Bipolar Junction Transistors (BJTs)

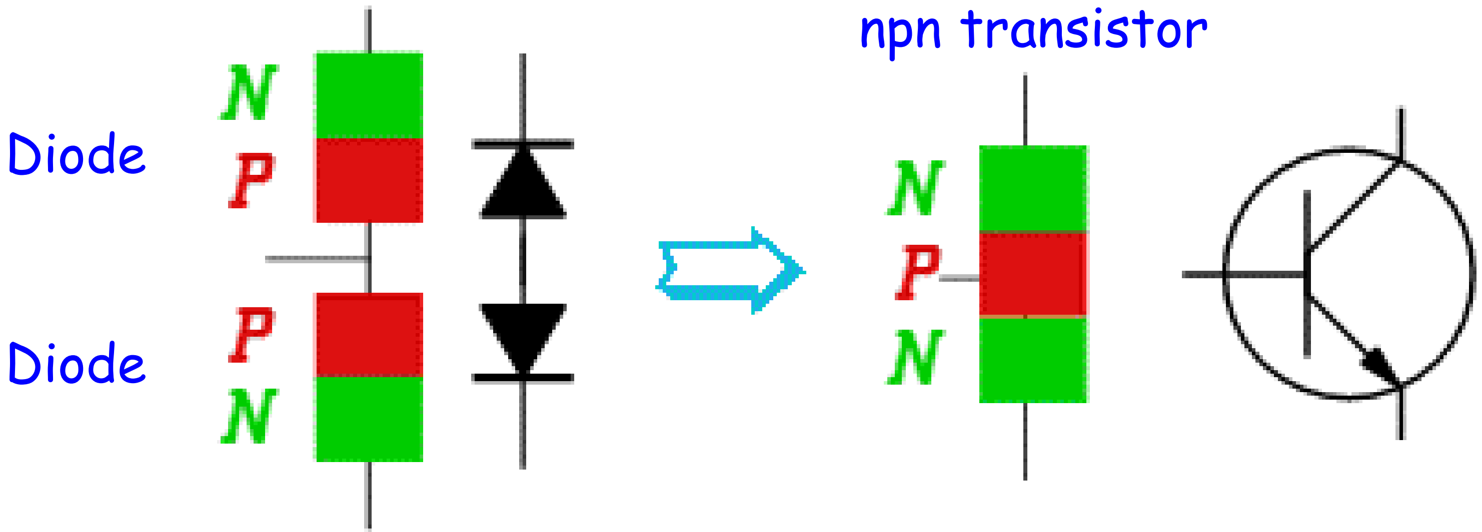
Introduction

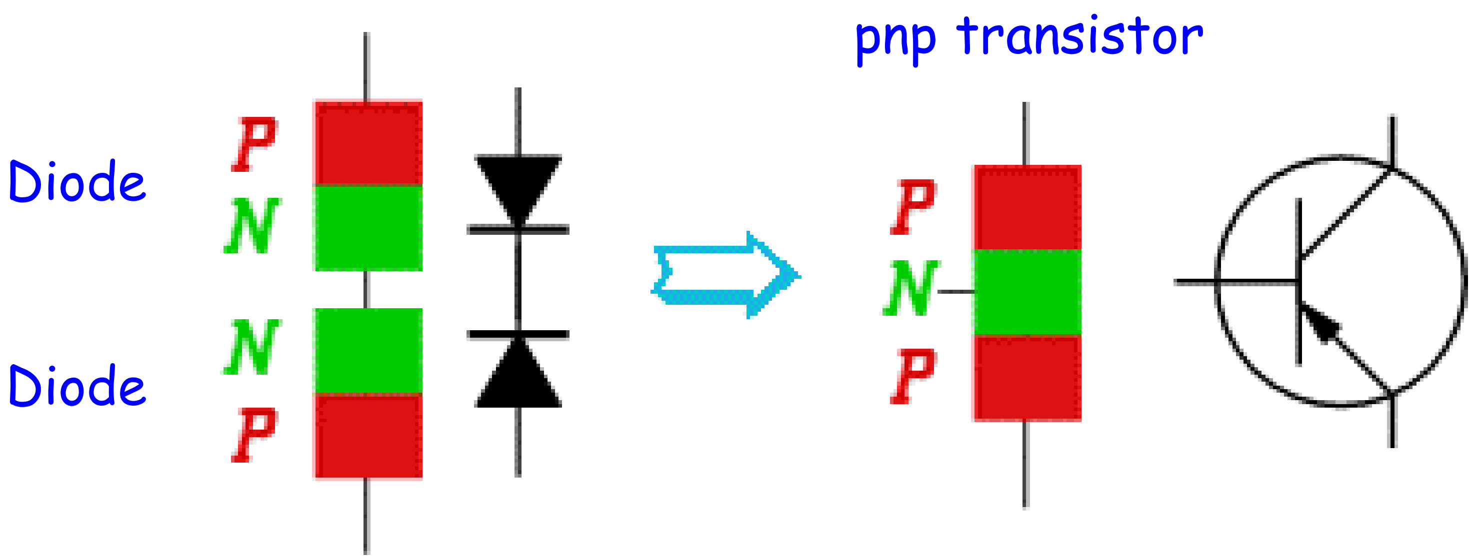
- The basic of electronic system nowadays is semiconductor device.
- The famous and commonly use of this device is BJTs
  (Bipolar Junction Transistors).
- It can be use as amplifier and logic switches.
- BJT consists of three terminal:
  → collector : C
  → base : B
  →emitter : E
- Two types of BJT : pnp and npn

Transistor Construction

- 3 layer semiconductor device consisting:
  - 2 n- and 1 p-type layers of material → npn transistor
  - 2 p- and 1 n-type layers of material →pnp transistor
- The term bipolar reflects the fact that holes and electrons participate in the injection process into the oppositely polarized material
- A single pn junction has two different types of bias:
  - forward bias
  - reverse bias
- Thus, a two-pn-junction device has four types of bias.

Basic models of BJT





Qualitative basic operation of BJTs

A BJT consists of two back-to-back p-n junctions.

The middle region, the base, is very thin.

The three regions are the emitter, base, and collector.

Carriers are injected (“emitted”) into the base from the emitter.

Since the base is thin, most carriers injected into base diffuse into collector.

What does a “thin base thickness” mean? → Base thickness is much thinner than the diffusion length of carriers injected from the emitter.

Position of the terminals and symbol of BJT.

- Base is located at the middle and more thin from the level of collector and emitter
- The emitter and collector terminals are made of the same type of semiconductor material, while the base of the other type of material

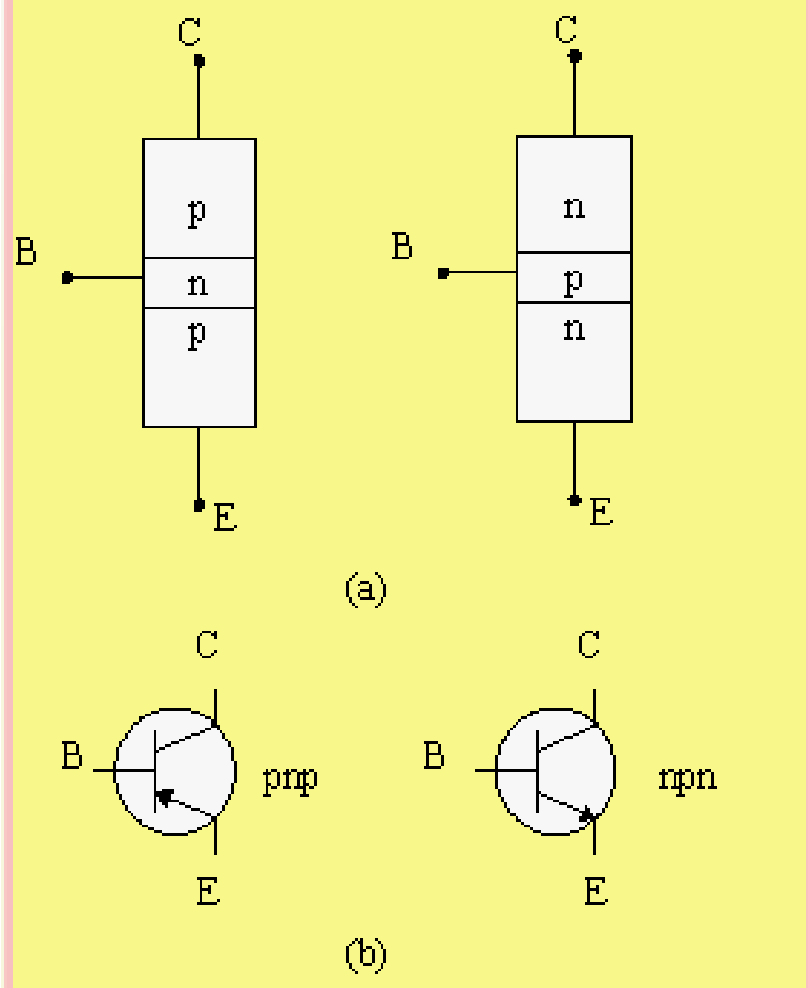
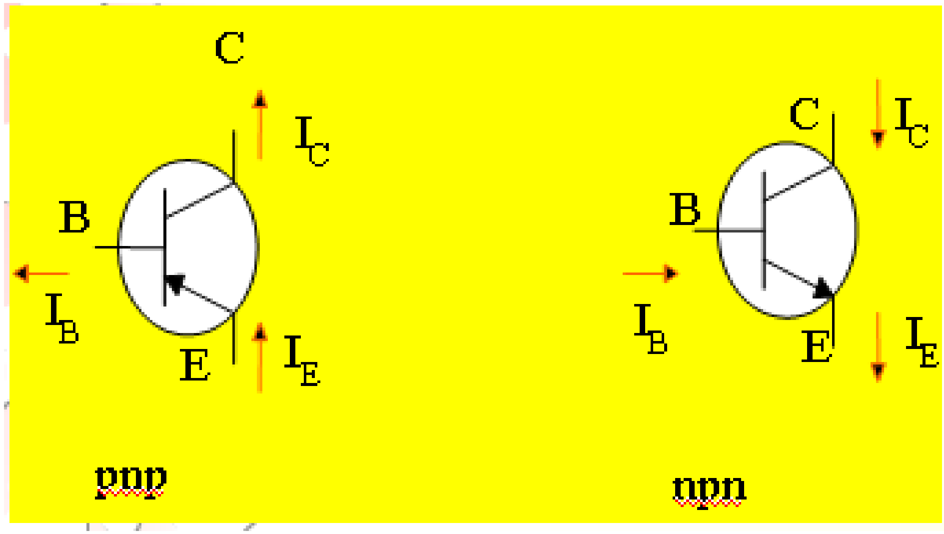


Fig. 4.1: (a) Position of terminals (b) Type of BJT

Transistor currents



I_C=the collector current
I_B= the base current
I_E= the emitter current

-The arrow is always drawn on the emitter

-The arrow always point toward the n-type

-The arrow indicates the direction of the emitter current:

pnp:E→ B
npn: B→ E

- By imaging the analogy of diode, transistor can be construct like two diodes that connetecd together.
- It can be conclude that the work of transistor is base on work of diode.

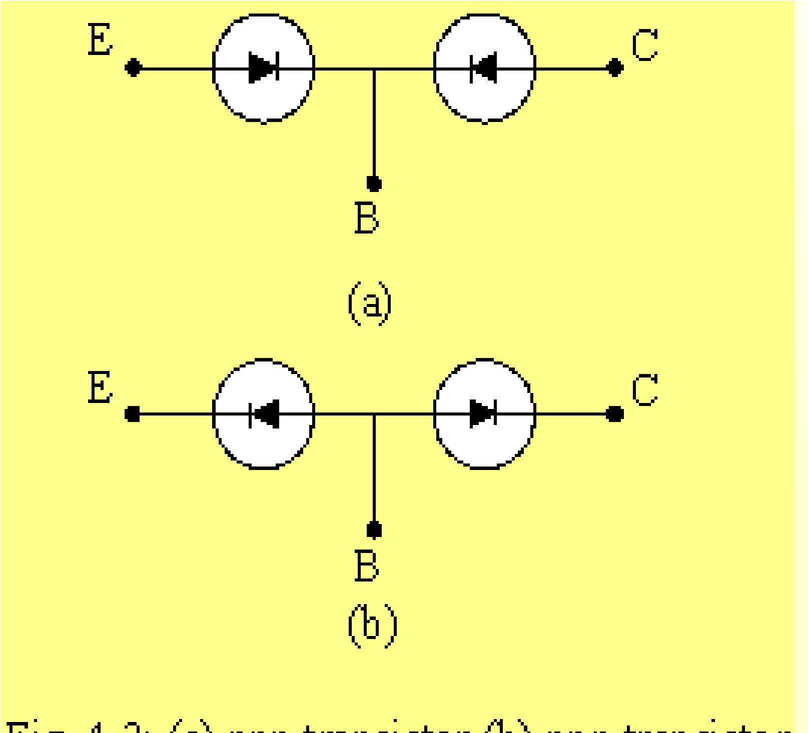
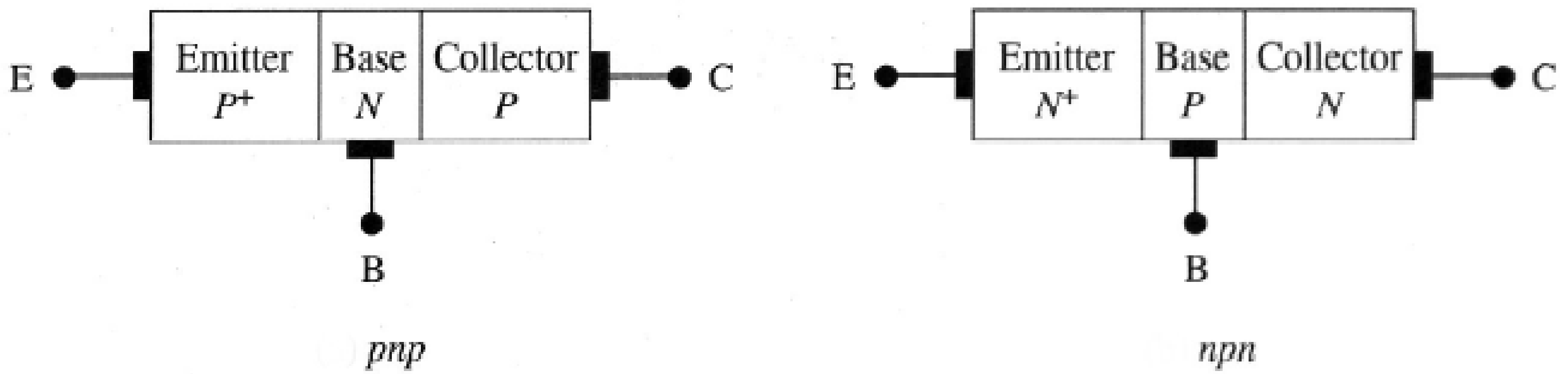


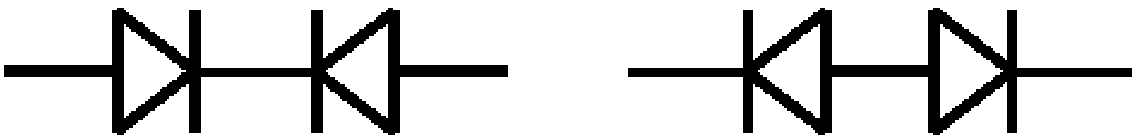
Fig. 4.2: (a) pnp transistor (b) npn transistor

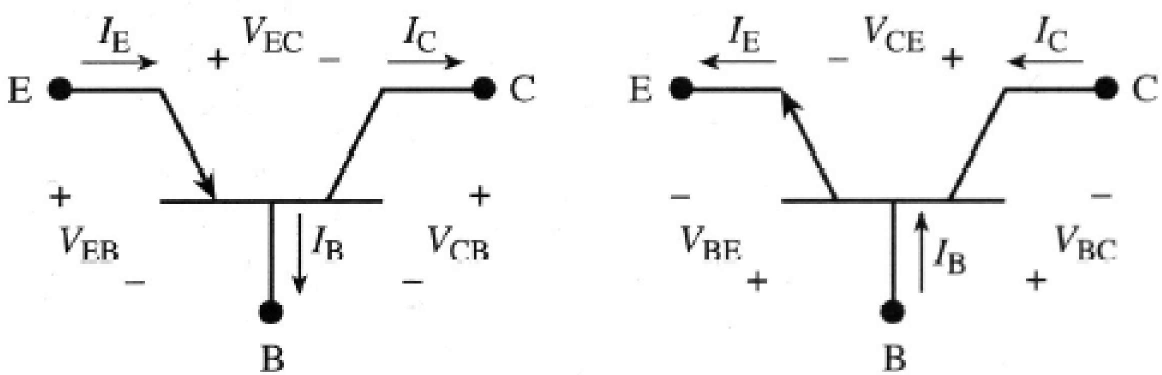
Basic models of BJT

Bipolar Junction Transistor Fundamentals

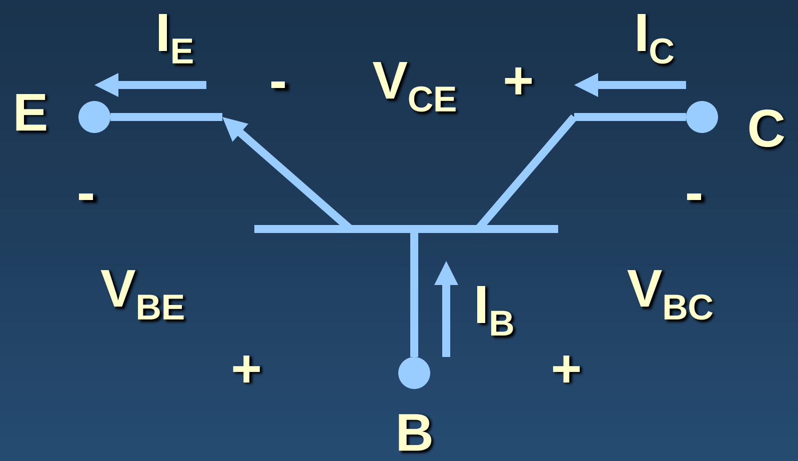


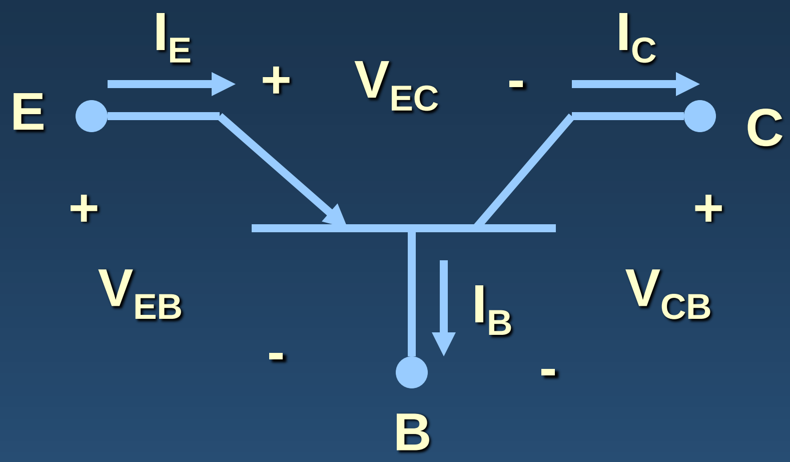
Looks sort of like two diodes back to back





BJT Relationships - Equations





npn

$$I_E = I_B + I_C$$

$$V_{CE} = -V_{BC} + V_{BE}$$

pnp

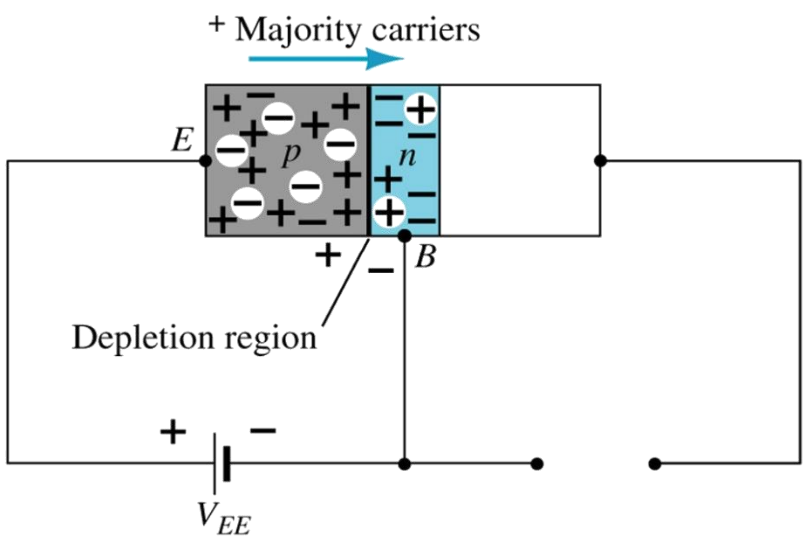
$$I_E = I_B + I_C$$

$$V_{EC} = V_{EB} - V_{CB}$$

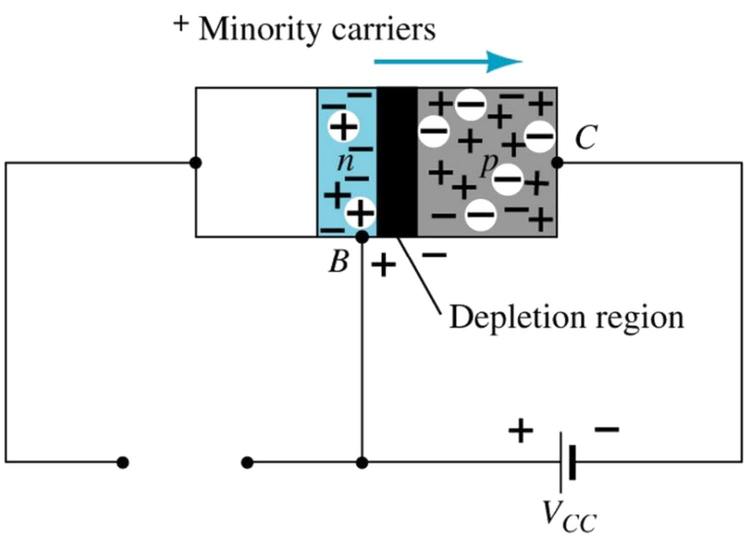
Note: The equations seen above are for the transistor, not the circuit.

Transistor Operation

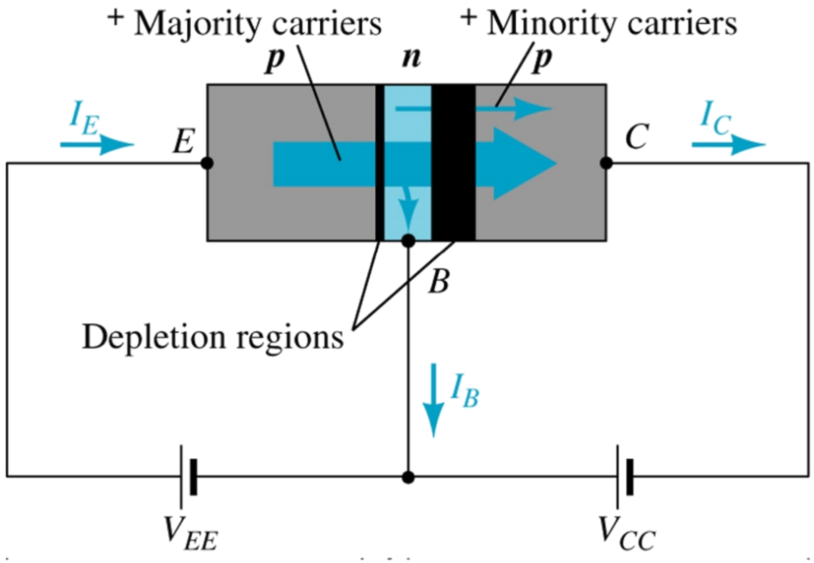
- The basic operation will be described using the pnp transistor. The operation of the pnp transistor is exactly the same if the roles played by the electron and hole are interchanged.
- One p-n junction of a transistor is reverse-biased, whereas the other is forward-biased.



Forward-biased junction of a pnp transistor



Reverse-biased junction of a pnp transistor



- Both biasing potentials have been applied to a pnp transistor and resulting majority and minority carrier flows indicated.
- Majority carriers (+) will diffuse across the forward-biased p-n junction into the n-type material.
- A very small number of carriers (+) will through n-type material to the base terminal. Resulting IB is typically in order of microamperes.
- The large number of majority carriers will diffuse across the reverse-biased junction into the p-type material connected to the collector terminal.

- Majority carriers can cross the reverse-biased junction because the injected majority carriers will appear as minority carriers in the n-type material.
- Applying KCL to the transistor :

$$I_E = I_C + I_B$$

- The comprises of two components – the majority and minority carriers

$$I_C = I_{Cmajority} + I_{COminority}$$

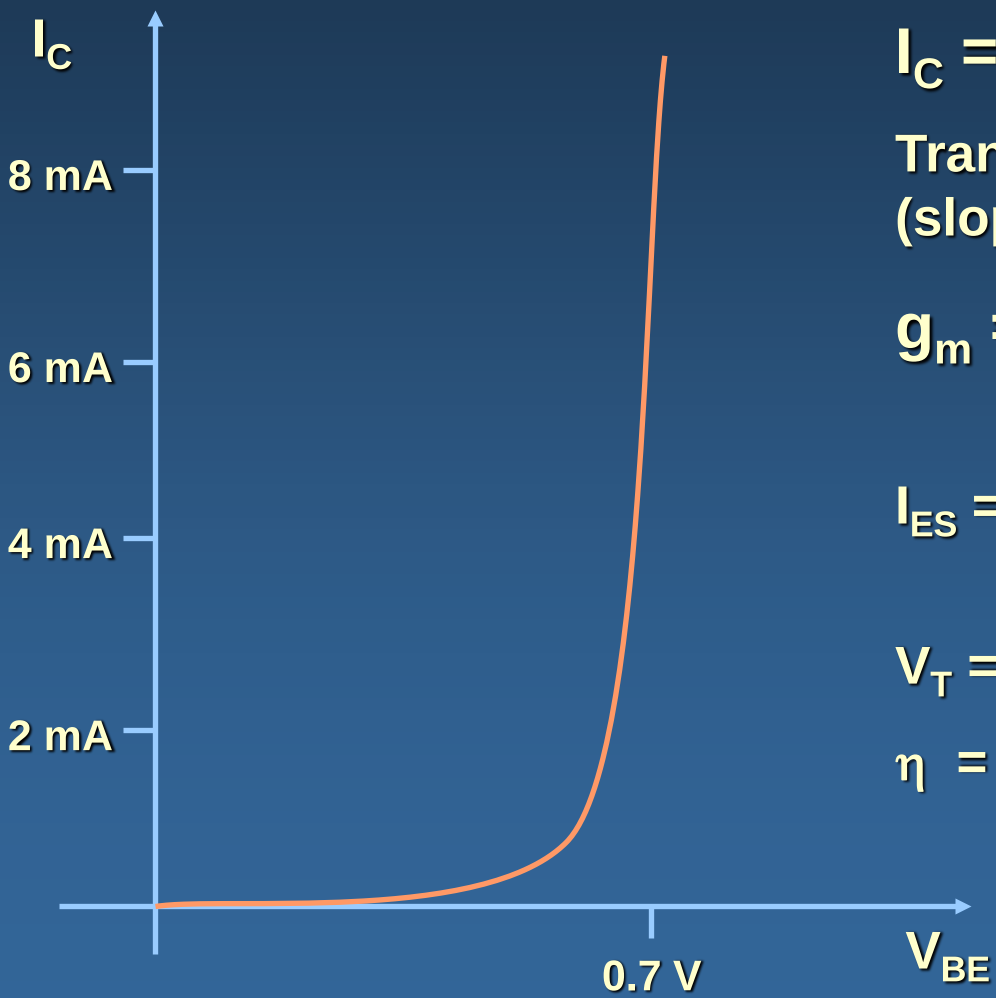
- I_{CO} – I_C current with emitter terminal open and is called leakage current.

Transistor Characteristics

- The complete behavior of a transistor may be observed with the help of some types of curves known as characteristics curves
- Two types of characteristics curves
  - **Input characteristics curves**
    - Relates input current and input voltage for a given value of output voltage
  - **Output characteristics curves**
    - Relates output current and output voltage for a given value of input voltage

BJT Transconductance Curve

Typical NPN Transistor [1]



Collector Current:

$$I_C = \alpha\, I_{ES}\, e^{V_{BE}/\eta V_T}$$

Transconductance:
(slope of the curve)

$$g_m = \Delta I_C \,/\, \Delta V_{BE}$$

I_{ES} = The reverse saturation current of the B-E Junction.

V_T = kT/q = 26 mV (@ T=300K)

η = the emission coefficient and is usually ~1

Modes of Operation

Active:

- Most important mode of operation
- Central to amplifier operation
- The region where current curves are practically flat

Saturation:

- Barrier potential of the junctions cancel each other out causing a virtual short

Cutoff:

- Current reduced to zero
- Ideal transistor behaves like an open switch

* Note: There is also a mode of operation called inverse active, but it is rarely used.

Three Types of BJT Biasing

Biasing the transistor refers to applying voltage to get the transistor to achieve certain operating conditions.

Common-Base Biasing (CB) : input $= V_{EB}$ & I_E

output $= V_{CB}$ & I_C

Common-Emitter Biasing (CE): input $= V_{BE}$ & I_B

output $= V_{CE}$ & I_C

Common-Collector Biasing (CC): input $= V_{BC}$ & I_B

output $= V_{EC}$ & I_E

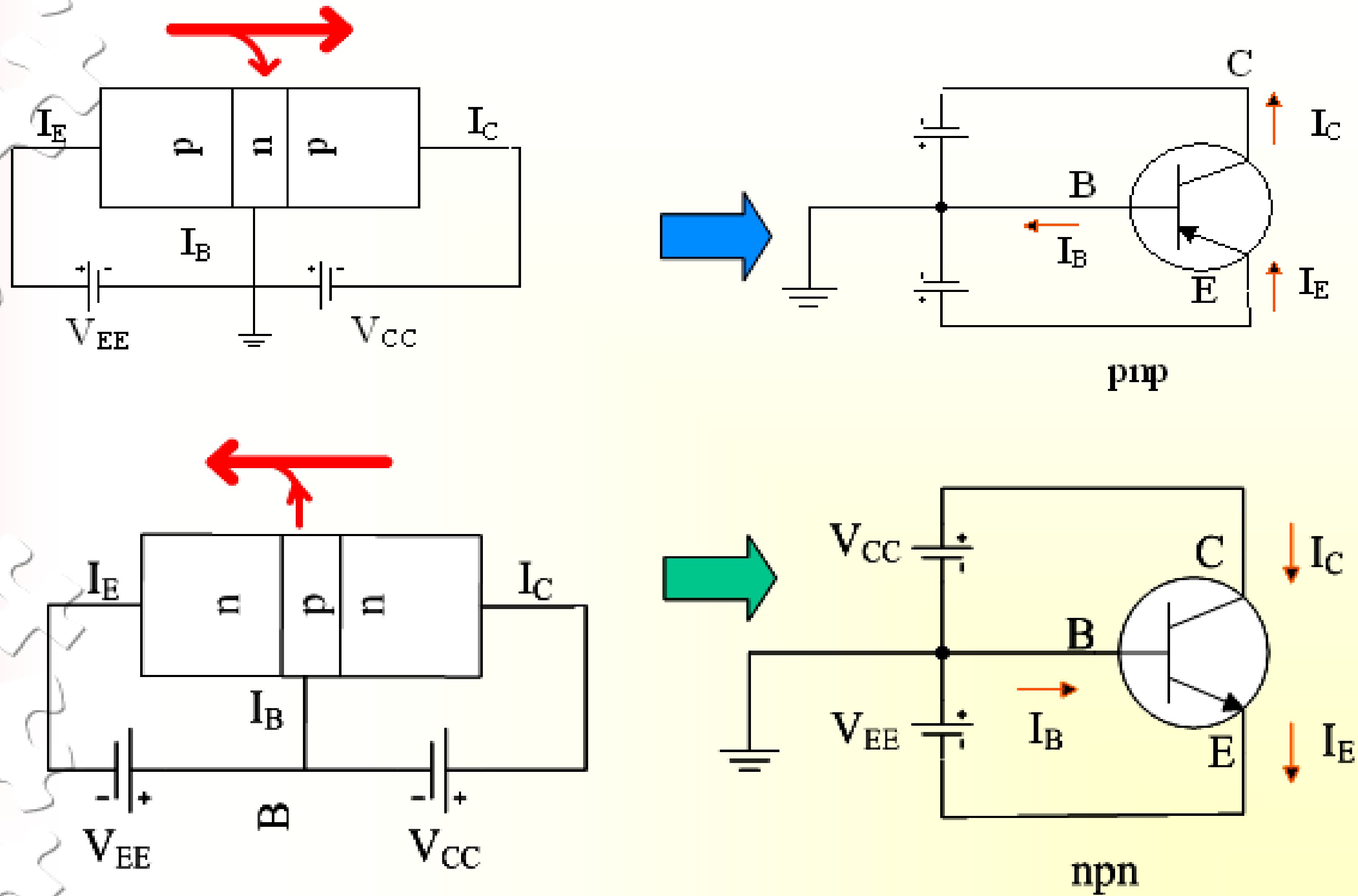
Common-Base Configuration

- Common-base terminology is derived from the fact that the :

  - base is common to both input and output of the configuration.

  - base is usually the terminal closest to or at ground potential.

- All current directions will refer to conventional (hole) flow and the arrows in all electronic symbols have a direction defined by this convention.
- Note that the applied biasing (voltage sources) are such as to establish current in the direction indicated for each branch.



I_E
p
n
p
I_C
I_B
V_{EE}
V_{CC}
C
I_C
B
I_B
E
I_E
pnp
I_E
n
p
n
I_C
I_B
V_{EE}
B
V_{CC}
V_{CC}
C
I_C
B
I_B
V_{EE}
E
I_E
npn

Transistor Characteristics in CB Configuration

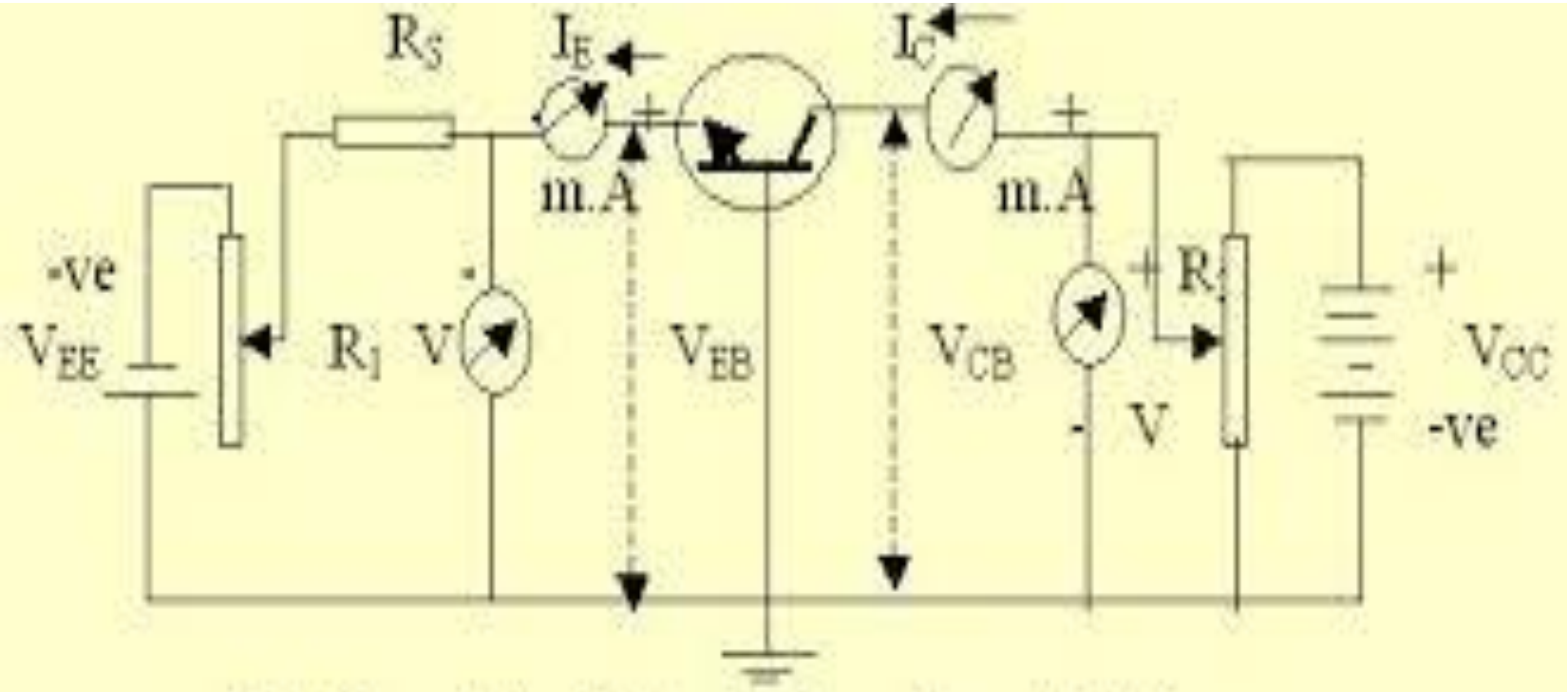
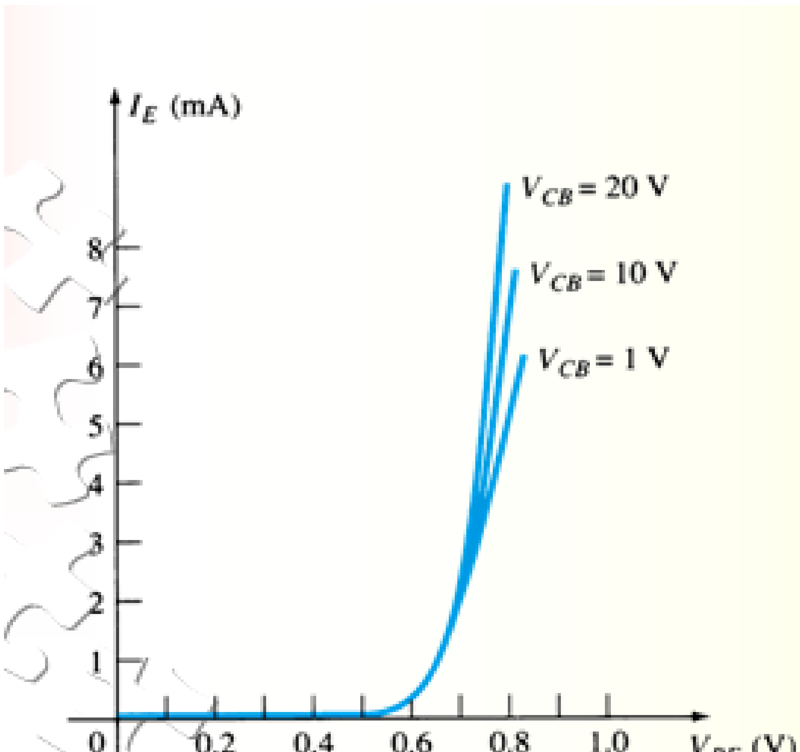
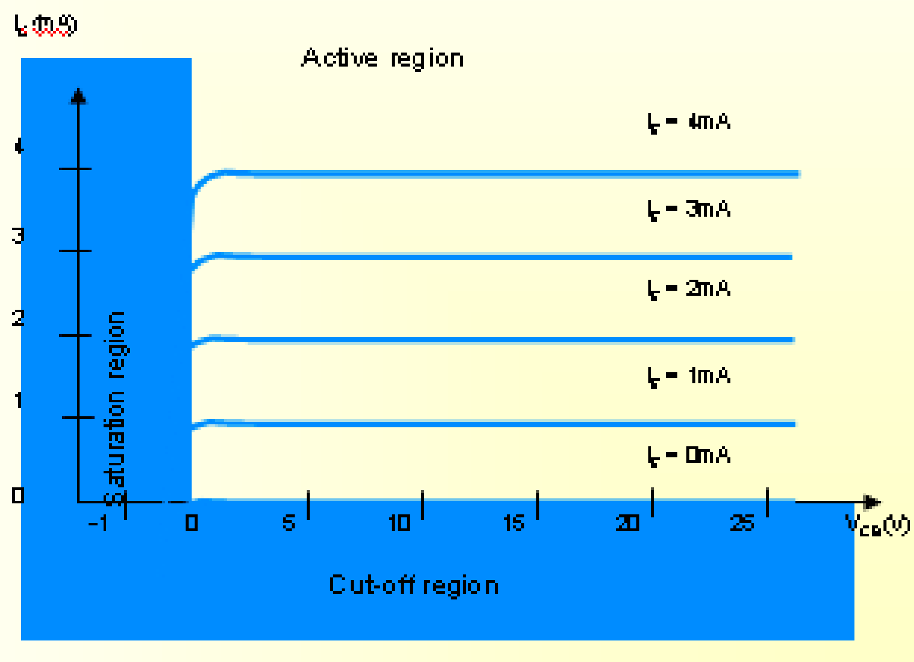


Fig: Circuit for deterring the characteristics of common base n-p-n transistor.

- To describe the behavior of common-base configuration requires two set of characteristics:
  - Input or driving point characteristics.
  - Output or collector characteristics
- The output characteristics has 3 basic regions:
  - Active region –defined by the biasing arrangements
  - Cutoff region – region where the collector current is 0A
  - Saturation region- region of the characteristics to the left of V_{CB} = 0V



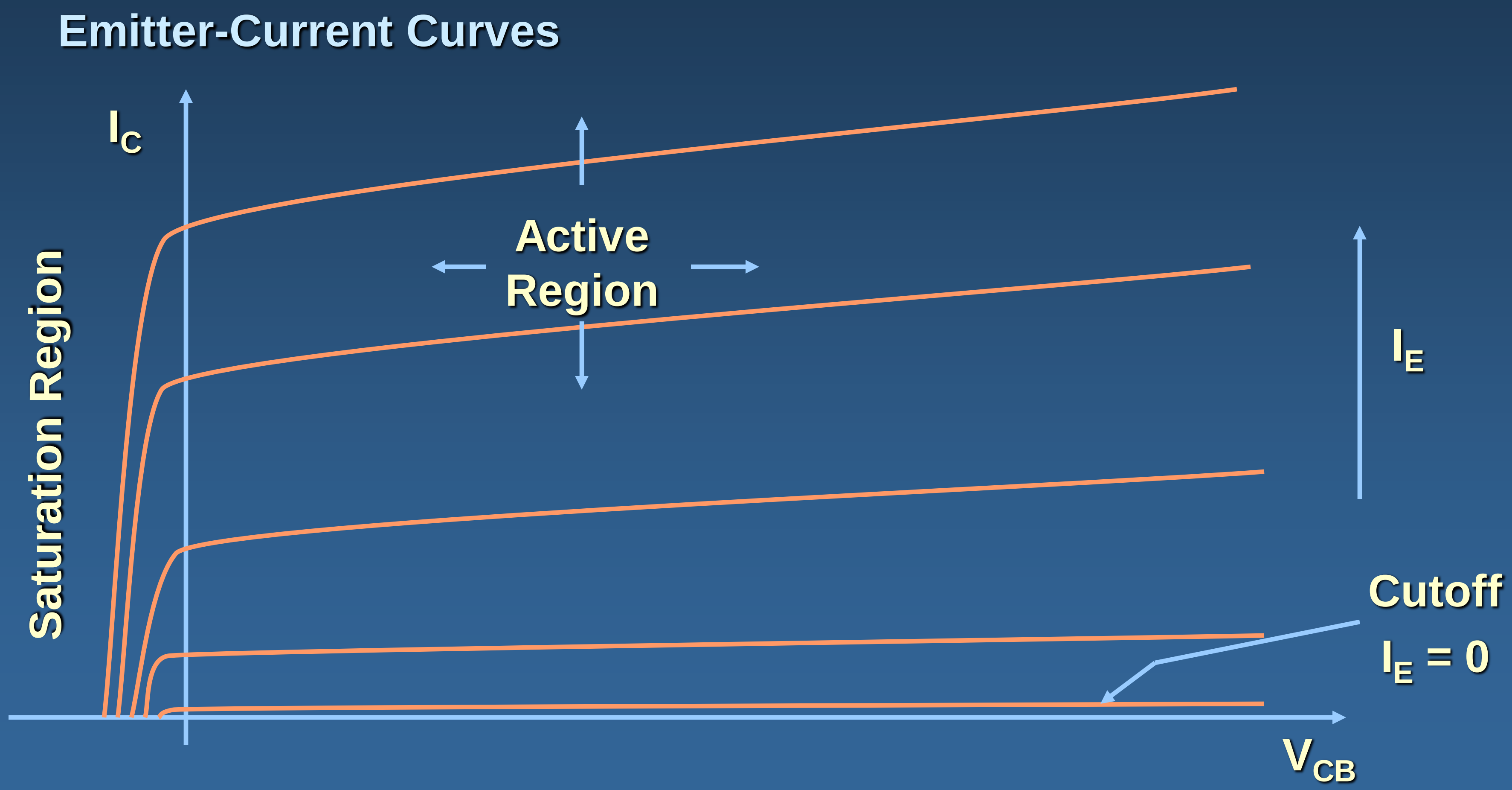
Input characteristics for a common silicon transistor



Output of collector characteristics for common-base transistor amplifier

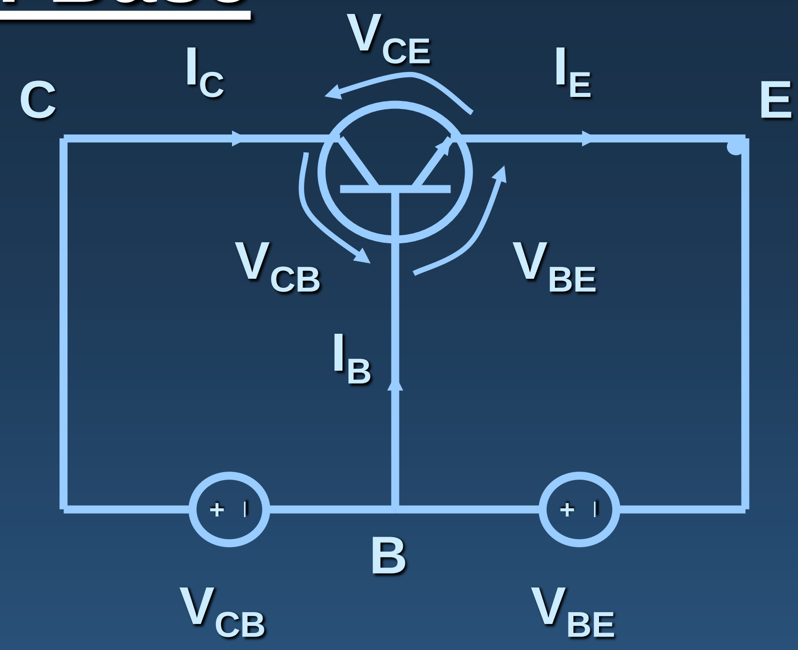
Common-Base

Although the Common-Base configuration is not the most common biasing type, it is often helpful in the understanding of how the BJT works.



Common-Base

Circuit Diagram: NPN Transistor



The Table Below lists assumptions that can be made for the attributes of the common-base biased circuit in the different regions of operation. Given for a Silicon NPN transistor.

Region of Operation	I_C	V_{CE}	V_{BE}	V_{CB}	C-B Bias	E-B Bias
Active	βI_B	$=V_{BE}+V_{CE}$	~0.7V	❍ 0V	Rev.	Fwd.
Saturation	Max	~0V	~0.7V	$-0.7V<V_{CE}<0$	Fwd.	Fwd.
Cutoff	~0	$=V_{BE}+V_{CE}$	☯ 0V	❍ 0V	Rev.	None /Rev.

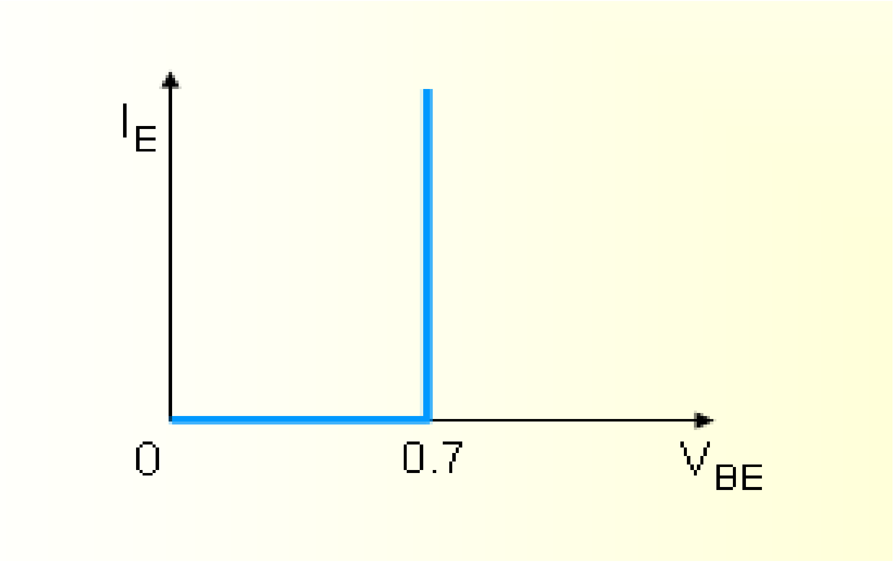
Active region	Saturation region	Cut-off region
• I_E increased, I_C increased • BE junction forward bias and CB junction reverse bias • Refer to the graf, $I_C \approx I_E$ • I_C not depends on V_{CB} • Suitable region for the transistor working as amplifier	• BE and CB junction is forward bias • Small changes in V_{CB} will cause big different to I_C • The allocation for this region is to the left of V_{CB} = 0 V.	• Region below the line of I_E=0 A • BE and CB is reverse bias • no current flow at collector, only leakage current

- The curves (output characteristics) clearly indicate that a first approximation to the relationship between I_E and I_C in the active region is given by

$$I_C \approx I_E$$

- Once a transistor is in the 'on' state, the base-emitter voltage will be assumed to be

$$V_{BE} = 0.7V$$



- In the dc mode the level of I_C and I_E due to the majority carriers are related by a quantity called alpha

$$\alpha = \frac{I_C}{I_E}$$

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

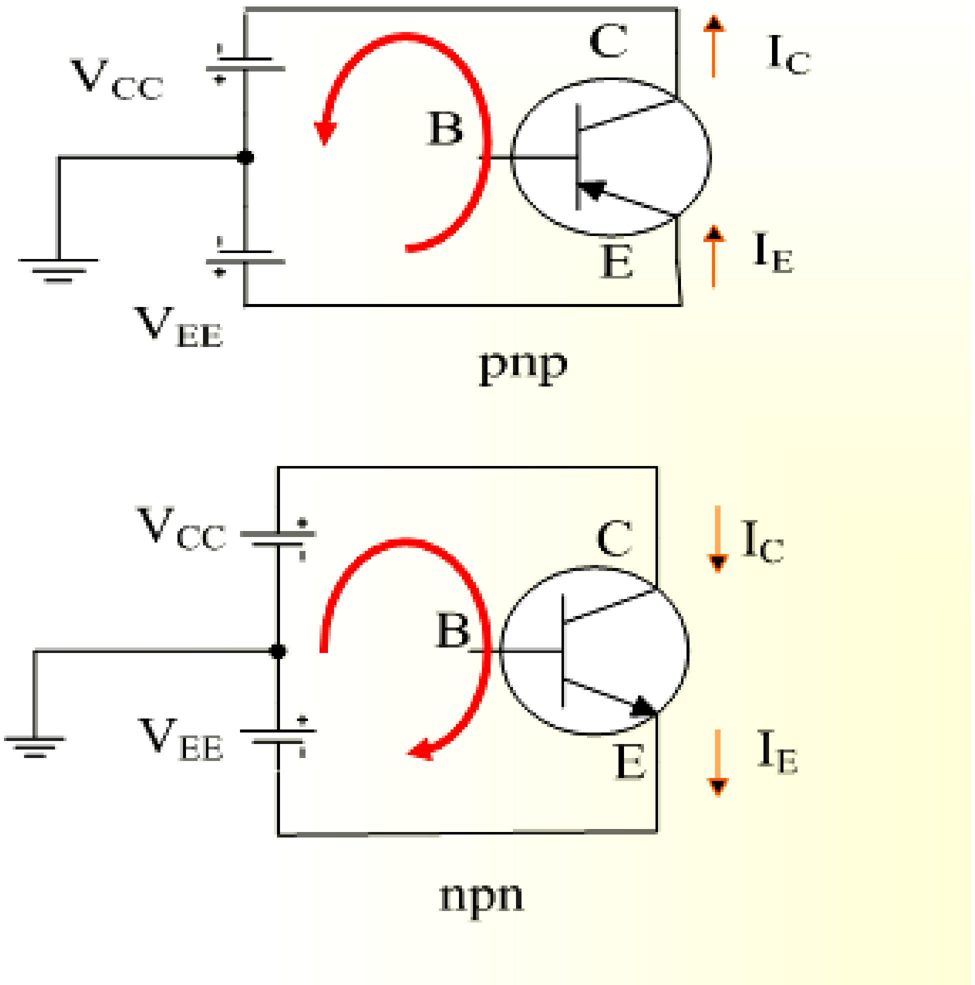
- It can then be summarize to $I_C = \alpha I_E$ (ignore I_{CBO} due to small value)
- For ac situations where the point of operation moves on the characteristics curve, an ac alpha is defined by

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

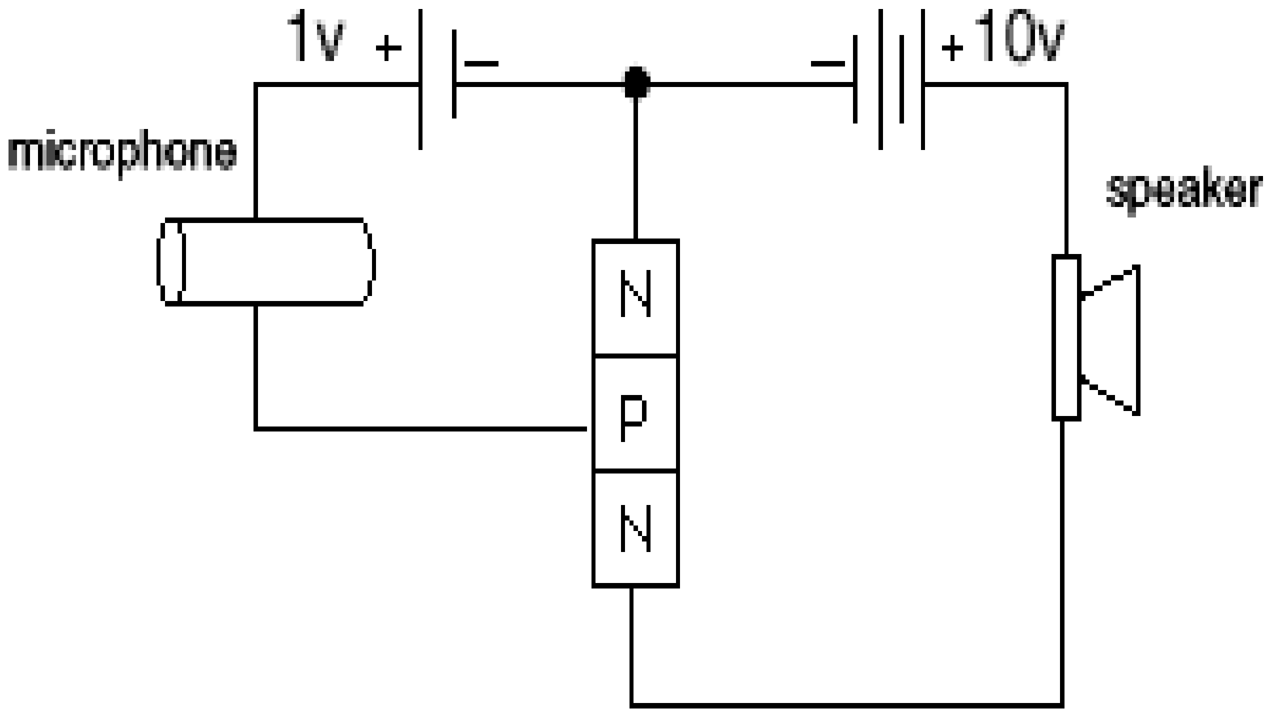
- Alpha is a common base current gain factor that shows the efficiency by calculating the current percent from current flow from emitter to collector. The value of α is typical from 0.9 ~ 0.998.

Biasing

- Proper biasing CB configuration in active region by approximation $I_C \approx I_E$ ($I_B \approx 0$ uA)



Simulation of transistor as an amplifier



Common-Emitter Configuration

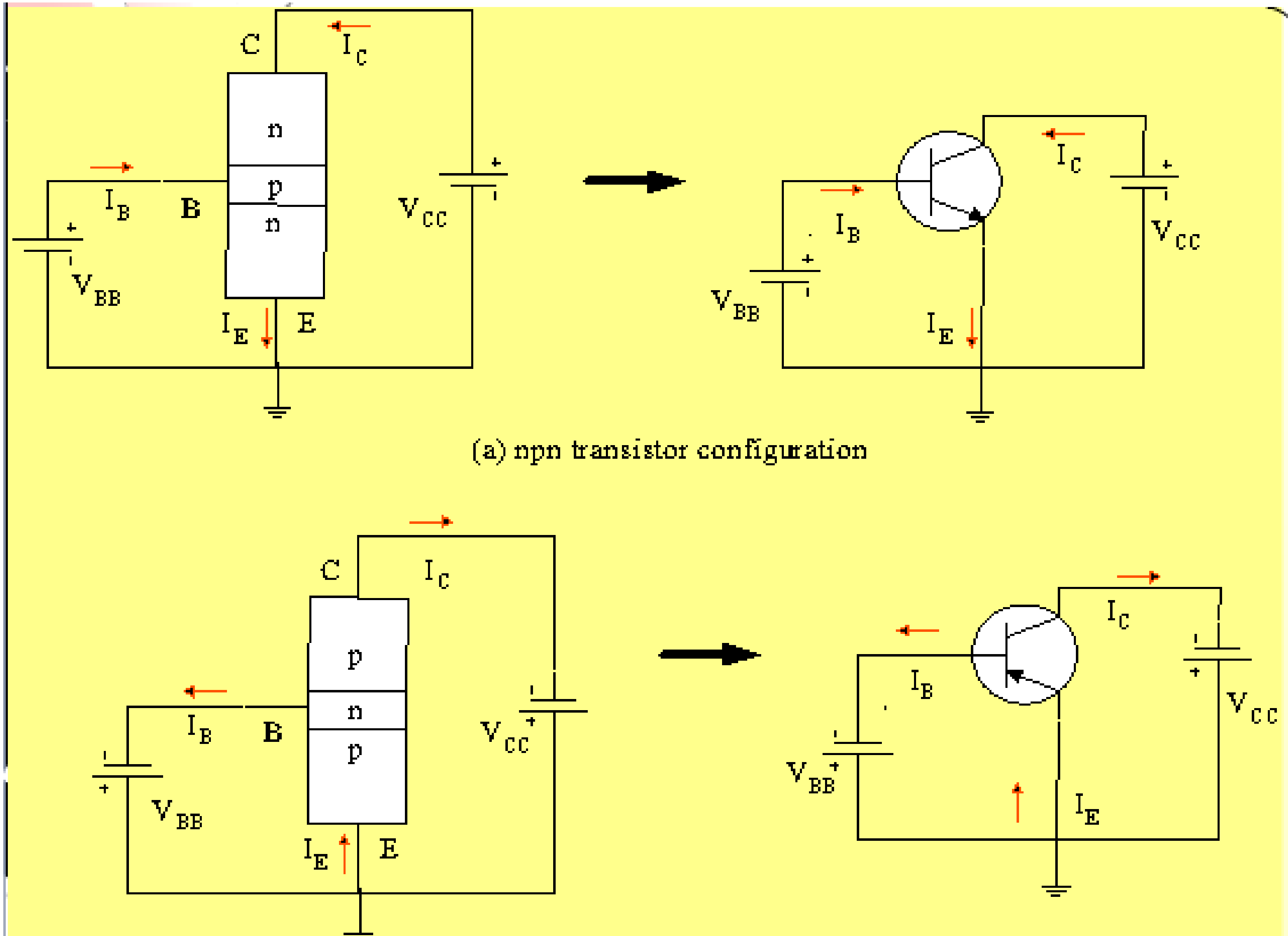
- It is called common-emitter configuration since :

  - emitter is common or reference to both input and output terminals.

  - emitter is usually the terminal closest to or at ground

  potential.
- Almost amplifier design is using connection of CE due to the high gain for current and voltage.
- Two set of characteristics are necessary to describe the behavior for CE ;input (base terminal) and output (collector terminal) parameters.

Proper Biasing common-emitter configuration in active region

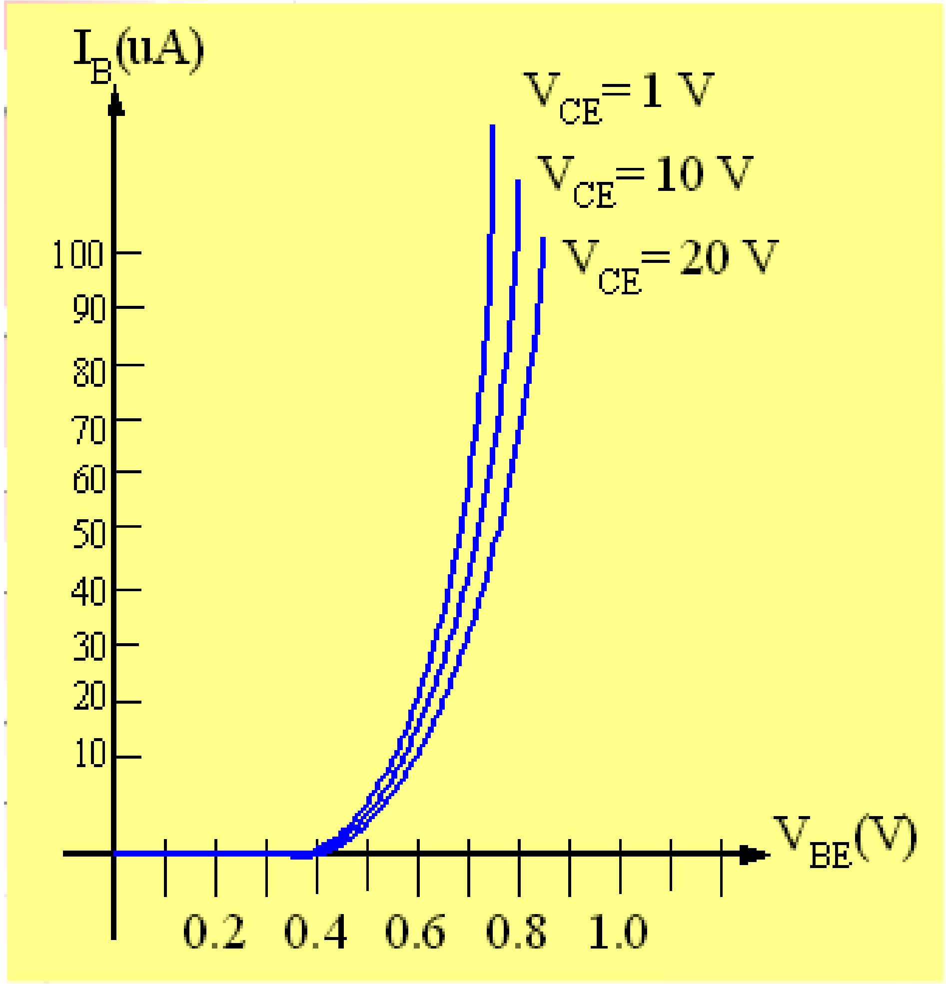


(a) npn transistor configuration

(b) pnp transistor configuration

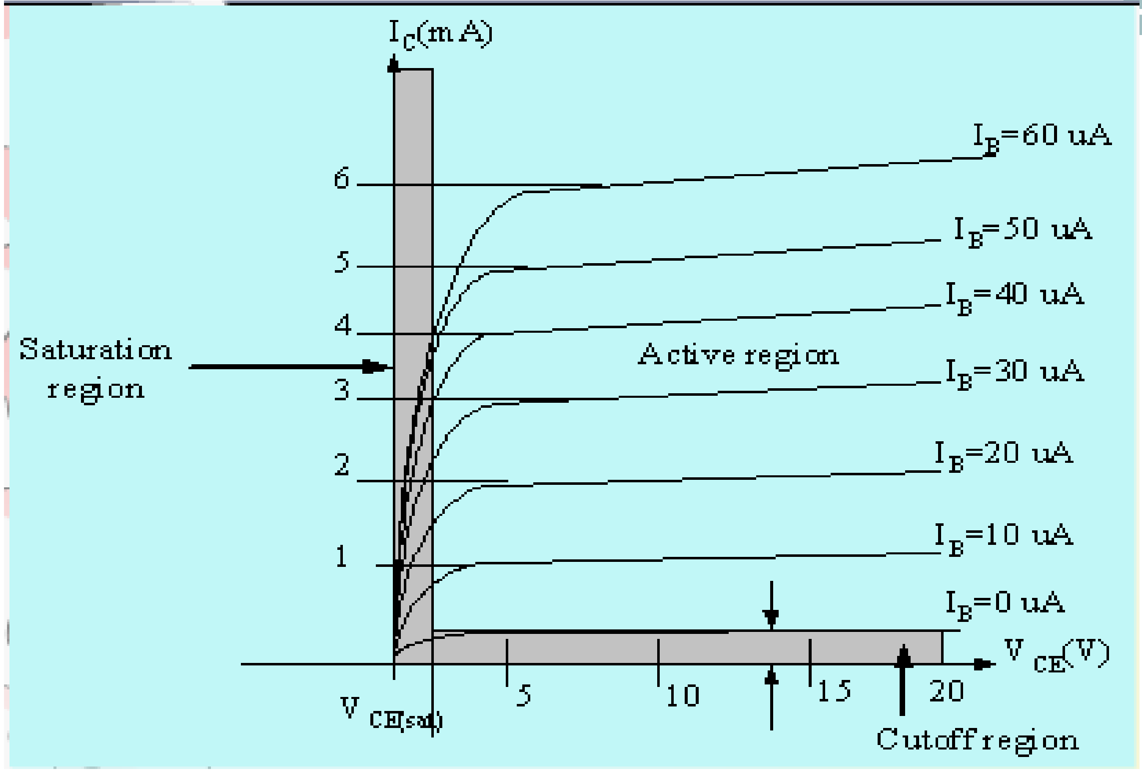
Fig 4.7 : Common-emitter configuration

$$I_E = I_C + I_B$$



Input characteristics for a common-emitter NPN transistor

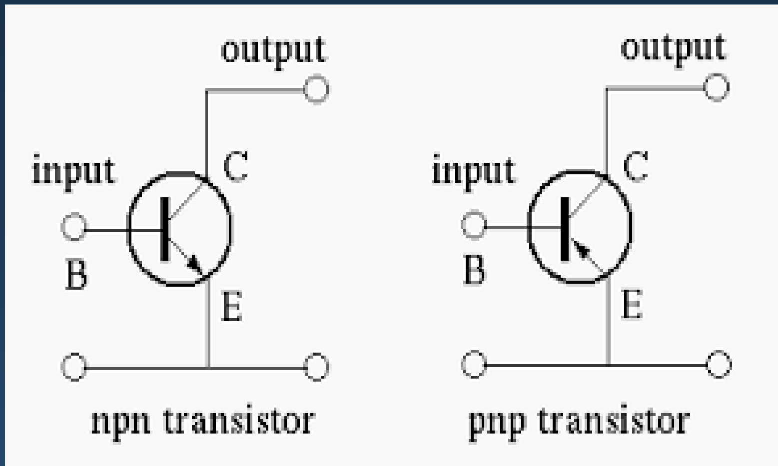
- I_B is microamperes compared to miliamperes of I_C.
- I_B will flow when V_{BE} > 0.7V for silicon and 0.3V for germanium
- Before this value I_B is very small and no I_B.
- Base-emitter junction is forward bias
- Increasing V_{CE} will reduce I_B for different values.



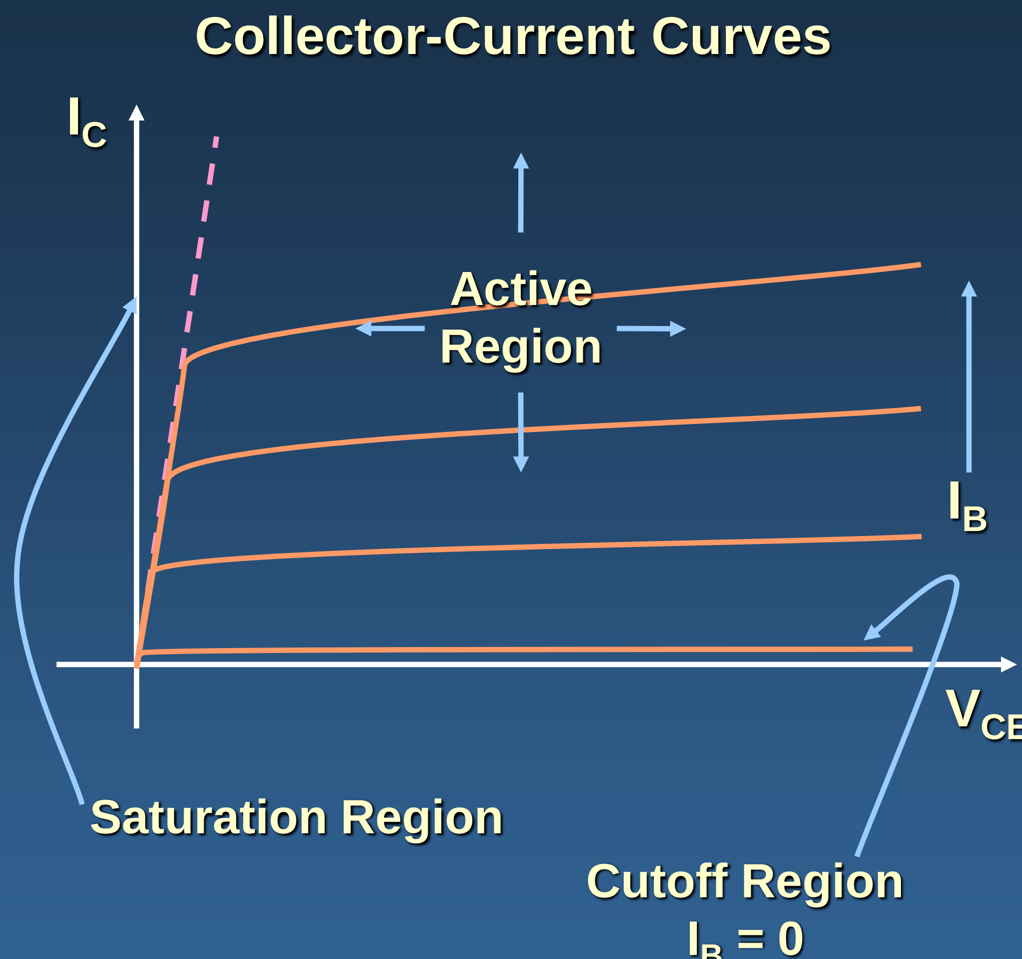
Output characteristics for a common-emitter npn transistor

- For small V_{CE} ($V_{CE} < V_{CESAT}$, I_C increase linearly with increasing of V_{CE}
- $V_{CE} > V_{CESAT}$ I_C not totally depends on V_{CE} → constant I_C
- I_B(uA) is very small compare to I_C (mA). Small increase in I_B cause big increase in I_C
- I_B=0 A → I_{CEO} occur.
- Noticing the value when I_C=0A. There is still some value of current flows.

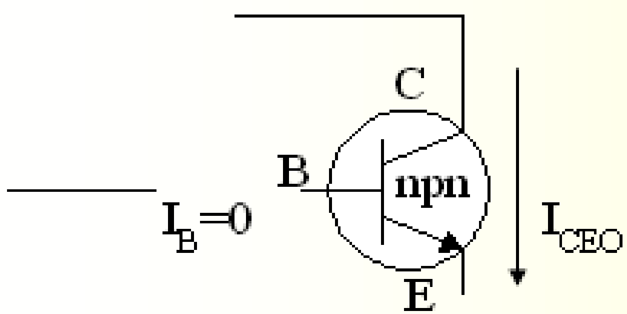
Common-Emitter

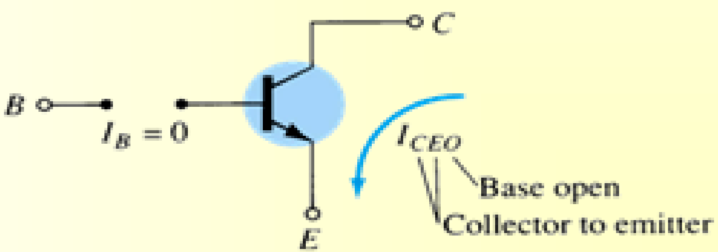


Region of Operation	Description
Active	Small base current controls a large collector current
Saturation	$V_{CE(sat)}$ ~ 0.2V, V_{CE} increases with I_C
Cutoff	Achieved by reducing I_B to 0, Ideally, I_C will also equal 0.



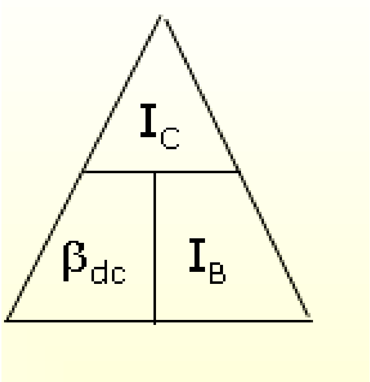
Active region	Saturation region	Cut-off region
• B-E junction is forward bias • C-B junction is reverse bias • can be employed for voltage, current and power amplification	• B-E and C-B junction is forward bias, thus the values of I_B and I_C is too big. • The value of V_{CE} is so small. • Suitable region when the transistor as a logic switch. • NOT and avoid this region when the transistor as an amplifier.	• region below $I_B=0\mu A$ is to be avoided if an undistorted o/p signal is required • B-E junction and C-B junction is reverse bias • $I_B=0$, I_C not zero, during this condition $I_C=I_{CEO}$ where is this current flow when B-E is reverse bias.





Beta (β) or amplification factor

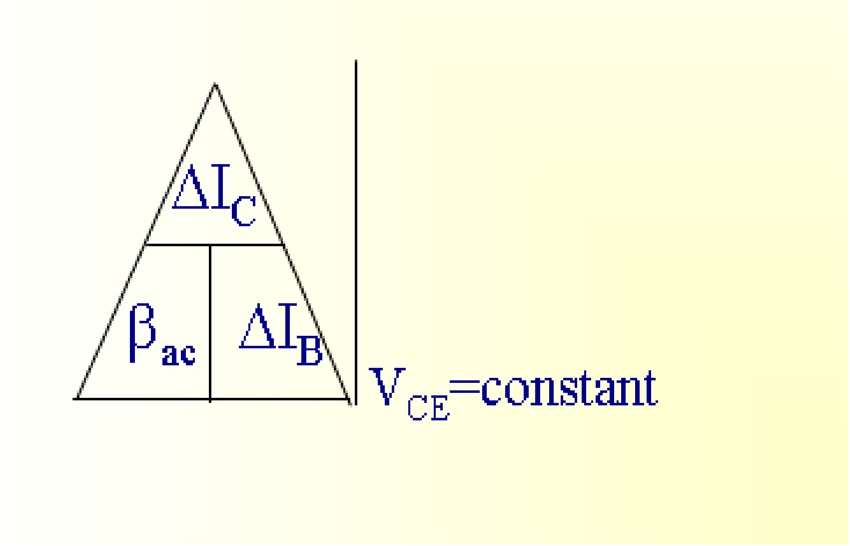
- The ratio of dc collector current (I_C) to the dc base current (I_B) is dc beta (β_{dc}) which is dc current gain where I_C and I_B are determined at a particular operating point, Q-point (quiescent point).
- It's define by the following equation:



$$30 < \beta_{dc} < 300 \rightarrow 2N3904$$

- On data sheet, $\beta_{dc}=h_{FE}$ with h is derived from ac hybrid equivalent cct. FE are derived from forward-current amplification and common-emitter configuration respectively.

- For ac conditions an ac beta has been defined as the changes of collector current (I_C) compared to the changes of base current (I_B) where I_C and I_B are determined at operating point.
- On data sheet, $\beta_{ac}=h_{fe}$
- It can defined by the following equation:



Relationship analysis between α and β

CASE 1

$$I_E = I_C + I_B \qquad (1)$$

subtitute equ. $I_C = \beta I_B$ into (1) we get

$$\underline{\underline{I_E = (\beta + 1) I_B}}$$

CASE 2

$$\text{known} \quad : \alpha = \frac{I_C}{I_E} \Rightarrow I_E = \frac{I_C}{\alpha} \qquad (2)$$

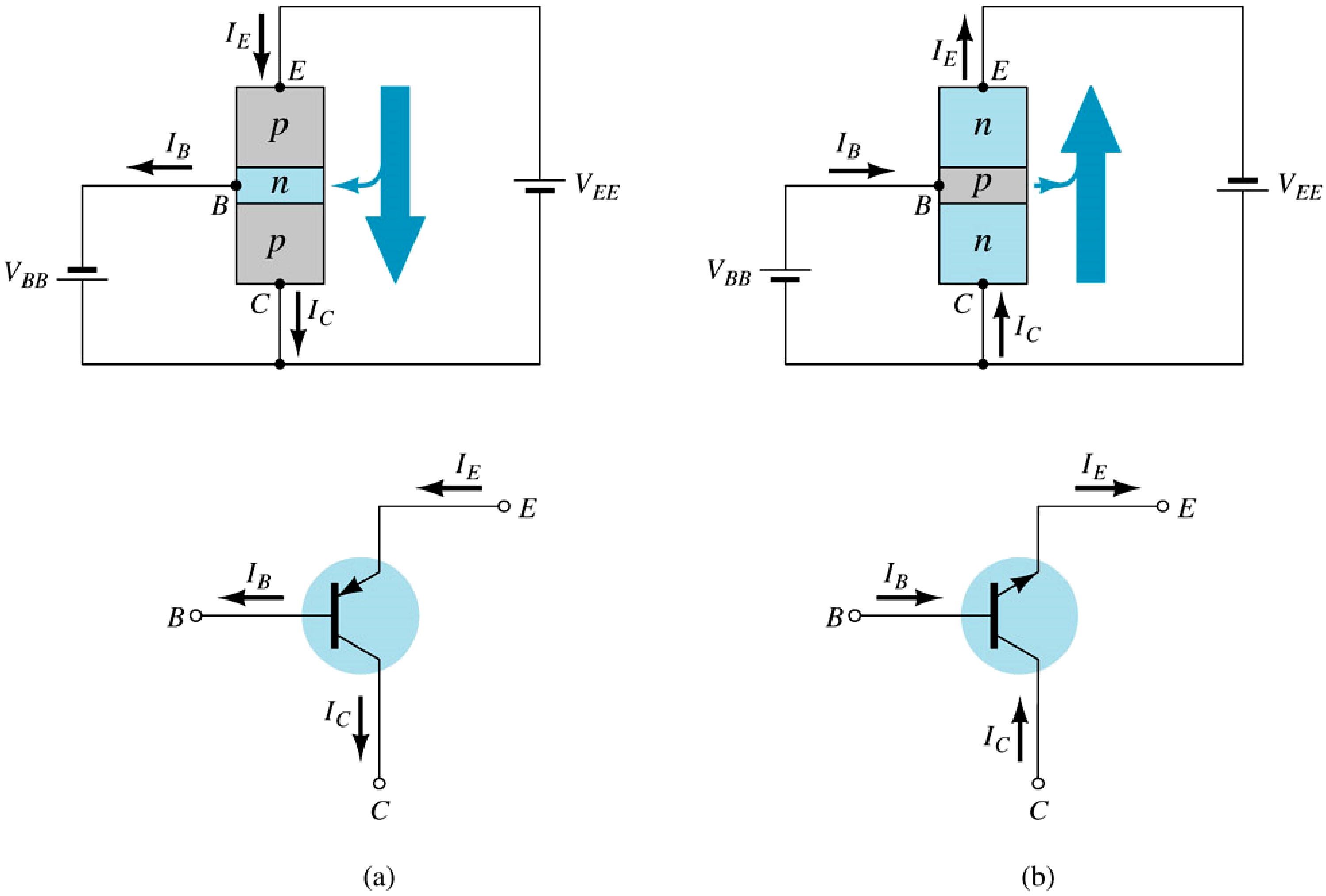
$$\text{known} \quad : \beta = \frac{I_C}{I_B} \Rightarrow I_B = \frac{I_C}{\beta} \qquad (3)$$

subtitute (2) and (3) into (1) we get,

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

Common – Collector Configuration

- Also called emitter-follower (EF).
- It is called common-emitter configuration since both the signal source and the load share the collector terminal as a common connection point.
- The output voltage is obtained at emitter terminal.
- The input characteristic of common-collector configuration is similar with common-emitter. configuration.
- Common-collector circuit configuration is provided with the load resistor connected from emitter to ground.
- It is used primarily for impedance-matching purpose since it has high input impedance and low output impedance.



Notation and symbols used with the common-collector configuration:
(a) pnp transistor ; (b) npn transistor.

- For the common-collector configuration, the output characteristics are a plot of I_E vs V_{CE} for a range of values of I_B.

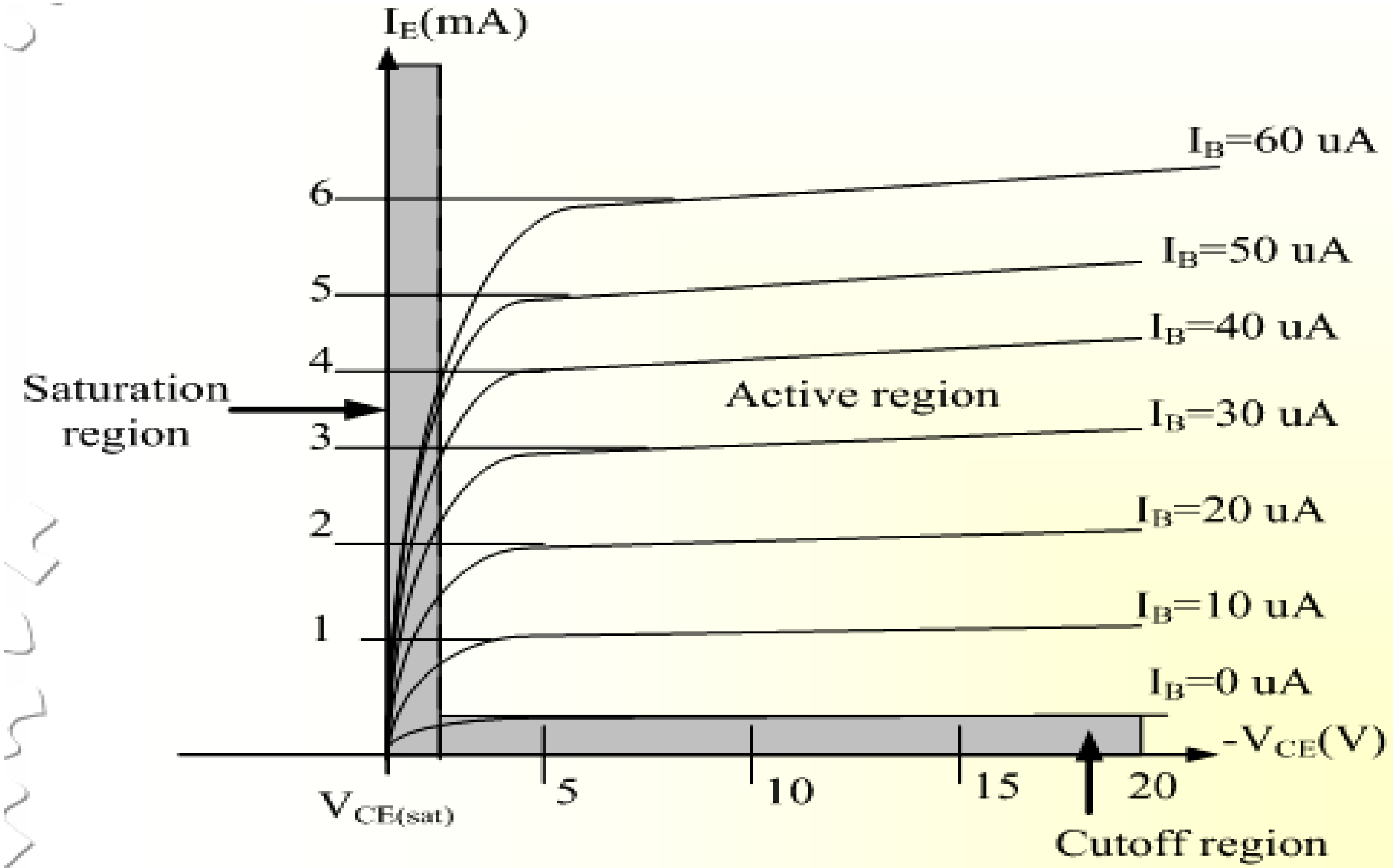


Fig 4.9 : Output characteristic in CC configuration for npn transistor

Limits of Operation

- Many BJT transistor are used as an amplifier. Thus it is important to notice the limits of operations.
- At least 3 maximum values is mentioned in data sheet.
- These are:

  a) Maximum power dissipation at collector: P_{Cmax} or P_D

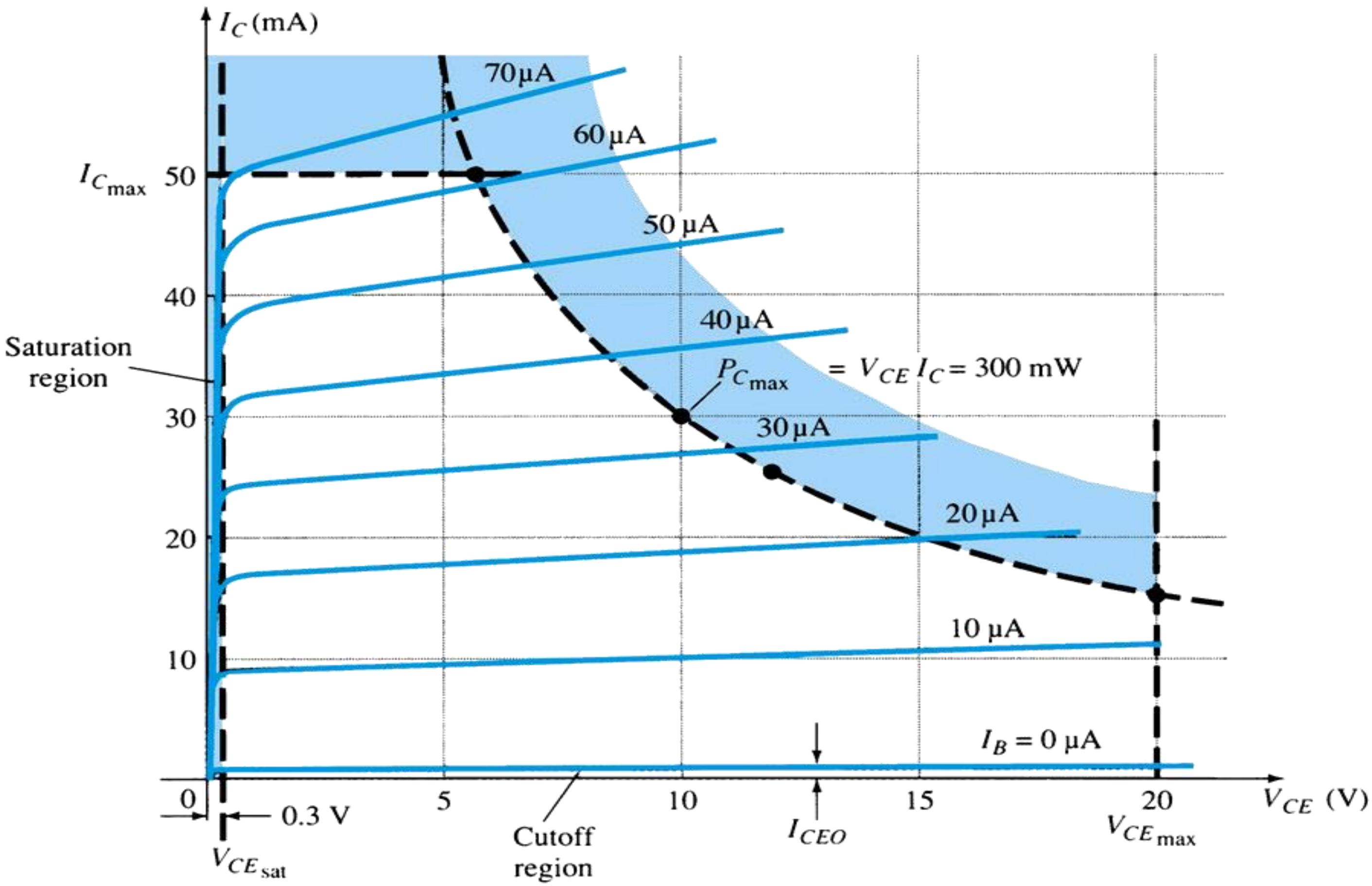
  b) Maximum collector-emitter voltage: V_{CEmax} sometimes named as $V_{BR(CEO)}$) or V_{CEO}.

  c) Maximum collector current: ICmax
- There are few rules that need to be followed for BJT transistor used as an amplifier. The rules are:

  i) transistor need to be operate in active region!

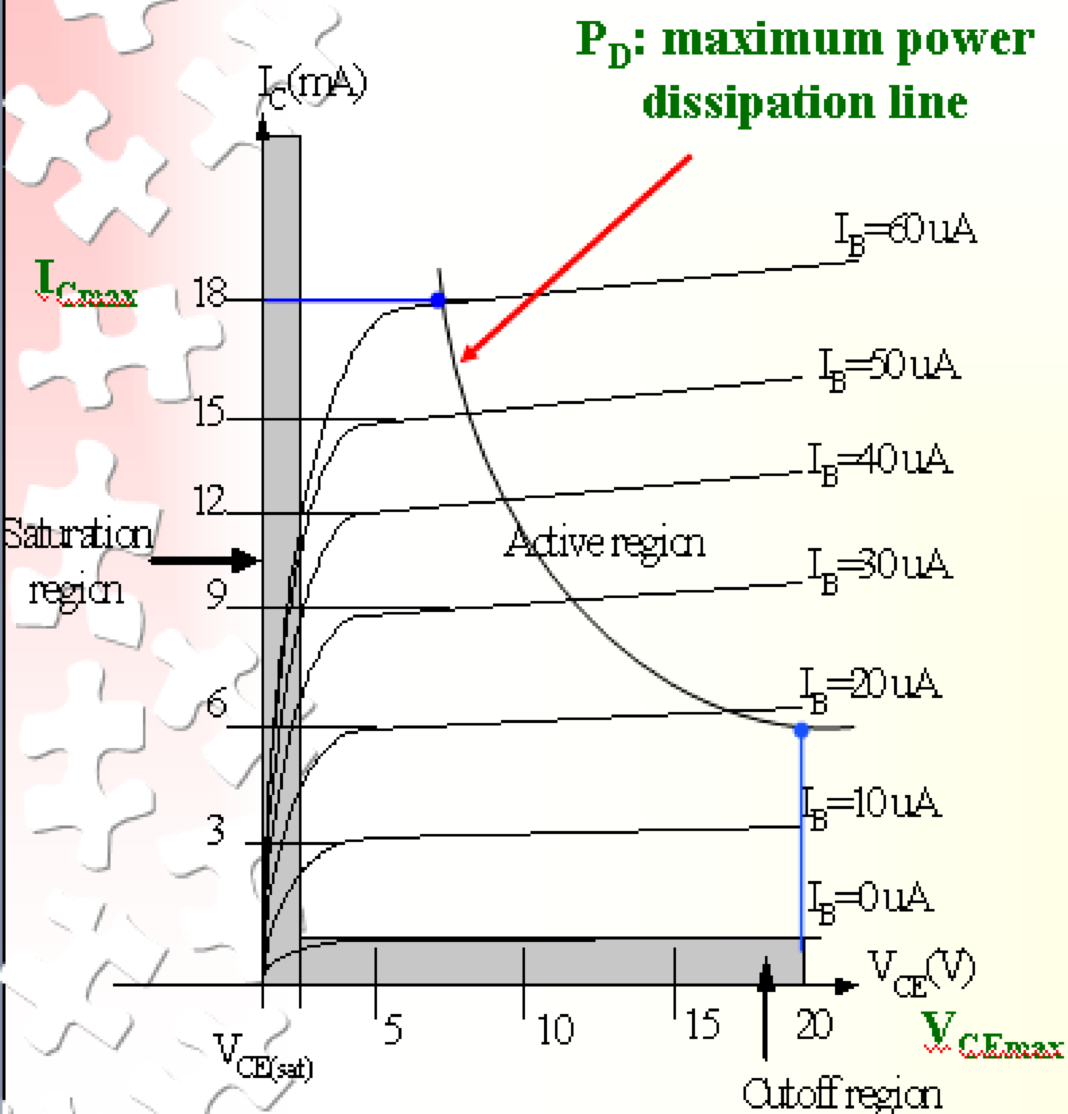
  ii) $I_C < I_{Cmax}$

  ii) $P_C < P_{Cmax}$



Note: V_{CE} is at maximum and I_C is at minimum ($I_{Cmax}=I_{CEO}$) in the cutoff region. I_C is at maximum and V_{CE} is at minimum (V_{CE} max = V_{CEsat} = V_{CEO}) in the saturation region. The transistor operates in the active region between saturation and cutoff.

Example 1:



Refer to the fig.

Step1:

The maximum collector power dissipation,

$$\mathbf{P_D = I_{Cmax} \times V_{CEmax}} \qquad \mathbf{(1)}$$

$$= 18\text{m} \times 20 = 360 \text{ mW}$$

Step 2:

At any point on the characteristics the product of and must be equal to 360 mW.

Ex. 1. If choose I_{Cmax}= 5 mA, subtitute into the (1), we get

$V_{CEmax}I_{Cmax}$= 360 mW

V_{CEmax}(5 m)=360/5=7.2 V

Ex.2. If choose V_{CEmax}=18 V, subtitute into (1), we get

$V_{CEmax}I_{Cmax}$= 360 mW

(10) I_{Cmax}=360m/18=20 mA

Derating P_{Dmax}

- P_{Dmax} is usually specified at 25°C.
- The higher temperature goes, the less is P_{Dmax}
- Example;
  - A derating factor of 2mW/°C indicates the power dissipation is reduced 2mW each degree centigrade increase of temperature.

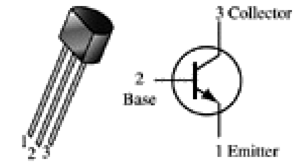
Transistor Specification Sheet

MAXIMUM RATINGS

Rating	Symbol	2N4123	Unit
Collector-Emitter Voltage	V_{CEO}	30	Vdc
Collector-Base Voltage	V_{CBO}	40	Vdc
Emitter-Base Voltage	V_{EBO}	5.0	Vdc
Collector Current – Continuous	I_C	200	mAdc
Total Device Dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	625 5.0	mW mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	–55 to +150	°C

2N4123

CASE 29-04, STYLE 1
TO-92 (TO-226AA)



GENERAL PURPOSE TRANSISTOR
NPN SILICON

THERMAL CHARACTERISTICS

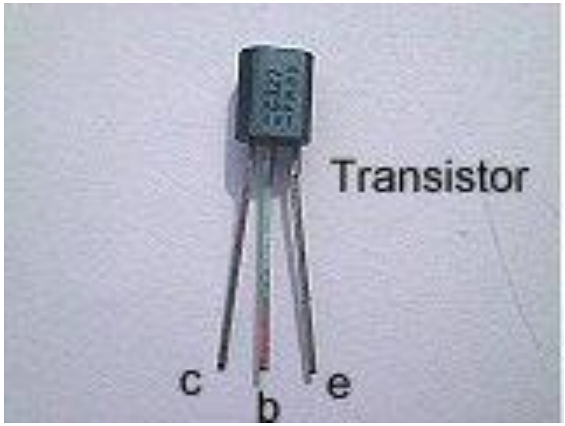
Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	°C/W
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	200	°C/W

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

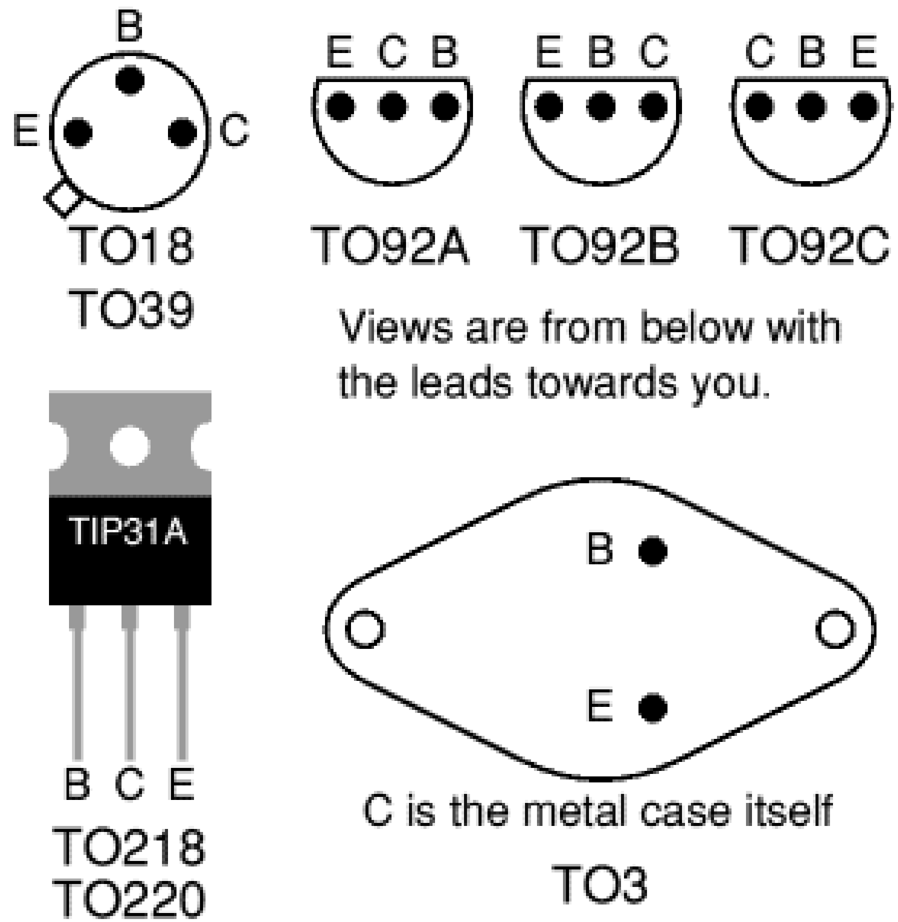
Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Emitter Breakdown Voltage (1) ($I_C = 1.0$ mAdc, $I_E = 0$)	$V_{(BR)CEO}$	30		Vdc
Collector-Base Breakdown Voltage ($I_C = 10$ µAdc, $I_E = 0$)	$V_{(BR)CBO}$	40		Vdc
Emitter-Base Breakdown Voltage ($I_E = 10$ µAdc, $I_C = 0$)	$V_{(BR)EBO}$	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
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%

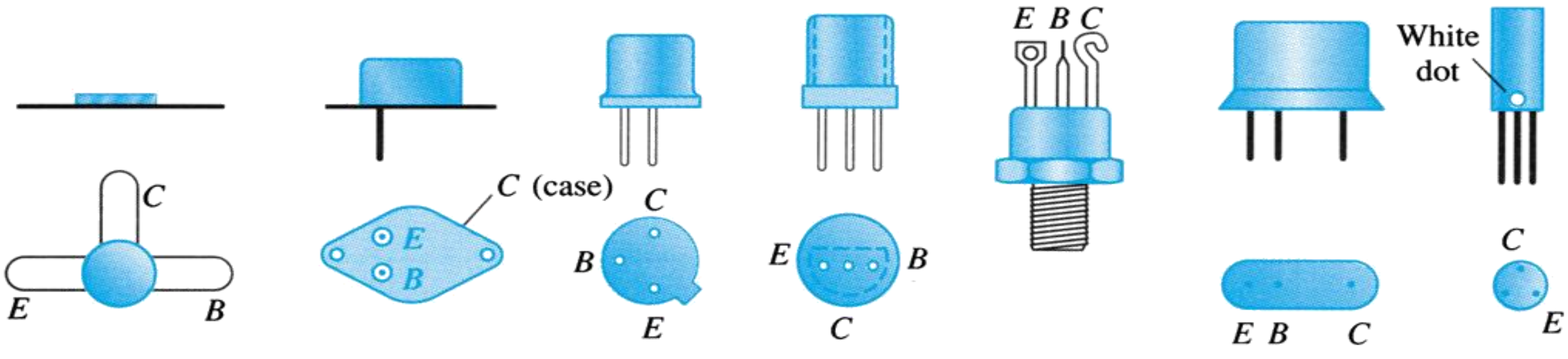
BJTs – Practical Aspects



Heat sink

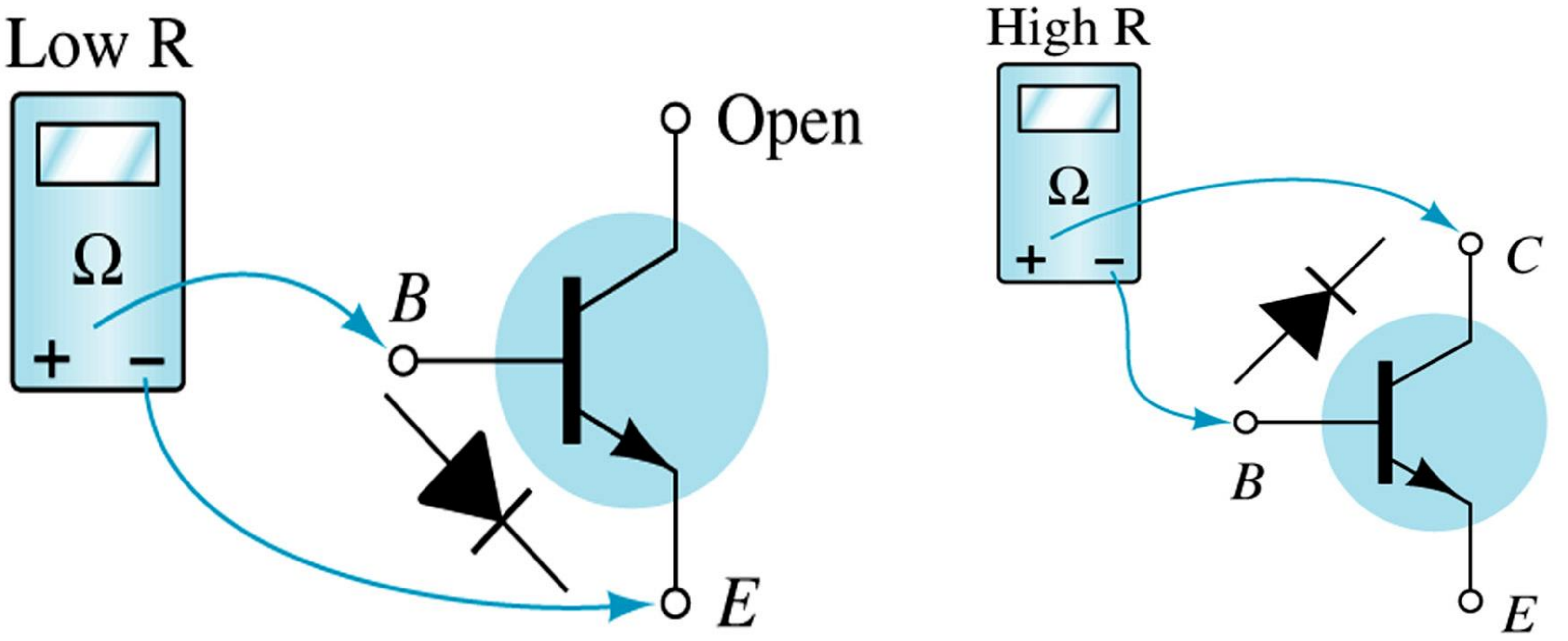


Transistor Terminal Identification

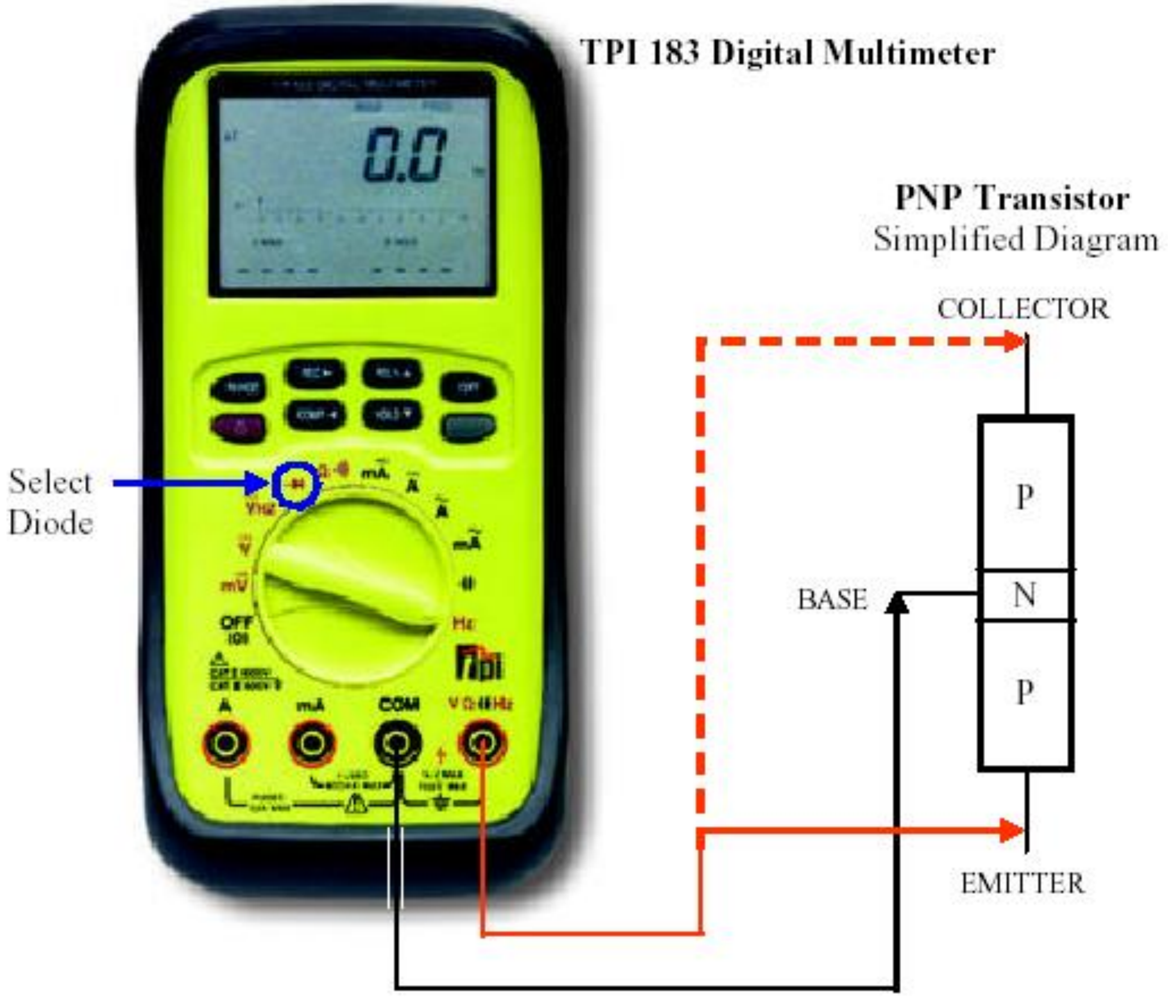


Transistor Testing

1. Curve Tracer
   Provides a graph of the characteristic curves.
2. DMM
   Some DMM’s will measure βDC or HFE.
3. Ohmmeter



BJTs - Testing



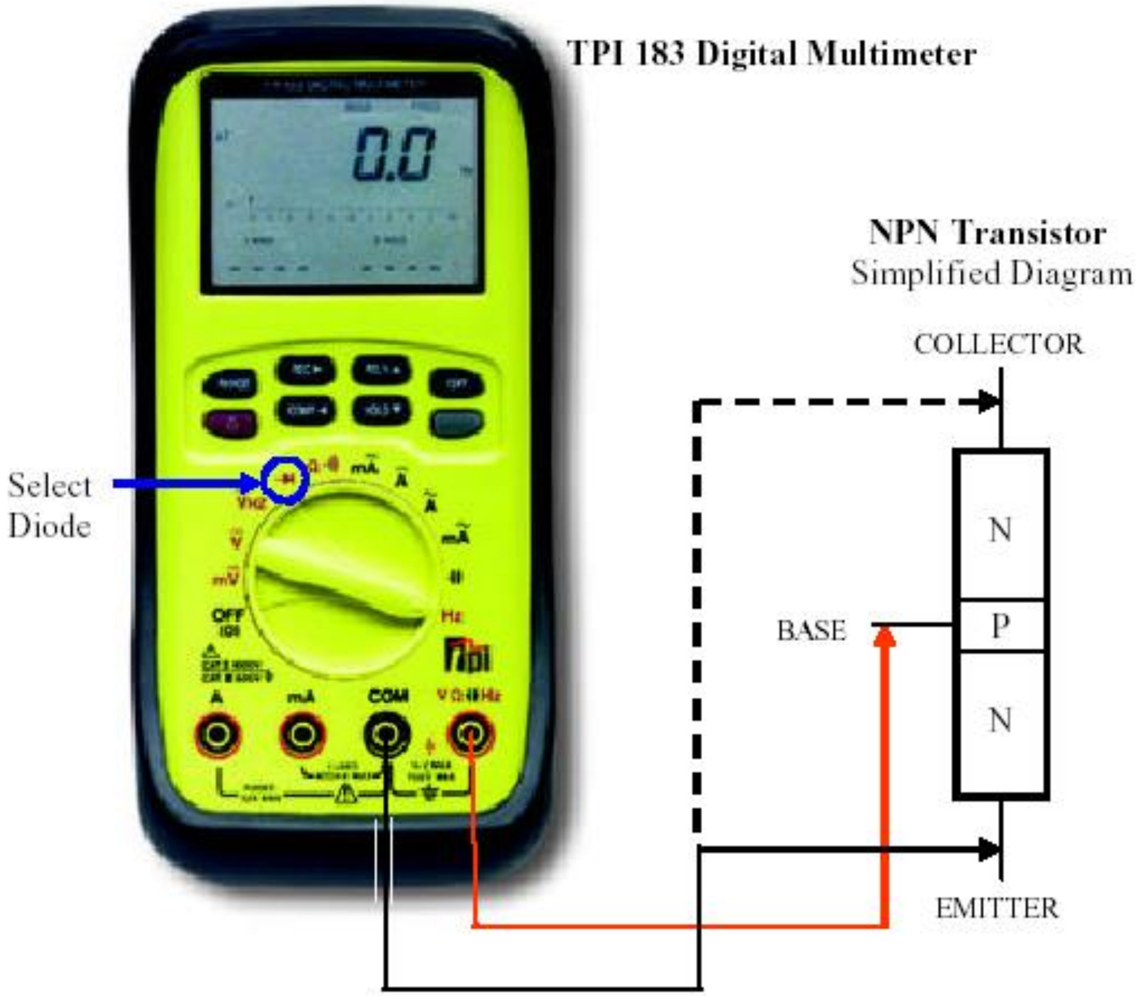
PNP Test Procedure

Connect the meter leads with the polarity as shown and verify that the base-to-emitter and base-to-collector junctions read as a forward biased diode: 0.5 to 0.8 VDC.

Reverse the meter connections to the transistor and verify that both PN junctions do not conduct. Meter should indicate an open circuit. (Display = OUCH or OL.)

Finally read the resistance from emitter to collector and verify an open circuit reading in both directions. (Note: A short can exist from emitter to collector even if the individual PN junctions test properly.)

BJTs – Testing



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…that’s all folks…

…thanks for your time…