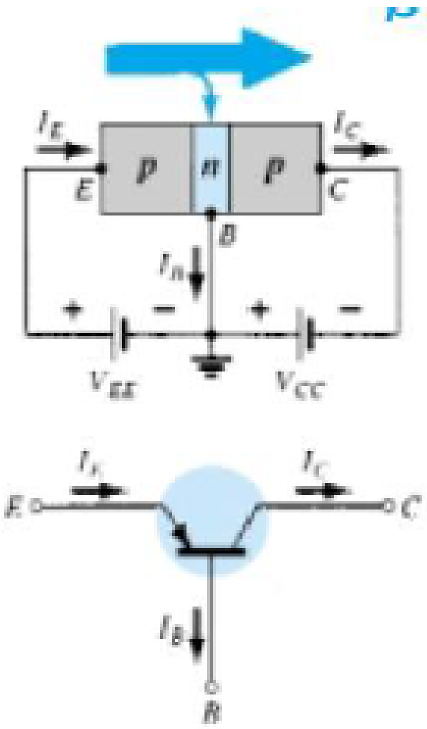


Figure 3.5 Majority and minority carrier flow of a *pnp* transistor.

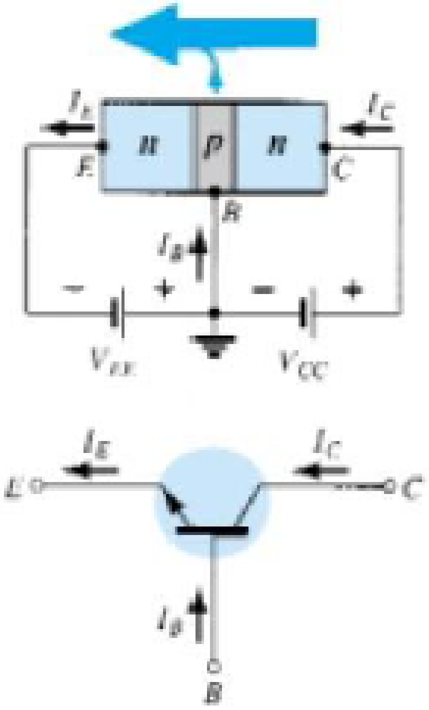
- Combining this with the fact that all the minority carriers in the depletion region will cross the reverse-biased junction of a diode accounts for the flow indicated

Basic Current Equation

- Applying KCL to the transistor as if it were a single node, we obtain

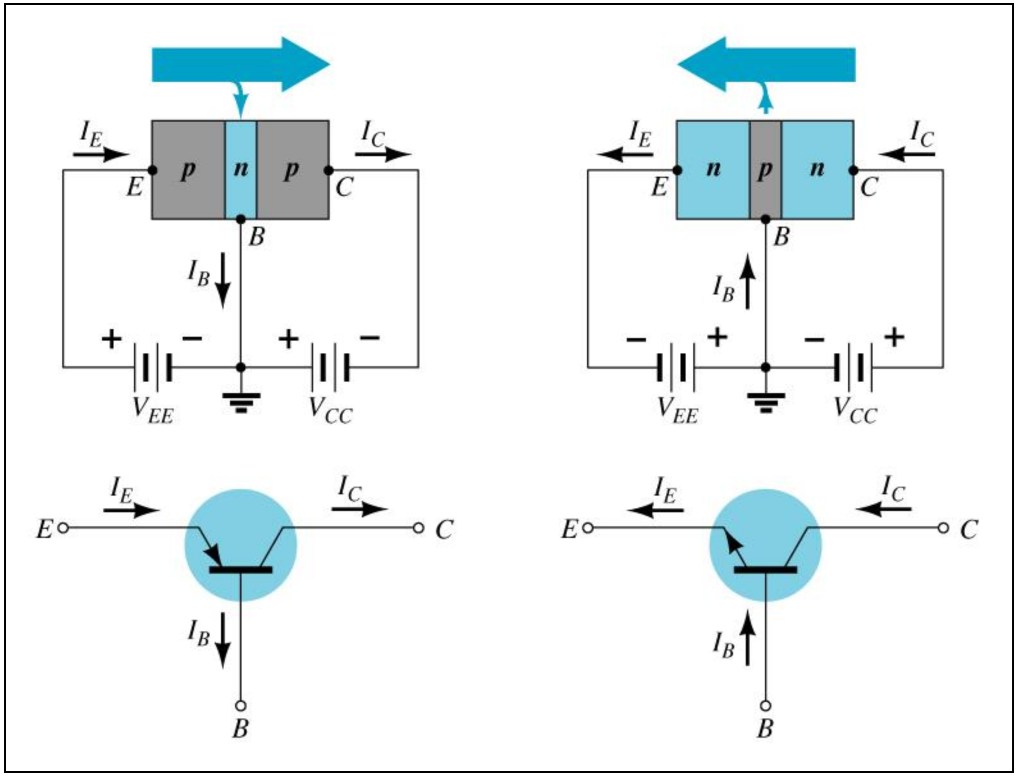


$$I_E = I_C + I_B$$



Common Base Configuration

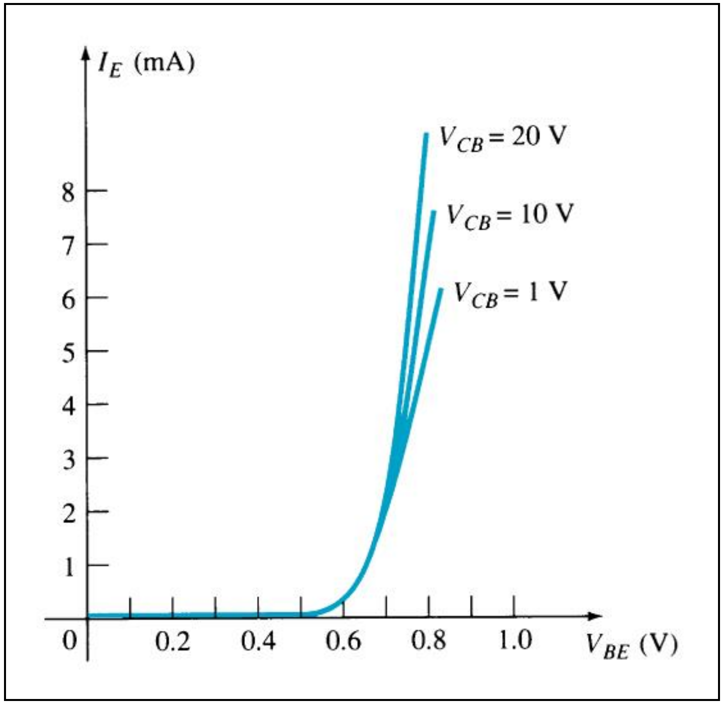
- The common-base terminology is derived from the fact that the base is common to both the input and output sides of the configuration
- In addition, the base is usually the terminal closest to , or at, ground potential) through the device
- Throughout this course all current directions will refer to conventional (hole) flow rather than electron flow
- The arrow in the graphic symbol defines the direction of emitter current(conventional flow) through the device



Common-Base Amplifier

Input Characteristics

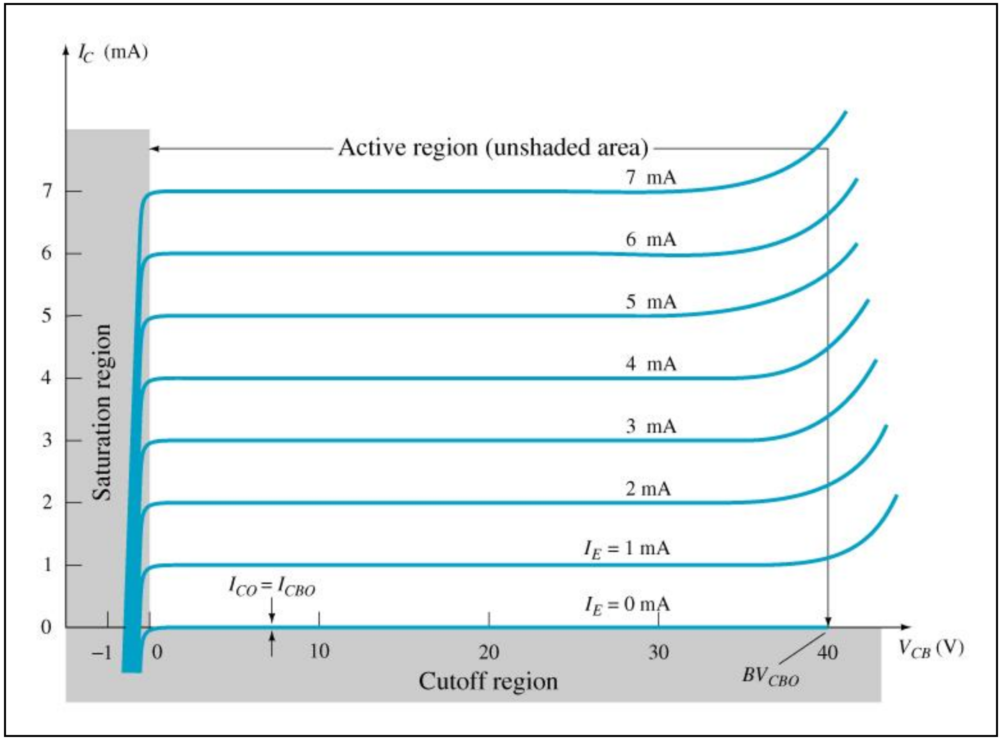
This curve shows the relationship between of input current (I_E) to input voltage (V_{BE}) for three output voltage (V_{CB}) levels.



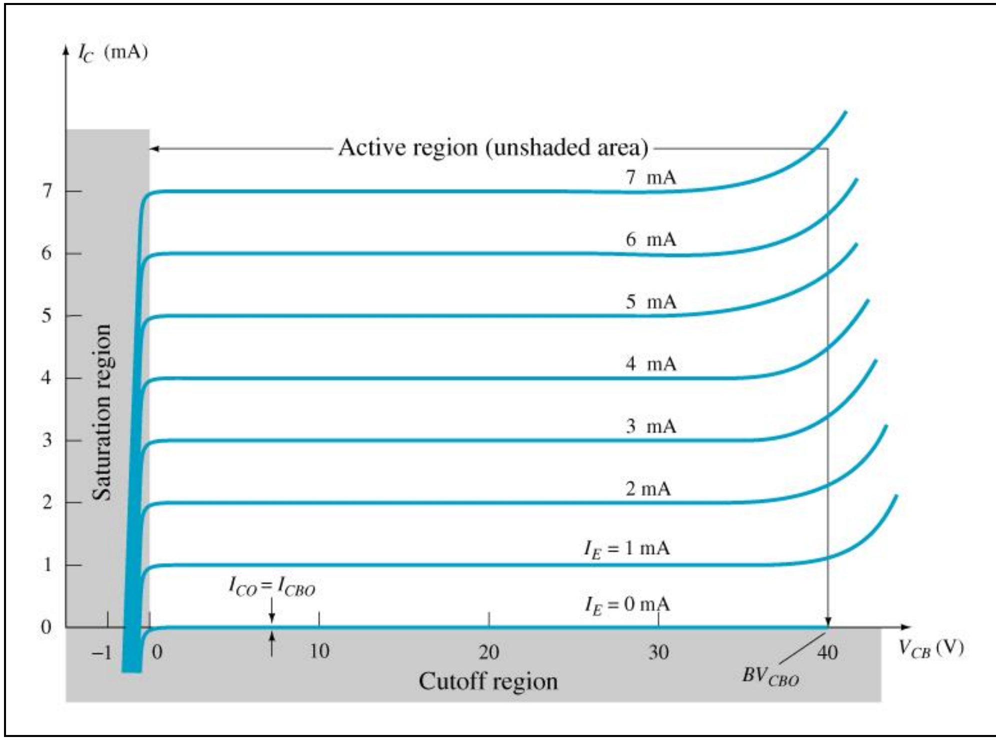
Common-Base Amplifier

Output Characteristics

This graph demonstrates the output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E).



Operating Regions



Active

Operating range of the amplifier.

Cutoff

The amplifier is basically off. There is voltage, but little current.

Saturation

The amplifier is fully on. There is current, but little voltage.

Operation Modes

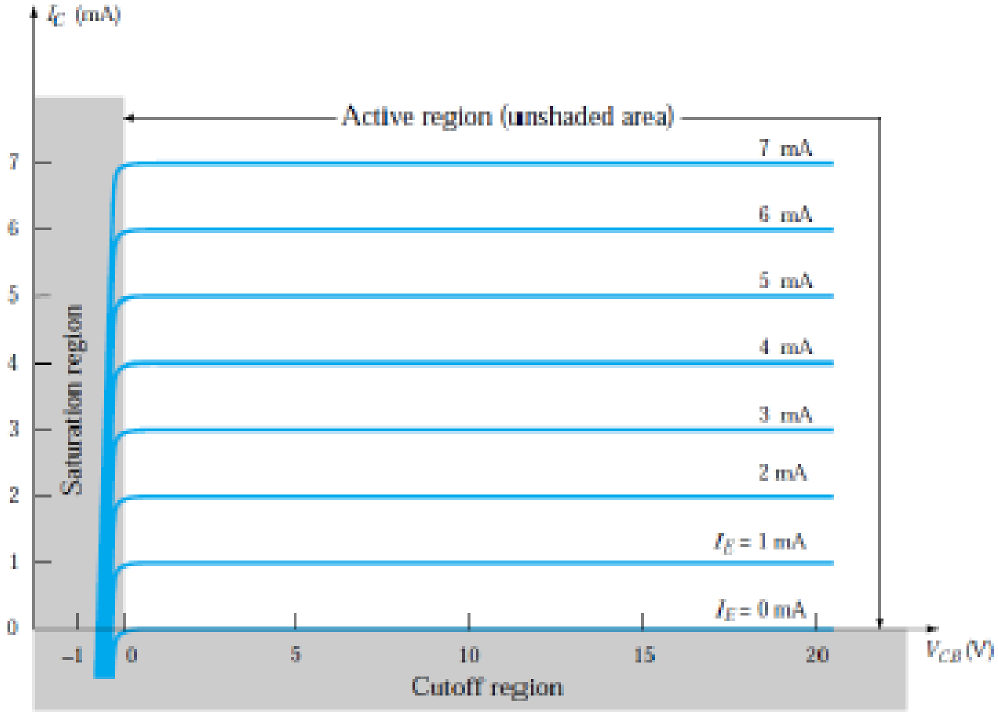
- Cutoff region: defined as that region where collector current is 0A
- In this region both junctions are reverse biased
- Saturation region is defined as the region where both junctions are forward biased

Operation Modes of BJT

- **The saturation region** is defined as that region of the characteristics to the left of V_{CB}= 0 V.
- The horizontal scale in this region was expanded to clearly show the dramatic change in characteristics in this region.

Note the exponential increase in collector current as the voltage V_{CB} increases toward 0 V.

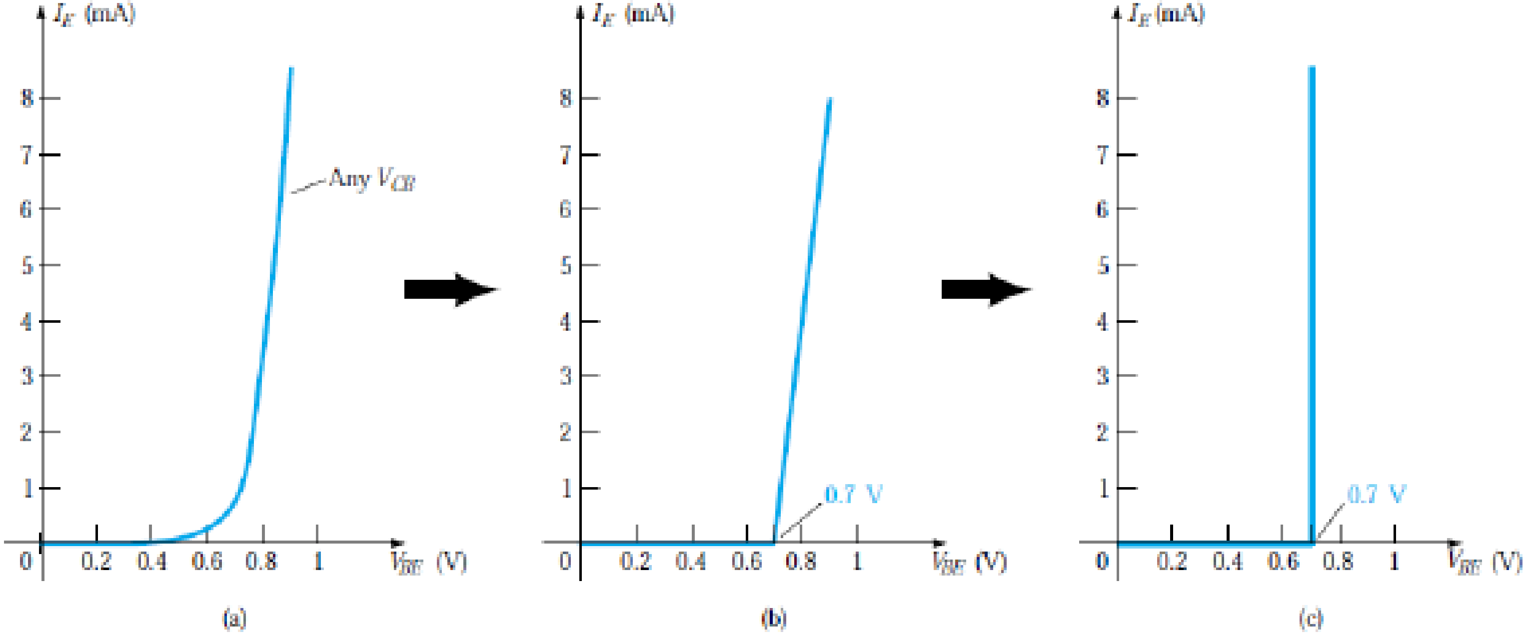
EN



Operation Modes of BJT

- Once a transistor is in the “on” state, the base-to-emitter voltage will be assumed to be the following:

$$\boxed{V_{BE} = 0.7\ \text{V}}$$



(a) (b) (c)

Approximations

Emitter and collector currents:

$$\boxed{I_C \cong I_E}$$

Base-emitter voltage:

$$\boxed{V_{BE} = 0.7\ V \quad (for\ Silicon)}$$

Alpha (α)

Alpha (α) is the ratio of I_C to I_E :

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

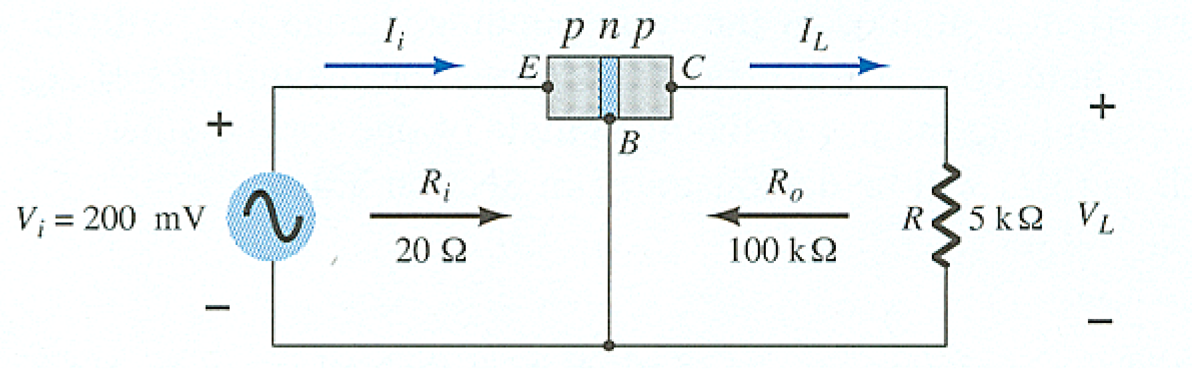
Ideally: $\alpha = 1$

In reality: α falls somewhere between 0.9 and 0.998

Alpha (α) in the AC mode:

$$\alpha_{ac} = \frac{\Delta I_C}{\Delta I_E}$$

Transistor Amplifier



Currents and Voltages:

$$I_E = I_i = \frac{V_i}{R_i} = \frac{200\,\text{mV}}{20\Omega} = 10\,\text{mA}$$

$$I_C \cong I_E$$

$$I_L \cong I_i = 10\,\text{mA}$$

$$V_L = I_L R = (10\,mA)(5\,k\Omega) = 50\,\text{V}$$

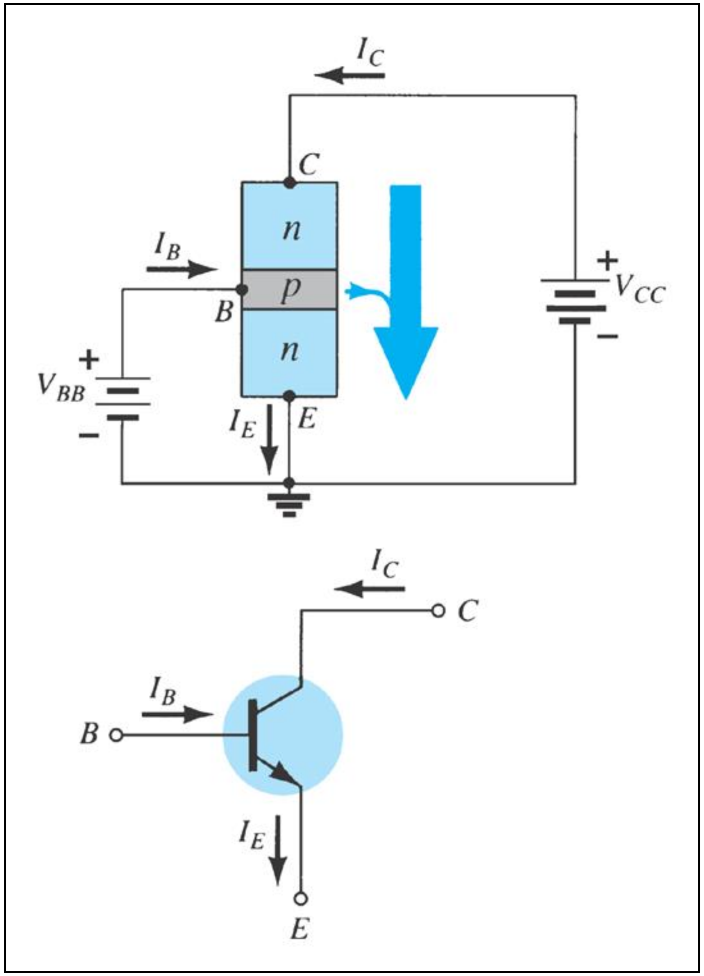
Voltage Gain:

$$A_V = \frac{V_L}{V_i} = \frac{50V}{200\,mV} = 250$$

Common-Emitter Configuration

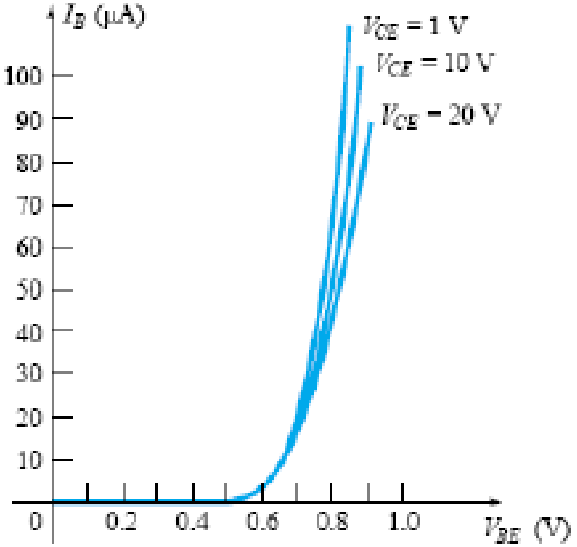
The emitter is common to both input (base-emitter) and output (collector-emitter) circuits.

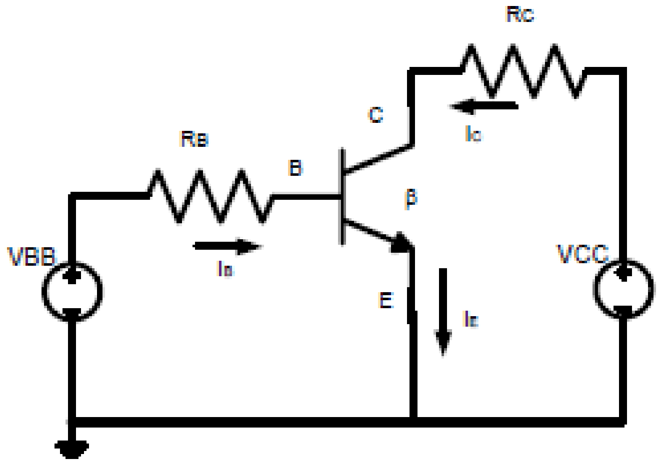
The input is applied to the base and the output is taken from the collector.



Common Emitter Configuration

Input characteristics : Input current (I_B) versus the input voltage (V_{BE}) for a range of values of output voltage (V_{CE}).



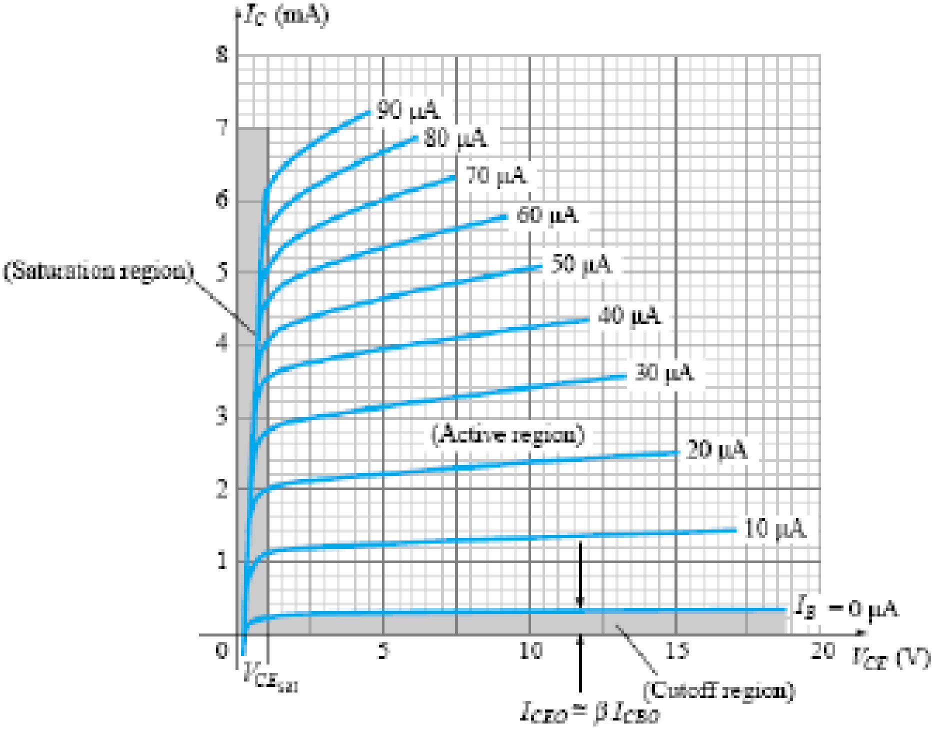


CE output Characteristic (npn)

Active Region:

- is that portion of the upper-right quadrant that has the greatest linearity, that is, that region in which the curves for I_B are nearly straight and equally spaced.
- This region exists to the right of the vertical dashed line at V_{CEsat} and above the curve for I_B equal to zero.
- BE forward & BC is reverse
- Note I_B is small compared to I_C. ($I_B << I_C$)
- Transistor amplifies current

  $I_C = \beta I_B$

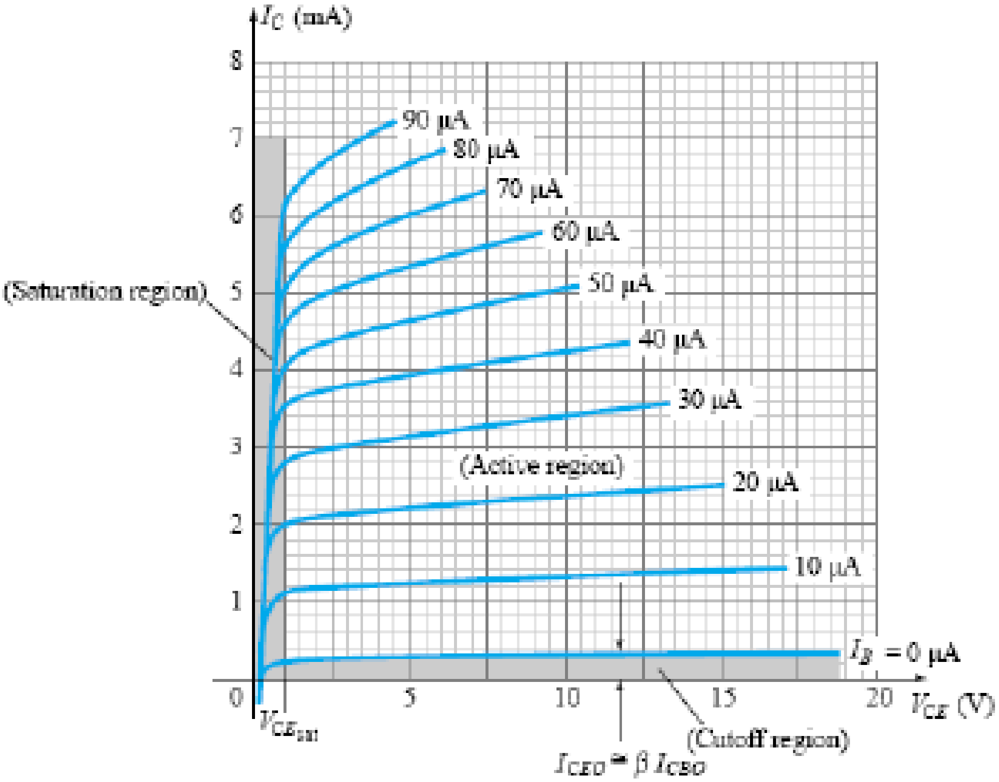


CE output Characteristic (npn)

Cutoff Region:

- This region exists above the curve for I_B equal to zero.
- BE reverse & BC is reverse
- Note I_B =0 while I_C is only the reverse leakage current compared
- Transistor acts as an open switch

Saturation Region: BE & BC both forward and I_B increase

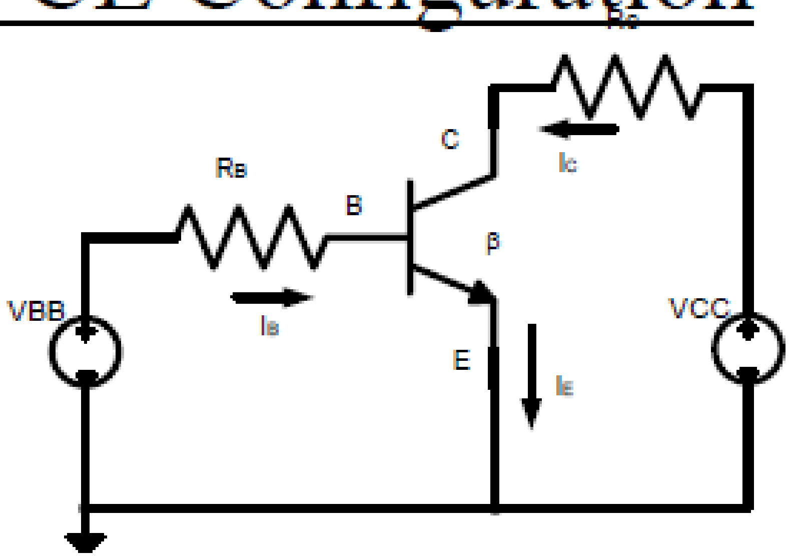


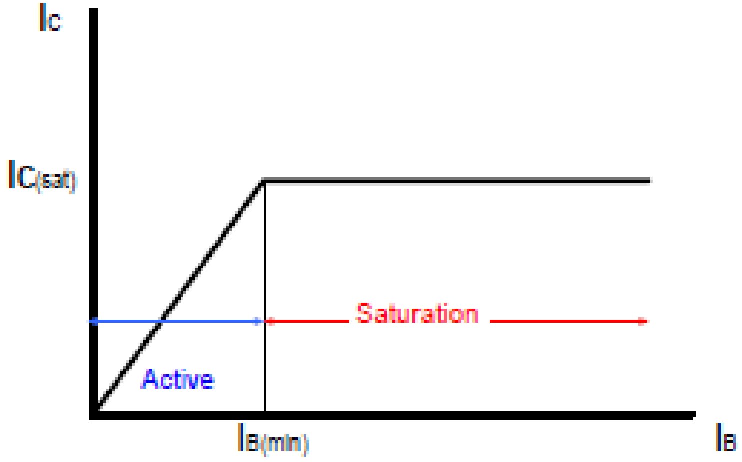
Saturation Mode for CE Configuration

- BE forward & BC become forward
- As I_B increase and I_C increase
- Since $V_{CE}= V_{CC}-I_CR_C$ V_{CE} becomes smaller since I_CR_C increase
- V_{CE} reaches its saturation value $V_{CE(sat)}=0.2V$
- Now BC become forward and IC cannot increase any more even with increase ob IB and the relationship between them $I_C = \beta I_B$ is not valid anymore
- Transistor acts as a closed switch
- $I_B > I_{B(min)} \rightarrow I_{B(min)} = I_{C(sat)} / \beta$

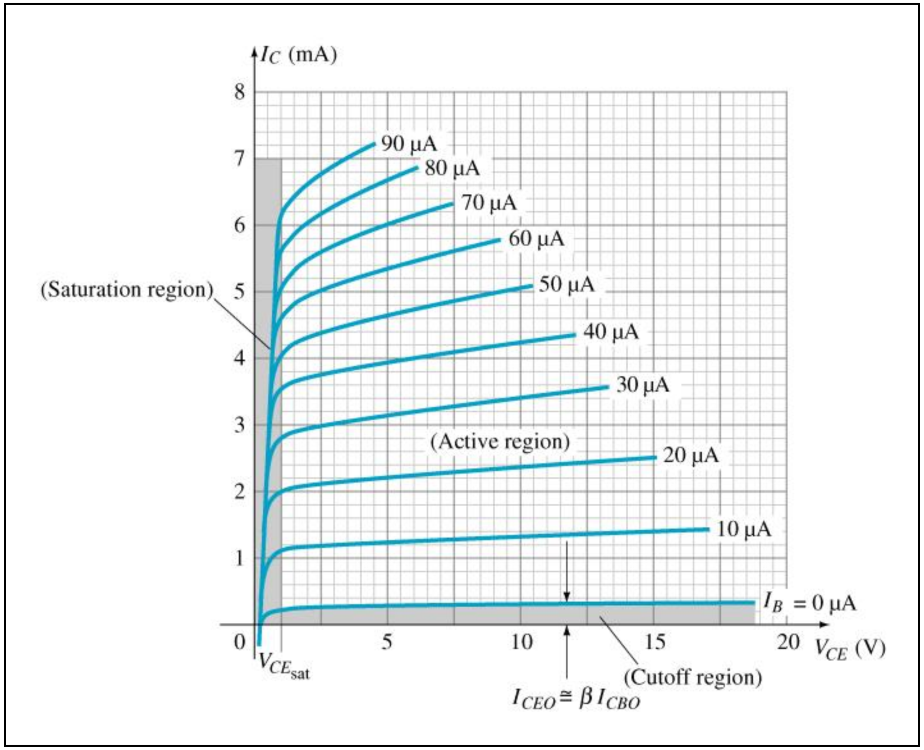
  $V_{CE}=V_{CE(sat)}$

  $I_C=I_{C(sat)} =[V_{CC}-V_{CE(sat)}] / R_C$

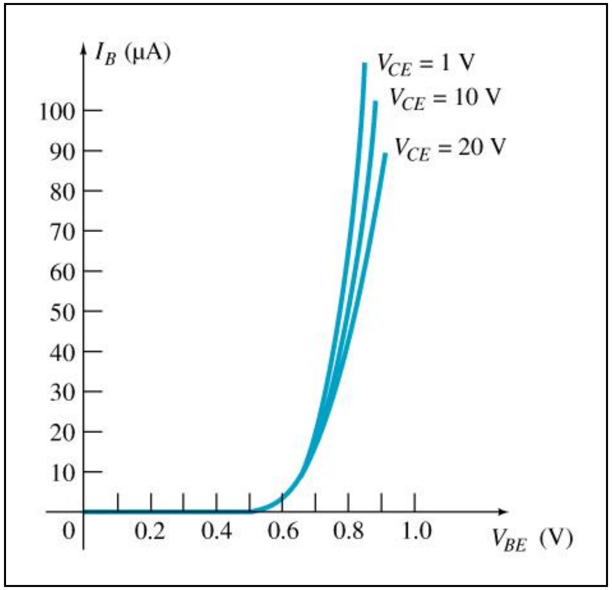




Common-Emitter Characteristics



Collector Characteristics



Base Characteristics

Common-Emitter Amplifier Currents

Ideal Currents

$$I_E = I_C + I_B \qquad I_C = \alpha I_E$$

Actual Currents

$$I_C = \alpha I_E + I_{CBO}$$

where I_{CBO} = minority collector current

I_{CBO} is usually so small that it can be ignored, except in high power transistors and in high temperature environments.

When $I_B = 0\ \mu A$ the transistor is in cutoff, but there is some minority current flowing called I_{CEO}.

$$I_{CEO} = \frac{I_{CBO}}{1-\alpha}\bigg|_{I_B = 0\ \mu A}$$

Beta (β)

β represents the amplification factor of a transistor.

In DC mode:

$$\beta_{dc} = \frac{I_C}{I_B}$$

In AC mode:

$$\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=constant}$$

β_{ac} *is sometimes referred to as* h_{fe}*, a term used in transistor modeling calculations*

Beta (β)

Determining β from a Graph

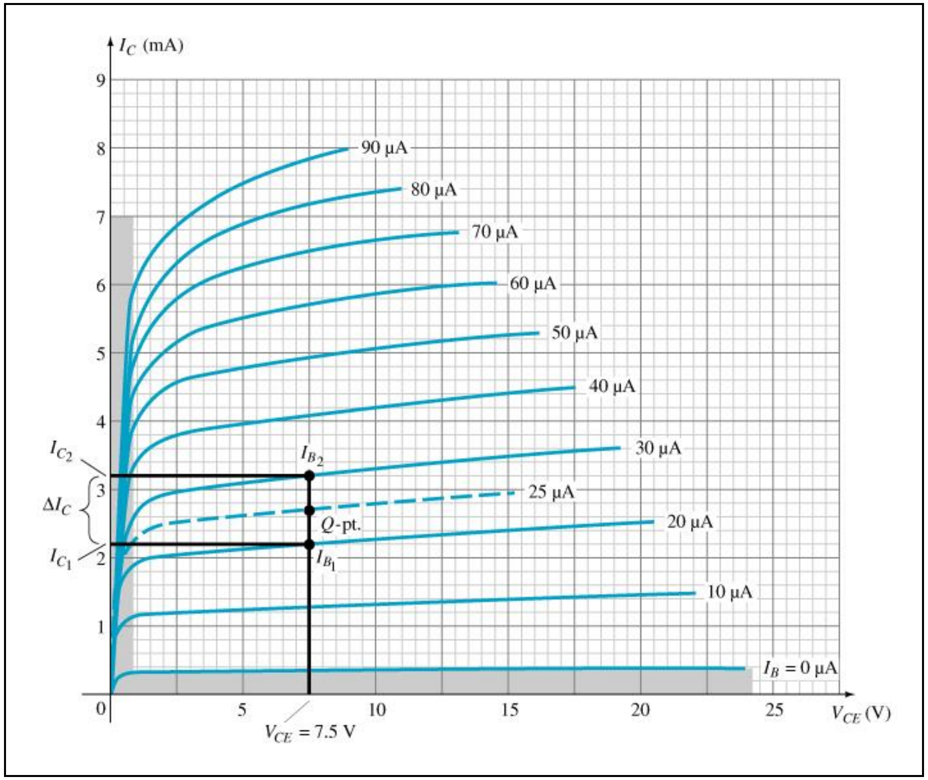
$$\beta_{AC} = \frac{(3.2\ mA - 2.2\ mA)}{(30\ \mu A\ -\ 20\ \mu A)}$$

$$= \frac{1\, mA}{10\ \mu A}\bigg|_{V_{CE}=7.5V}$$

$$= 100$$

$$\beta_{DC} = \frac{2.7\ mA}{25\ \mu A}\bigg|_{V_{CE}=7.5V}$$

$$= 108$$



Beta (β)

Relationship between amplification factors β and α :

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

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

Relationship Between Currents:

$$I_C = \beta I_B$$

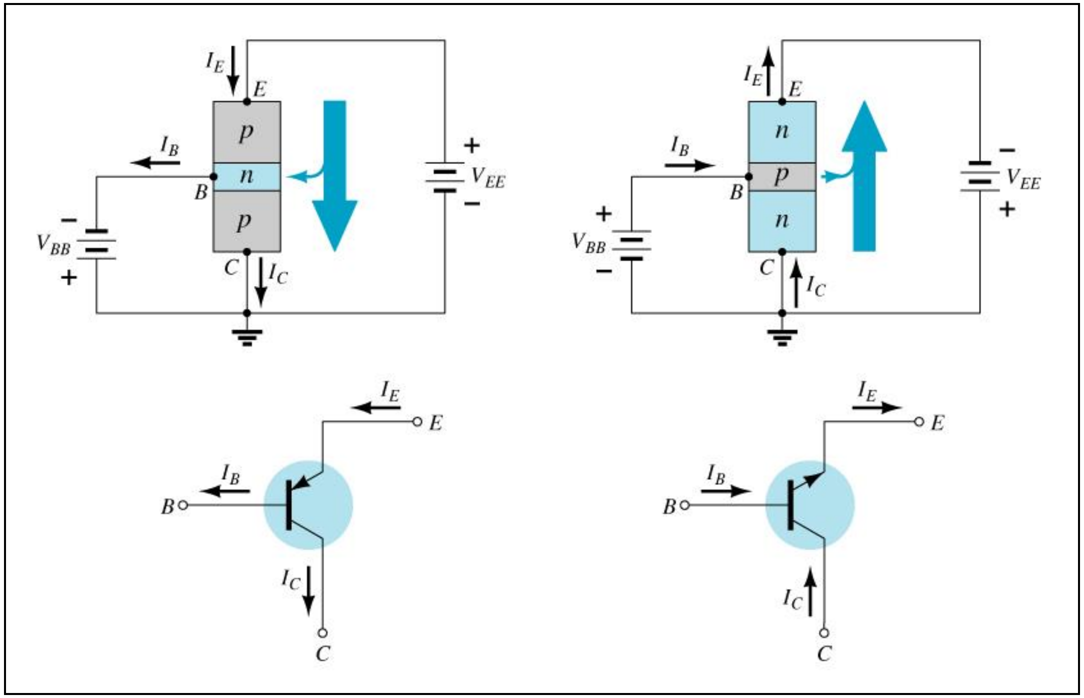
$$I_E = (\beta + 1) I_B$$

Common Collector Configuration

- The third and final transistor configuration is the *common-collector configuration,*
- The common-collector configuration is used primarily for impedance-matching purposes since it has a high input impedance and low output impedance, opposite to that of the common-base and common-emitter configurations.

Common-Collector Configuration

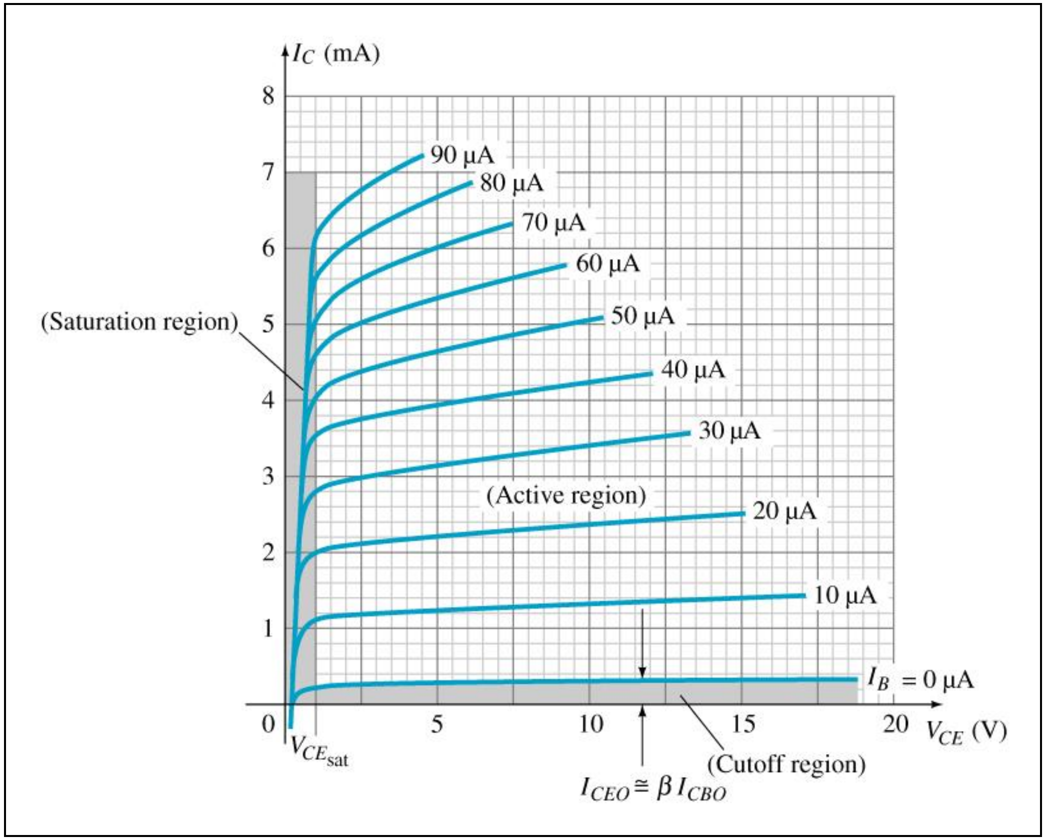
The input is on the base and the output is on the emitter.



- From a design viewpoint, there is no need for a set of common collector characteristics to choose the parameters of the circuit.
- It can be designed using the common-emitter characteristics.
- For all practical purposes, the output characteristics of the common-collector configuration are the same as for the common-emitter configuration.
- For the common-collector configuration the output characteristics are a plot of *IE versus VEC for a range of values of IB.*
- The input current, therefore, is the same for both the common-emitter and common collector
- characteristics

Common-Collector Configuration

The characteristics are similar to those of the common-emitter amplifier, except the vertical axis is I_E.



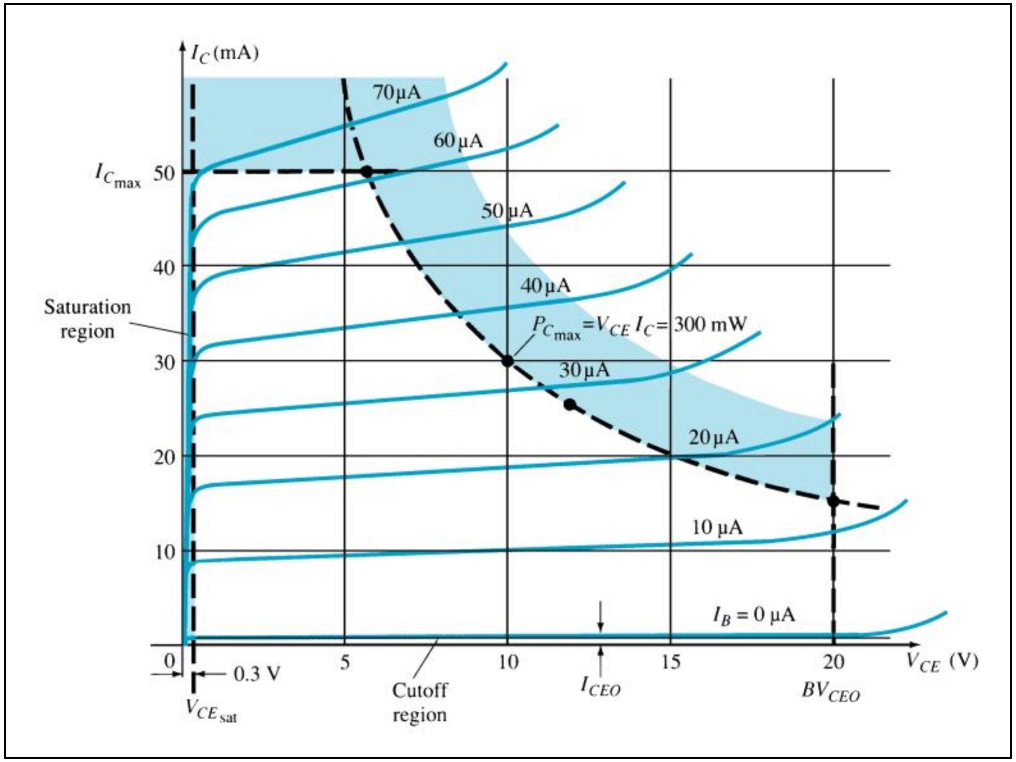
Operating Limits

V_{CE} is maximum and I_C is minimum in the cutoff region.

$$I_{C(\max)} = I_{CEO}$$

I_C is maximum and V_{CE} is minimum in the saturation region.

$$V_{CE(\max)} = V_{CE(sat)} = V_{CEO}$$



The transistor operates in the active region between saturation and cutoff.

Power Dissipation

Common-base:

$$P_{C\max} = V_{CB} I_C$$

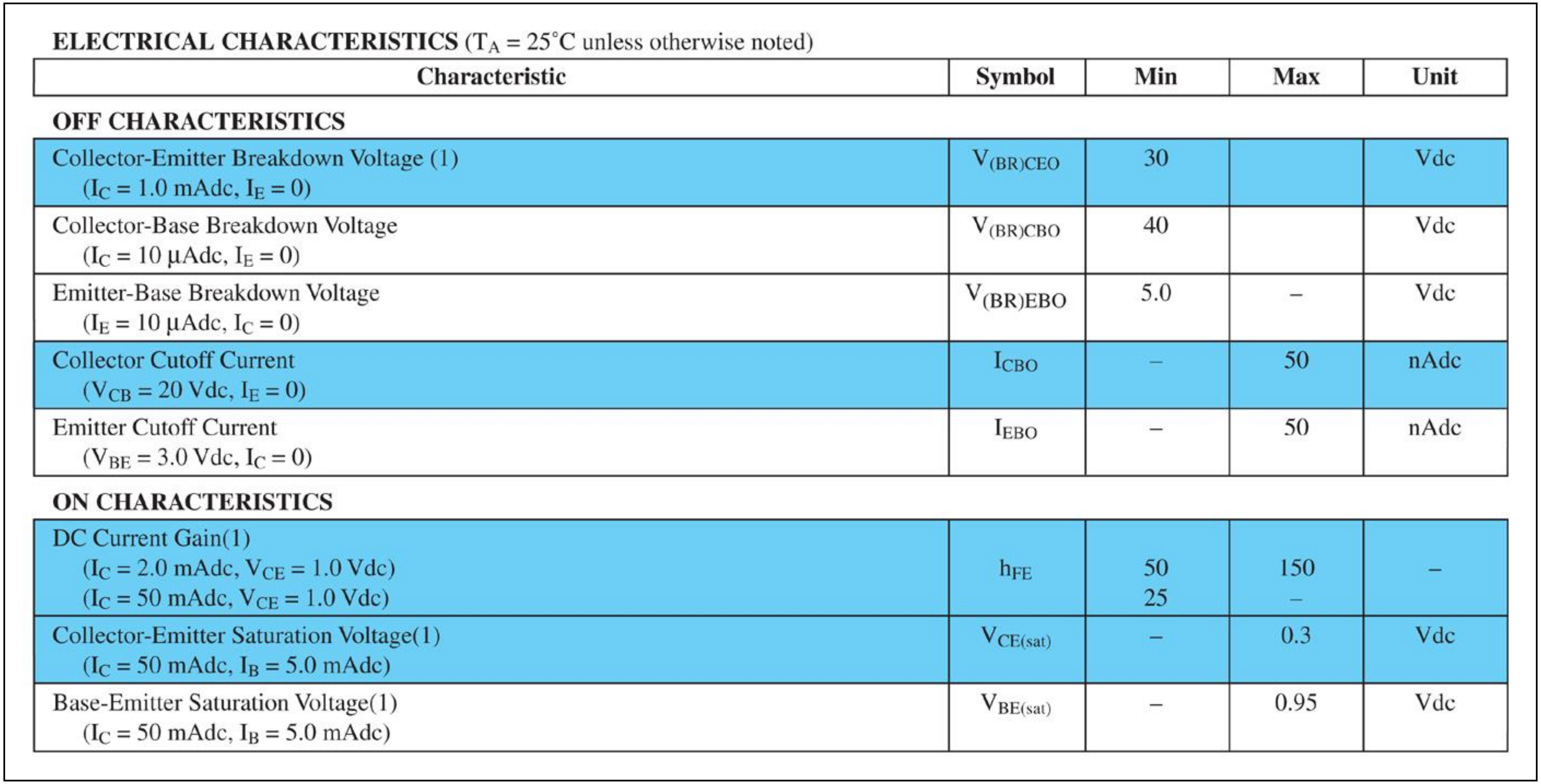
Common-emitter:

$$P_{C\max} = V_{CE} I_C$$

Common-collector:

$$P_{C\max} = V_{CE} I_E$$

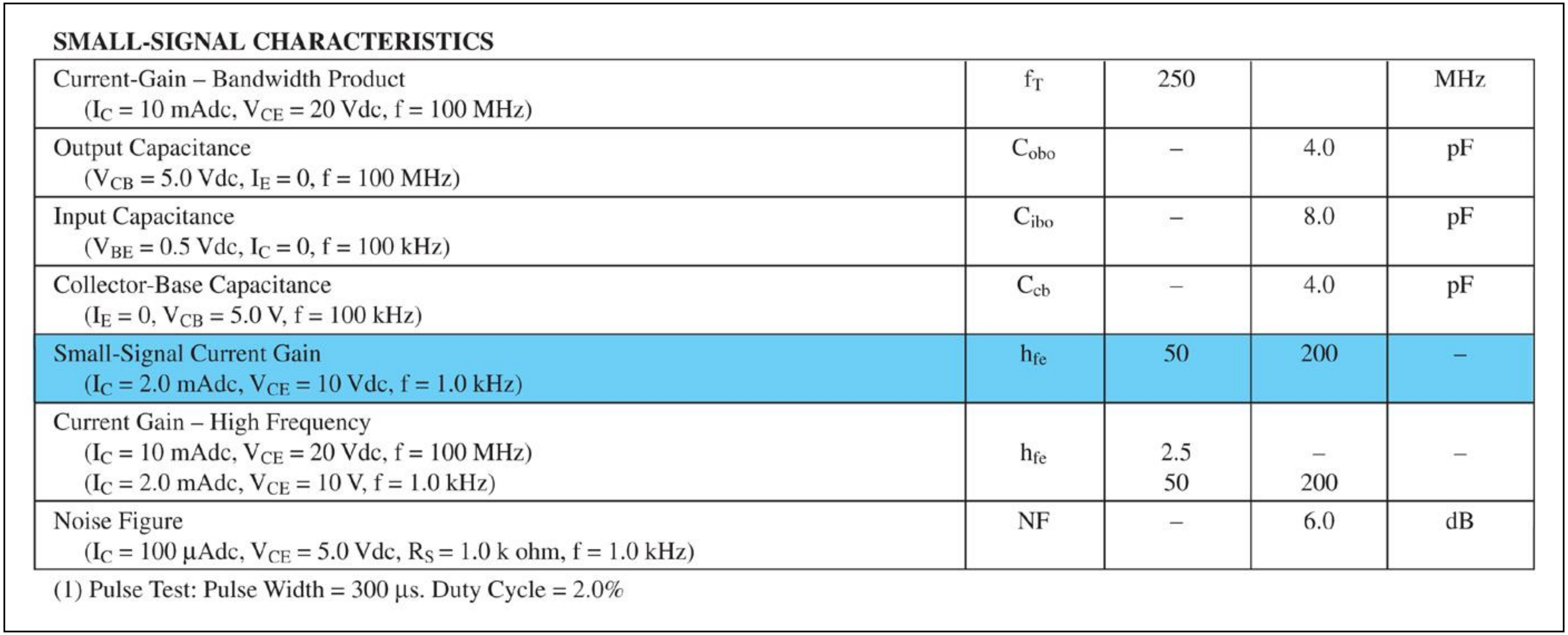
Transistor Specification Sheet



ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Emitter Breakdown Voltage (1) (I_C = 1.0 mAdc, I_E = 0)	$V_{(BR)CEO}$	30		Vdc
Collector-Base Breakdown Voltage (I_C = 10 μAdc, I_E = 0)	$V_{(BR)CBO}$	40		Vdc
Emitter-Base Breakdown Voltage (I_E = 10 μAdc, I_C = 0)	$V_{(BR)EBO}$	5.0	–	Vdc
Collector Cutoff Current (V_{CB} = 20 Vdc, I_E = 0)	I_{CBO}	–	50	nAdc
Emitter Cutoff Current (V_{BE} = 3.0 Vdc, I_C = 0)	I_{EBO}	–	50	nAdc
ON CHARACTERISTICS				
DC Current Gain(1) (I_C = 2.0 mAdc, V_{CE} = 1.0 Vdc) (I_C = 50 mAdc, V_{CE} = 1.0 Vdc)	h_{FE}	50 25	150 –	–
Collector-Emitter Saturation Voltage(1) (I_C = 50 mAdc, I_B = 5.0 mAdc)	$V_{CE(sat)}$	–	0.3	Vdc
Base-Emitter Saturation Voltage(1) (I_C = 50 mAdc, I_B = 5.0 mAdc)	$V_{BE(sat)}$	–	0.95	Vdc

Transistor Specification Sheet



SMALL-SIGNAL CHARACTERISTICS

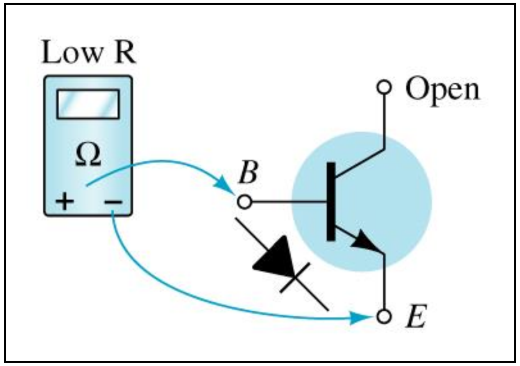
Current-Gain – Bandwidth Product (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	f_T	250		MHz
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 100 MHz)	C_{obo}	–	4.0	pF
Input Capacitance (V_{BE} = 0.5 Vdc, I_C = 0, f = 100 kHz)	C_{ibo}	–	8.0	pF
Collector-Base Capacitance (I_E = 0, V_{CB} = 5.0 V, f = 100 kHz)	C_{cb}	–	4.0	pF
Small-Signal Current Gain (I_C = 2.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{fe}	50	200	–
Current Gain – High Frequency (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz) (I_C = 2.0 mAdc, V_{CE} = 10 V, f = 1.0 kHz)	h_{fe}	2.5 50	– 200	–
Noise Figure (I_C = 100 µAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k ohm, f = 1.0 kHz)	NF	–	6.0	dB

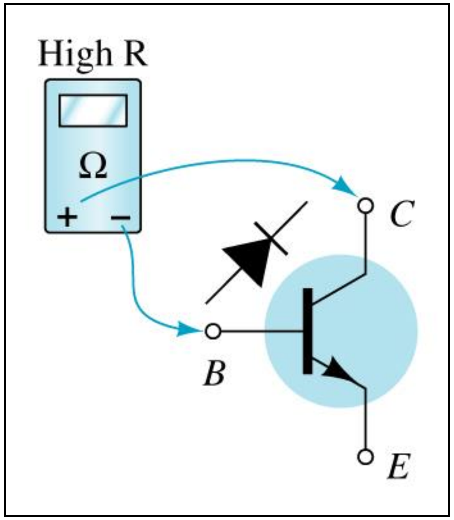
(1) Pulse Test: Pulse Width = 300 µs. Duty Cycle = 2.0%

Transistor Testing

Curve Tracer	Provides a graph of the characteristic curves.
DMM	Some DMMs measure β_{DC} or h_{FE}.

Ohmmeter:





Transistor Terminal Identification