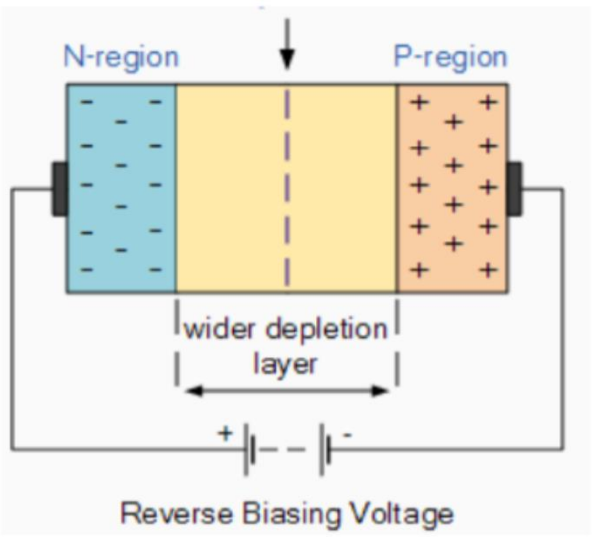
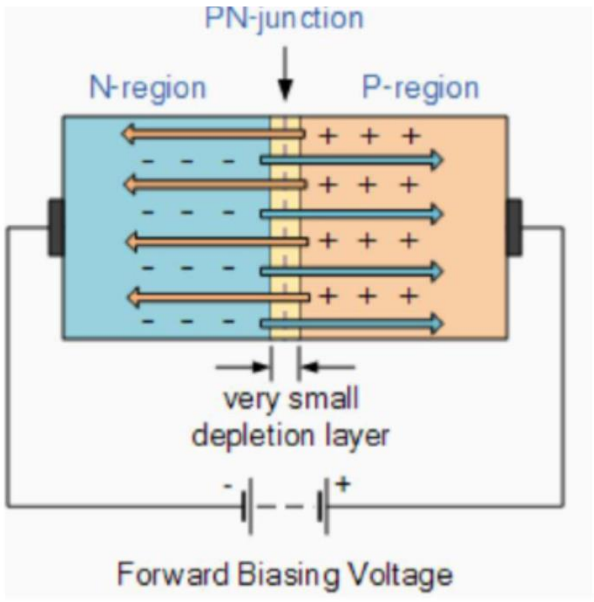
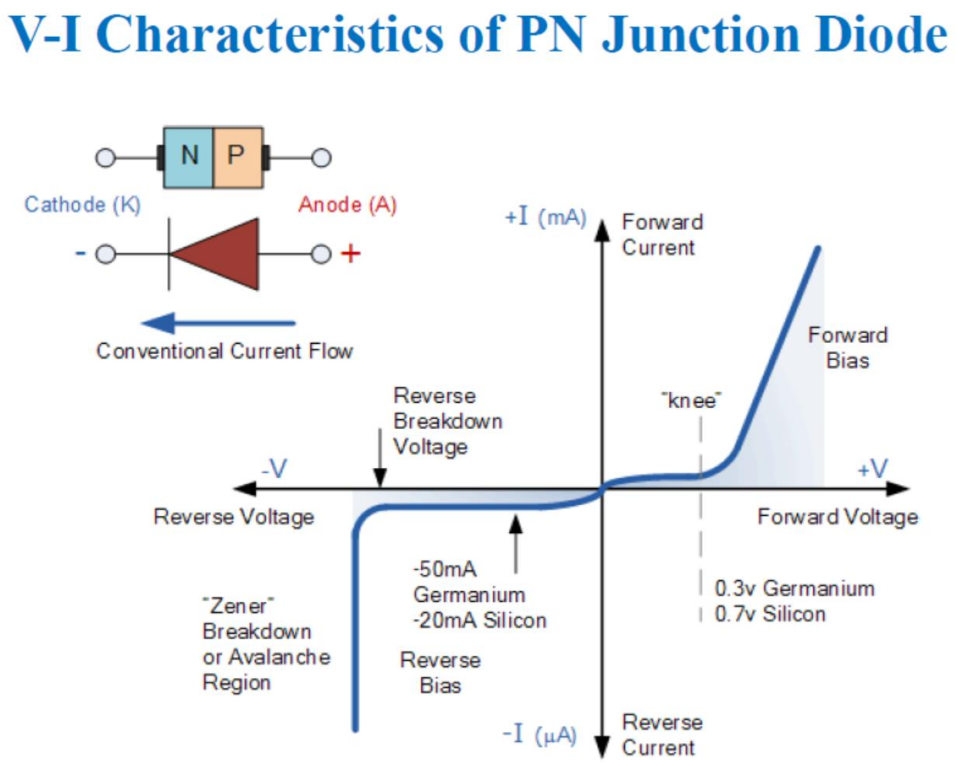
Diode





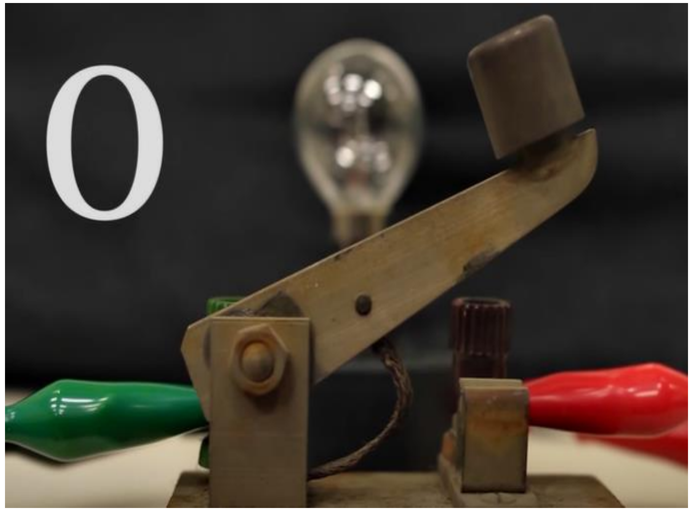


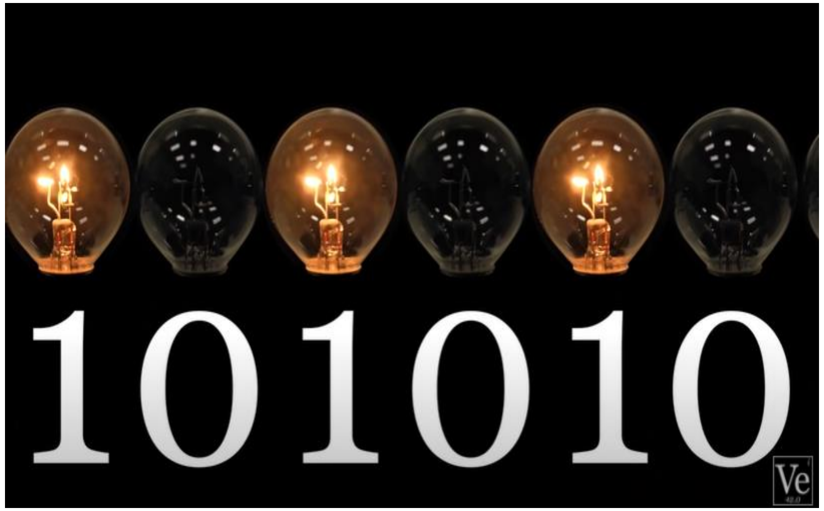
Its allows the current in one direction cannot **control the current or carriers or amplify**

Applications

- Its act as rectifier (AC to DC)
- Voltage regulator
- LED, Photo diode, solar cell, etc.

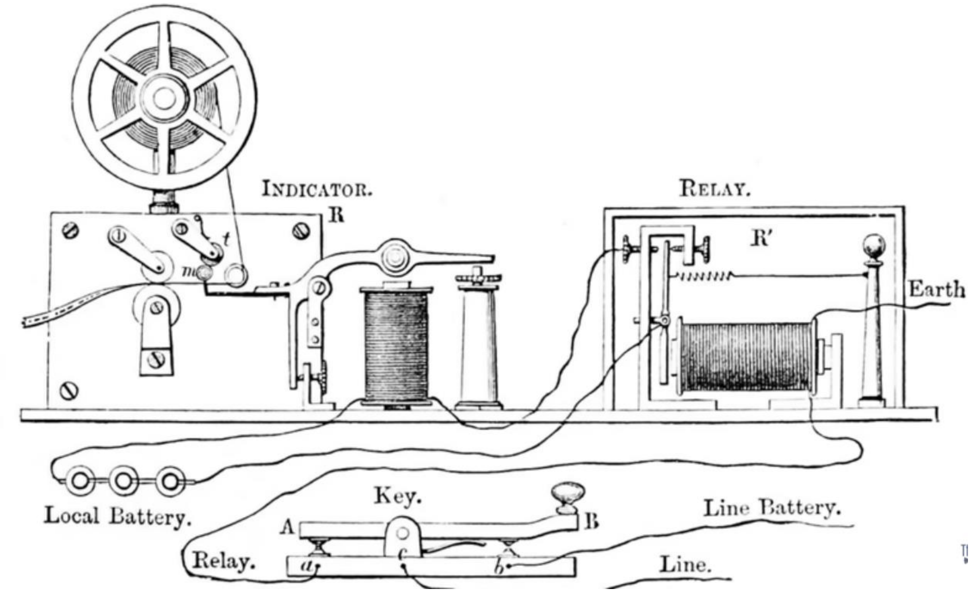
Transistor

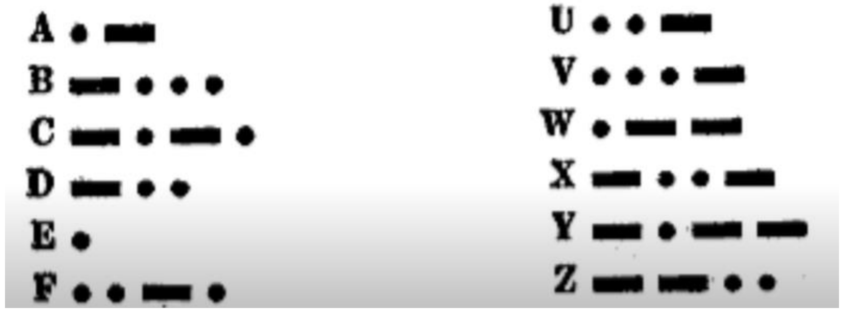


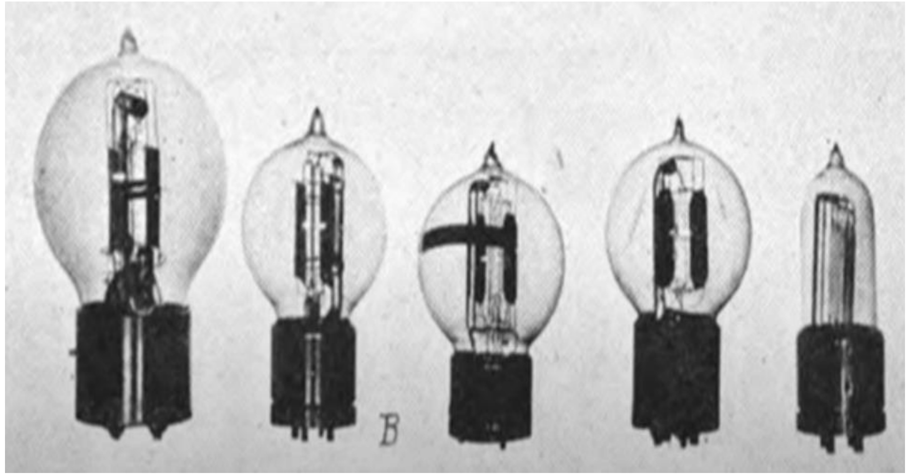


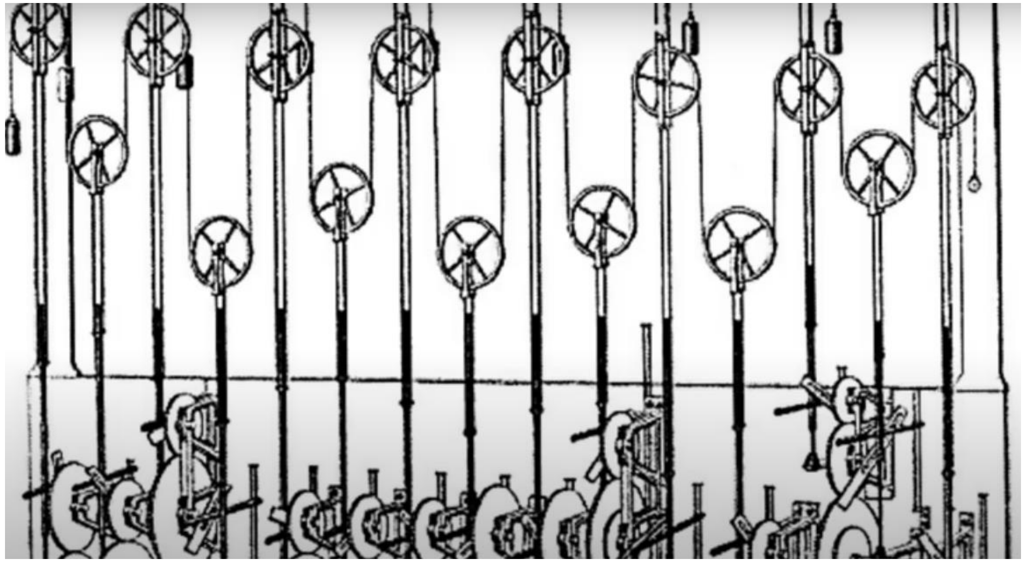
Controls the flow of Current

Transistor

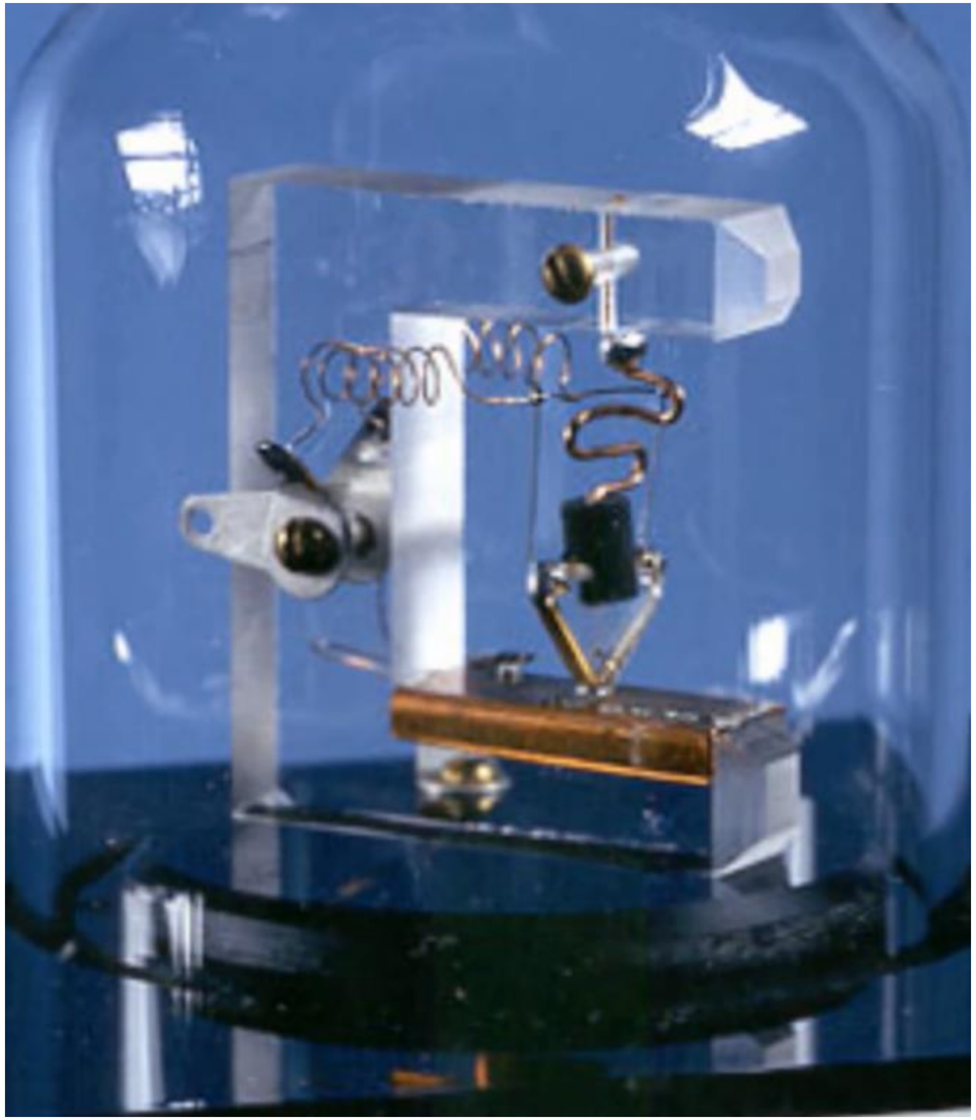

INDICATOR.
R
RELAY.
R'
Earth
Local Battery.
Key.
A
B
Line Battery.
Relay.
a
c
b
Line.


A
B
C
D
E
F
U
V
W
X
Y
Z

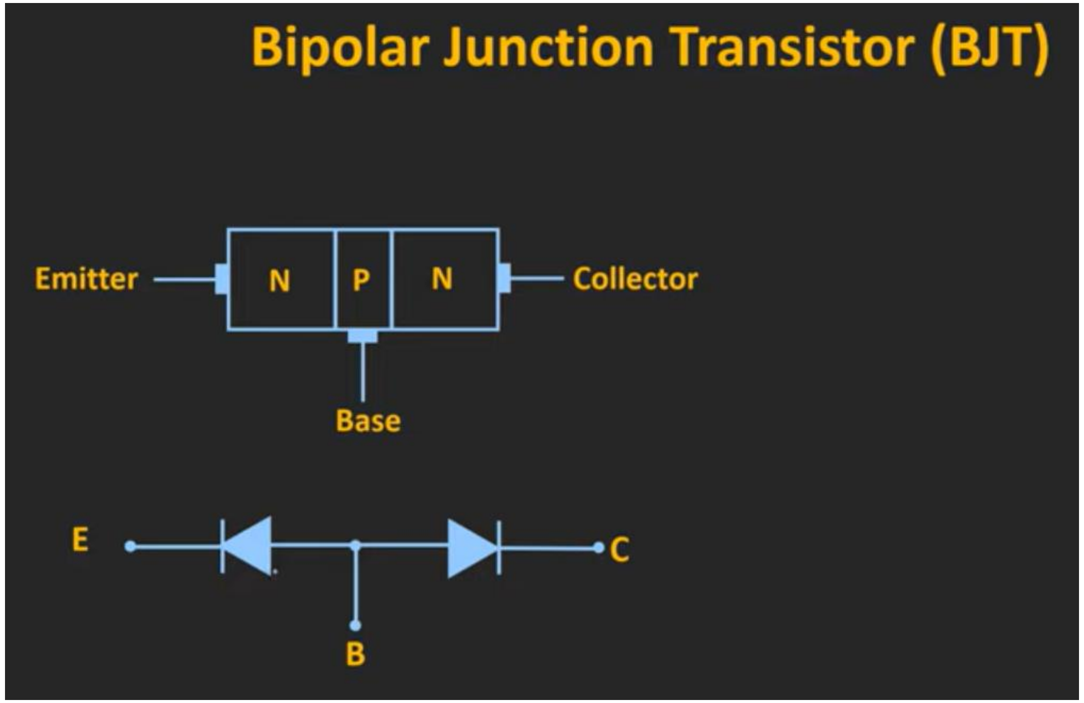

B



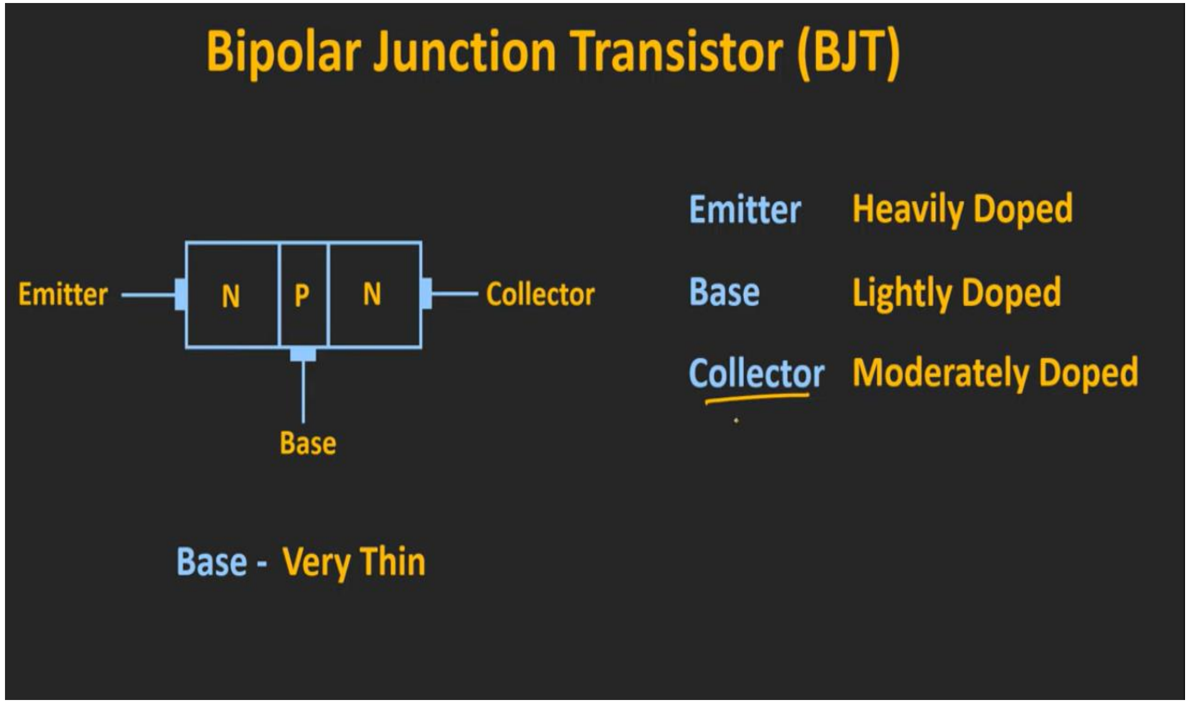
Transistor



Transistor

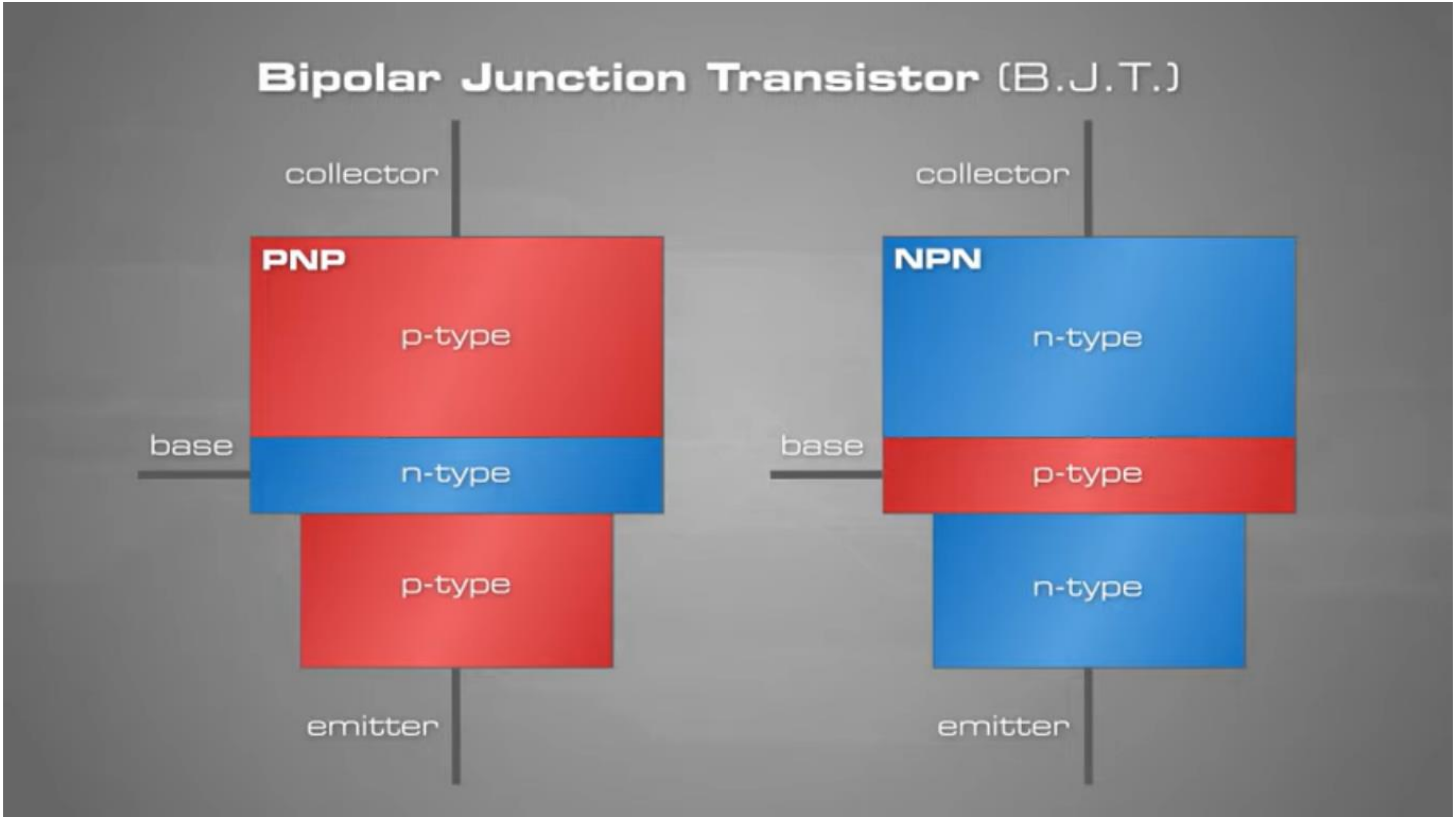


Bipolar Junction Transistor (BJT)
Emitter
N
P
N
Collector
Base
E
C
B

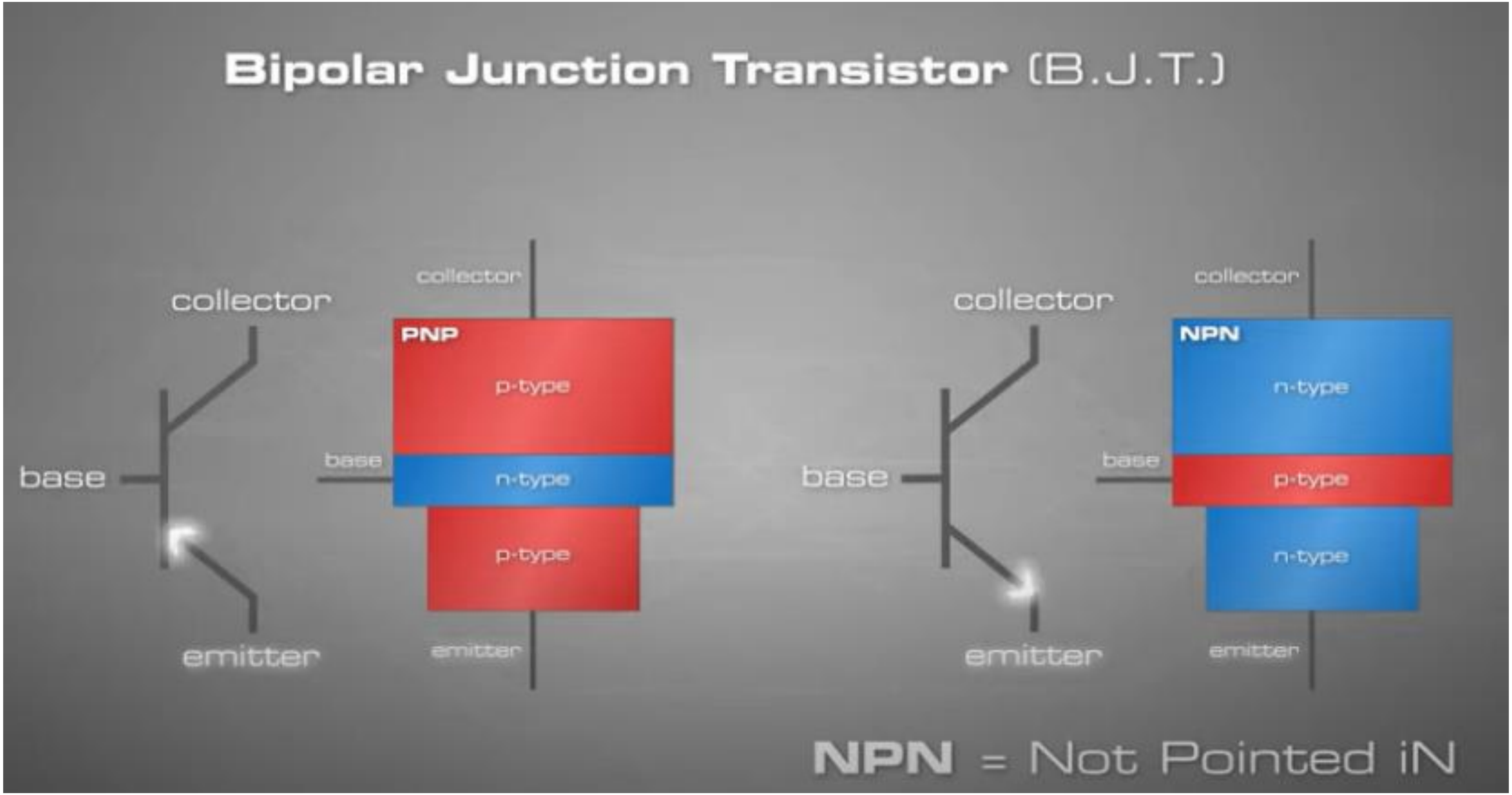


Bipolar Junction Transistor (BJT)
Emitter
N
P
N
Collector
Base
Emitter Heavily Doped
Base Lightly Doped
Collector Moderately Doped
Base - Very Thin

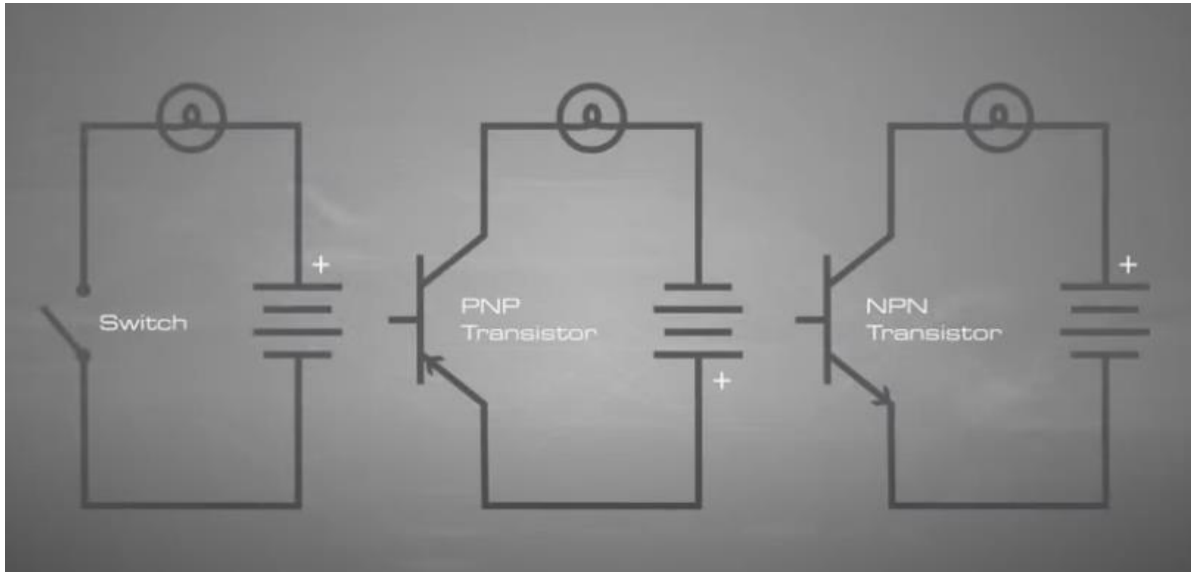
PNP/ NPN Transistor

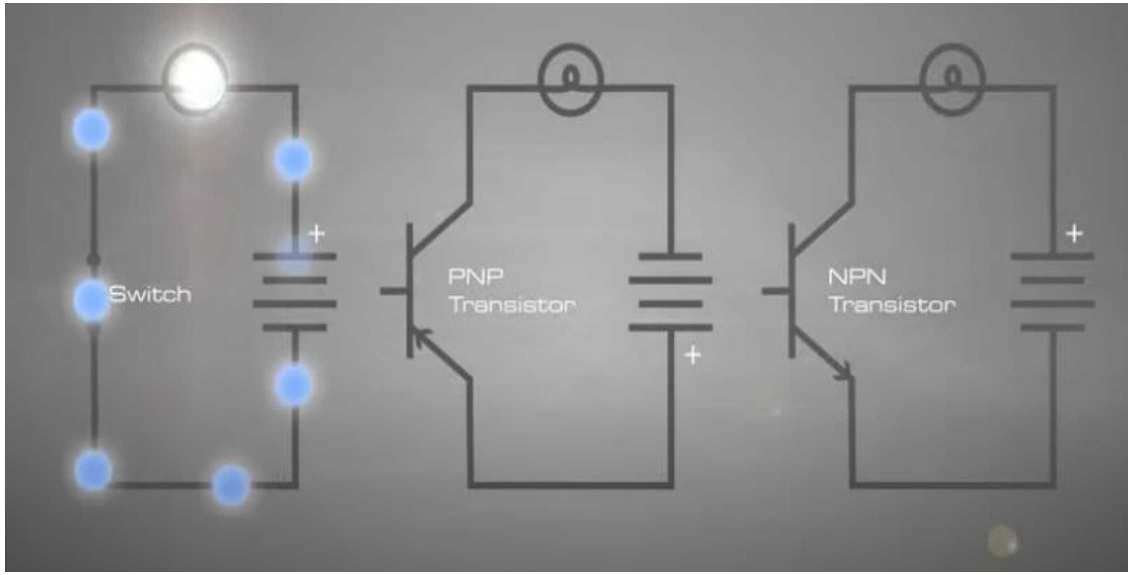


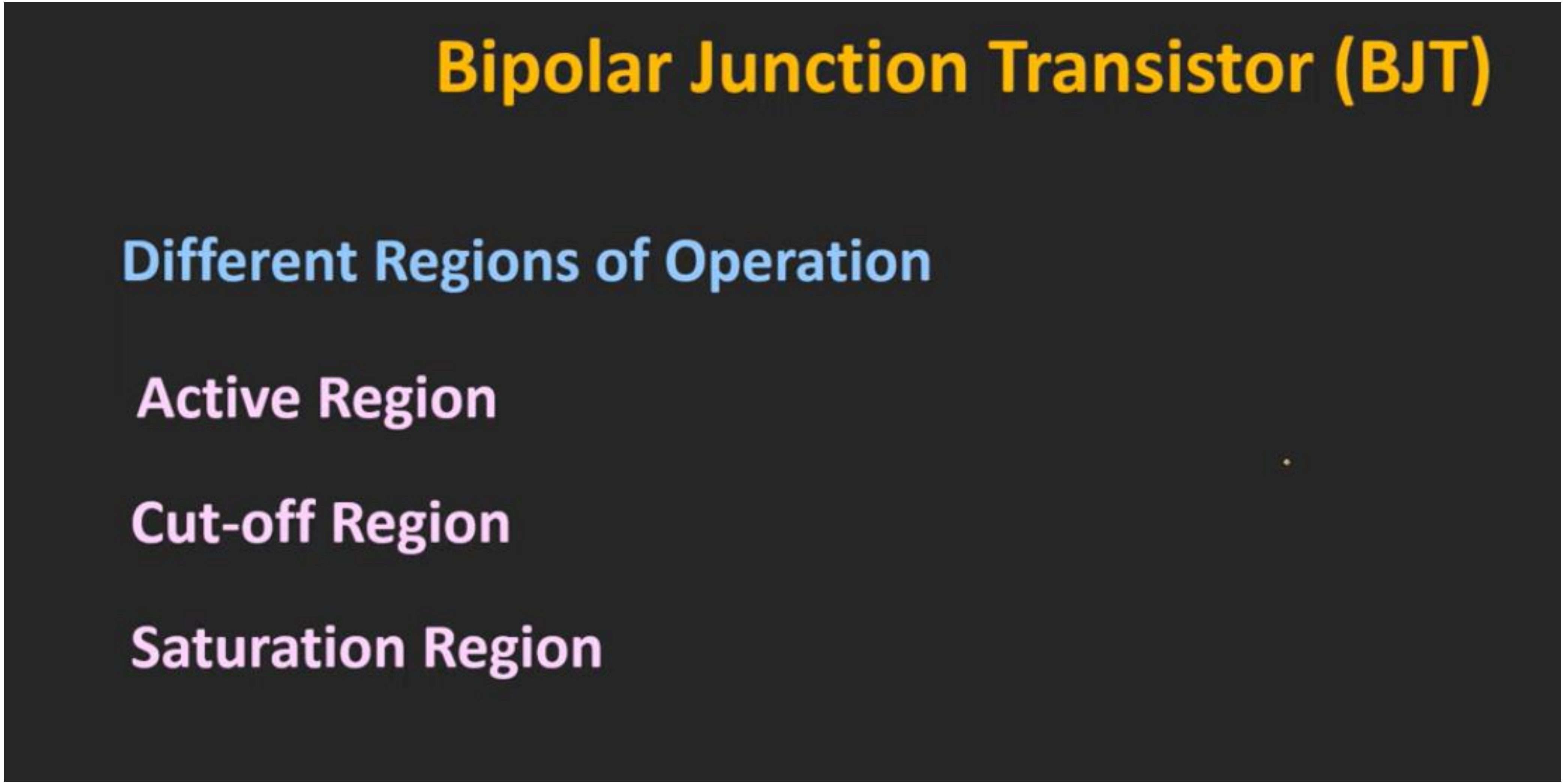
PNP/ NPN Transistor

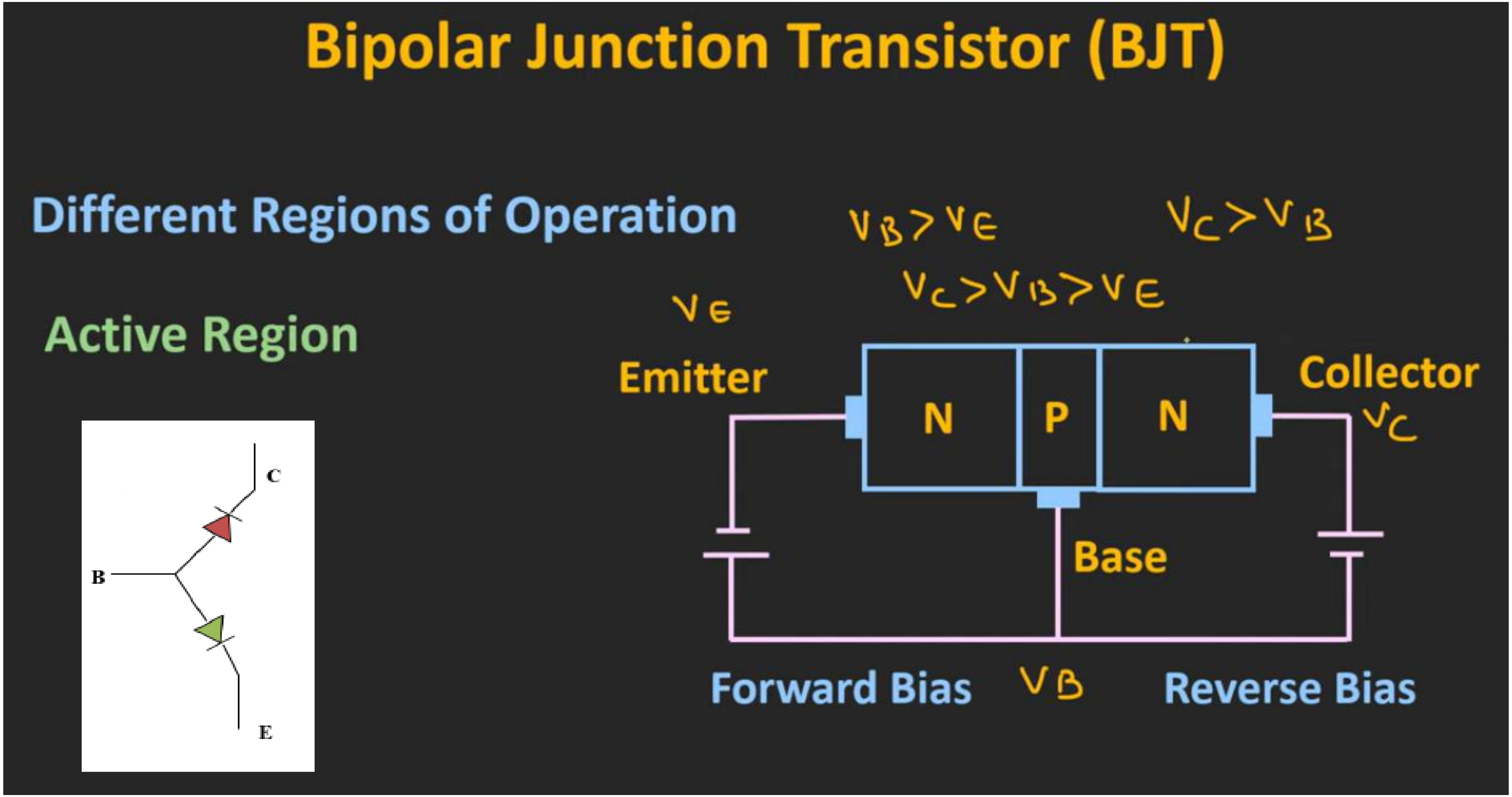


PNP/ NPN Transistor

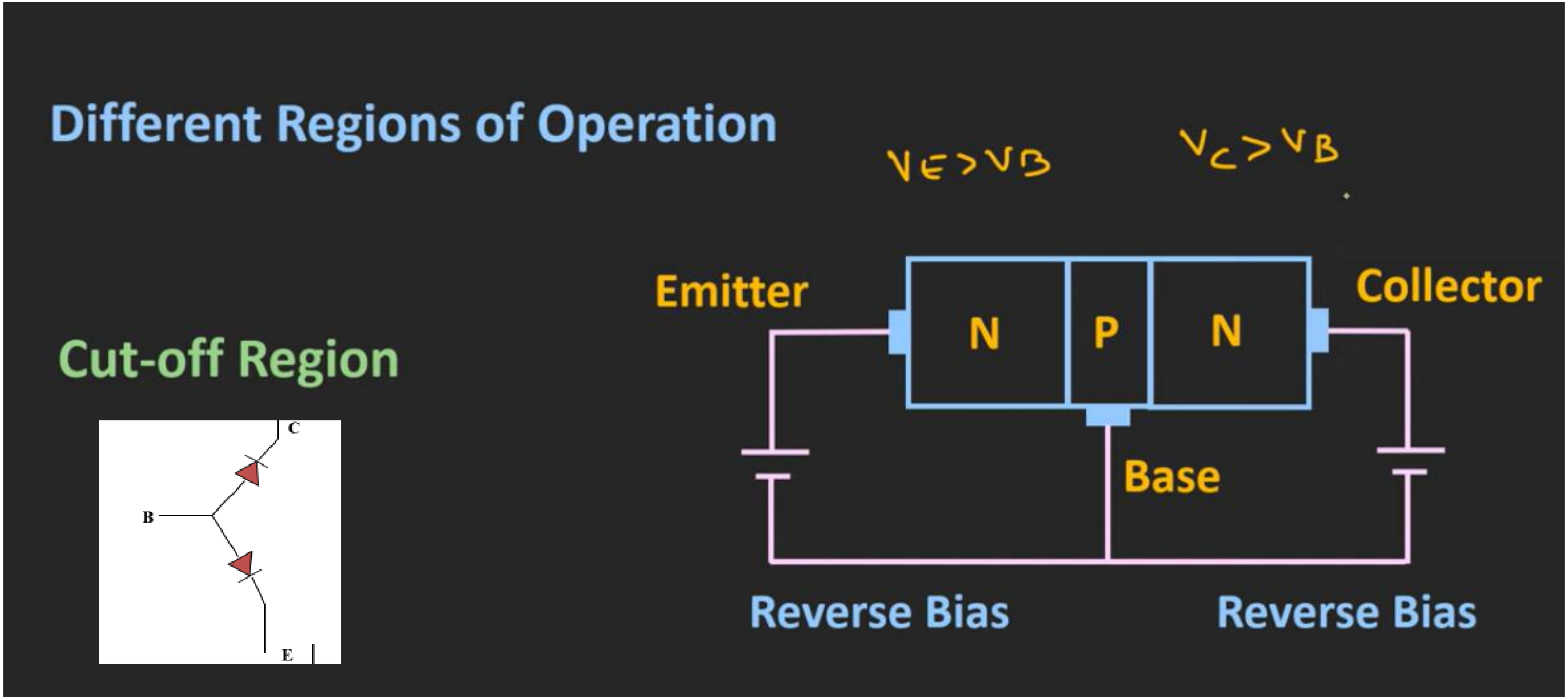


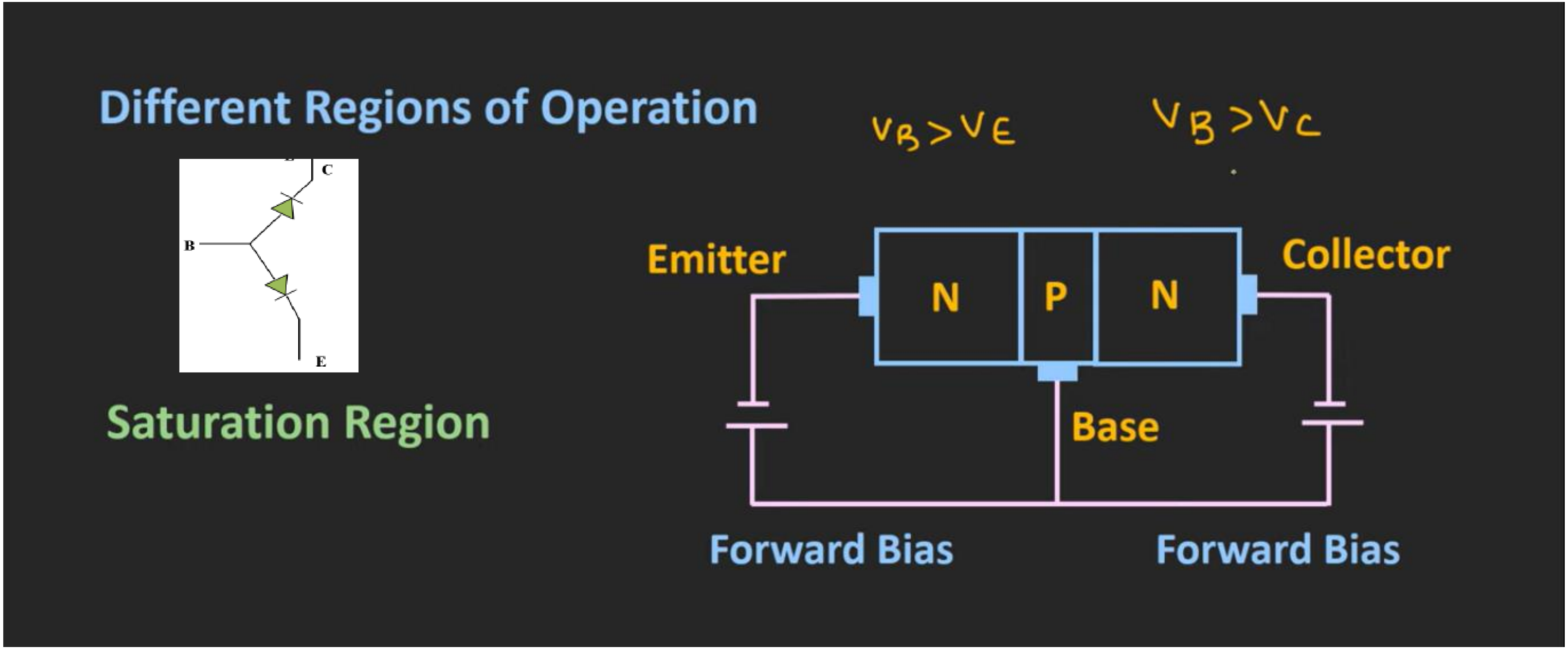



Bipolar Junction Transistor (BJT)
Different Regions of Operation
Active Region
Cut-off Region
Saturation Region

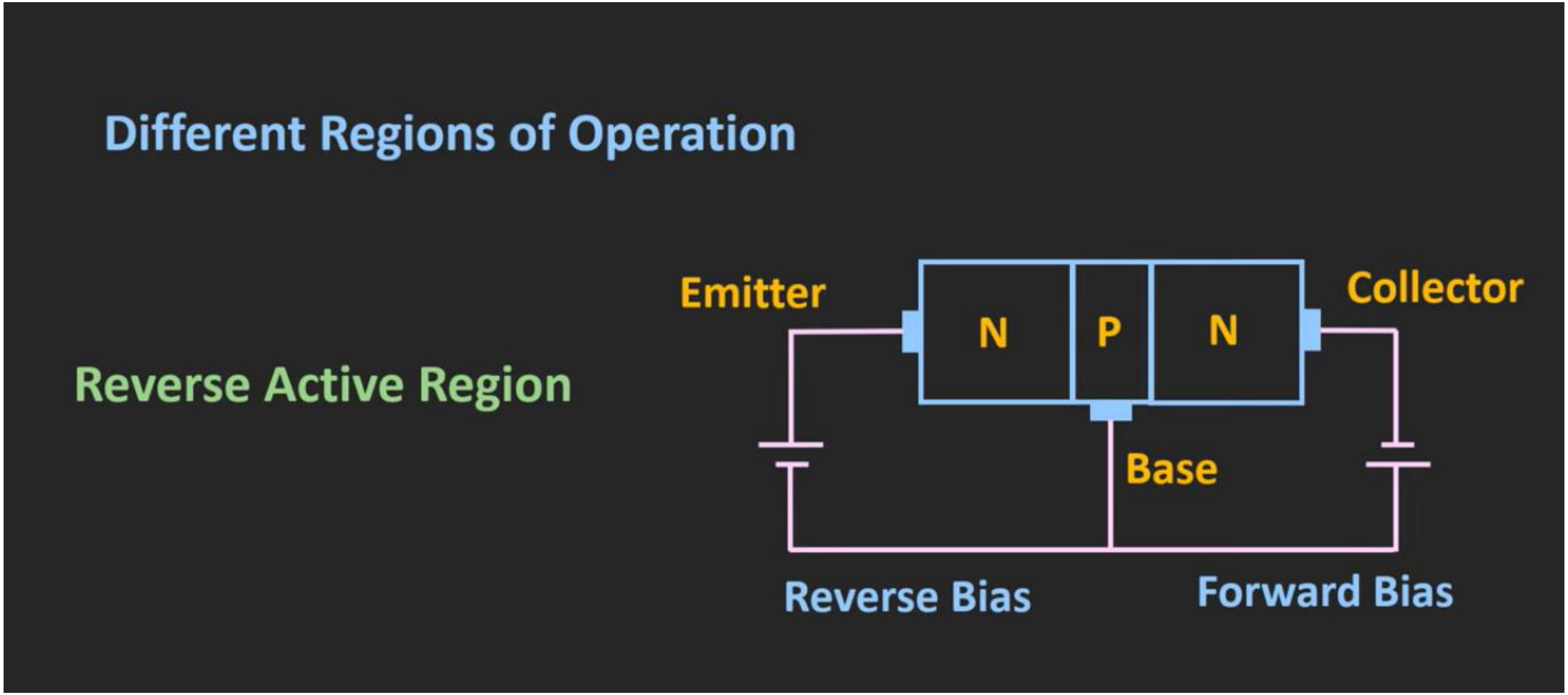

Bipolar Junction Transistor (BJT)
Different Regions of Operation
Active Region
C
B
E
VB > VE
VC > VB
VC > VB > VE
VE
Emitter
N
P
N
Collector
VC
Base
Forward Bias
VB
Reverse Bias

BJT


Different Regions of Operation
Cut-off Region
C
B
E
$V_E > V_B$
$V_C > V_B$
Emitter
Collector
N
P
N
Base
Reverse Bias
Reverse Bias

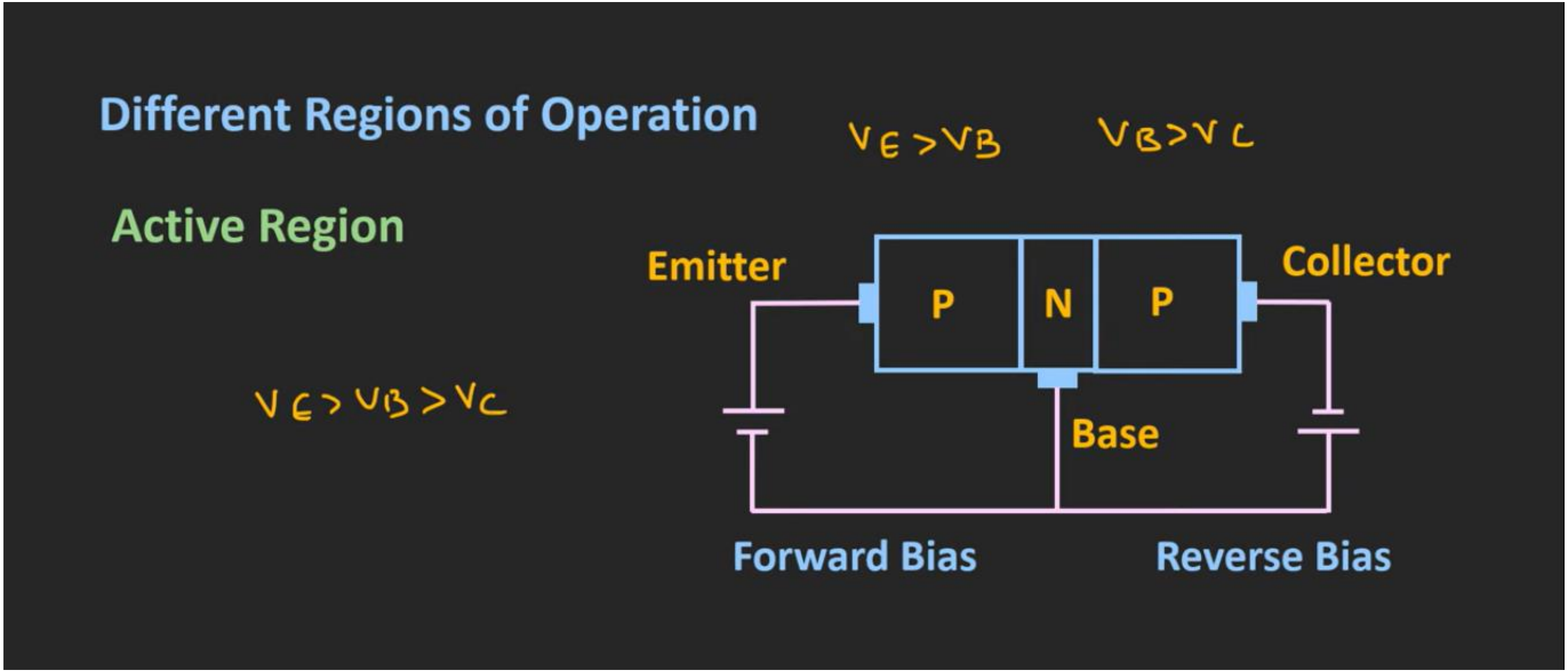

Different Regions of Operation
$V_B > V_E$
$V_B > V_C$
C
B
E
Saturation Region
Emitter
N
P
N
Collector
Base
Forward Bias
Forward Bias

BJT



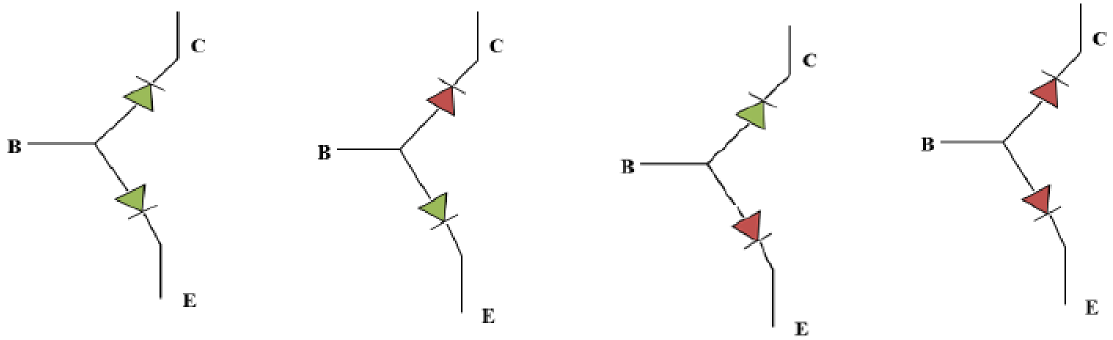
Different Regions of Operation
Reverse Active Region
Emitter
N
P
N
Collector
Base
Reverse Bias
Forward Bias

BJT



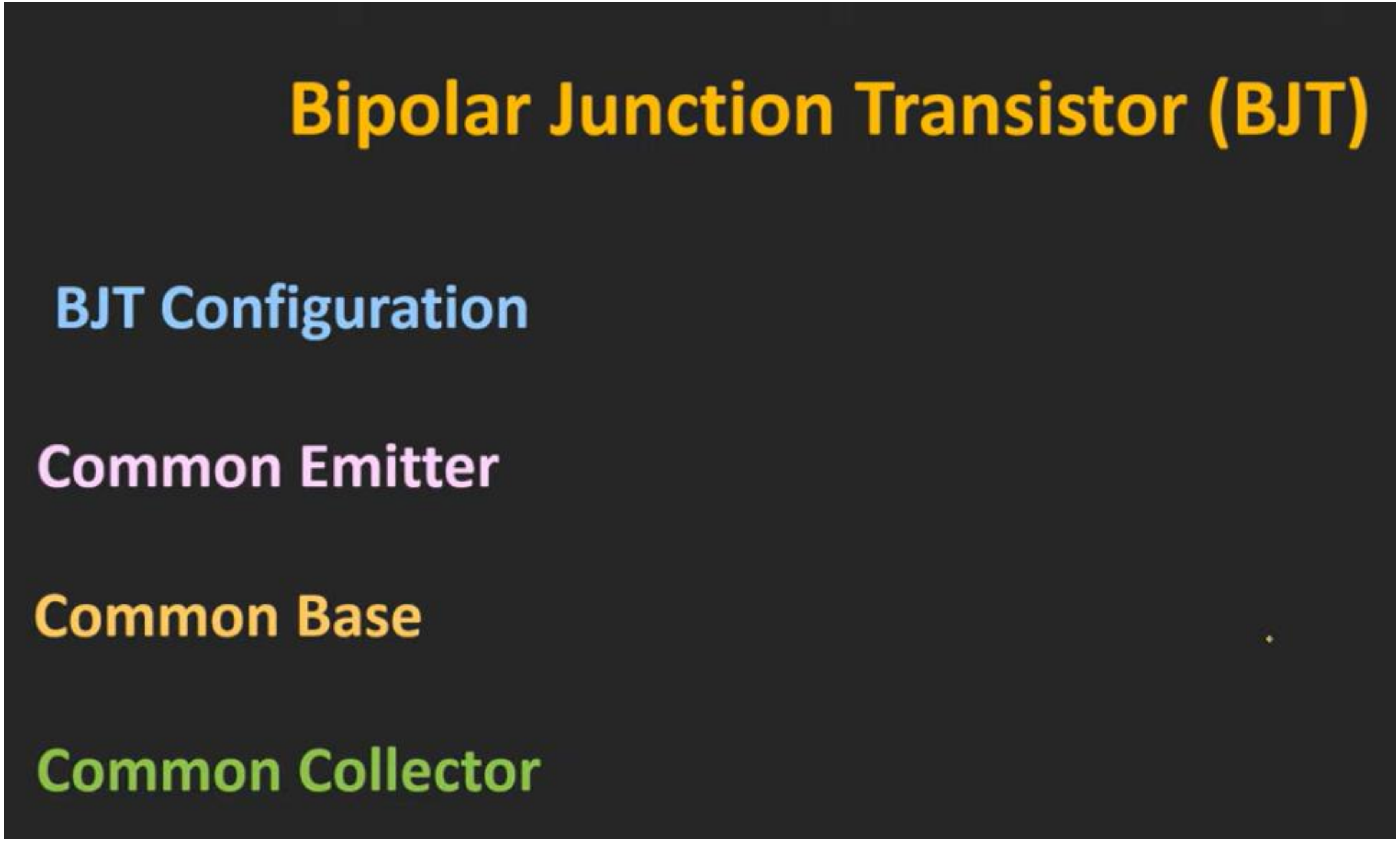
Different Regions of Operation
VE > VB
VB > VC
Active Region
Emitter
P
N
P
Collector
Base
VE > VB > VC
Forward Bias
Reverse Bias

Bipolar Junction Transistors: Basics

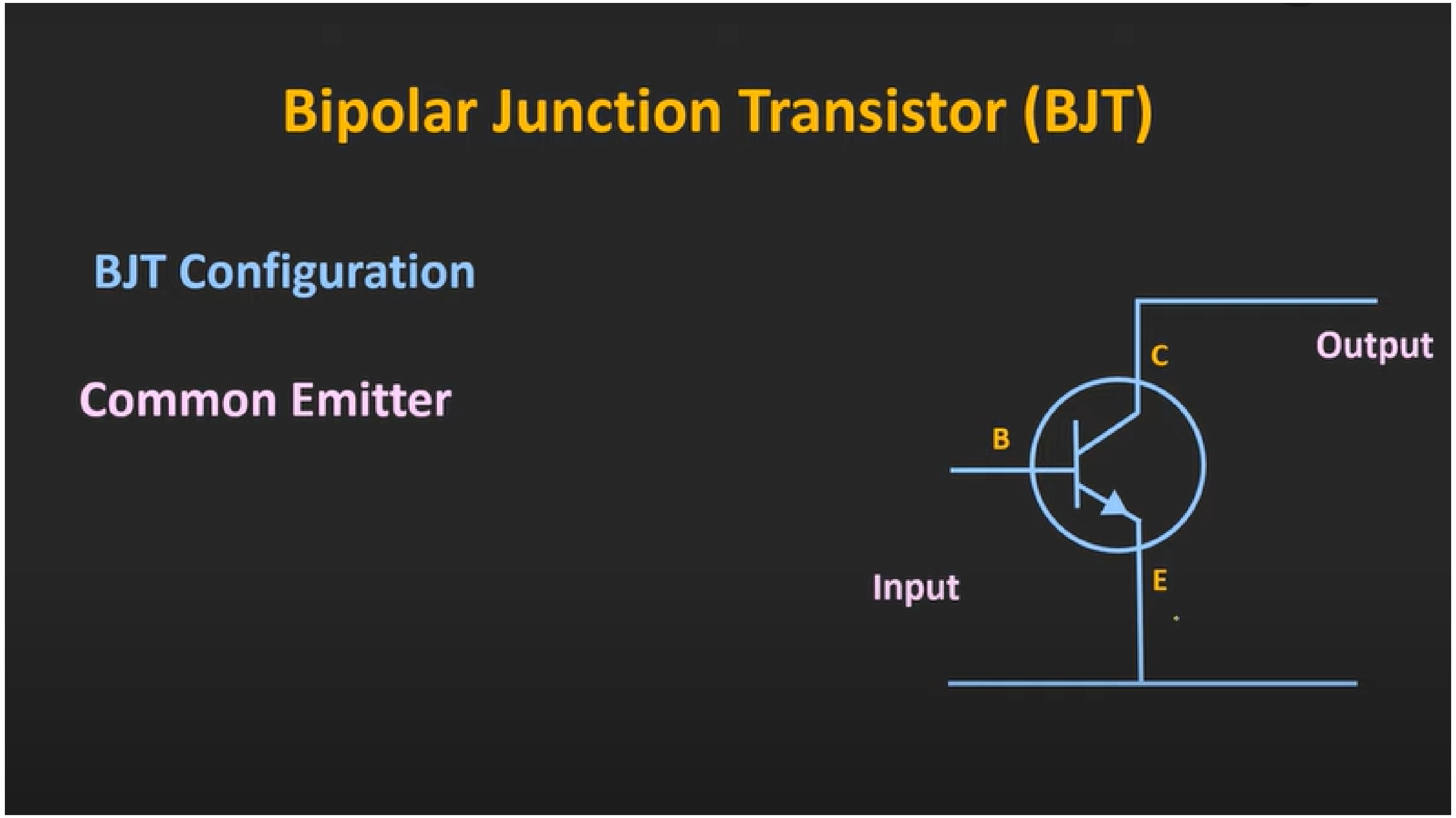


Bias Mode	E-B Junction	C-B Junction
Saturation	Forward	Forward

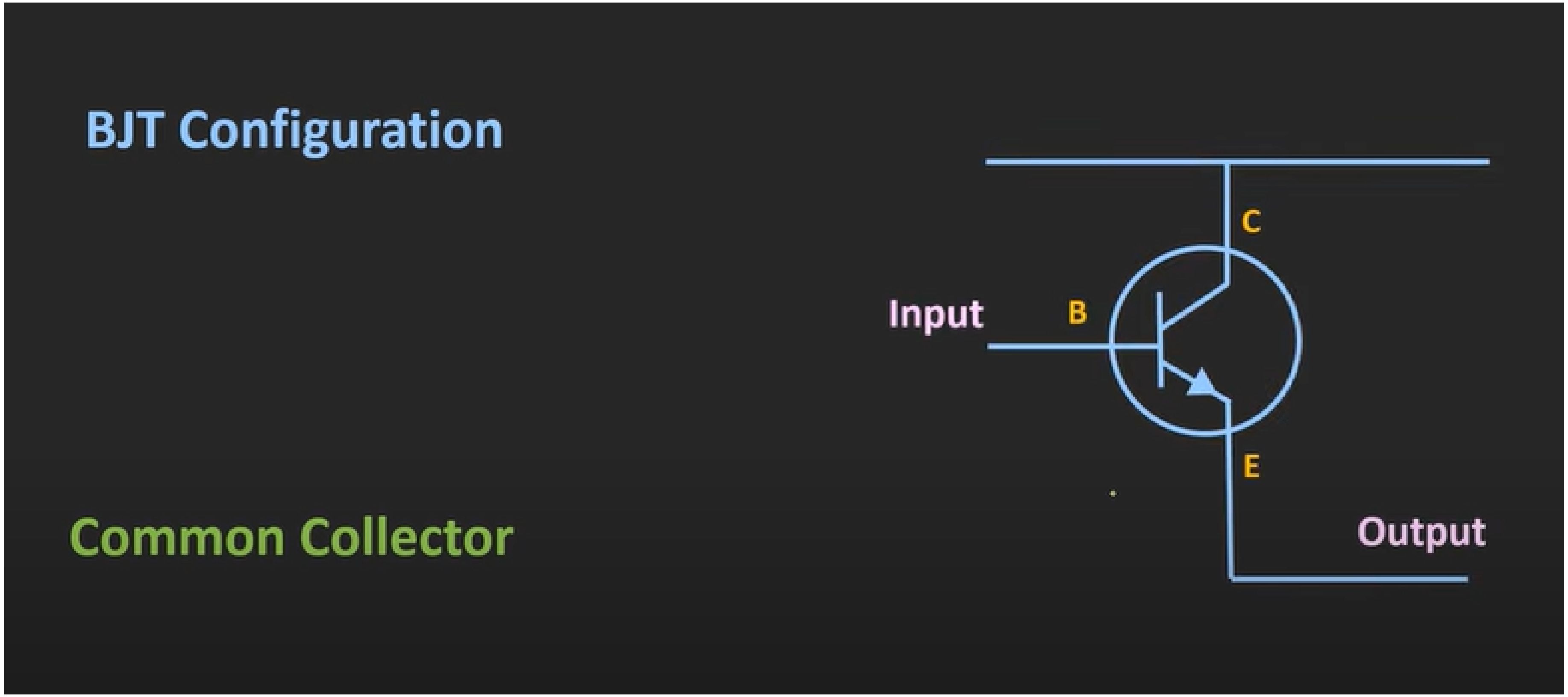
BJT


Bipolar Junction Transistor (BJT)
BJT Configuration
Common Emitter
Common Base
Common Collector

BJT

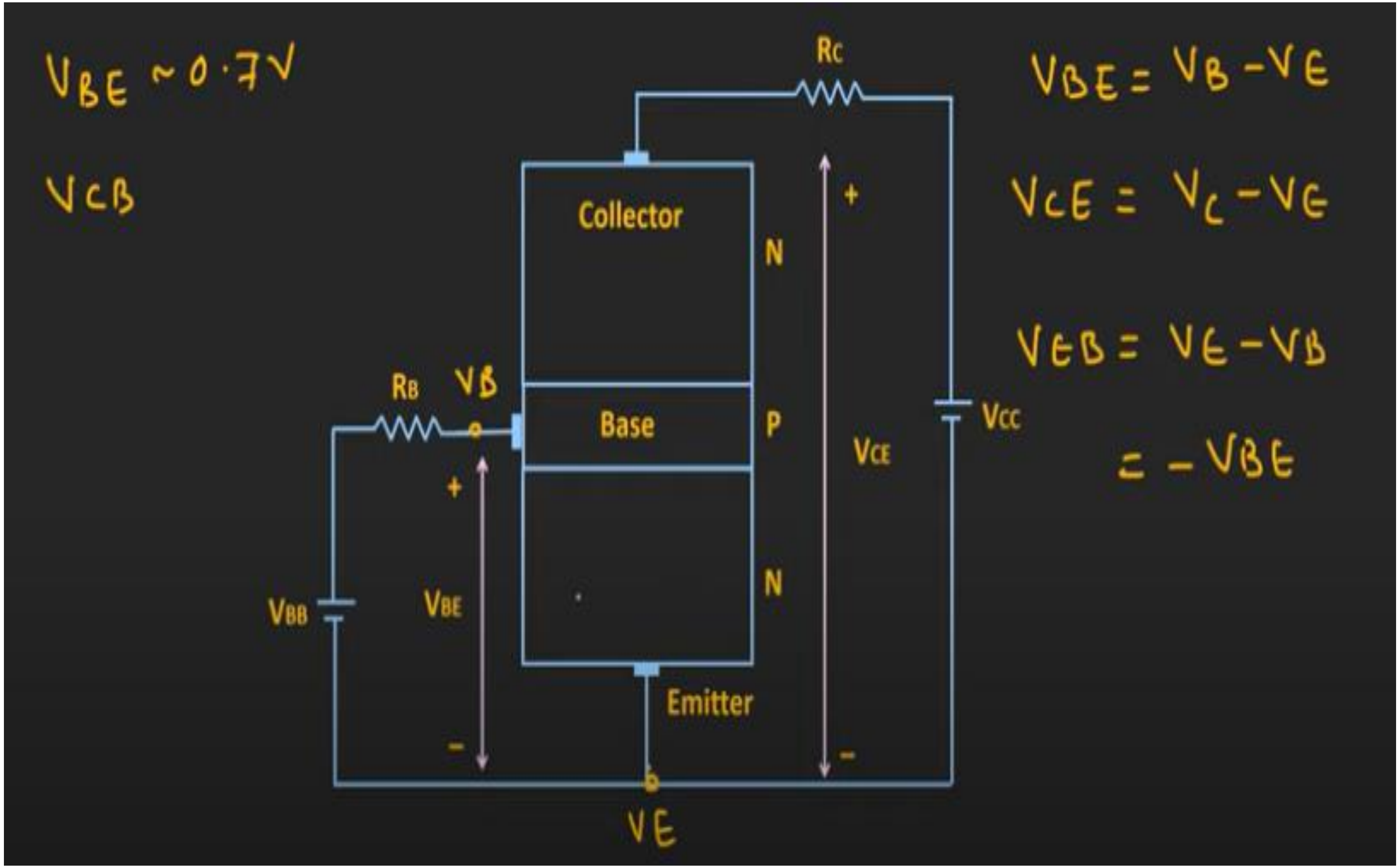

Bipolar Junction Transistor (BJT)
BJT Configuration
Common Emitter
C
Output
B
Input
E

BJT



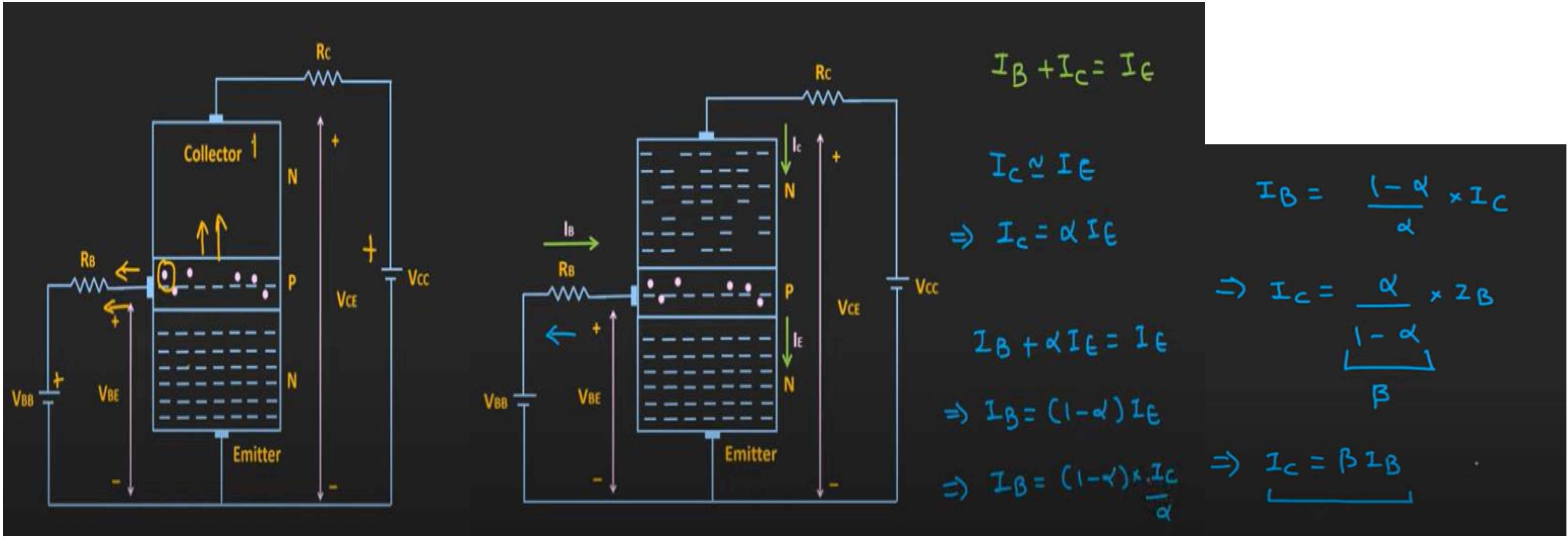
BJT

Working of BJT



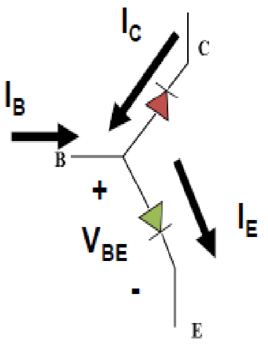
Working of BJT

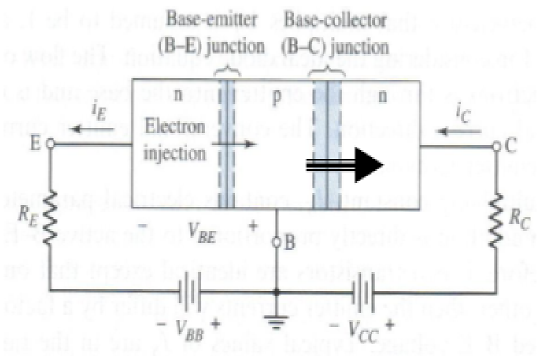
Current equations



Working of BJT

Mathematical Expressions





$I_E = I_S\,[\,e^{VBE/VT} - 1\,] = I_S\,e^{VBE/VT}$

Based on KCL: $I_E = I_C + I_B$

No. of electrons crossing the base region and then directly into the collector region is a constant factor β of the no. of electrons exiting the base region

$I_C = \beta I_B$

No. of electrons reaching the collector region is directly proportional to the no. of electrons injected or crossing the base region.

$I_C = \alpha I_E$

Ideally $\alpha = 1$, but in reality it is between 0.9 and 0.998.

Mathematical Expressions

Based on KCL: $I_E = I_C + I_B$ $\quad I_C = \beta I_B$ $\quad I_C = \alpha I_E$

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

With $I_C = \beta I_B \rightarrow I_B = I_C / \beta$

$I_E = [\,I_C / \beta\,]\ (\beta + 1)$

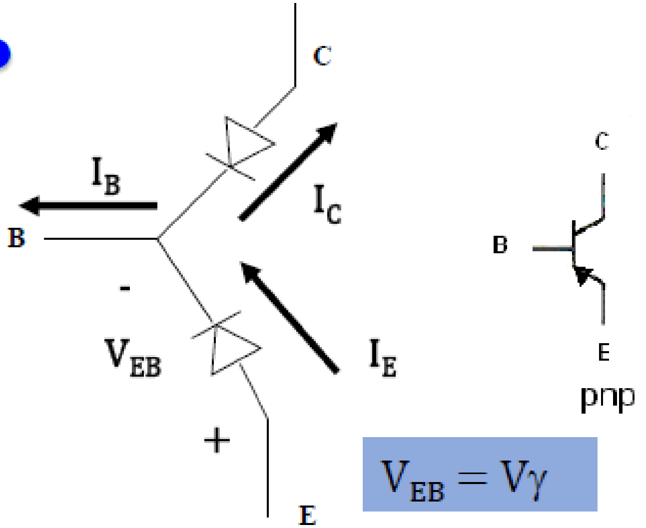
$I_C = I_E\,[\,\beta / \beta + 1\,]$

Comparing with $I_C = \alpha I_E \Longrightarrow \alpha = [\,\beta / \beta + 1\,]$

BJT – Current Controlled Current Source

FET – Voltage Controlled Current Source

OPERATIONS - PNP



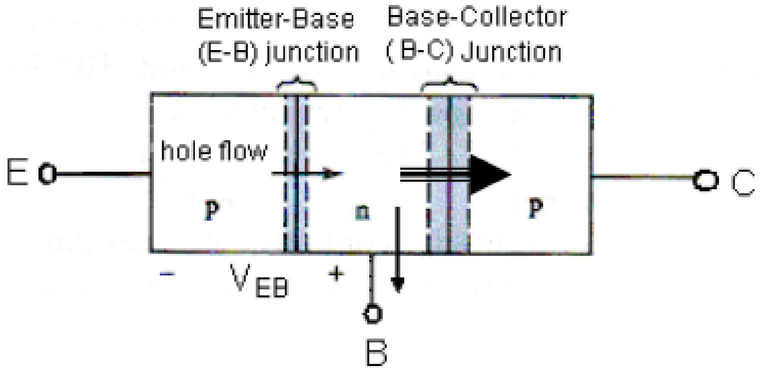
FORWARD ACTIVE MODE

- The **emitter – base (E- B) junction** is forward biased and the **base-collector (B- C) junction** is reverse-biased,.

$V_{EB} = V\gamma$

$$I_E = I_S [\, e^{V_{EB}/V_T} - 1 \,] = I_S\, e^{V_{EB}/V_T}$$

**Notice that it is V_{EB}



Based on KCL: $I_E = I_C + I_B$

BJT

NPN

$I_E = I_S [e^{VBE / VT}]$

PNP

$I_E = I_S [e^{VEB / VT}]$

$I_C = \beta I_B$

$I_C = \alpha I_E$

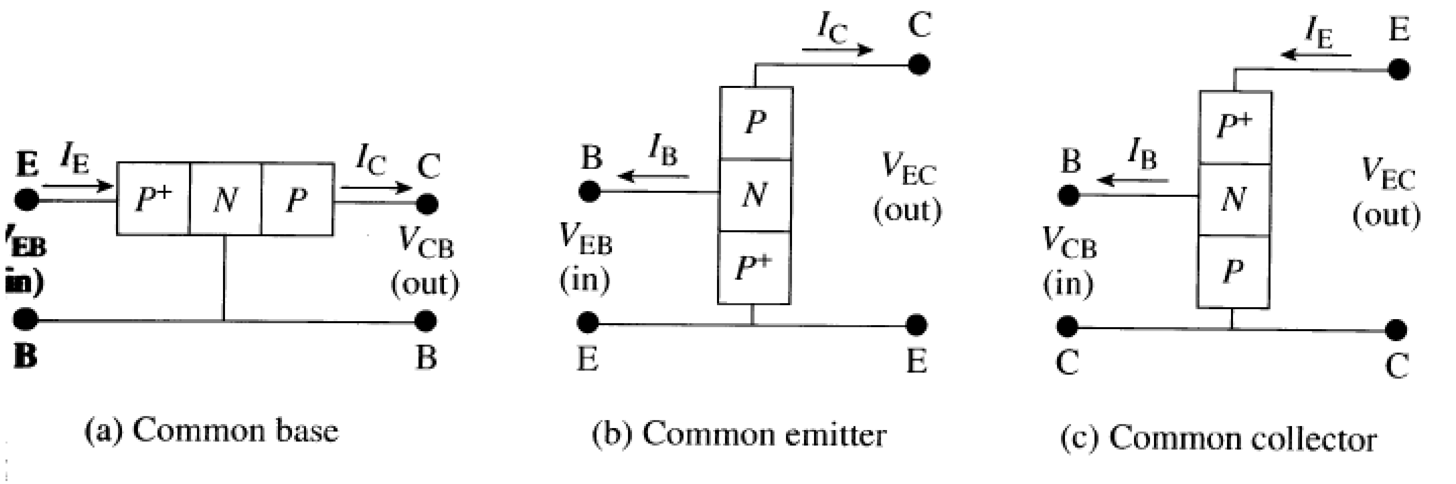
$I_E = I_B(\beta + 1)$

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

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

Based on KCL: $I_E = I_C + I_B$

BJT configurations

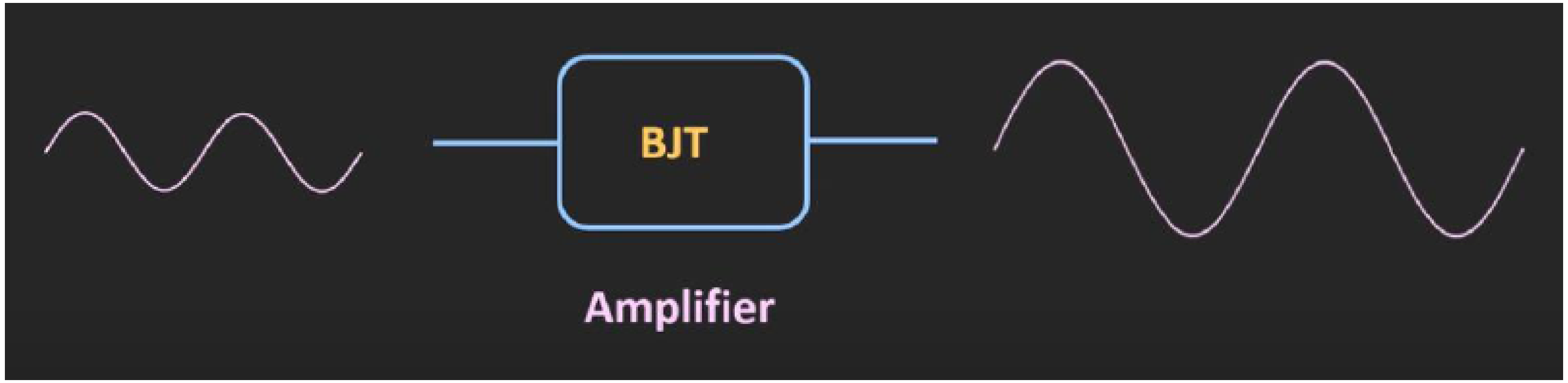


Common Base Configuration – has Voltage Gain but no Current Gain.

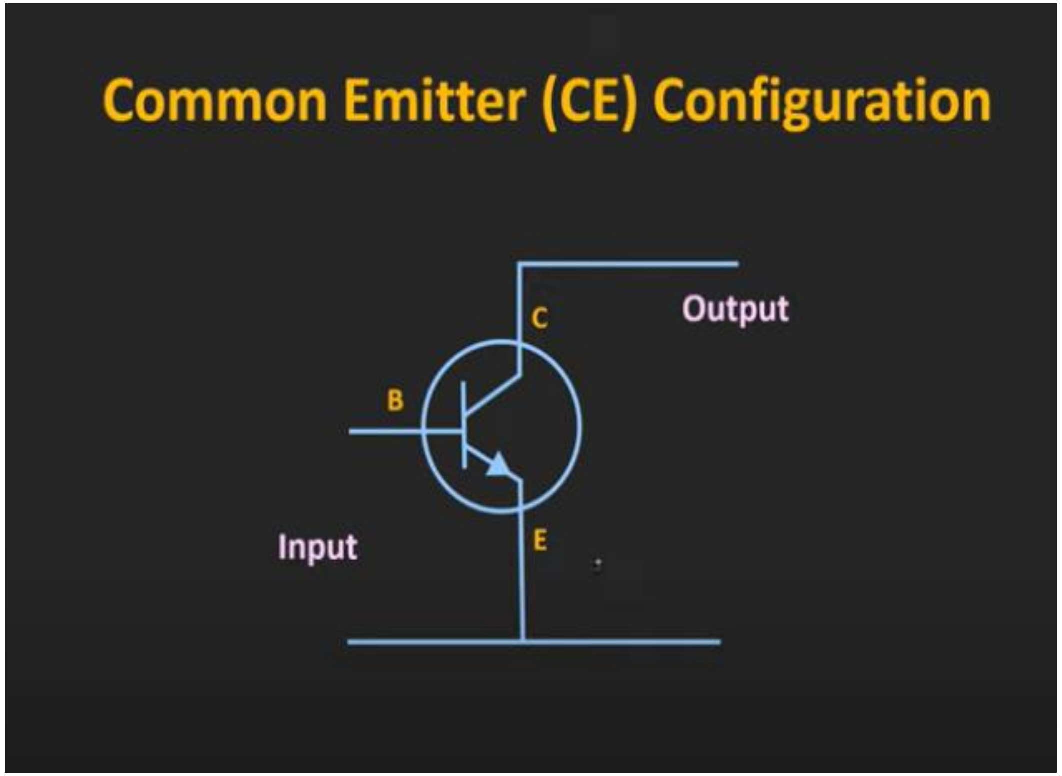
Common Emitter Configuration – has both Current and Voltage Gain.

Common Collector Configuration – has Current Gain but no Voltage Gain.

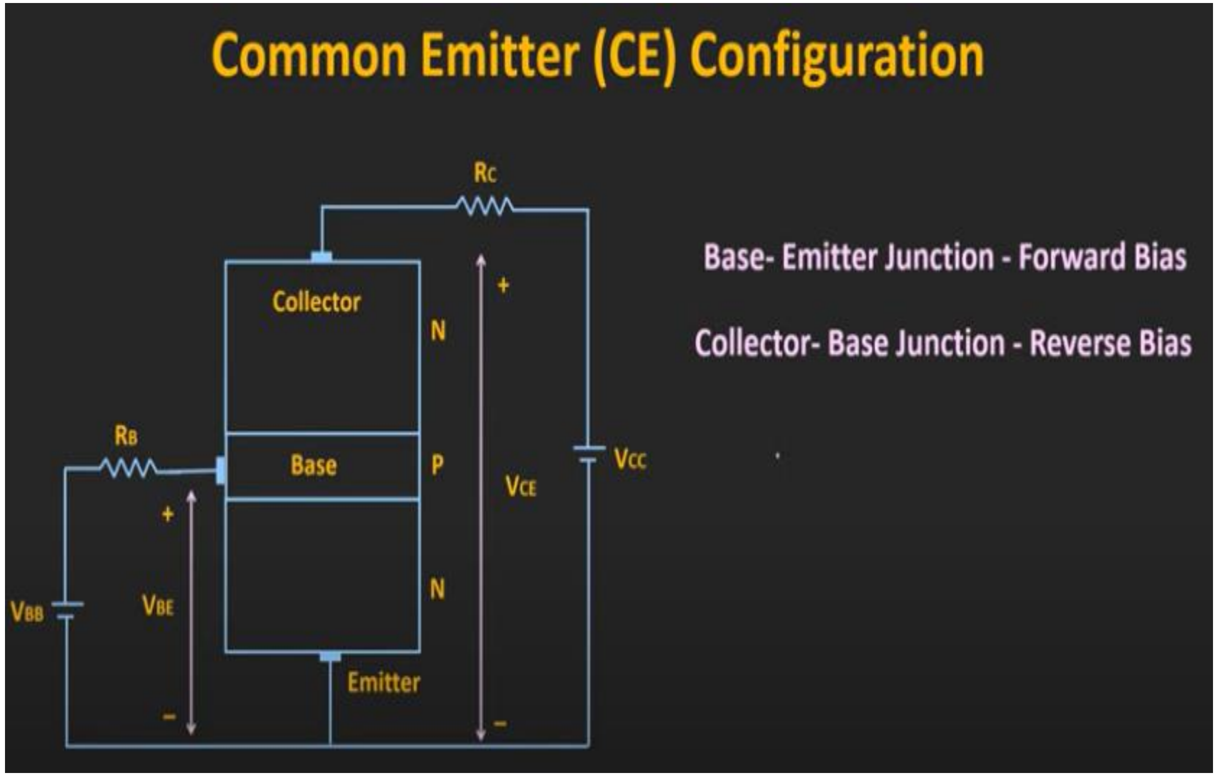
Amplifier



CE BJT

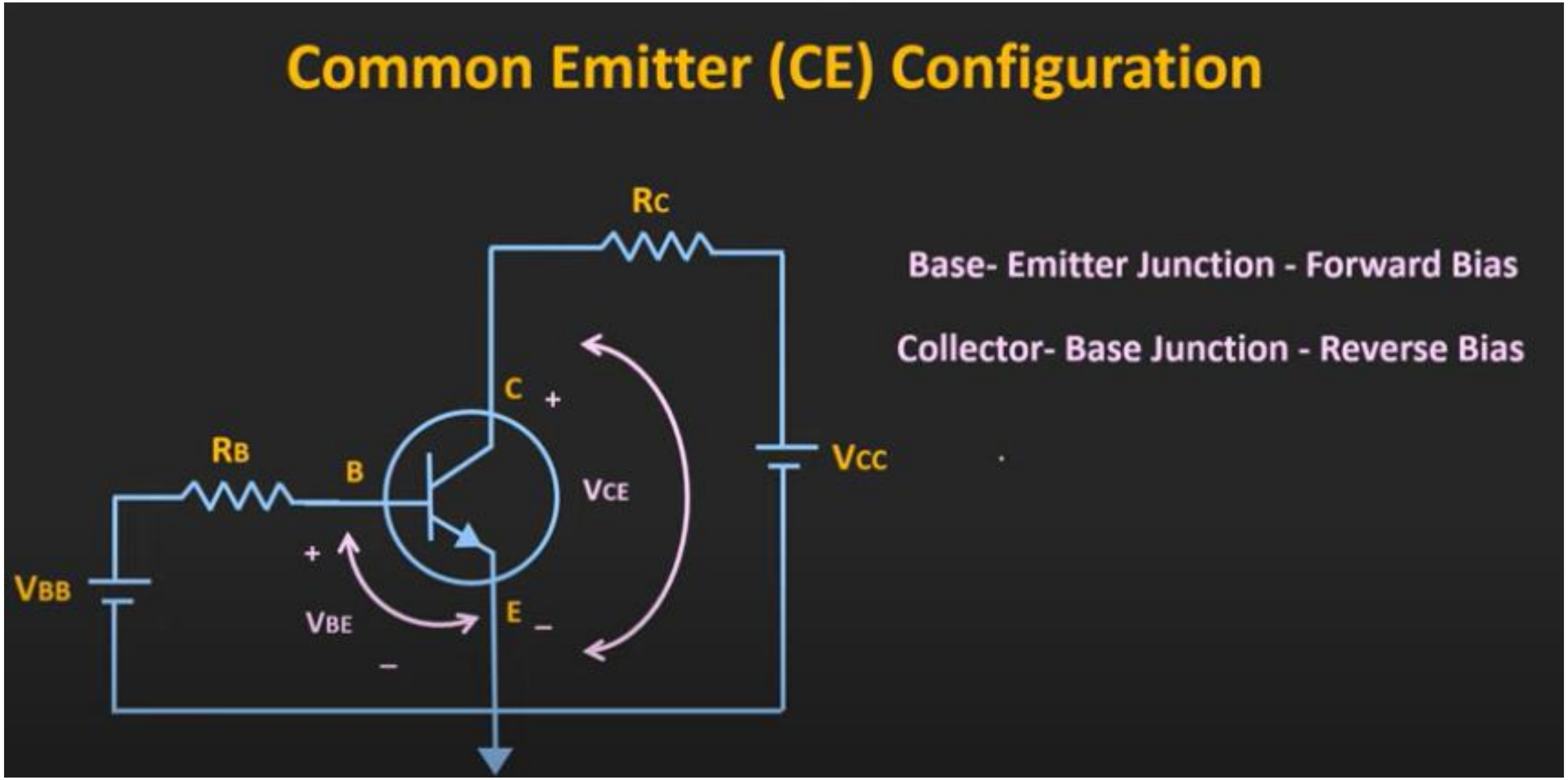


Common Emitter (CE) Configuration
C
Output
B
Input
E



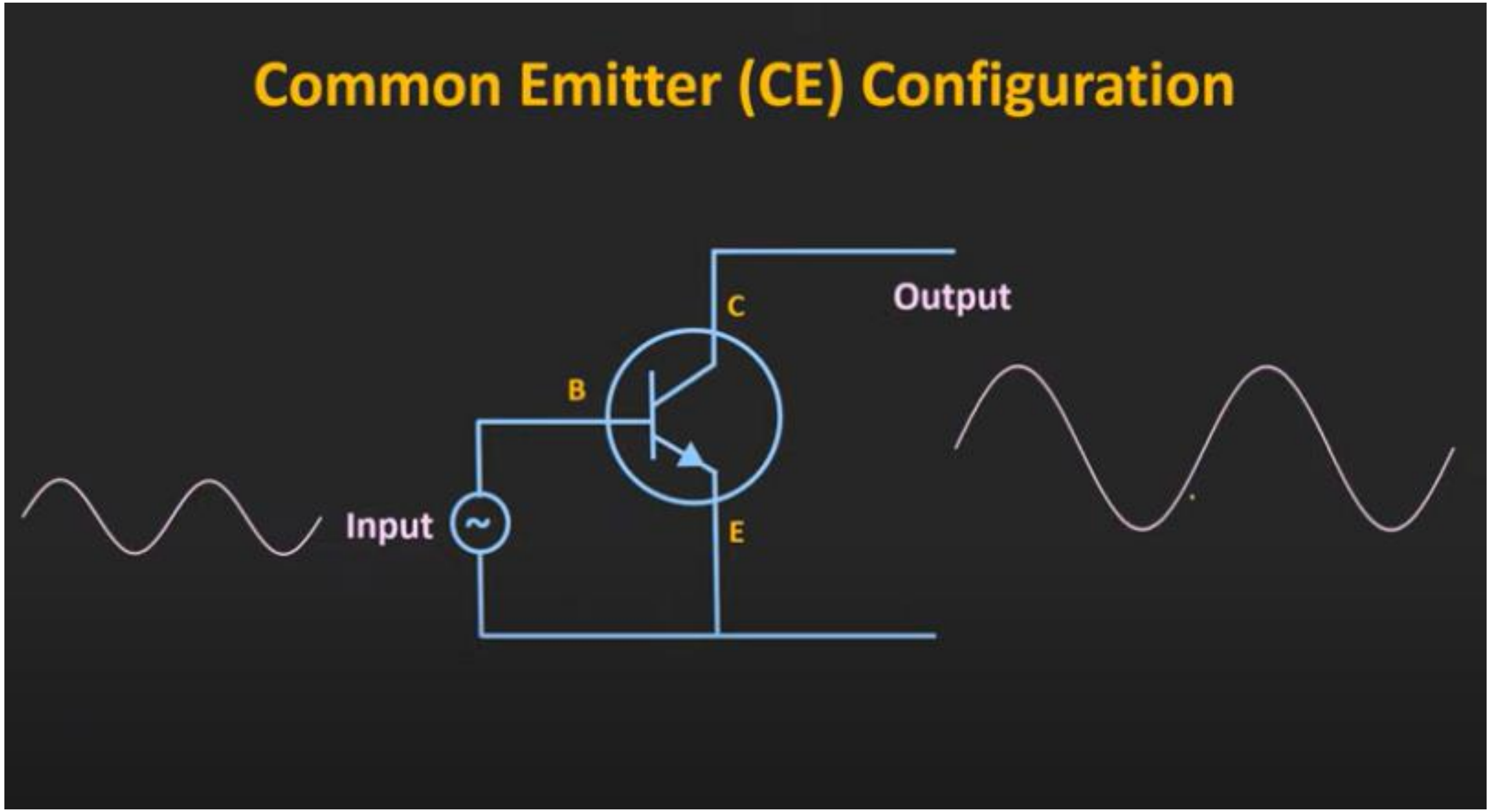
Common Emitter (CE) Configuration
Rc
Base- Emitter Junction - Forward Bias
Collector- Base Junction - Reverse Bias
Collector
N
+
RB
Base
P
VCE
Vcc
+
VBB
VBE
N
Emitter
–
–

CE BJT

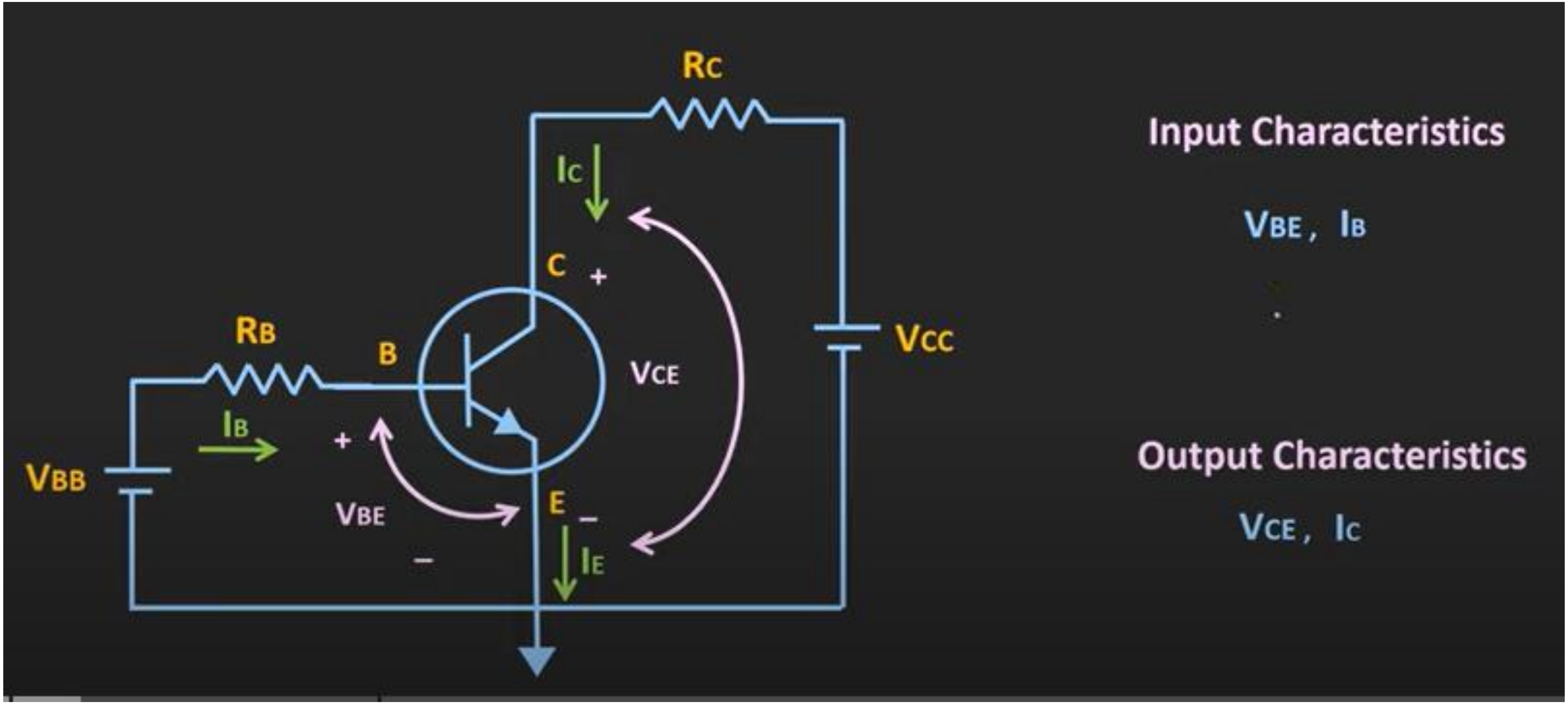


Common Emitter (CE) Configuration
Rc
Base- Emitter Junction - Forward Bias
Collector- Base Junction - Reverse Bias
C
+
RB
B
VCE
Vcc
VBB
+
VBE
E
–
–

CE BJT

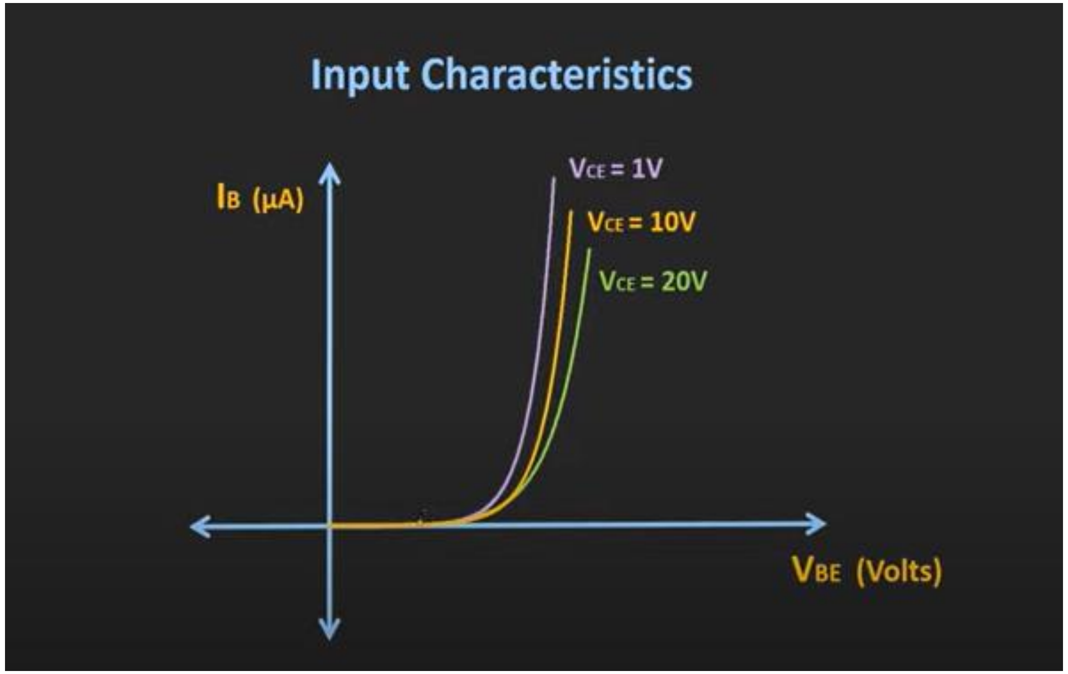


CE BJT

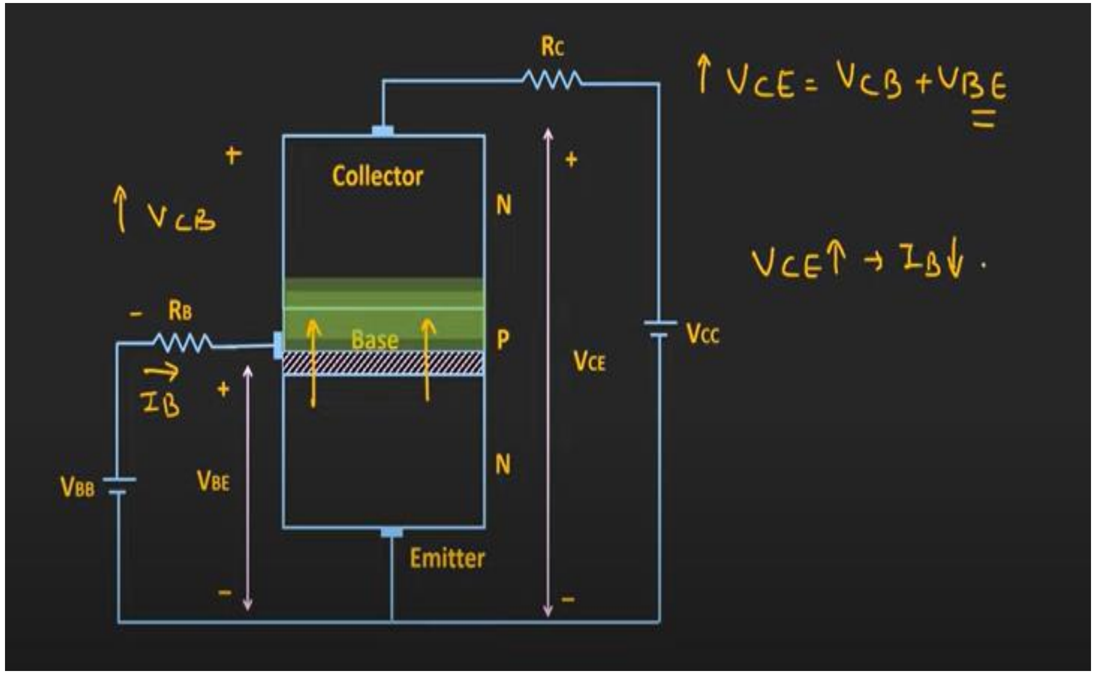


RC
IC
C
+
RB
B
VCC
VCE
IB
+
VBB
VBE
E
–
IE
–
Input Characteristics
VBE , IB
Output Characteristics
VCE , IC

CE BJT

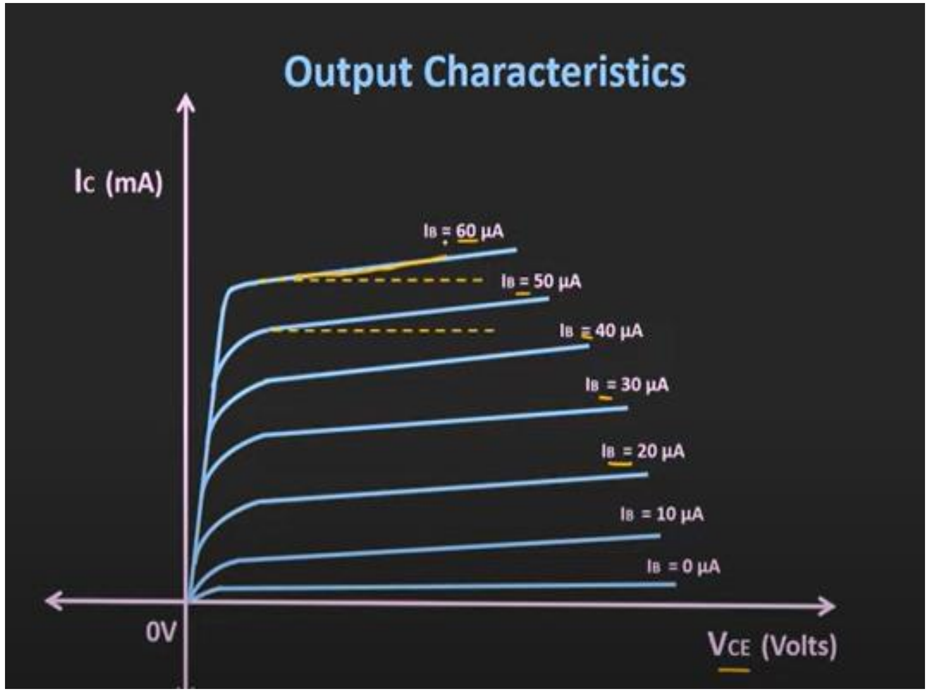


Input Characteristics
I_B (µA)
V_{CE} = 1V
V_{CE} = 10V
V_{CE} = 20V
V_{BE} (Volts)

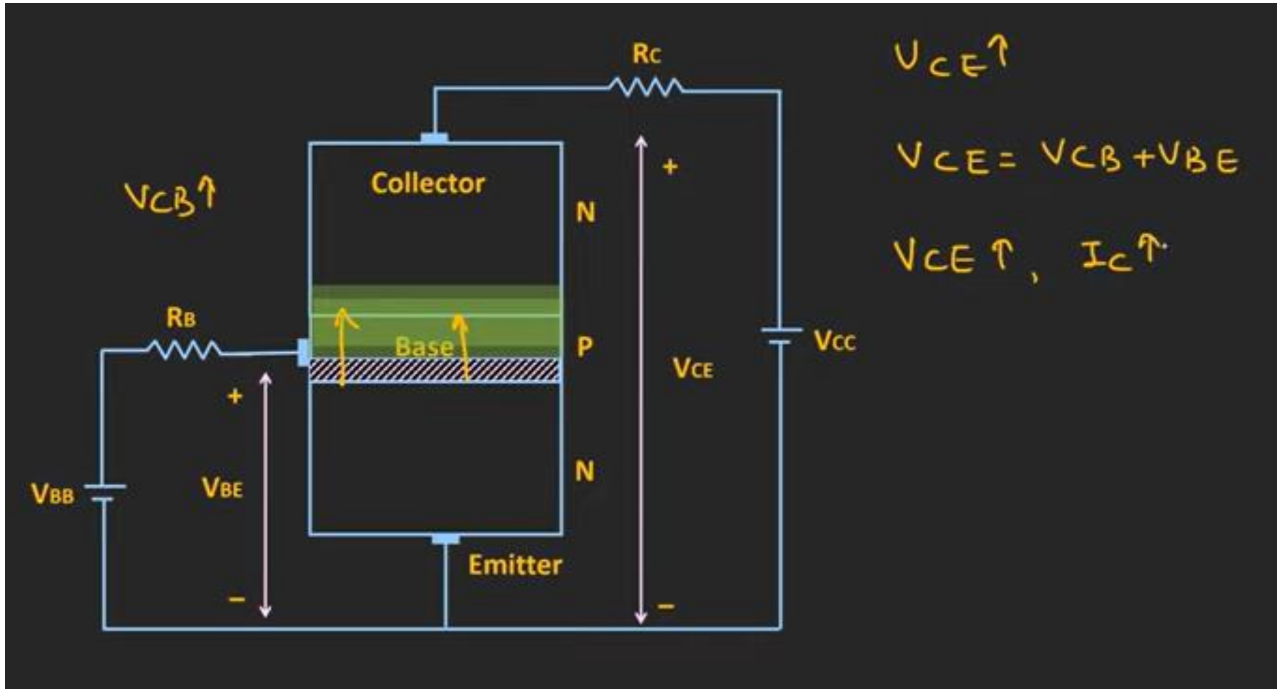


R_C
$\uparrow V_{CE} = V_{CB} + V_{BE}$
$\uparrow V_{CB}$
Collector
N
Base
P
N
Emitter
R_B
I_B
V_{BB}
V_{BE}
V_{CE}
V_{CC}
$V_{CE}\uparrow \rightarrow I_B\downarrow$.

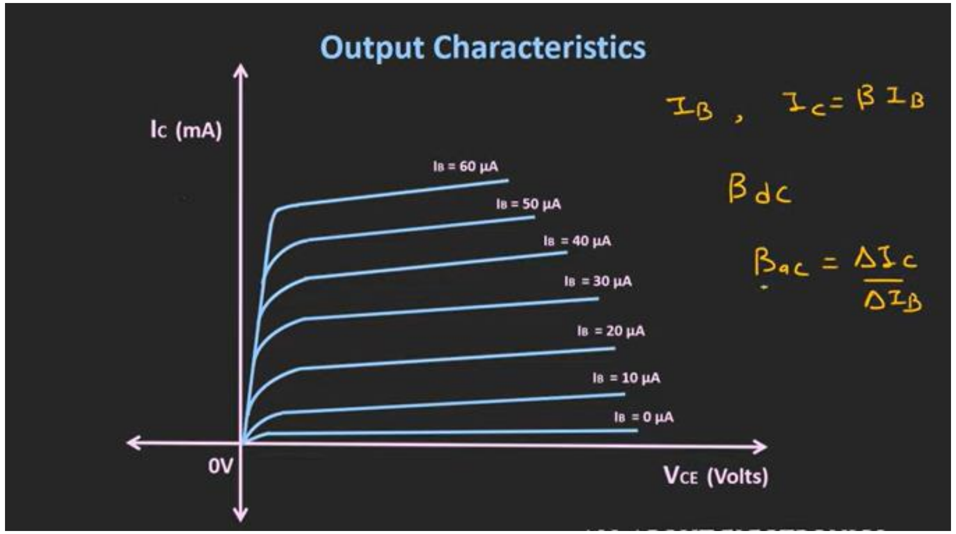
CE BJT



Output Characteristics
Ic (mA)
IB = 60 µA
IB = 50 µA
IB = 40 µA
IB = 30 µA
IB = 20 µA
IB = 10 µA
IB = 0 µA
0V
VCE (Volts)

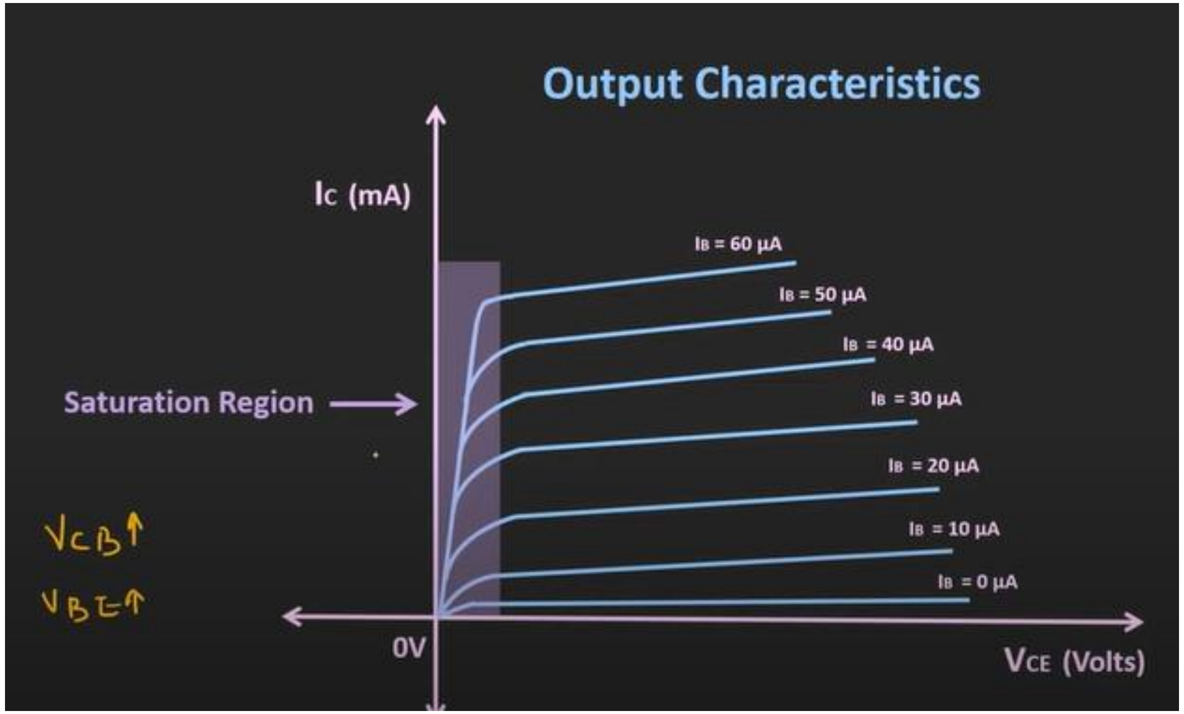


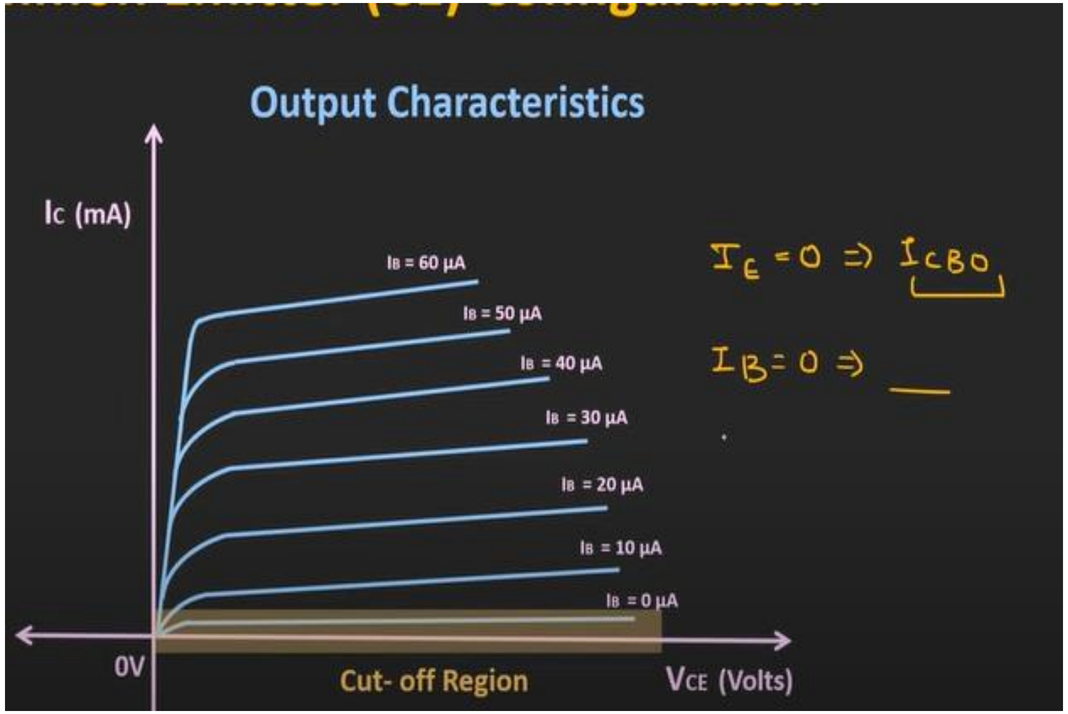
RC
VCE↑
VCE = VCB + VBE
VCE↑ , IC↑
VCB↑
Collector
N
+
RB
Base
P
VCE
VCC
+
VBB
VBE
N
Emitter
−
−



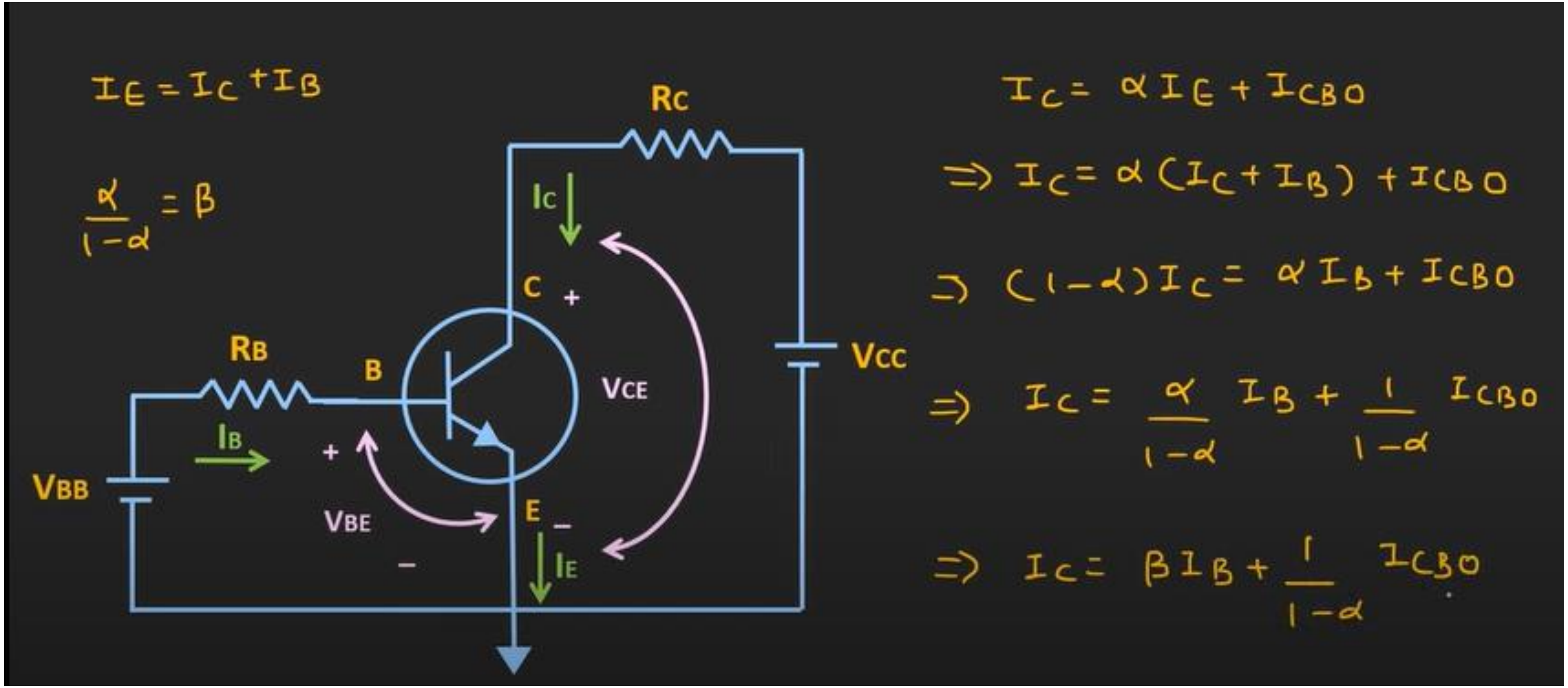
Output Characteristics
Ic (mA)
IB , IC = β IB
βdc
βac = ΔIC / ΔIB
IB = 60 µA
IB = 50 µA
IB = 40 µA
IB = 30 µA
IB = 20 µA
IB = 10 µA
IB = 0 µA
0V
VCE (Volts)

CE BJT


Output Characteristics
Ic (mA)
IB = 60 µA
IB = 50 µA
IB = 40 µA
IB = 30 µA
IB = 20 µA
IB = 10 µA
IB = 0 µA
Saturation Region
VCB↑
VBE↑
0V
VCE (Volts)

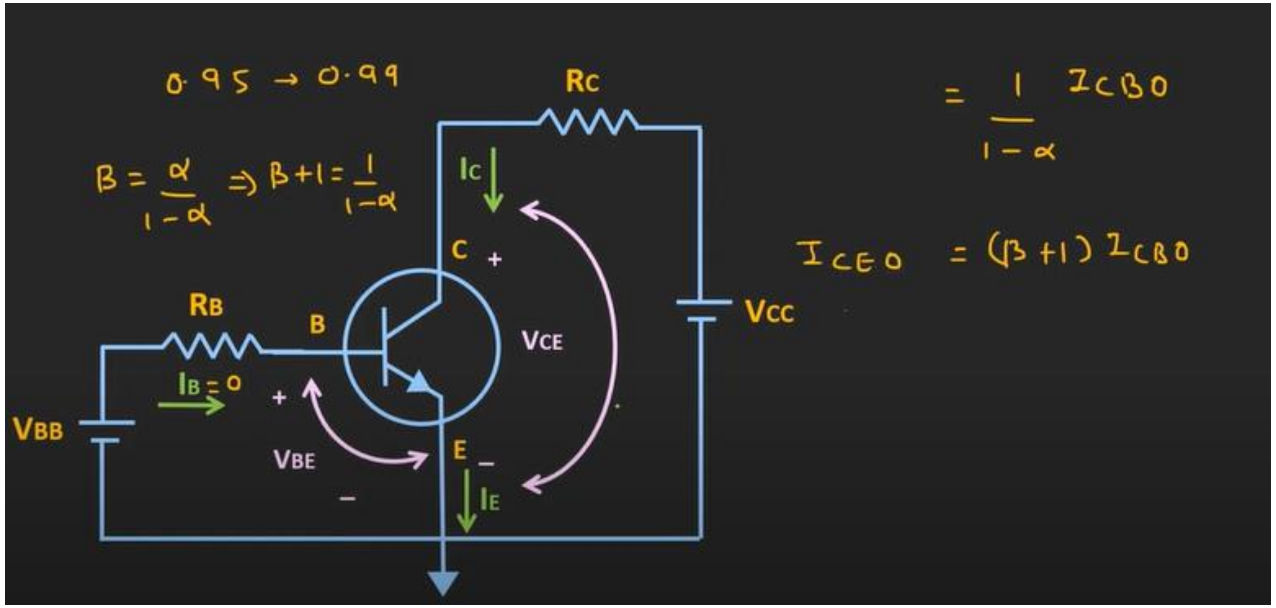

Output Characteristics
Ic (mA)
IB = 60 µA
IB = 50 µA
IB = 40 µA
IB = 30 µA
IB = 20 µA
IB = 10 µA
IB = 0 µA
IE = 0 ⇒ ICBO
IB = 0 ⇒
0V
Cut- off Region
VCE (Volts)

CE BJT

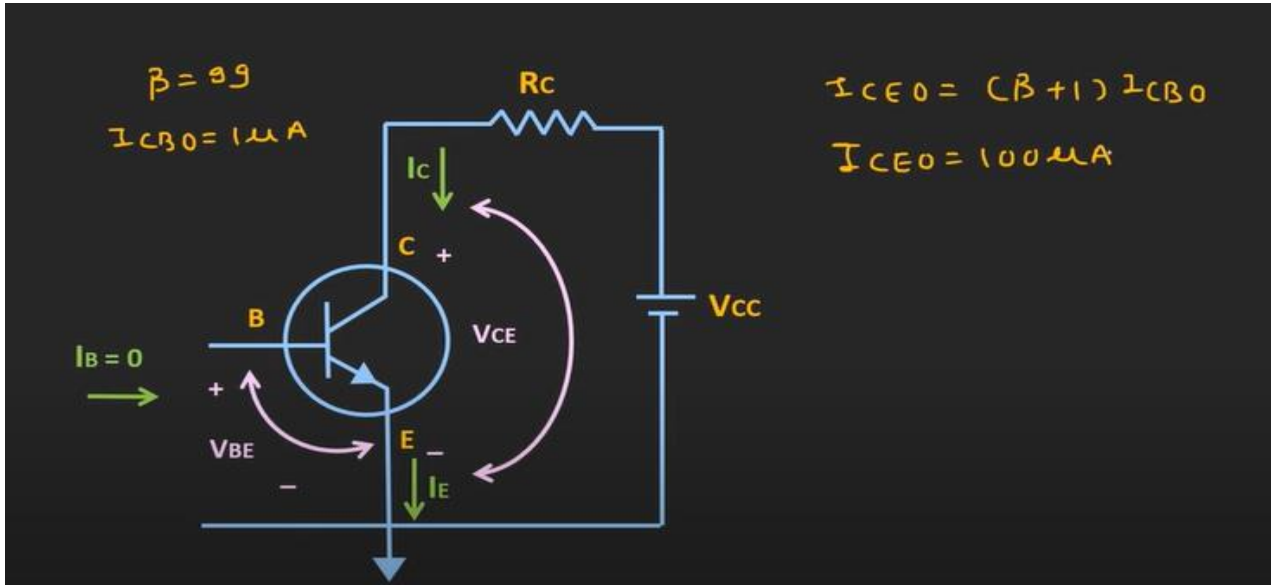


$I_E = I_C + I_B$
$\frac{\alpha}{1-\alpha} = \beta$
RC
IC
C
+
RB
B
VCE
VCC
IB
VBB
+
VBE
E
–
–
IE
$I_C = \alpha I_E + I_{CBO}$
$\Rightarrow I_C = \alpha(I_C + I_B) + I_{CBO}$
$\Rightarrow (1-\alpha) I_C = \alpha I_B + I_{CBO}$
$\Rightarrow I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$
$\Rightarrow I_C = \beta I_B + \frac{1}{1-\alpha} I_{CBO}$

CE BJT



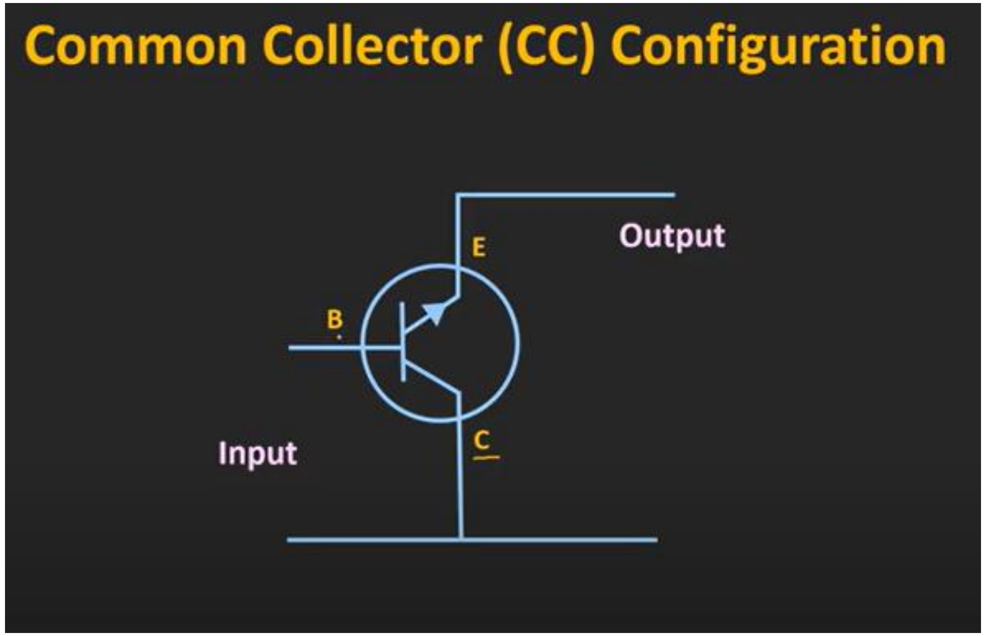
0.95 → 0.99
B = α / (1−α) ⇒ B+1 = 1 / (1−α)
Rc
= 1 / (1−α) ICBO
ICEO = (β+1) ICBO
Ic
C
+
RB
B
VCE
Vcc
IB = 0
+
VBB
VBE
E
−
IE
−

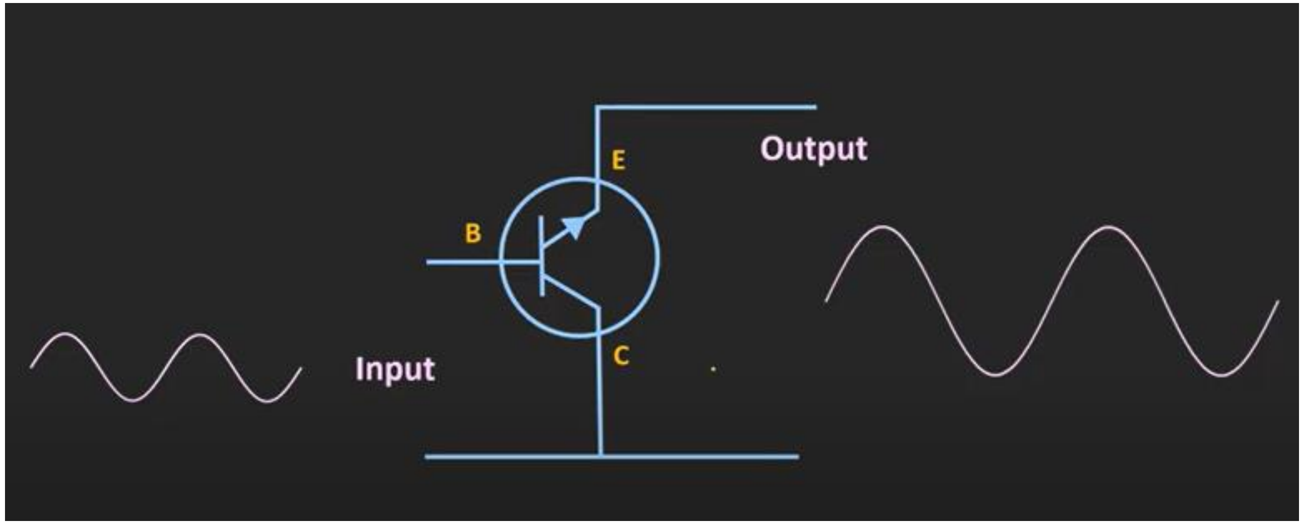


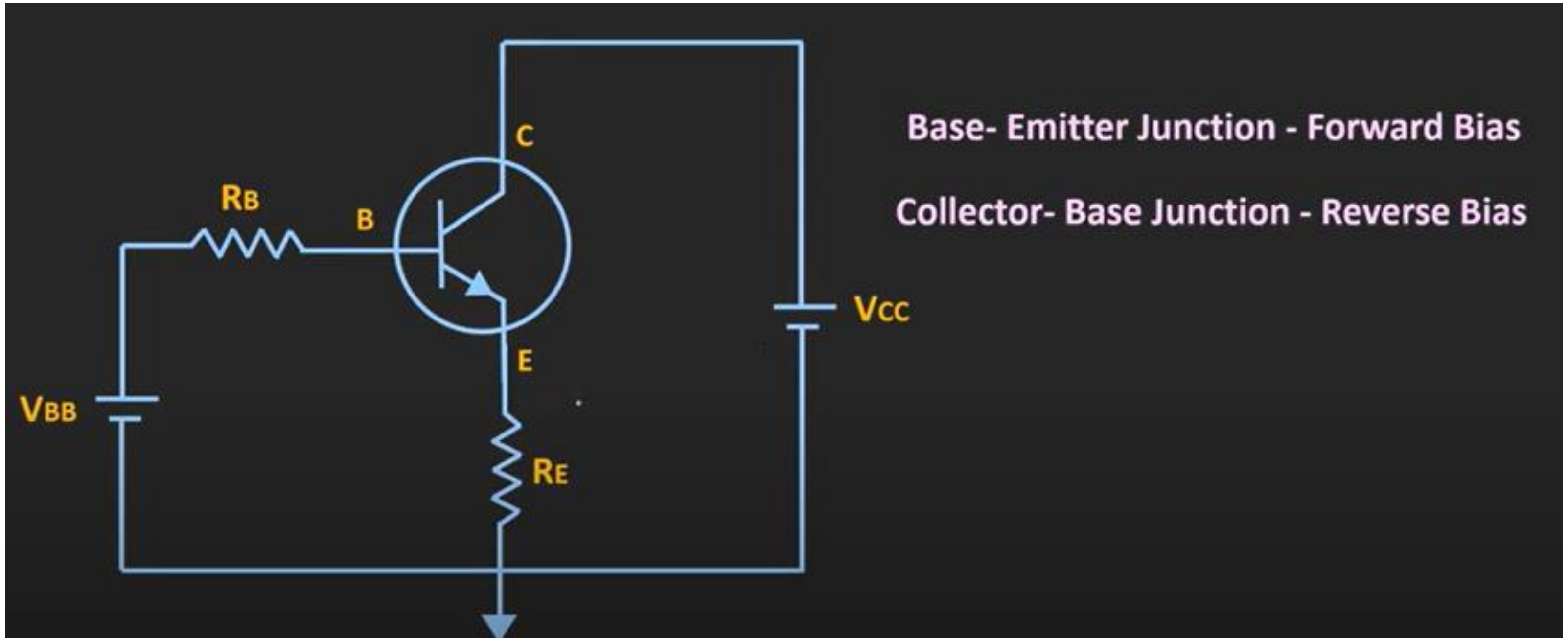
β = 99
ICBO = 1μA
Rc
ICEO = (β+1) ICBO
ICEO = 100μA
Ic
C
+
B
VCE
Vcc
IB = 0
+
VBE
E
−
IE
−

Moderate Current Gain
Moderate Voltage Gain
High Power Gain
Moderate Input Impedance
Moderate Output Impedance

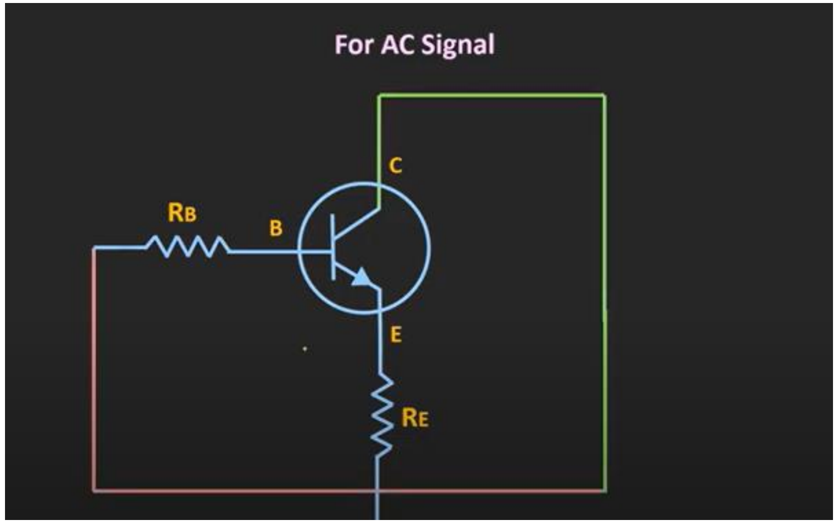
CC BJT

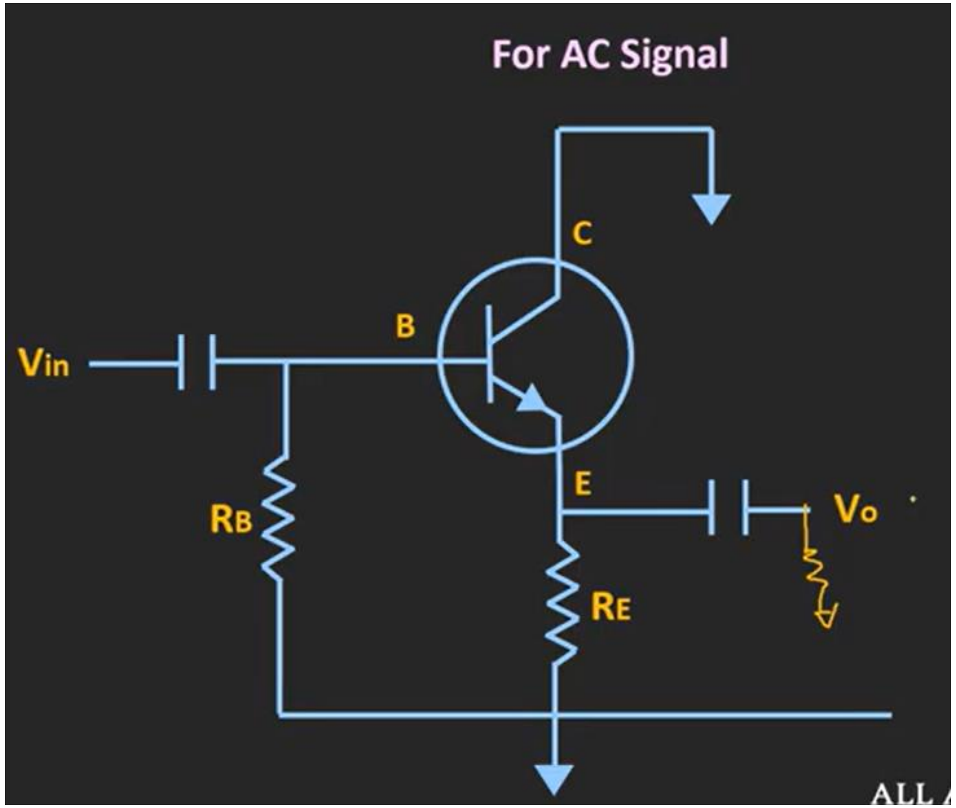

Common Collector (CC) Configuration
Output
E
B
C
Input

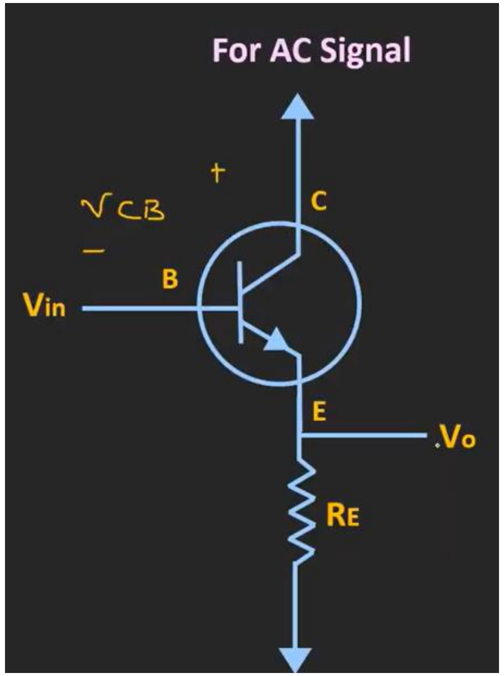

Output
E
B
C
Input

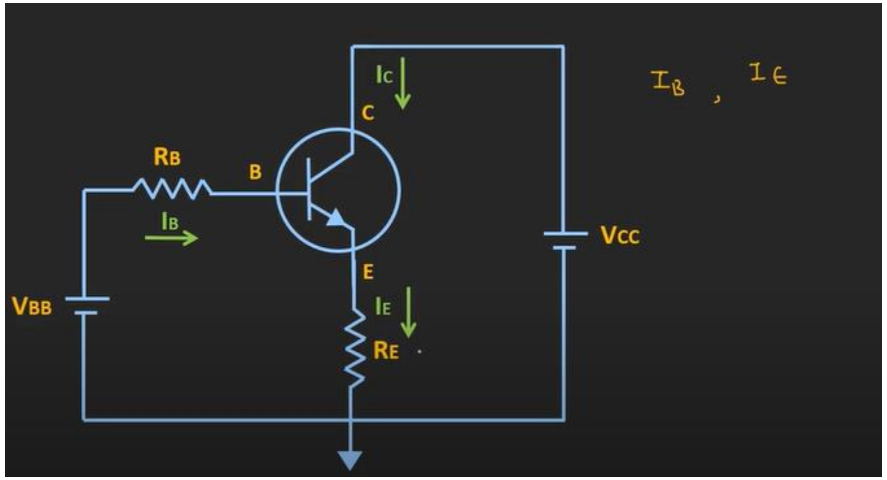

C
RB
B
E
VBB
RE
VCC
Base- Emitter Junction - Forward Bias
Collector- Base Junction - Reverse Bias

CE BJT

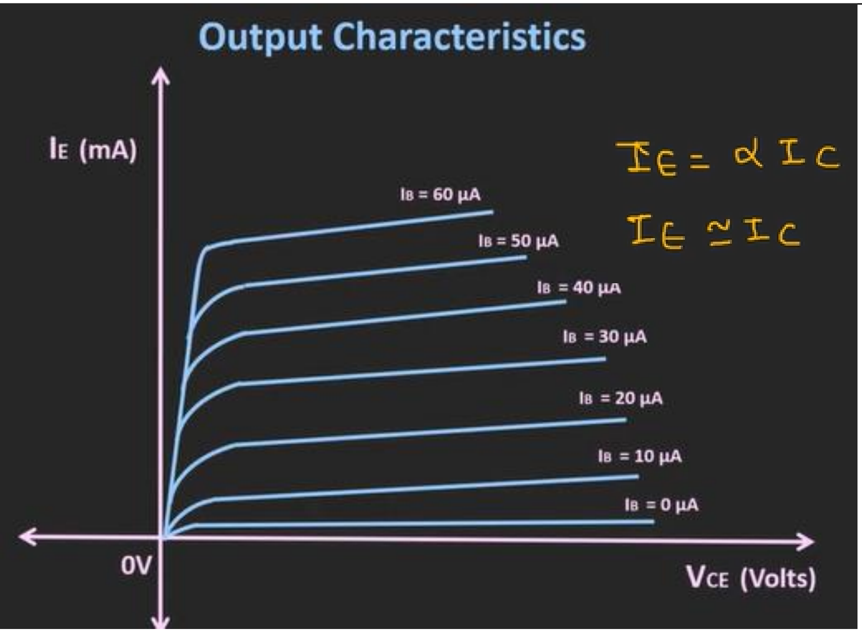

For AC Signal
RB
B
C
E
RE


For AC Signal
C
B
Vin
E
RB
Vo
RE

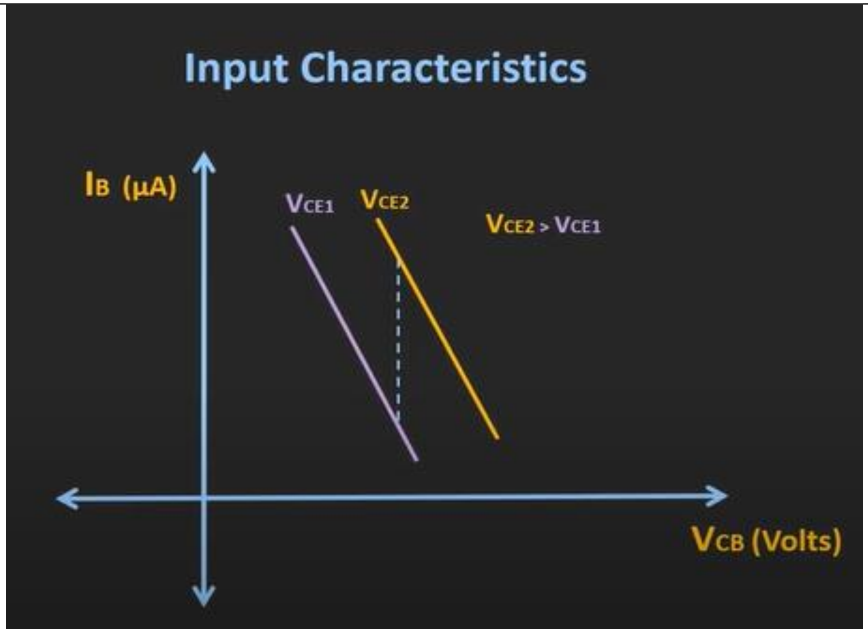

For AC Signal
+
VCB
−
C
B
Vin
E
Vo
RE


Ic
C
IB , IE
RB
B
IB
Vcc
VBB
E
IE
RE

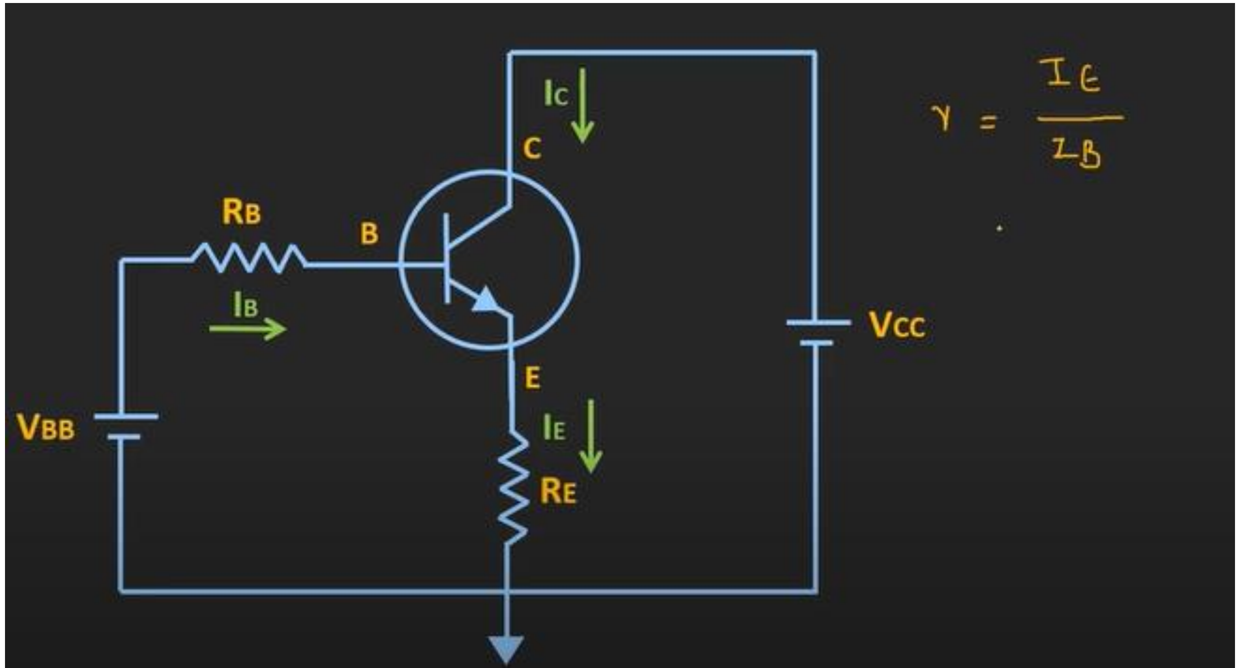
CC BJT



Output Characteristics
IE (mA)
IB = 60 μA
IB = 50 μA
IB = 40 μA
IB = 30 μA
IB = 20 μA
IB = 10 μA
IB = 0 μA
0V
VCE (Volts)
IE = α IC
IE ≃ IC



Input Characteristics
IB (μA)
VCE1
VCE2
VCE2 > VCE1
VCB (Volts)



IC
C
RB
B
IB
VCC
E
VBB
IE
RE
γ = IE / IB

Alpha (α):

- It is a large signal current gain in common base configuration.
- It is the ratio of collector current (output current) to the emitter current (input current).

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

- It indicates that the amount of emitter current reaching to collector.
- Its value is unity ideally and practically less than unity.

Beta (β):

- It is a current gain factor in the common emitter configuration. It is the ration of collector current (output current) to base current (output current).

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

- Normally Its value is greater than 100.

Gama (γ):

- It is a current gain in common collector configuration and it is the ration of emitter current (output current) to base current (input current).

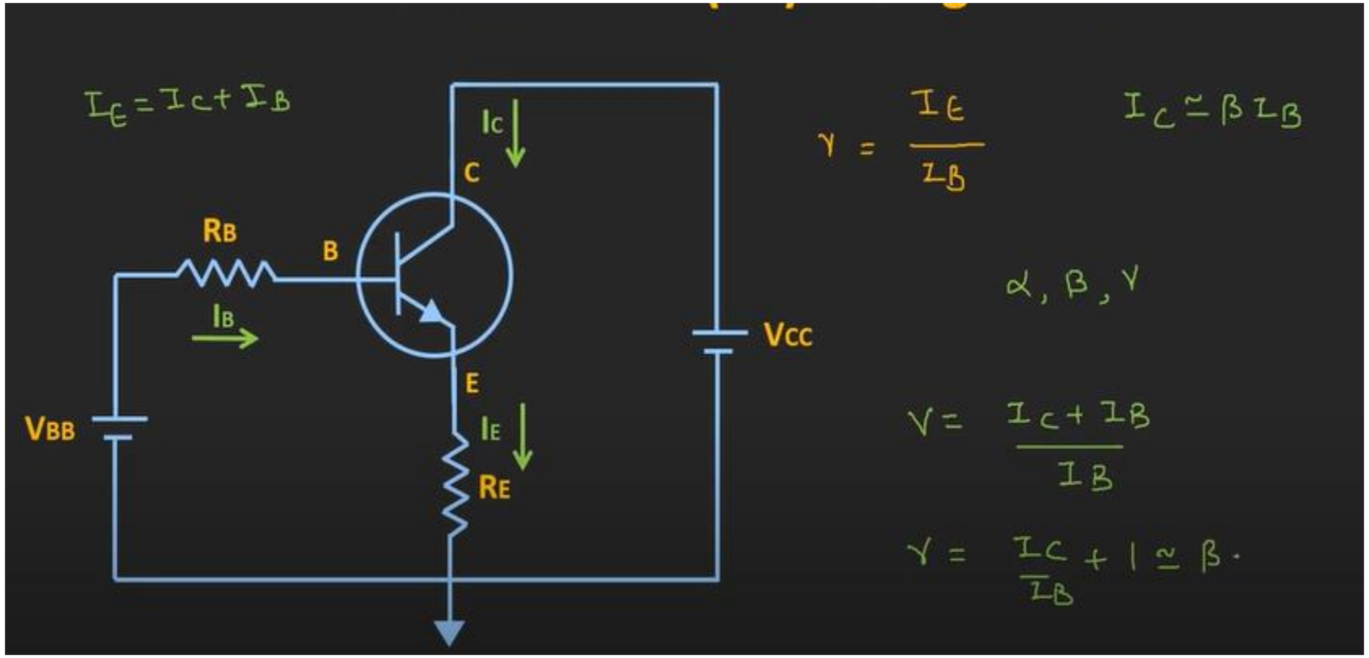
$$\gamma = \frac{I_E}{I_B}$$

- It is also called emitter efficiency that how much current is injected from the emitter to base after recombination of minority charge carriers in base.
- It's value is high compared to α, β
- Relation between α, β and γ

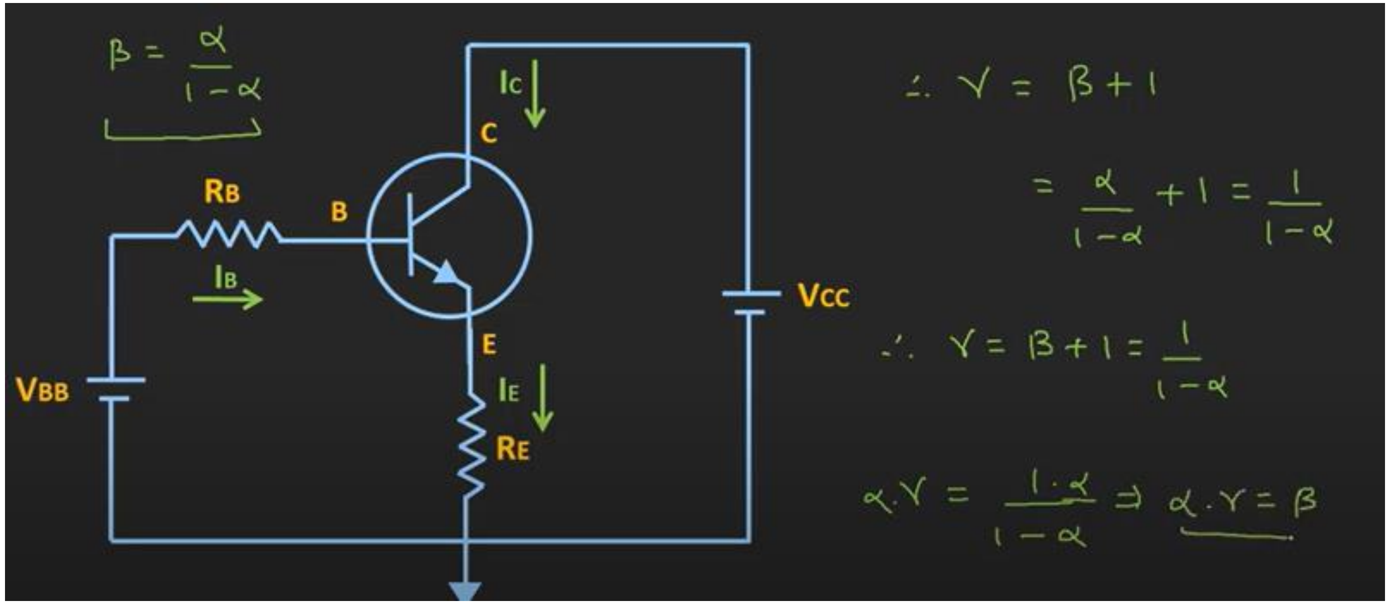
$$\gamma = \beta + 1 = \frac{1}{1-\alpha}$$

$$\alpha\,\gamma = \beta$$

CC BJT

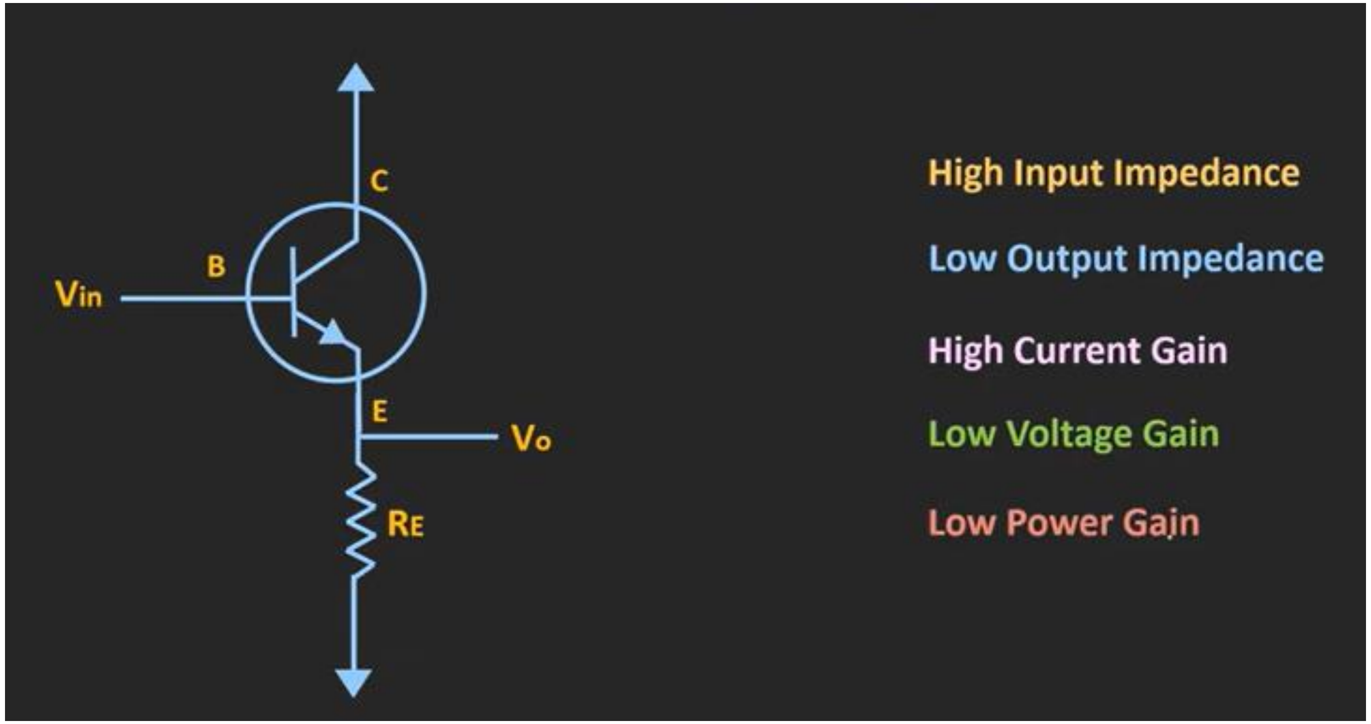


$I_E = I_C + I_B$
Ic
C
RB
B
IB
VBB
E
IE
RE
Vcc
$\gamma = \frac{I_E}{I_B}$
$I_C \simeq \beta I_B$
α, β, γ
$\gamma = \frac{I_C + I_B}{I_B}$
$\gamma = \frac{I_C}{I_B} + 1 \simeq \beta.$



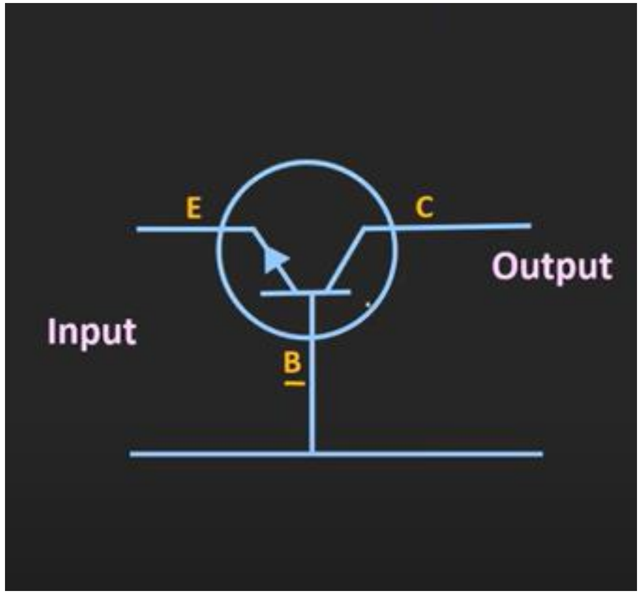
$\beta = \frac{\alpha}{1-\alpha}$
Ic
C
RB
B
IB
VBB
E
IE
RE
Vcc
$\therefore \gamma = \beta + 1$
$= \frac{\alpha}{1-\alpha} + 1 = \frac{1}{1-\alpha}$
$\therefore \gamma = \beta + 1 = \frac{1}{1-\alpha}$
$\alpha \cdot \gamma = \frac{1 \cdot \alpha}{1-\alpha} \Rightarrow \alpha \cdot \gamma = \beta$

CC BJT

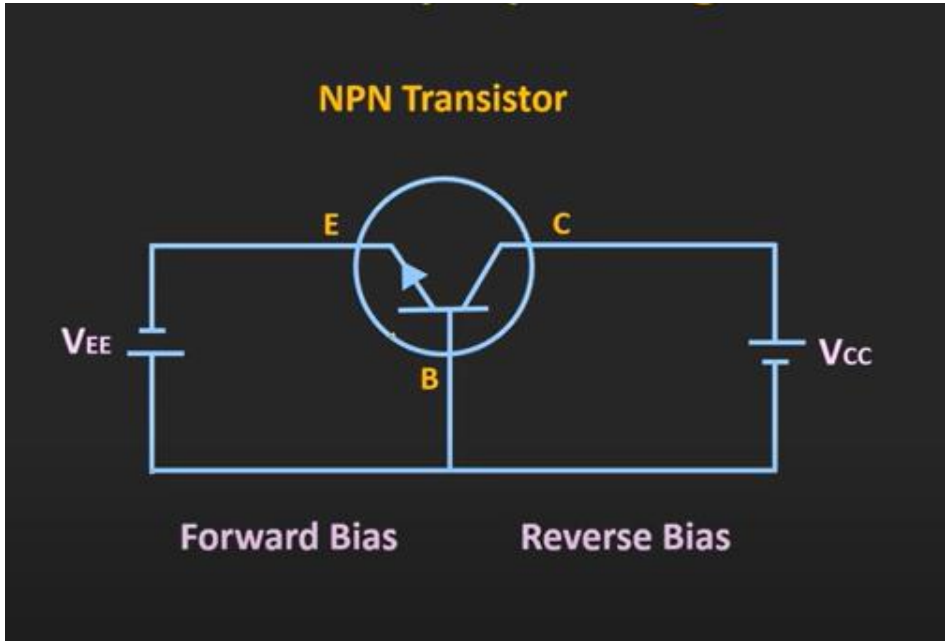


C
B
Vin
E
Vo
RE
High Input Impedance
Low Output Impedance
High Current Gain
Low Voltage Gain
Low Power Gain

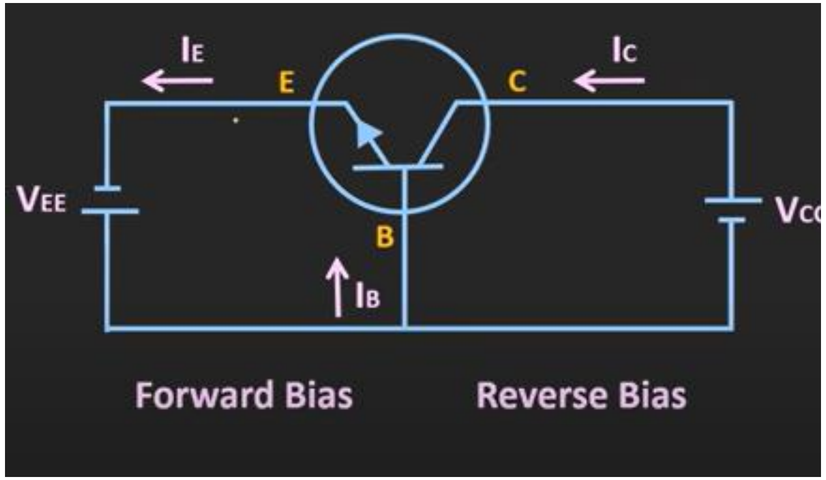
CB BJT



E
C
Output
Input
B

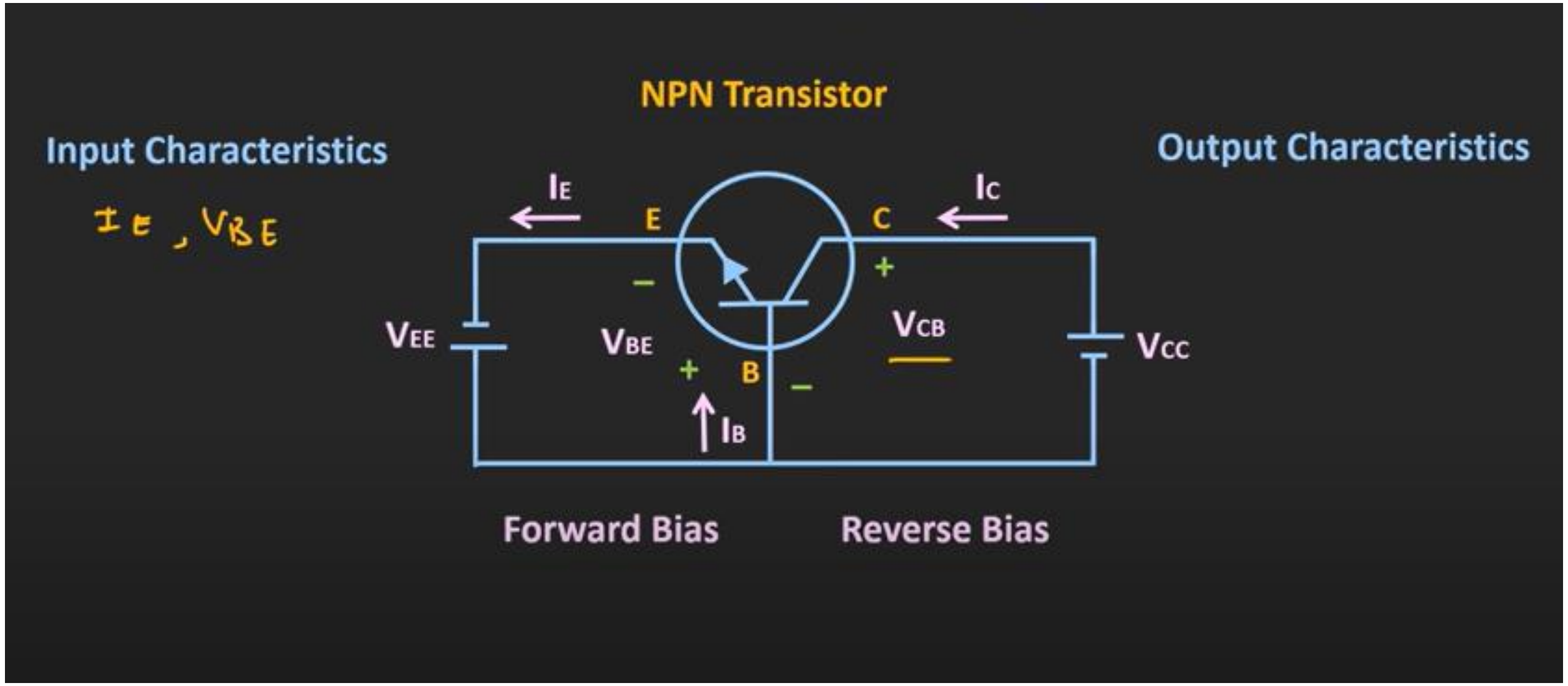


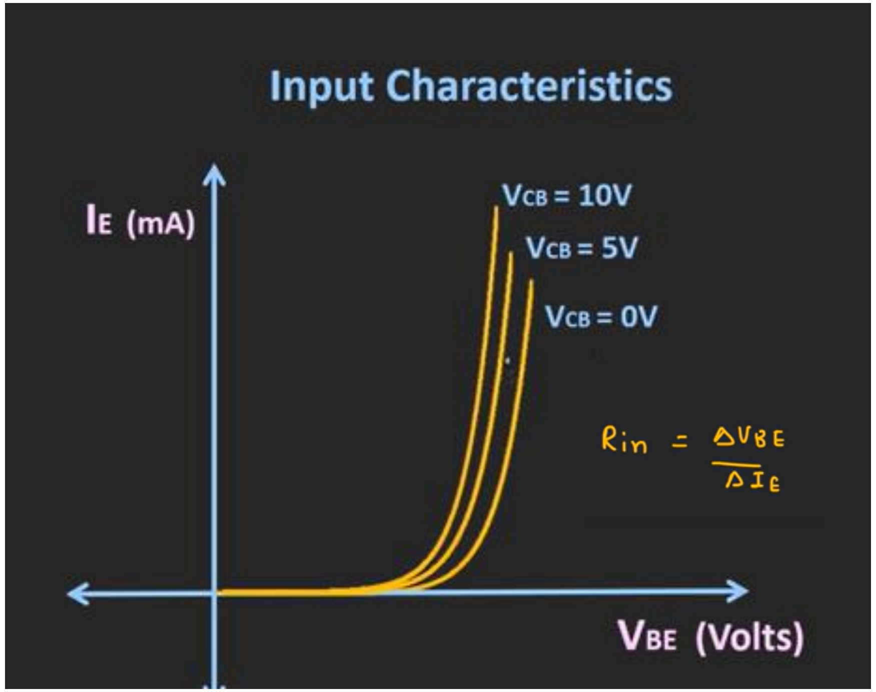
NPN Transistor
E
C
VEE
VCC
B
Forward Bias
Reverse Bias



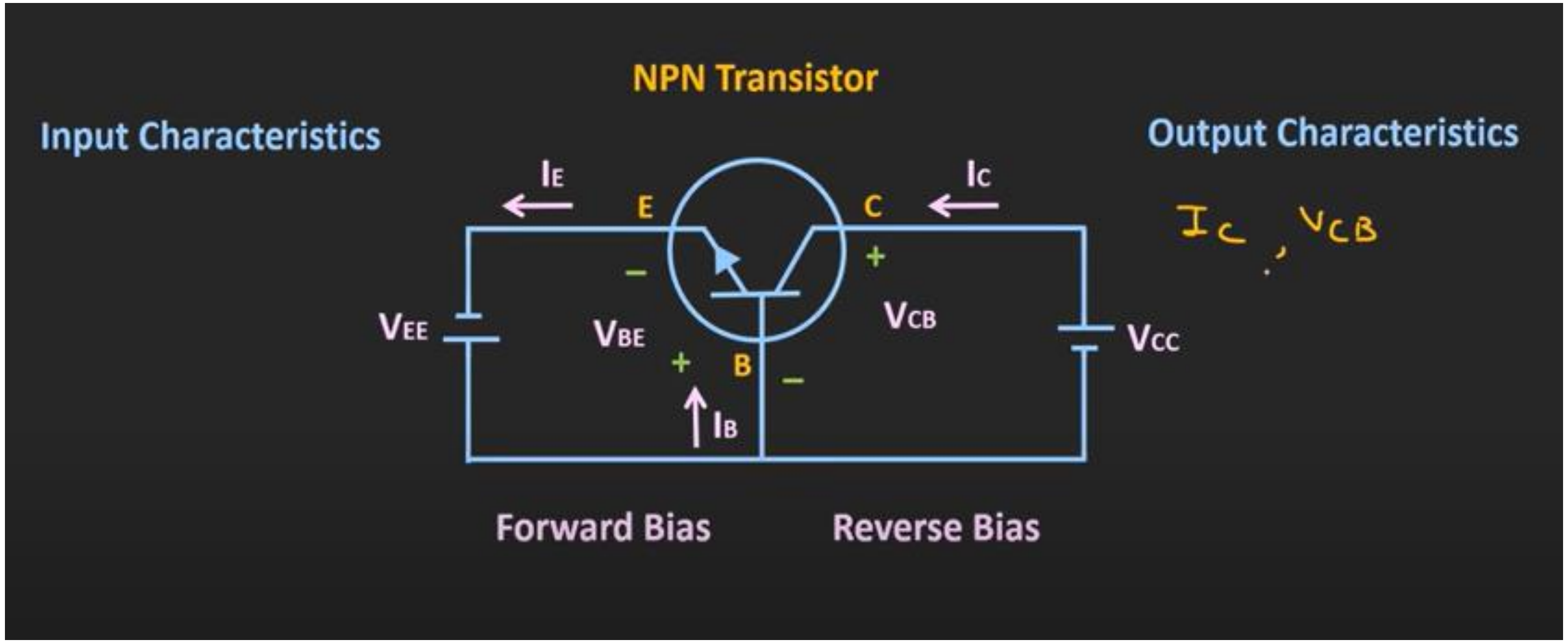
IE
IC
E
C
VEE
B
IB
Forward Bias
Reverse Bias

CB BJT

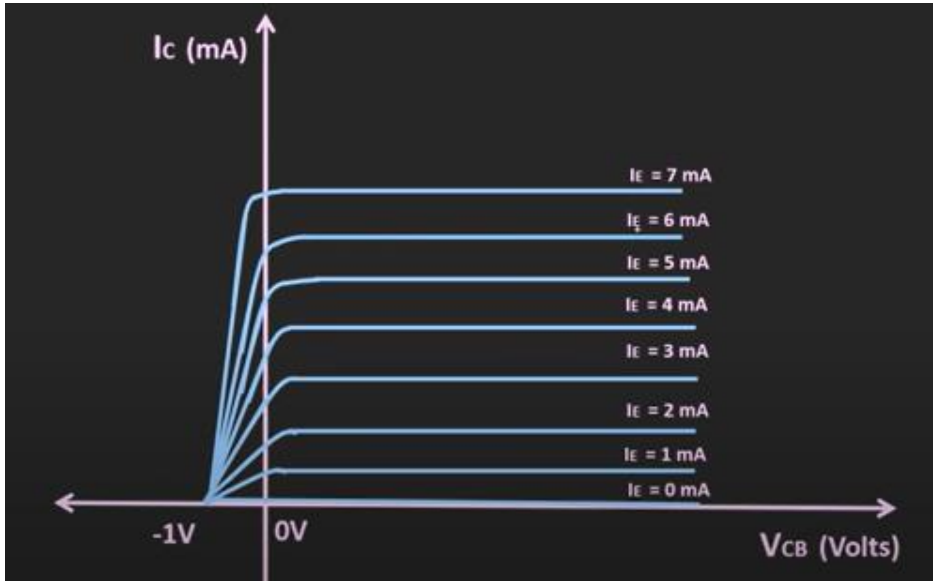

NPN Transistor
Input Characteristics
Output Characteristics
IE , VBE
IE
IC
E
C
B
VEE
VBE
VCB
VCC
IB
+
−
Forward Bias
Reverse Bias


Input Characteristics
IE (mA)
VCB = 10V
VCB = 5V
VCB = 0V
Rin = ΔVBE / ΔIE
VBE (Volts)

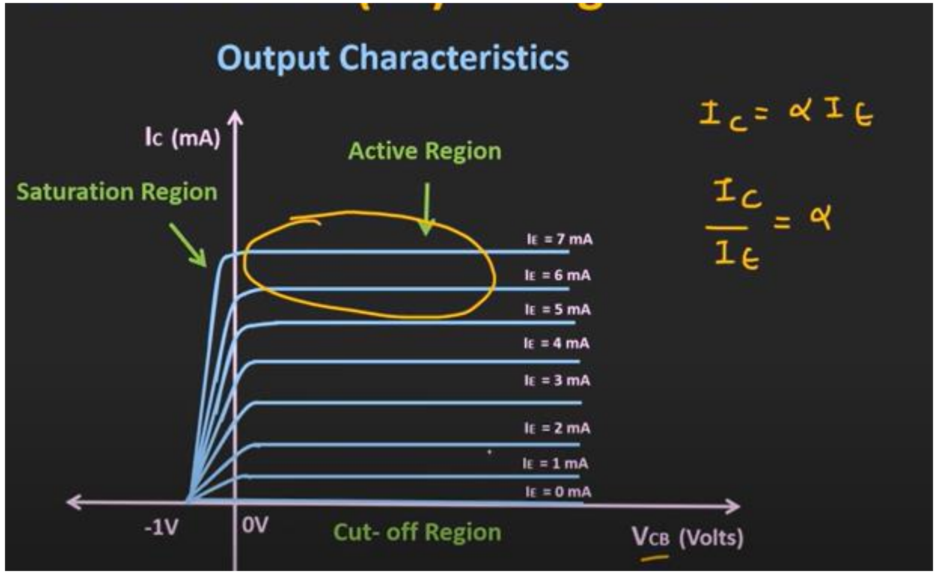
CB BJT



NPN Transistor
Input Characteristics
Output Characteristics
IE
IC
E
C
VEE
VBE
VCB
VCC
B
IB
Ic , VCB
Forward Bias
Reverse Bias

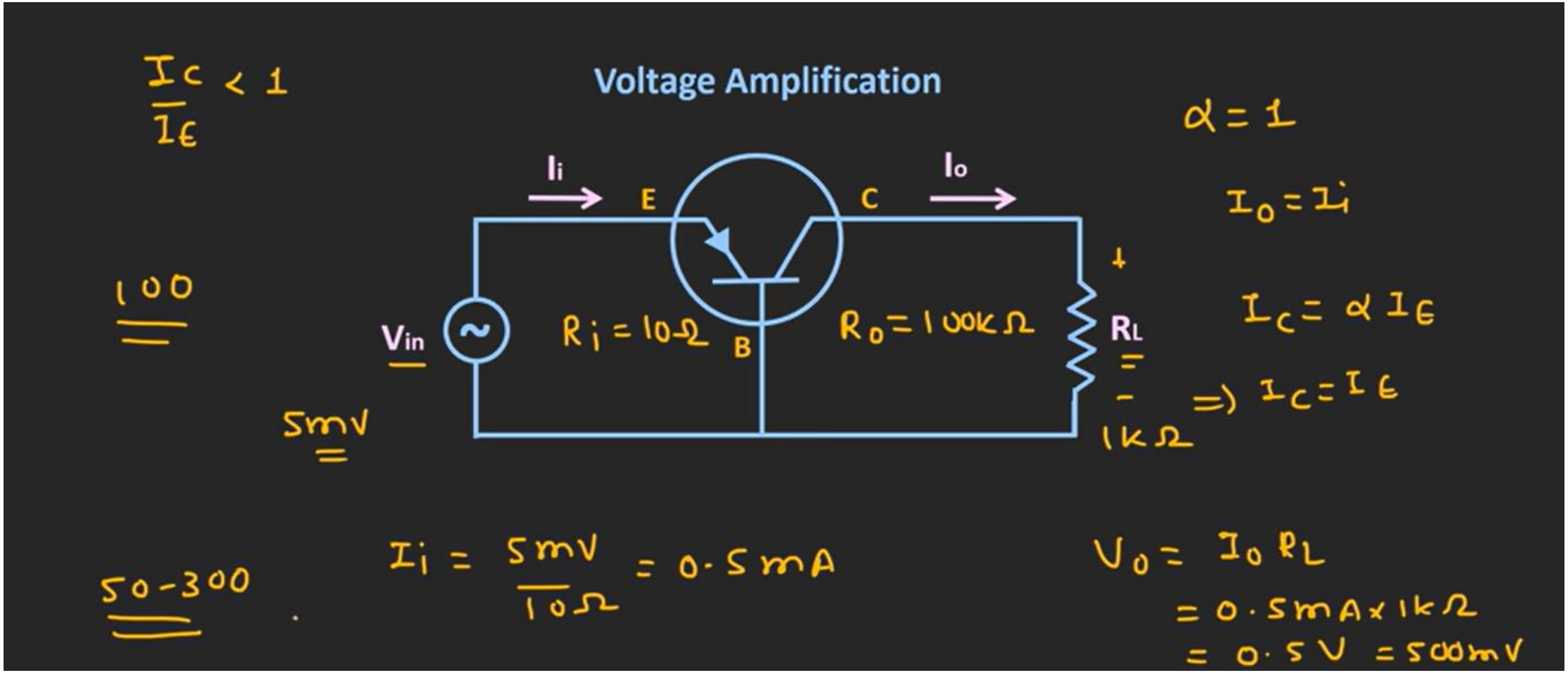


Ic (mA)
IE = 7 mA
IE = 6 mA
IE = 5 mA
IE = 4 mA
IE = 3 mA
IE = 2 mA
IE = 1 mA
IE = 0 mA
-1V
0V
VCB (Volts)



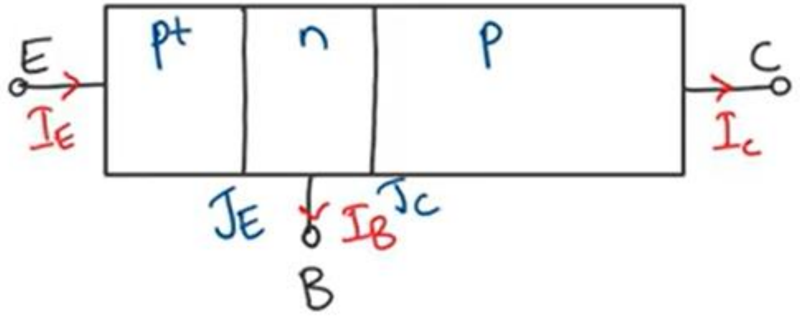
Output Characteristics
Ic (mA)
Active Region
Saturation Region
IE = 7 mA
IE = 6 mA
IE = 5 mA
IE = 4 mA
IE = 3 mA
IE = 2 mA
IE = 1 mA
IE = 0 mA
-1V
0V
Cut- off Region
VCB (Volts)
$I_C = \alpha I_E$
$\frac{I_C}{I_E} = \alpha$

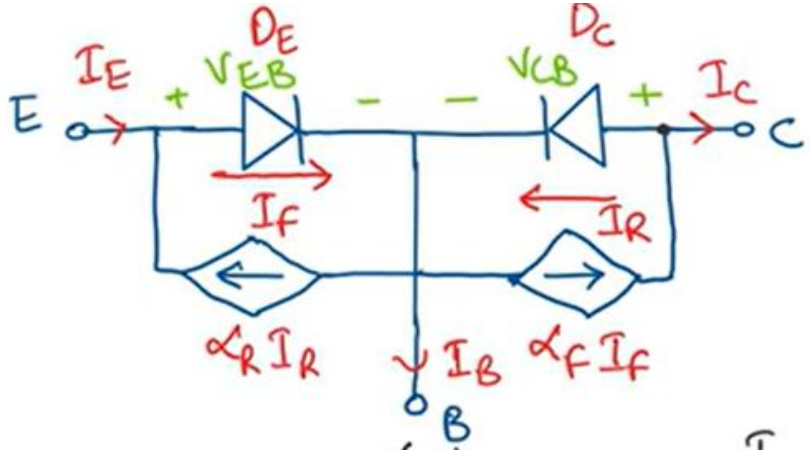
CB BJT



Voltage Amplification
$\frac{I_C}{I_E} < 1$
100
50-300
5mV
V_{in}
I_i
E
C
I_o
B
$R_i = 10\Omega$
$R_o = 100k\Omega$
R_L
+
-
$1k\Omega$
$\alpha = 1$
$I_o = I_i$
$I_C = \alpha I_E$
$\Rightarrow I_C = I_E$
$I_i = \frac{5mV}{10\Omega} = 0.5mA$
$V_o = I_o R_L$
$= 0.5mA \times 1k\Omega$
$= 0.5V = 500mV$

Ebers-Moll Model of BJT





Large Signal Model

All modes of operations.

$$I_E = I_F - \alpha_R I_R = I_{E0}\left(e^{V_{EB}/V_T} - 1\right) - \alpha_R I_{C0}\left(e^{V_{CB}/V_T} - 1\right)$$

$$I_C = \alpha_F I_F - I_R = \alpha_F I_{E0}\left(e^{V_{EB}/V_T} - 1\right) - I_{C0}\left(e^{V_{CB}/V_T} - 1\right)$$

$$I_B = I_F + I_R - \alpha_F I_F - \alpha_R I_R$$

$$= (I_F - \alpha_R I_R) - (\alpha_F I_F - I_R)$$

$$I_B = I_E - I_C$$

Active Mode:- J_E is F.B V_{EB} is +ve, J_C is R.B V_{CB} is −ve.

$$I_E = I_{E0}\left(e^{V_{EB}/V_T} - 1\right) + \alpha_R I_{C0}$$

$$I_C = \alpha_F I_{E0}\left(e^{V_{EB}/V_T} - 1\right) + I_{C0}$$

$$I_E = I_{E0}\left(e^{V_{EB}/V_T} - 1\right) + \frac{Aq D_p p_{n0}}{W}$$

$$I_C = \frac{Aq D_p p_{n0}}{W}\left(e^{V_{EB}/V_T} - 1\right) + I_{C0}$$

Ebers-Moll Model of BJT

$$\alpha_F I_{EO} = \alpha_R I_{CO} = I_S$$

$$I_{EO} = \frac{I_S}{\alpha_F} \qquad I_{CO} = \frac{I_S}{\alpha_R}$$

$$I_E = \frac{I_S}{\alpha_F}\left(e^{V_{EB}/V_T} - 1\right) - I_S\left(e^{V_{CB}/V_T} - 1\right)$$

$$I_C = I_S\left(e^{V_{EB}/V_T} - 1\right) - \frac{I_S}{\alpha_R}\left(e^{V_{CB}/V_T} - 1\right)$$

$$I_B = I_E - I_C \rightarrow I_S, \alpha_F, \alpha_R$$

$$\alpha_F = \frac{\beta_F}{1+\beta_F} \qquad \alpha_R = \frac{\beta_R}{1+\beta_R}$$

$$I_E = I_S\left[\left(e^{V_{EB}/V_T} - e^{V_{CB}/V_T}\right) + \frac{1}{\beta_F}\left(e^{V_{EB}/V_T} - 1\right)\right] \rightarrow I_S, \beta_F, \beta_R$$

$$I_C = I_S\left[\left(e^{V_{EB}/V_T} - e^{V_{CB}/V_T}\right) - \frac{1}{\beta_R}\left(e^{V_{CB}/V_T} - 1\right)\right]$$

$$I_B = I_S\left[\frac{1}{\beta_F}\left(e^{V_{EB}/V_T} - 1\right) - \frac{1}{\beta_R}\left(e^{V_{CB}/V_T} - 1\right)\right]$$

2.3 Modes of Operation

The Ebers-Moll BJT Model is a good large-signal, steady-state model of the transistor and allows the state of conduction of the device to be easily determined for different modes of operation of the device. The different modes of operation are determined by the manner in which the junctions are biased. The charge profiles for each mode are shown in Fig. 2.4.

(a)Forward Active Mode

B-E forward-biased, V_{BE} positive | **B-C reverse biased, V_{BC} negative**

$e^{V_{BE}/V_T} >> 1$ | $e^{V_{BC}/V_T} << 1$

Then from the model,

$$I_E \approx I_{ES} e^{V_{BE}/V_T}$$ relatively large

$$I_C \approx \alpha_F I_{ES} e^{V_{BE}/V_T} = \alpha_F I_E$$ relatively large

$$I_B \approx (1-\alpha_F) I_{ES} e^{V_{BE}/V_T} = (1-\alpha_F) I_E$$ small

(b)Reverse Active Mode

B-E reverse biased, V_{BE} negative **B-C forward biased, V_{BC} positive**

$e^{V_{BE}/V_T} << 1,$ $e^{V_{BC}/V_T} >> 1$

Essentially the transistor conducts in the opposite direction.
From the model,

$$I_E \approx -\alpha_R I_{CS} e^{V_{BC}/V_T}$$ **moderately high**

$$I_C \approx -I_{CS} e^{V_{BC}/V_T}$$ **moderate**

$$I_B \approx (1-\alpha_R) I_{CS} e^{V_{BC}/V_T}$$ **as high as $0.5\,|\,I_C\,|$**

This mode does not provide useful amplification but is used, mainly, for current steering in switching circuits, e.g. TTL.

(c)Cut-Off Mode

B-E unbiased, V_{BE} = 0V **B-C reverse biased, V_{BC} negative**

$$e^{V_{BE}/V_T} = 1, \qquad e^{V_{BC}/V_T} << 1.$$

Then,

$$I_E \approx \alpha_R I_{CS}$$ **leakage current nA**

$$I_C \approx I_{CS}$$ **leakage current nA**

$$I_B \approx -(1 - \alpha_R) I_{CS}$$

This is equivalent to a very low conductance between collector and emitter as shown in Fig. 2.5, i.e. an open switch.

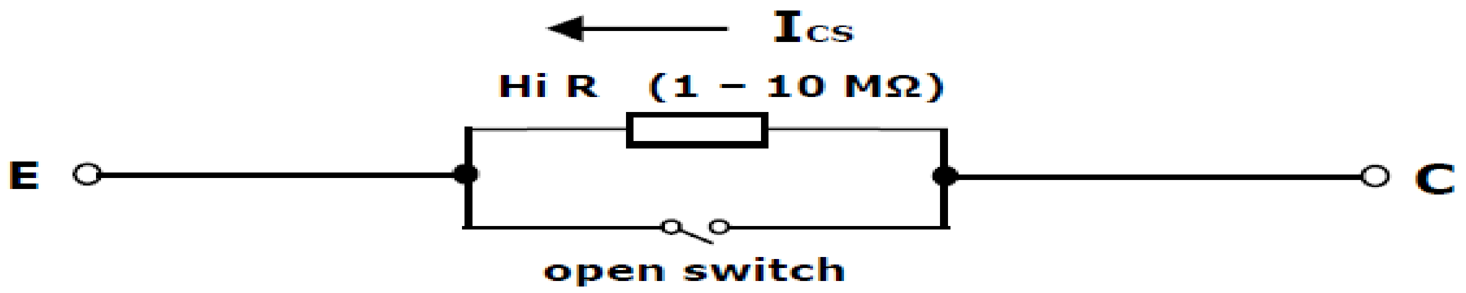


Fig. 2.5 The Cut-Off Mode of Operation as Equivalent to a Leaky Switch

(d)The Saturation Mode

B-E forward biased, V_{BE} positive

B-C forward biased, V_{BC} positive

$e^{V_{BE}/V_T} >> 1$

$e^{V_{BC}/V_T} >> 1$

Note: both junctions are forward biased

Then,

$$I_E \approx I_{ES}e^{V_{BE}/V_T} - \alpha_R I_{CS}e^{V_{BC}/V_T}$$

$$I_C \approx \alpha_F I_{ES}e^{V_{BE}/V_T} - I_{CS}e^{V_{BC}/V_T}$$

$$I_B \approx (1-\alpha_F)I_{ES}e^{V_{BE}/V_T} + (1-\alpha_R)I_{CS}e^{V_{BC}/V_T}$$

Ebers-Moll Model of BJT

In this case, with both junctions forward biased

$$V_{BE} \approx 0.8V$$

$$V_{BC} \approx 0.7V$$

$$V_{CE} = V_{BE} - V_{BC} = 0.1V$$

There is a 0.1V drop across the transistor from collector to emitter which is quite low while a substantial current flows through the device. In this mode it can be considered as having a very high conductivity and acts as a closed switch with a finite resistance or conductivity.

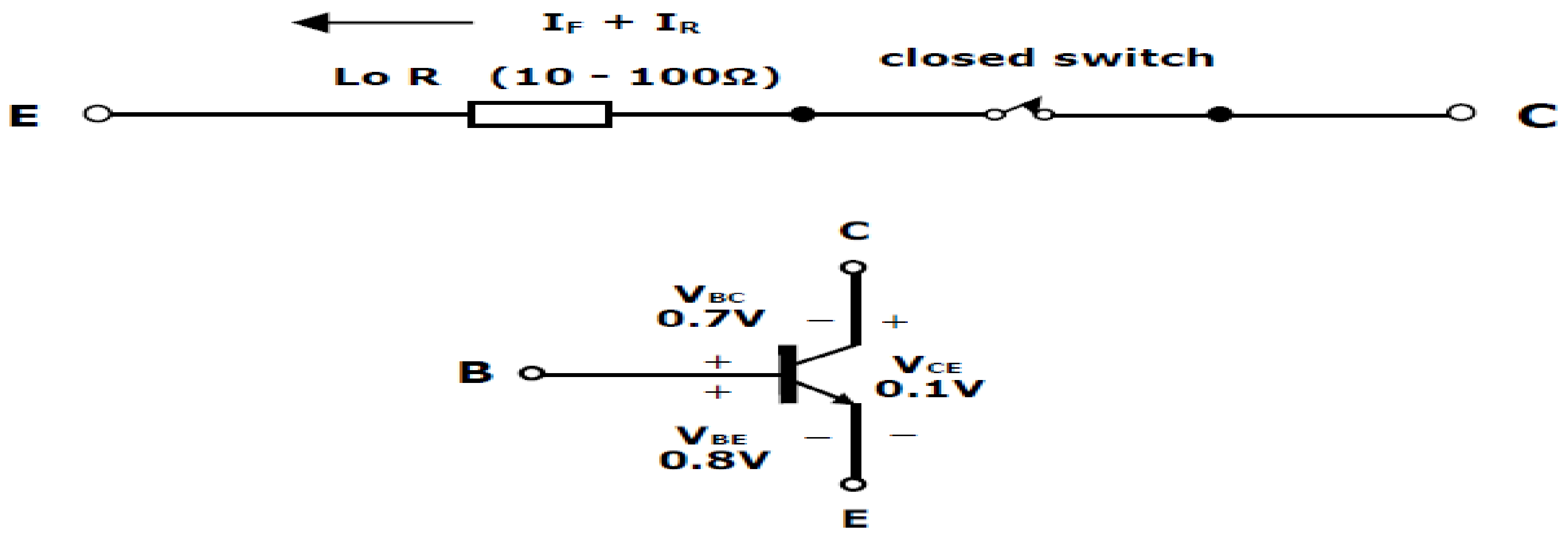
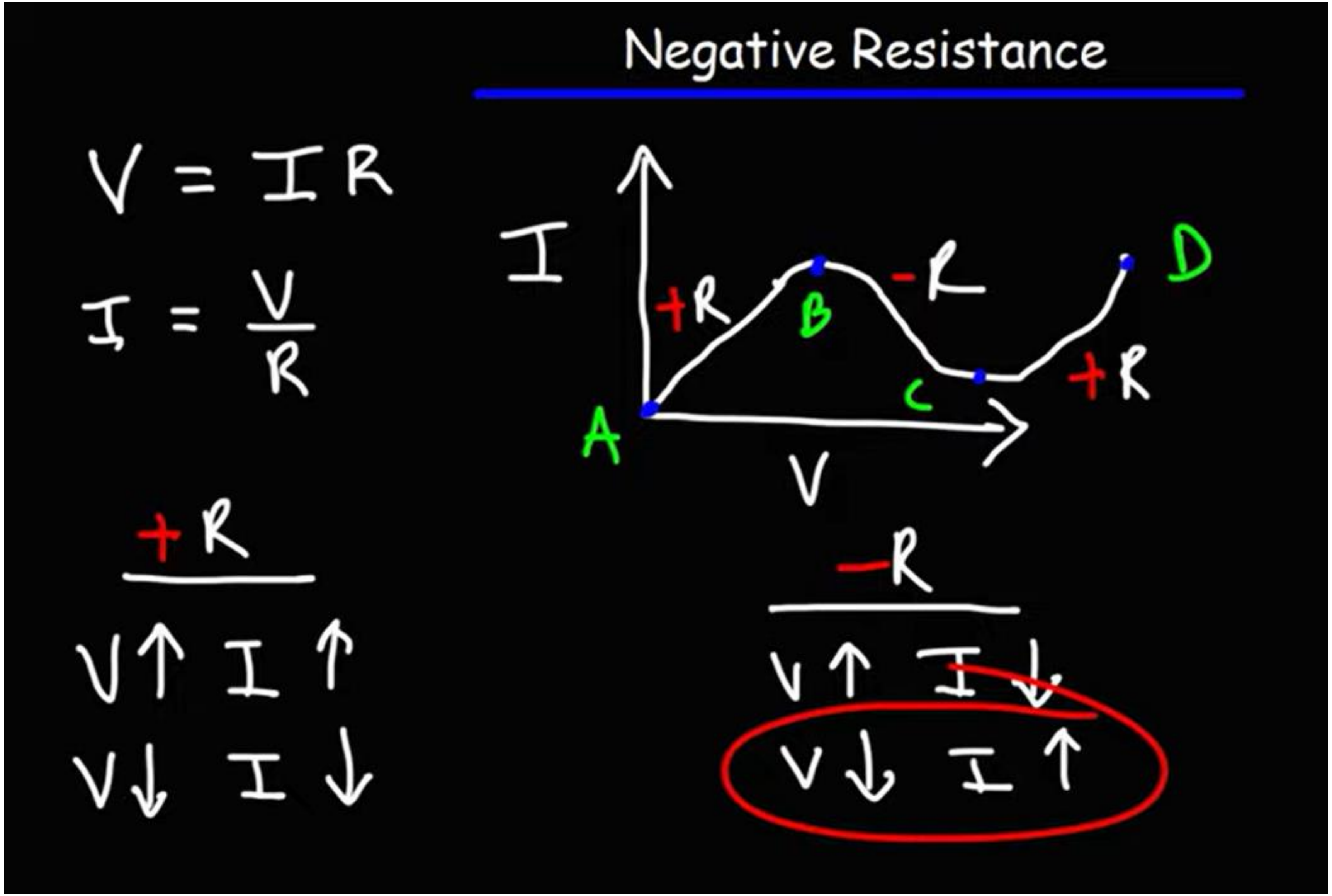


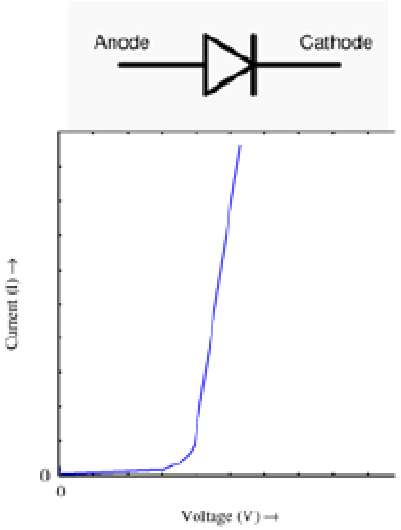
Fig. 2.6 Saturation Mode of Operation Equivalent to a Closed Switch

Negative Resistance

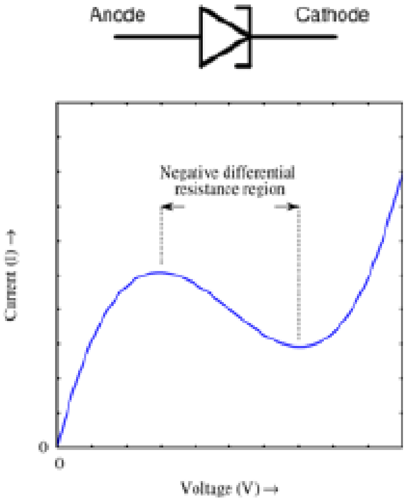


Tunnel Diodes (Esaki Diode)

Tunnel diode is the p-n junction device that exhibits negative resistance. That means when the voltage is increased the current through it decreases.

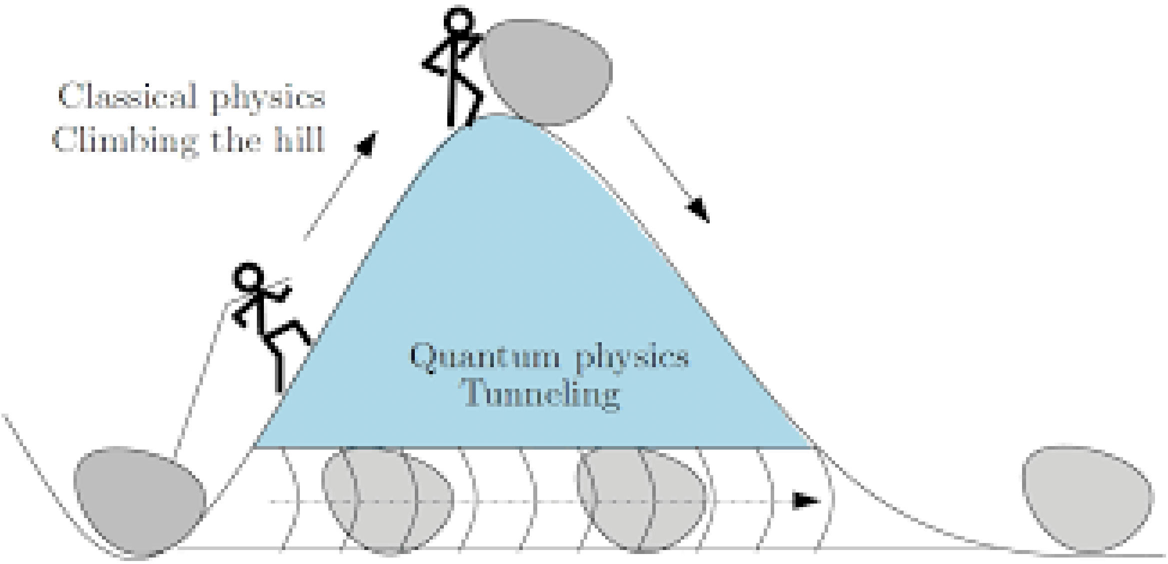


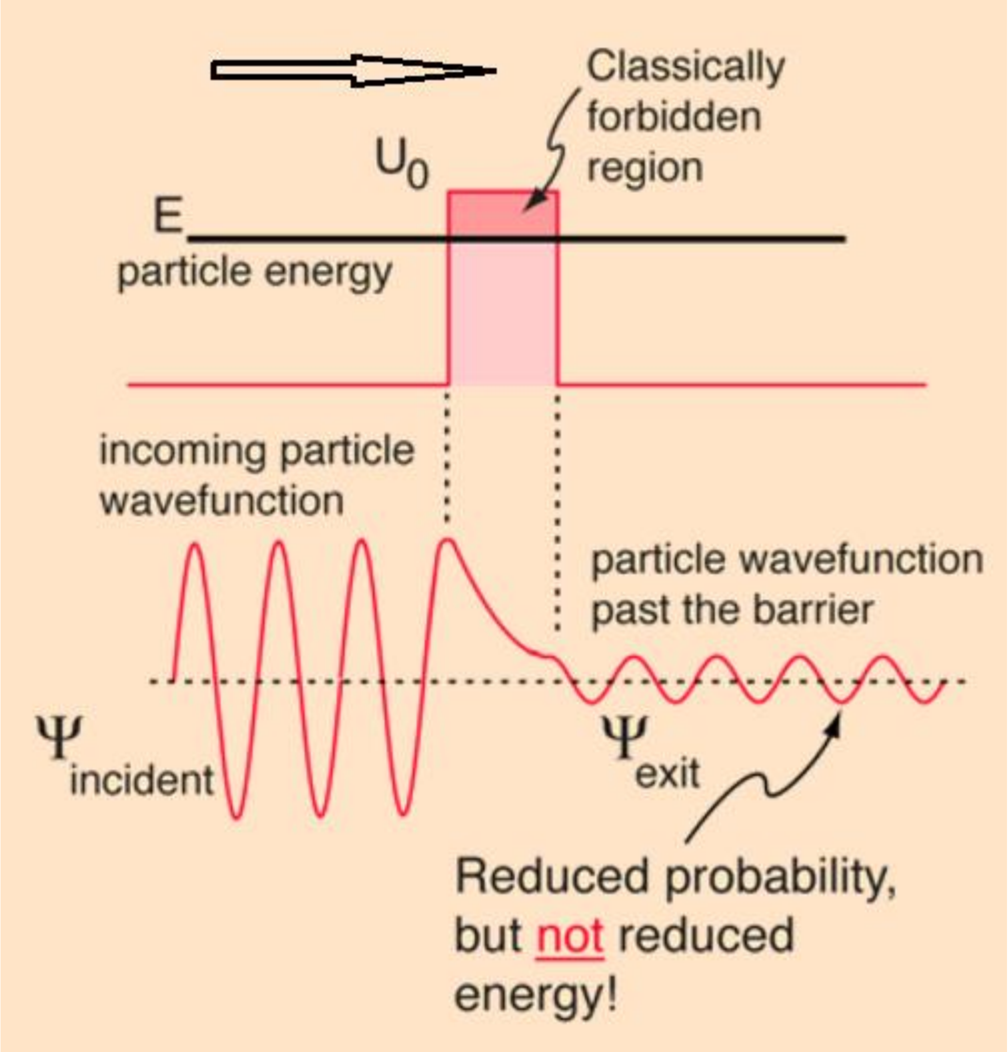
Regular p-n Diode

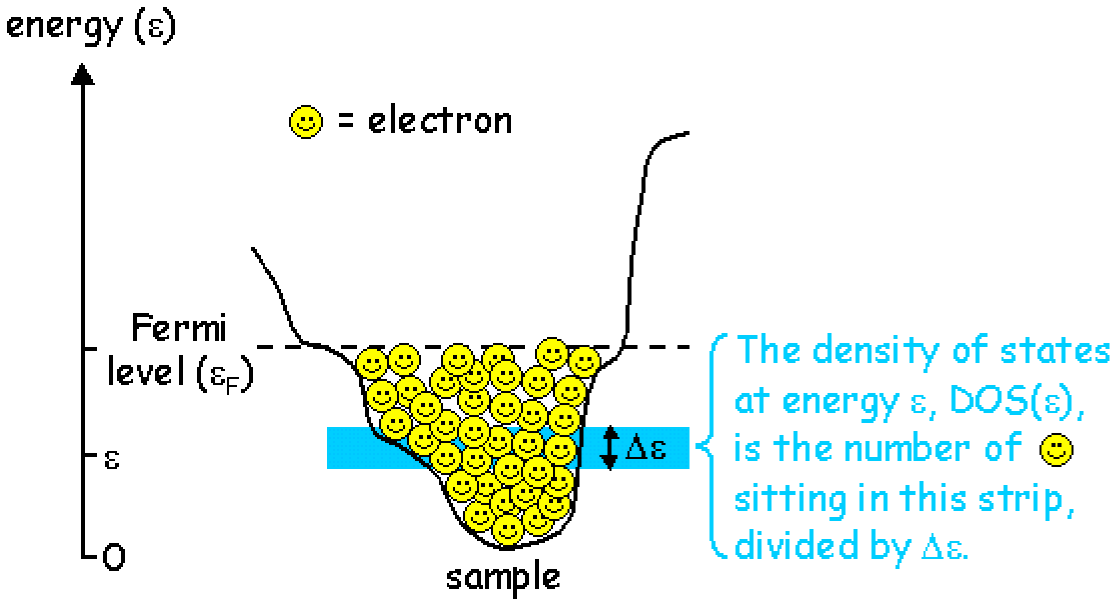


Tunnel Diode

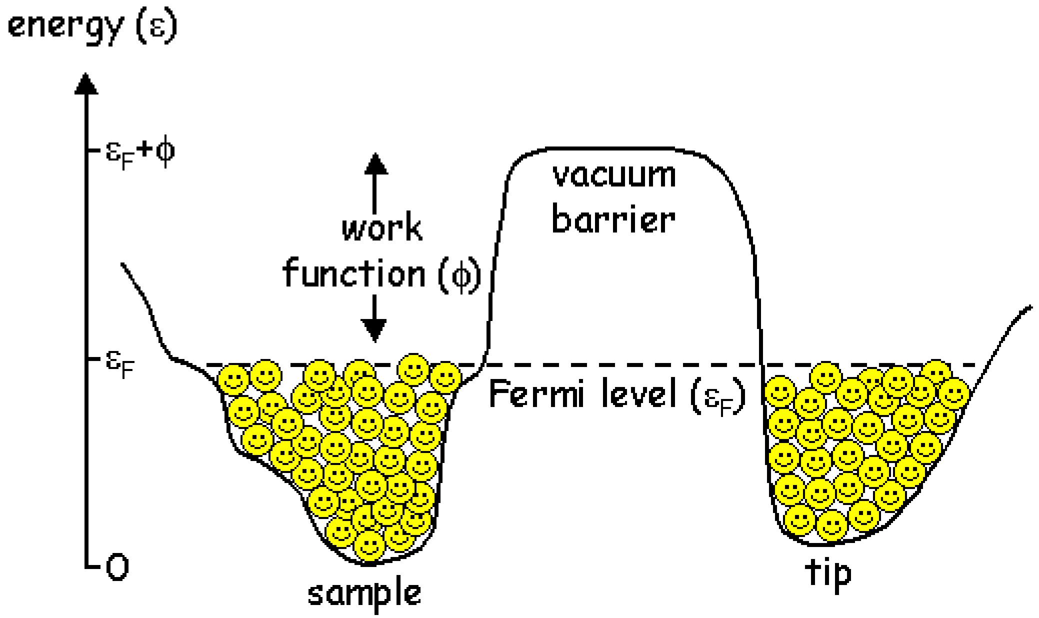
Tunneling effect



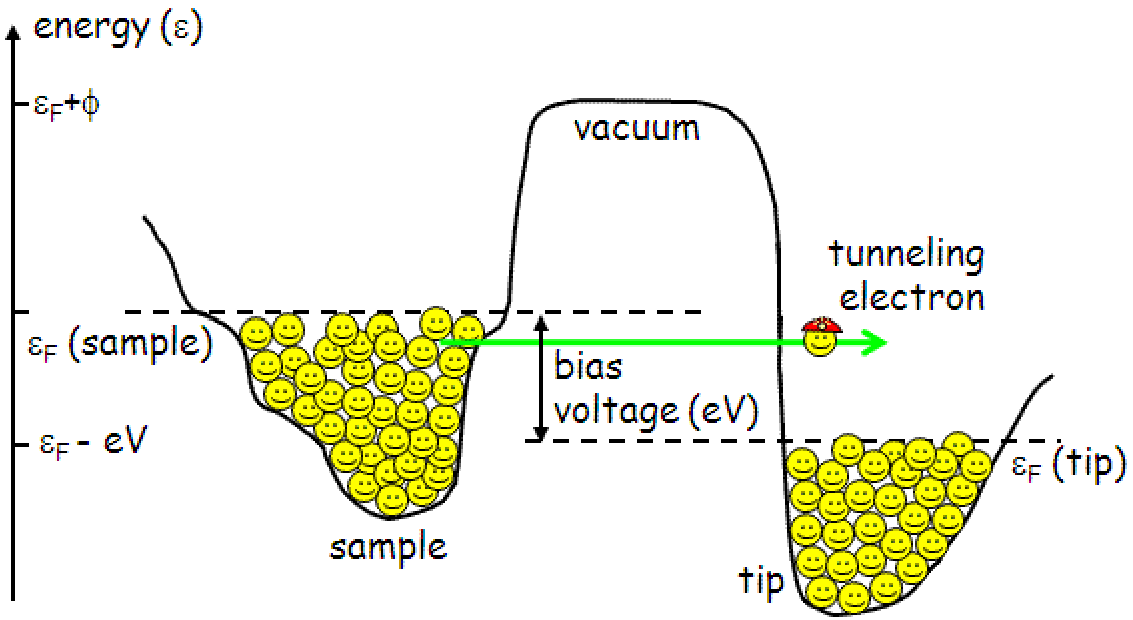




energy (ε)
= electron
Fermi level (ε_F)
ε
0
Δε
The density of states at energy ε, DOS(ε), is the number of sitting in this strip, divided by Δε.
sample



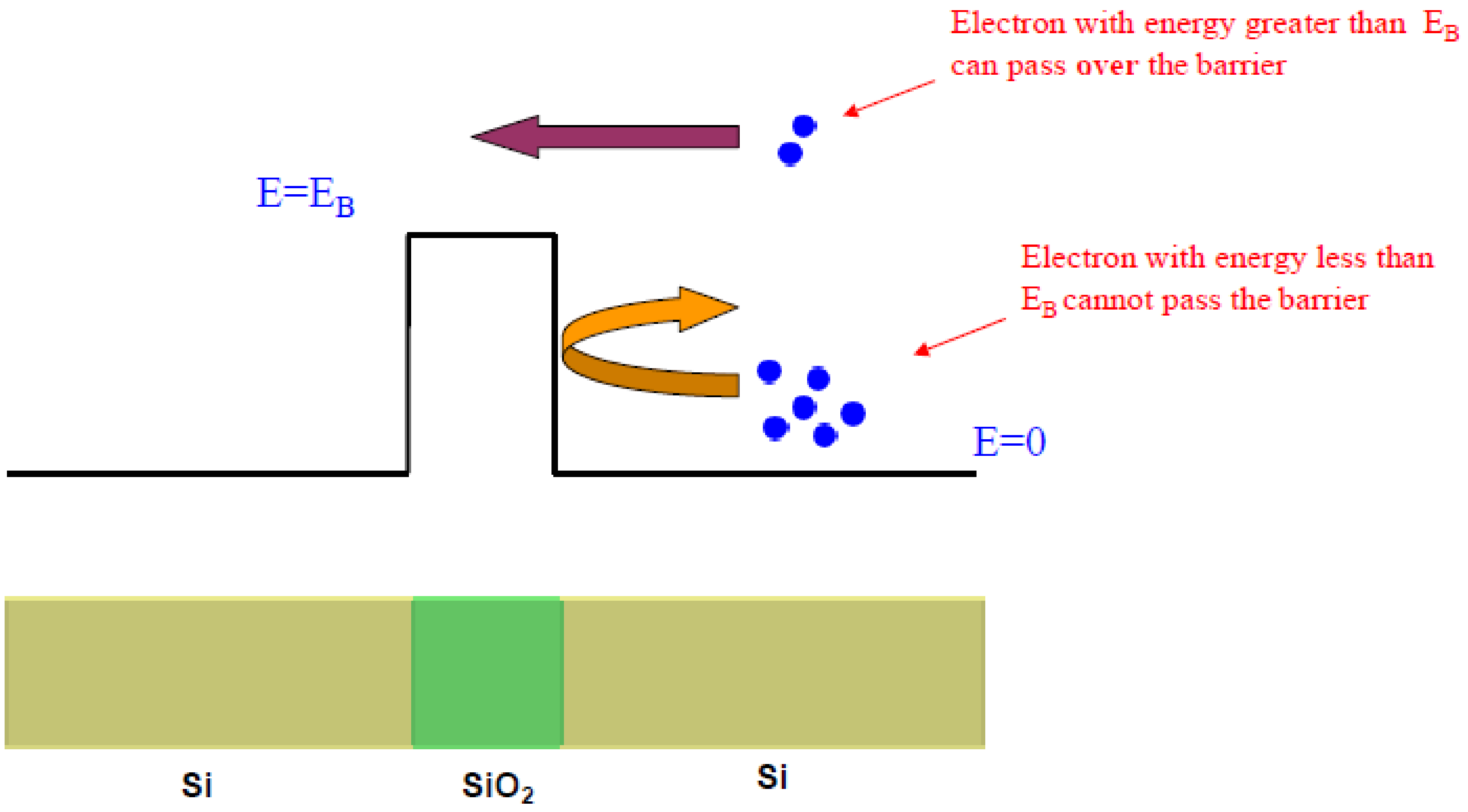
energy (ε)
$\varepsilon_F+\phi$
ε_F
0
work function (ϕ)
vacuum barrier
Fermi level (ε_F)
sample
tip



energy (ε)
$\varepsilon_F+\phi$
ε_F (sample)
ε_F - eV
vacuum
tunneling electron
bias voltage (eV)
ε_F (tip)
sample
tip

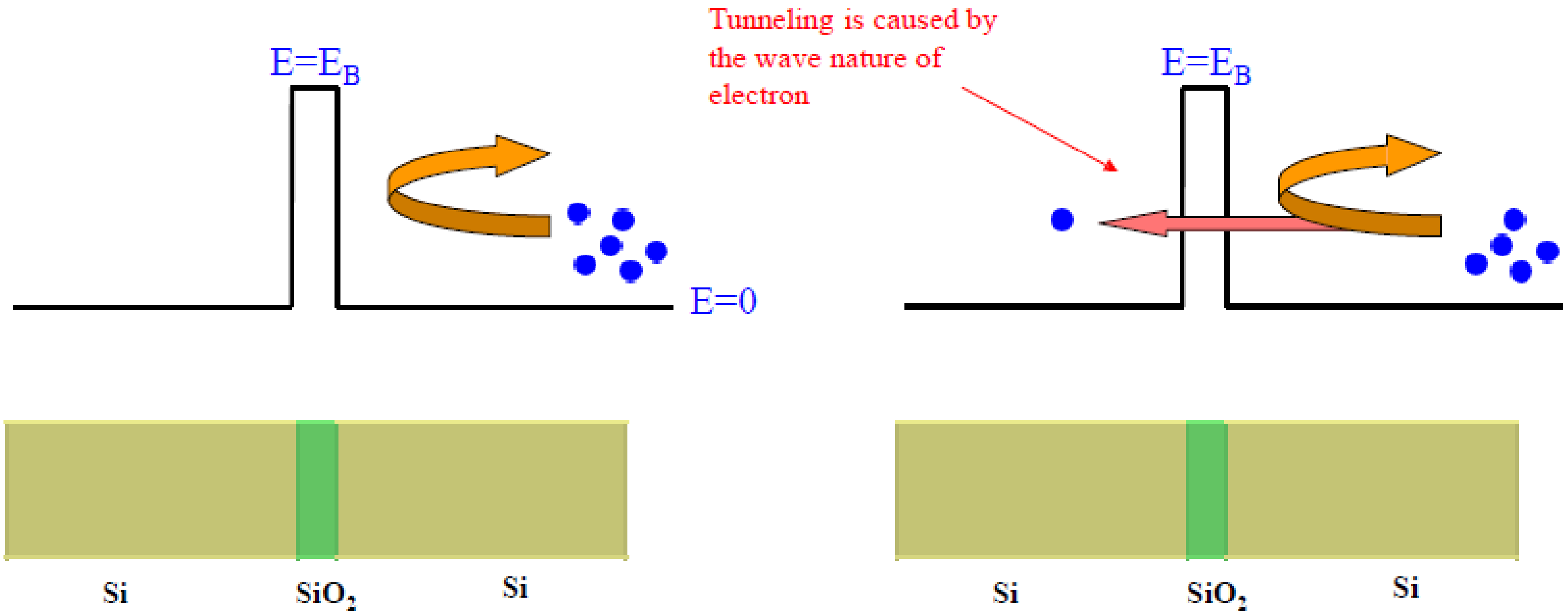
Electron Tunneling

- For **thick barrier**, both **Newtonian** and **Quantum** mechanics say that the electrons **cannot** cross the barrier.
- It can only pass the barrier if it has **more energy** than the barrier height.



Electron Tunneling

- For **thin barrier**, **Newtonian** mechanics still says that the electrons **cannot** cross the barrier.
- However, **Quantum** mechanics says that the electron wave nature will allow it to **tunnel** through the barrier.



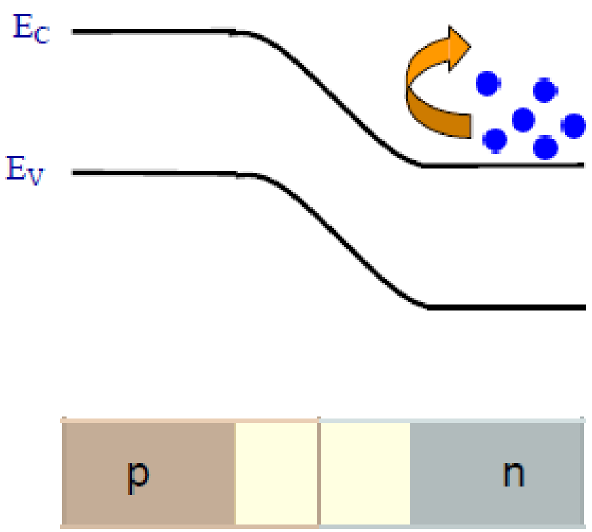
Newtonian Mechanics

Quantum Mechanics

Electron Tunneling in p-n junction

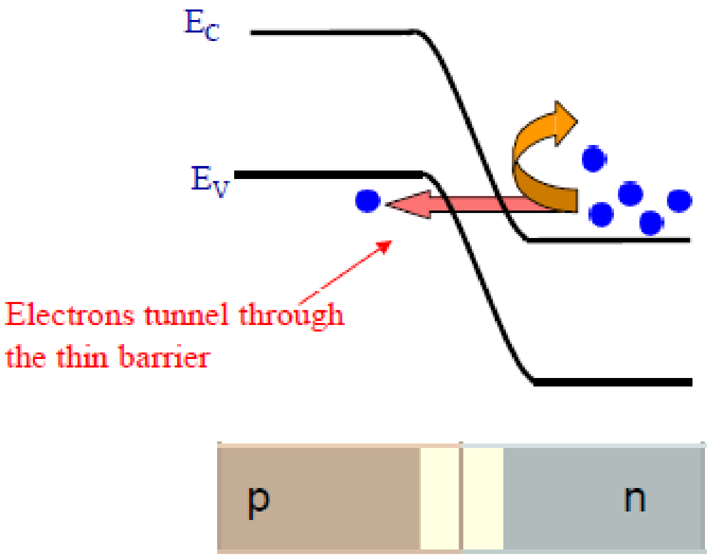
- When the p and n region are **highly doped**, the depletion region becomes **very thin** (~10nm).
- In such case, there is a **finite probability** that electrons can **tunnel** from the conduction band of n-region to the valence band of p-region
- During the tunneling the particle **Energy Does Not Change**

Thick depletion layer



High doping

Thin depletion layer

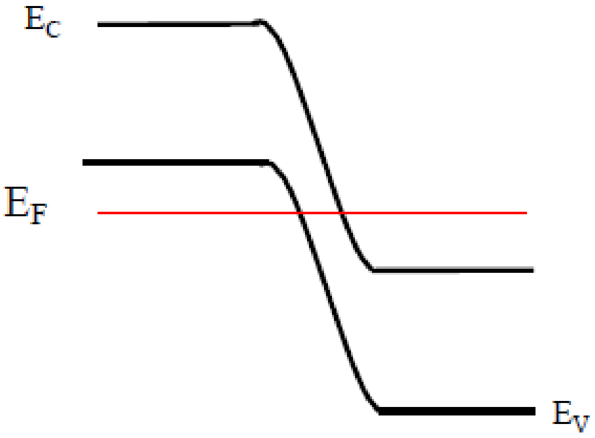


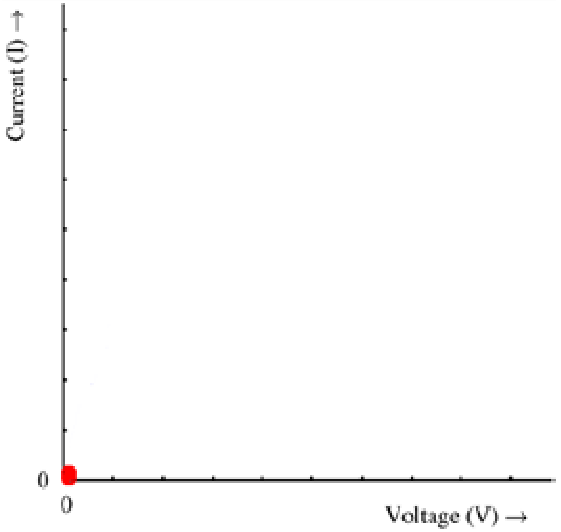
Tunnel Diode Operation

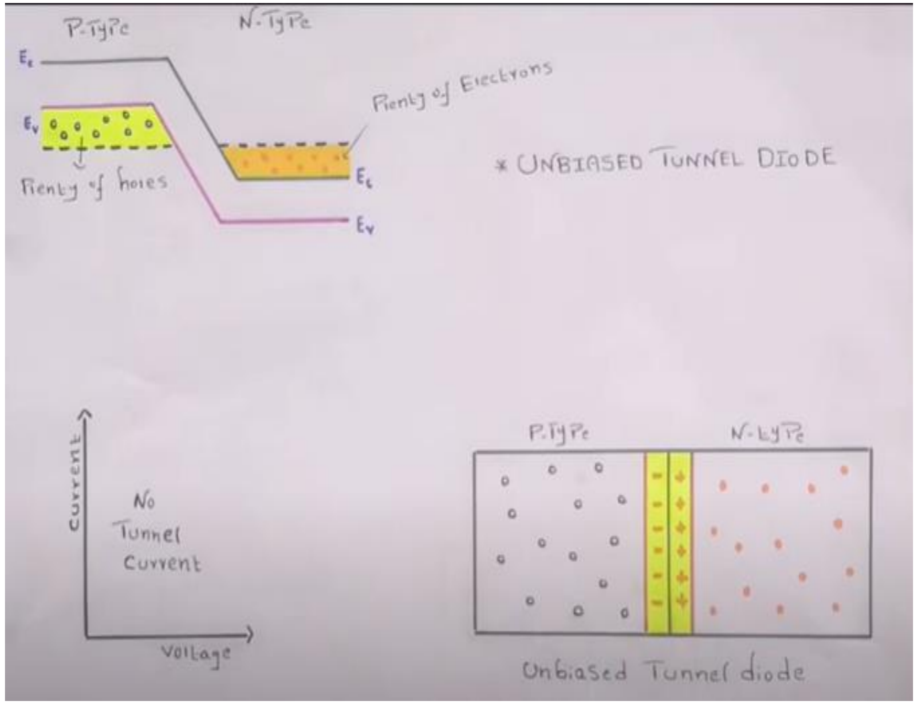
When the semiconductor is **very highly doped** the Fermi level goes **above** the conduction band for n-type and **below** valence band for p-type material. These are called **degenerate materials**.

Under Forward Bias:

Step 1: At zero bias there is no current flow



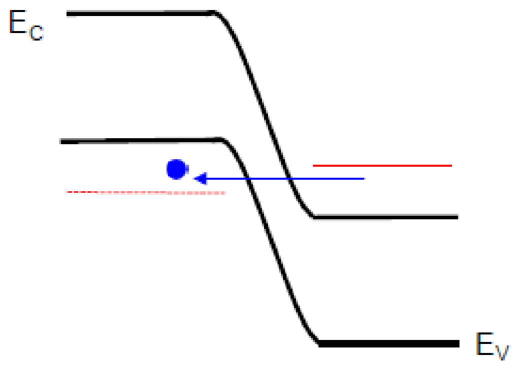


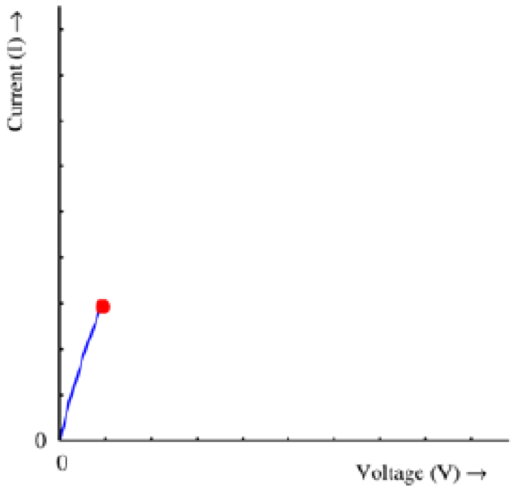


Tunnel Diode Operation

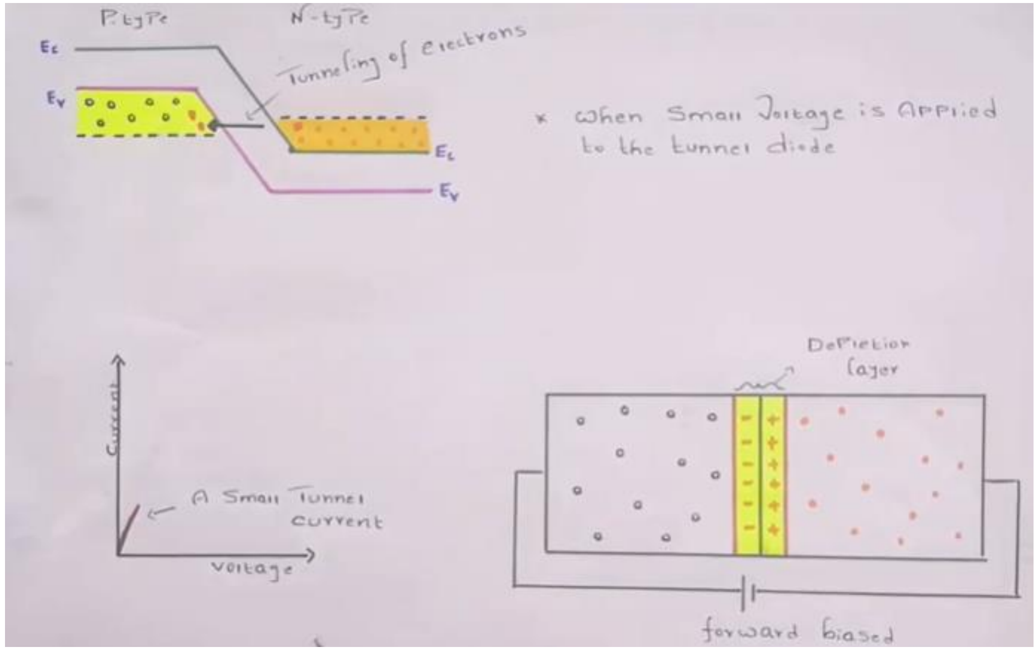
Step 2:

- A small forward bias is applied. Potential barrier is **still very high – no noticeable injection.**
- However, electrons in the conduction band of the n-region will **tunnel to the empty states** of the valence band in p-region. This will create a forward bias tunnel current





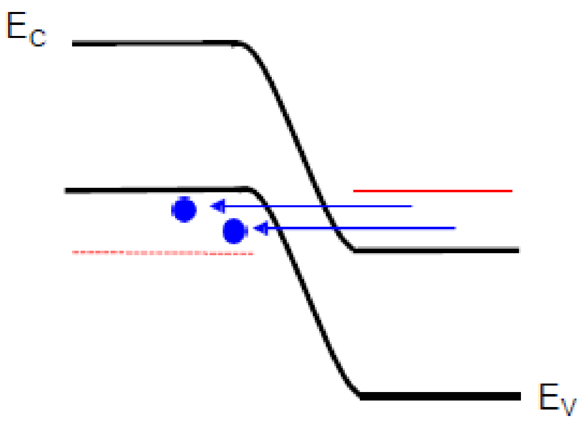
Direct tunneling current starts growing

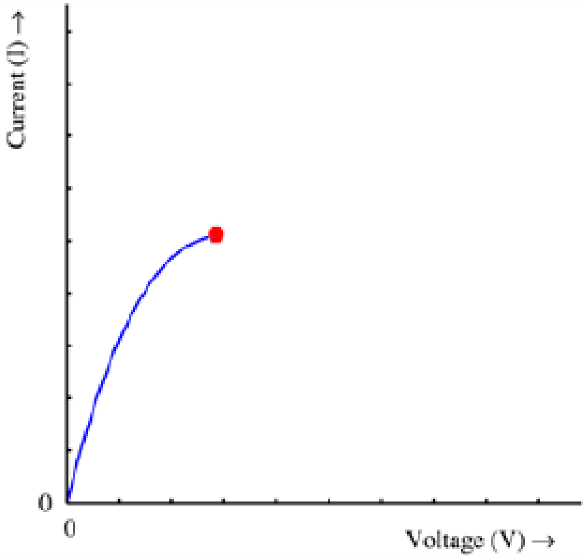


Tunnel Diode Operation

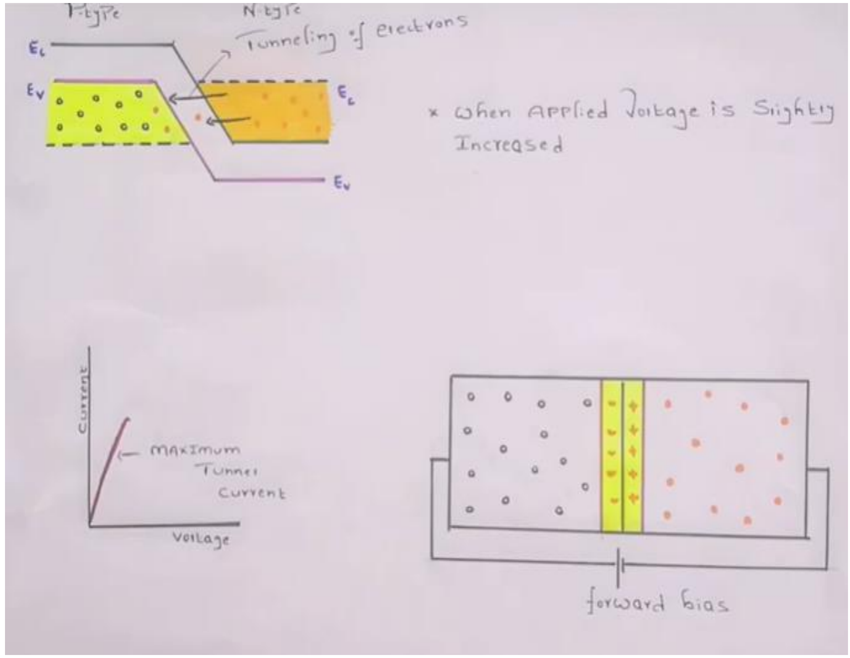
Step 3:

➢ With a **larger voltage** the energy of the majority of electrons in the n-region is equal to that of the empty states (holes) in the valence band of p-region; this will produce maximum tunneling current





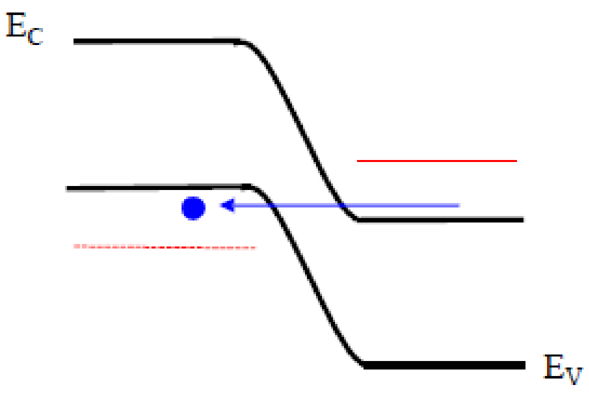
Maximum Direct tunneling current



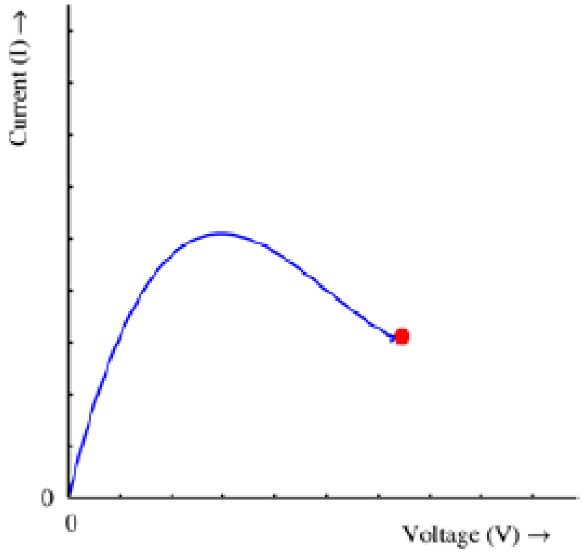
Tunnel Diode Operation

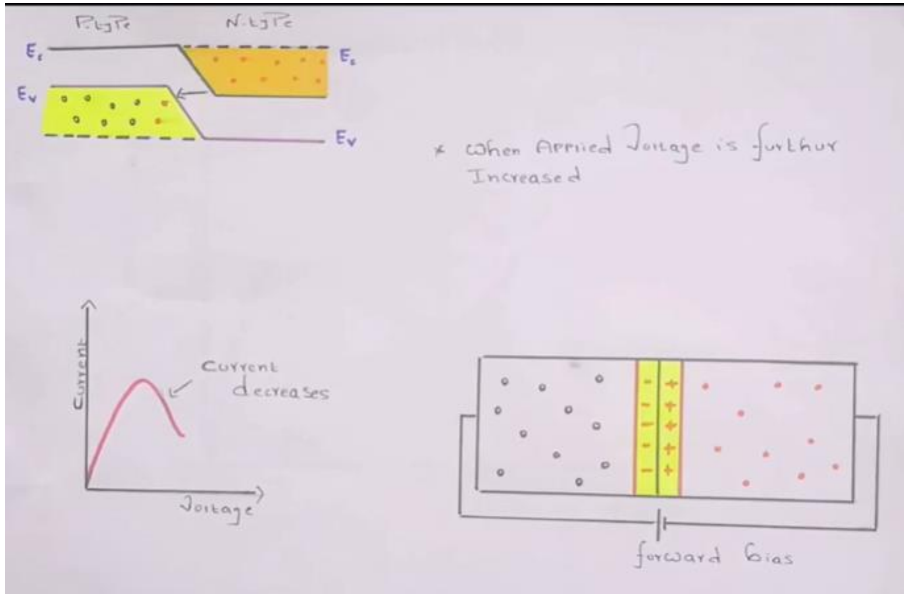
Step 4:

- As the forward bias **continues to increase**, the number of electrons in the n-side that are directly opposite to the empty states in the valence band (in terms of their energy) decrease. Therefore decrease in the tunneling current will start.



Direct tunneling current decreases

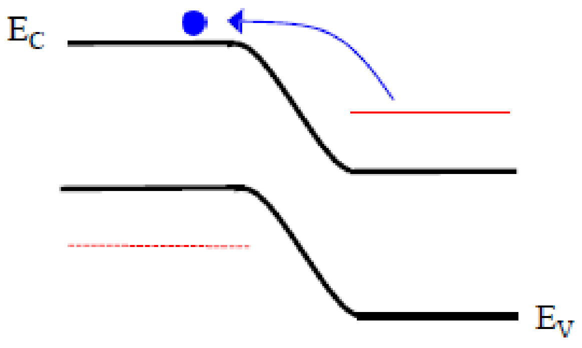


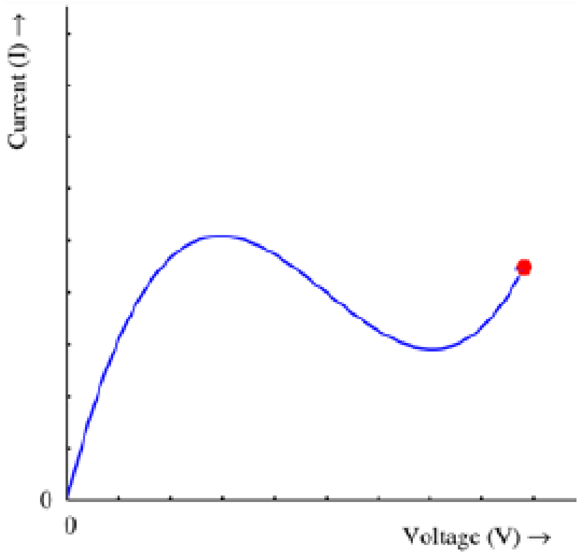


Tunnel Diode Operation

<u>**Step 5:**</u>

As more forward voltage is applied, the tunneling current drops to **zero**. But the regular diode forward current due to electron – hole injection increases due to **lower potential barrier**.



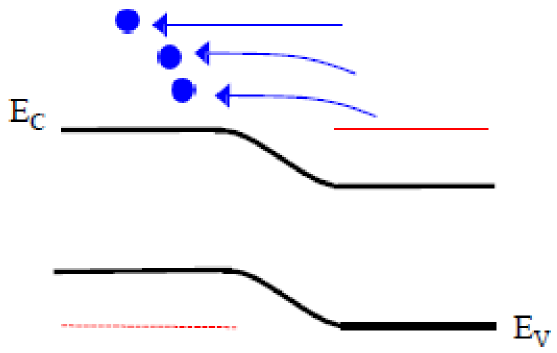


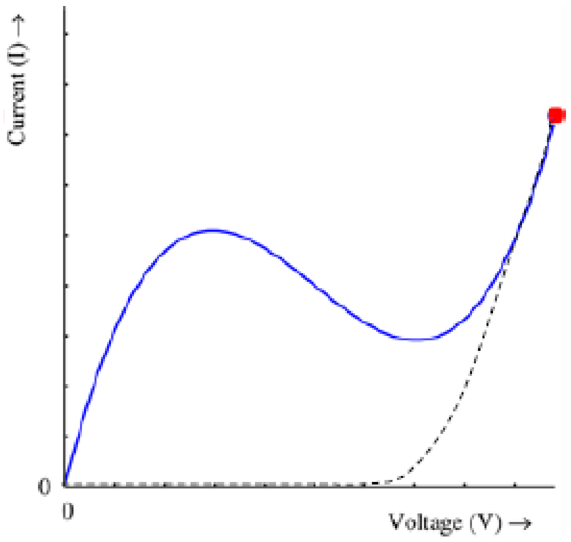
No tunneling current; diffusion current starts growing

Tunnel Diode Operation

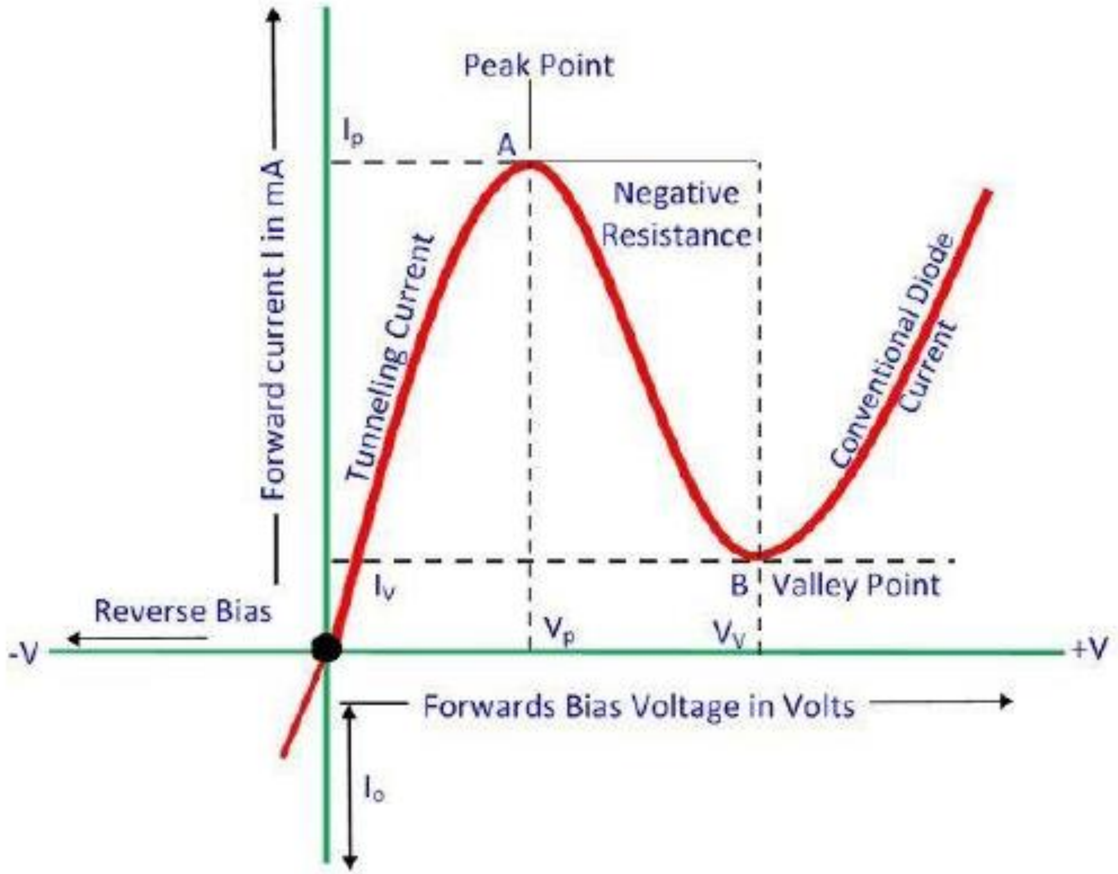
Step 6:

- With further voltage increase, the tunnel diode I-V characteristic is similar to that of a regular p-n diode.



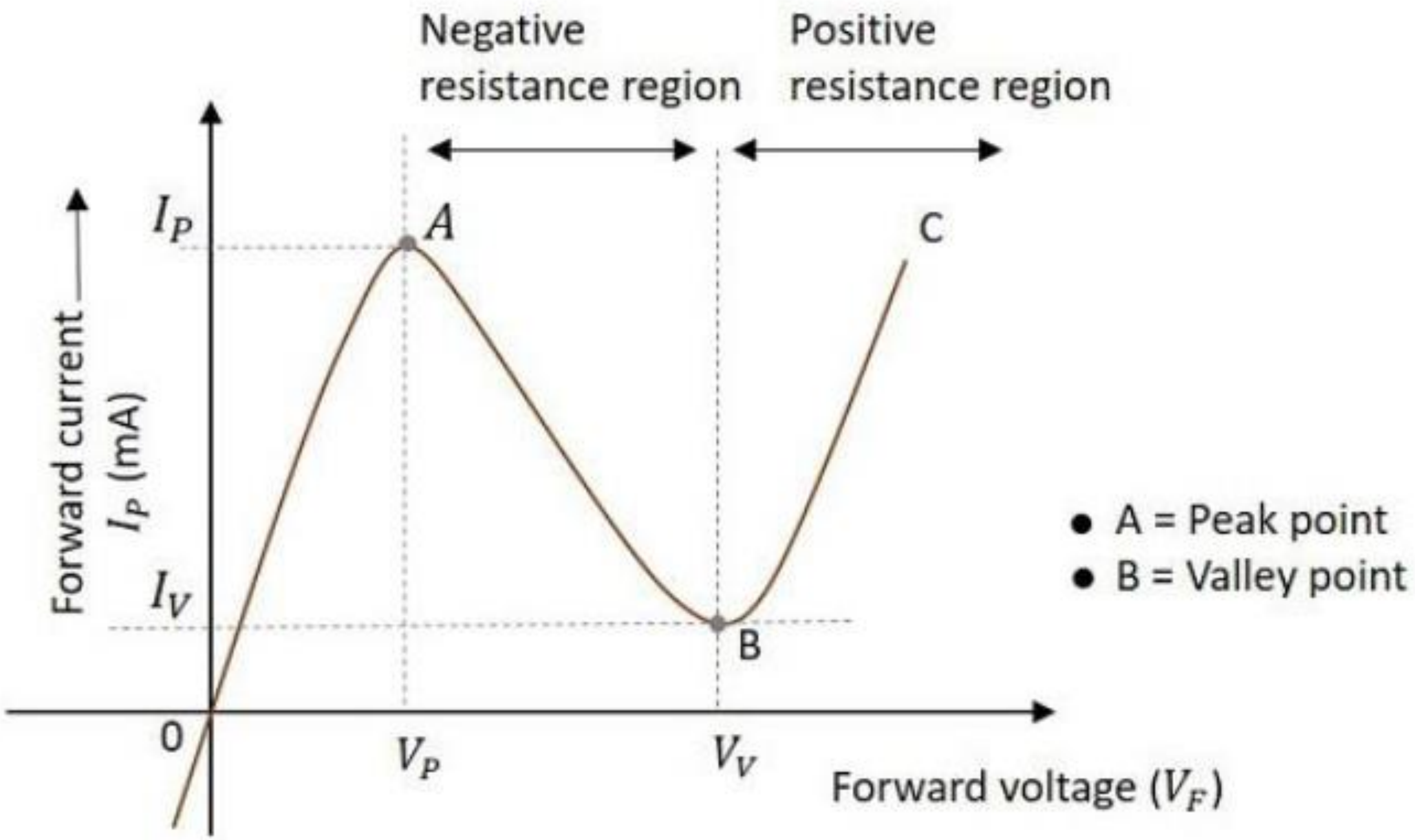


V-I Characteristics of Tunnel Diode



- The small minimal value of current is Iv. it is seen that from point A to B current reduces when voltage increases. That is the negative resistance region of diode.
- In this region, tunnel diode produces power instead of absorbing it.

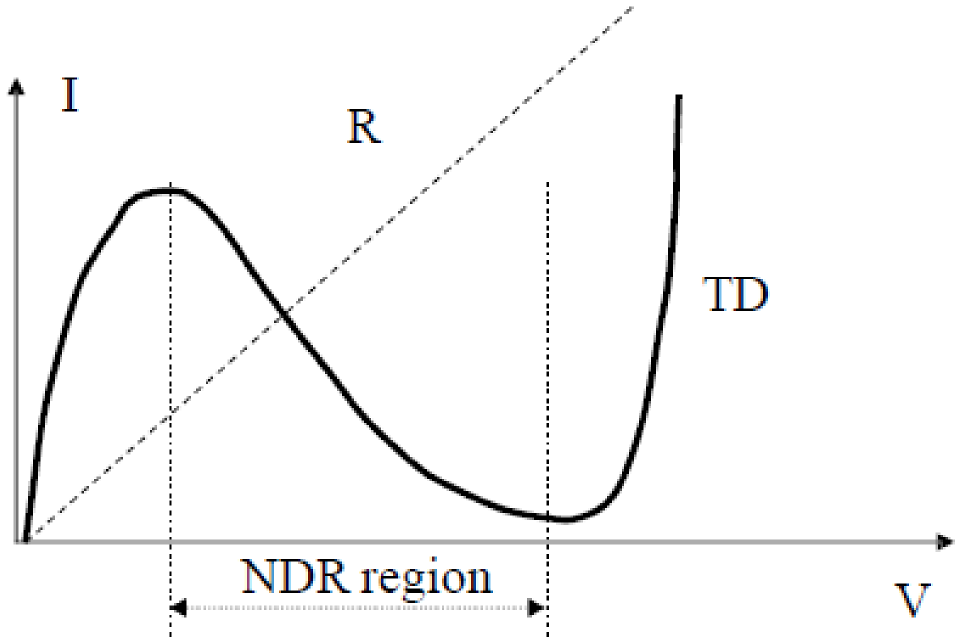
V-I Characteristics of Tunnel Diode



Applications of Tunnel Diode

- Tunnel diode can be used as a switch, amplifier, and oscillator.
- Since it shows a fast response, it is used as high frequency component.
- Tunnel diode acts as logic memory storage device.
- They are used in oscillator circuits, and in FM receivers.
- Since it is a low current device, it is not used more.

Circuits with the Tunnel Diodes



- Typical Tunnel Diode (TD) I-V characteristic has two distinct features: it is **Strongly non-linear** (compare to the resistor I-V).
- Current - Voltage relationships for TDs cannot be described using the Ohm's law
- it has a ***negative differential resistance*** (NDR) region.

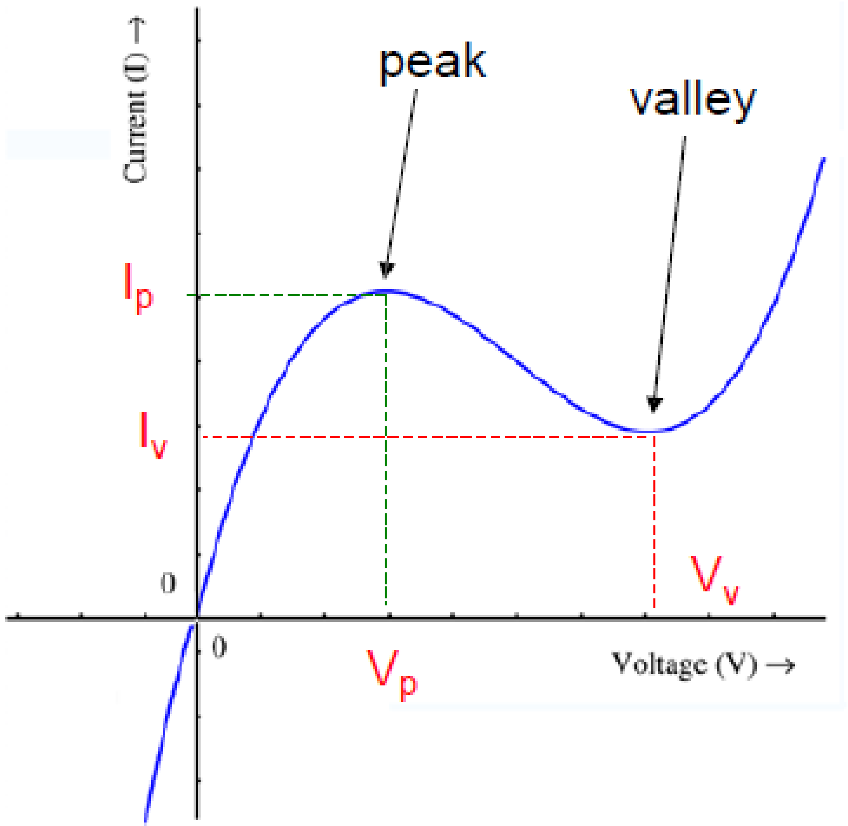
Tunnel Diode I-V

The total current I in a tunnel diode is given by

$$I = I_{tun} + I_{Diode} + I_{excess}$$

The p-n junction current,

$$I = I_0 \left[e^{V/\eta V_T} - 1\right]$$

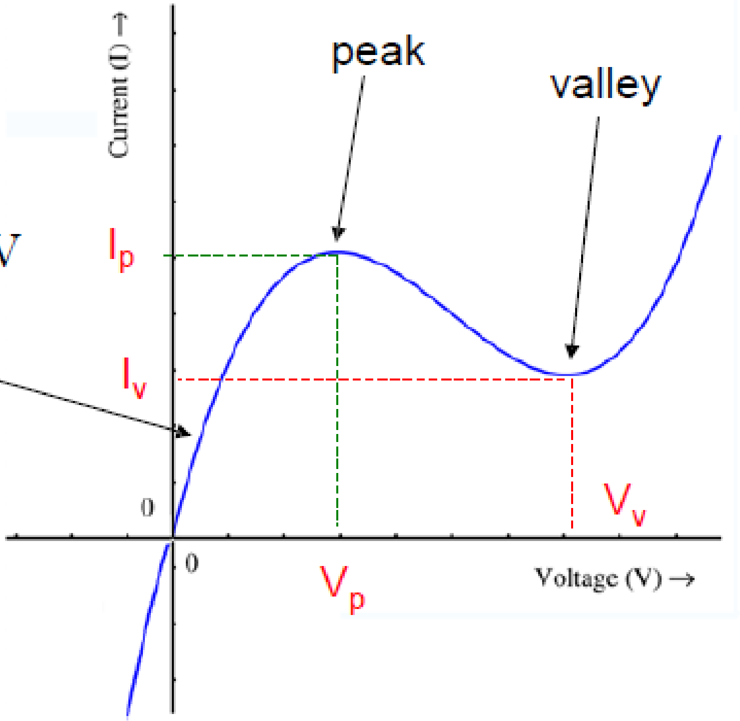


Tunnel Diode I-V

The tunnel current,

$$I_{tune} = \frac{V}{R_0} \exp\left[-\left(\frac{V}{V_0}\right)^m\right]$$

- Typically, m = 1….3; V_0 = 0.1….0.5 V
- R_0 is the TD resistance in the ohmic region



Ido – Reverse saturation current

Vt – Voltage equivalent of temperature

V – Voltage across the diode

η – Correction factor 1 for Ge and 2 for Si

The maximum |NDR| can be found as

$$|R_{D\,Max}| = R_0 \frac{\exp\left(\frac{1+m}{m}\right)}{m}$$

The peak voltage V_p:

$$V_p = \left(\frac{1}{m}\right)^{1/m} V_0$$

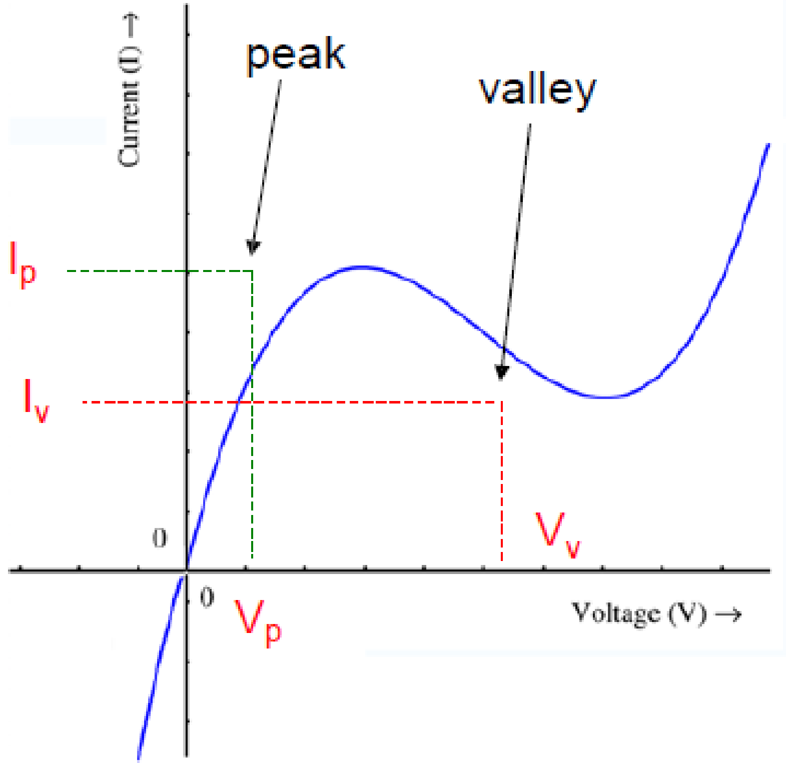
Tunnel Diode I-V

The excess current,

$$I_{excess} = \frac{V}{R_V} \exp\left[\left(\frac{V - V_V}{V_{ex}}\right)\right]$$

- I_{excess} is an additional tunneling current related to parasitic tunneling via impurities.

- This current usually determines the minimum (valley) current, I_v
- R_v and V_{ex} are the empirical parameters; in high-quality diodes, $R_v >> R_0$. $V_{ex} = 1\ldots..5V$



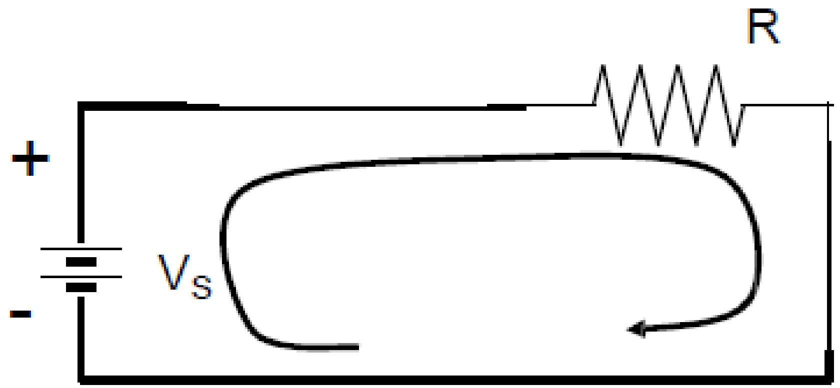
Tunnel diode current

The total current I in a tunnel diode is given by

$$I = I_{tun} + I_{Diode} + I_{excess}$$

$$I = \frac{V}{R_0}\exp\left[-\left(\frac{V}{V_0}\right)^m\right] + I_o\left[e^{V/\eta V_T} - 1\right] + \frac{V}{R_V}\exp\left[\left(\frac{V-V_V}{V_{ex}}\right)\right]$$

Energy dissipation in resistors and Energy generation in Negative Resistors

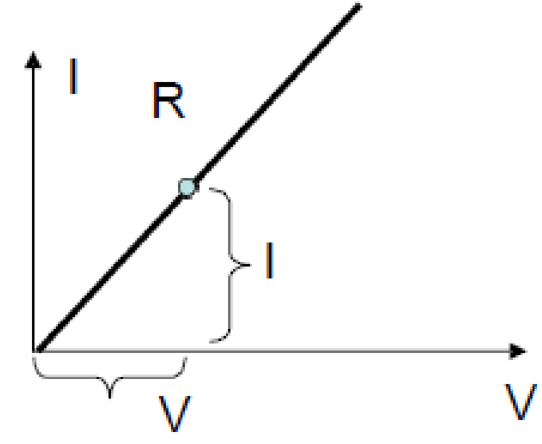


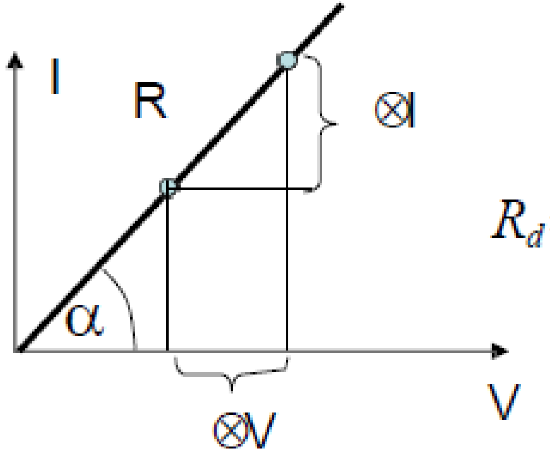
- Power = Voltage x Current = $I^2 R$
- Positive power means energy **DISSIPATION** (e.g. conversion into the Joule heat)
- Negative power corresponds to the power **GENERATION** (Energy supply);

Differential resistance and negative differential resistance

Static resistance: R = V/I

Differential resistance: $R_d = \frac{\partial V}{\partial I} \approx \frac{\otimes V}{\otimes I}$

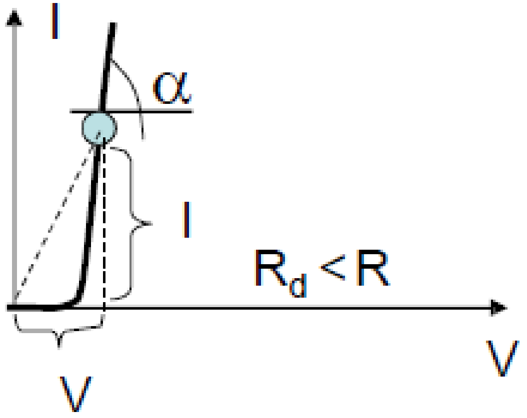




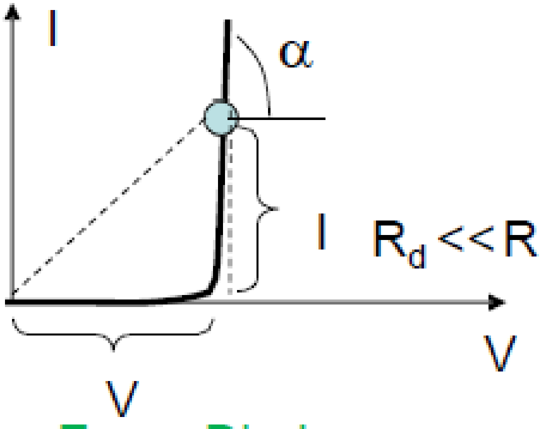
$R_d = \cot(\alpha)$

For linear (“Ohmic”) components, R = R_d.

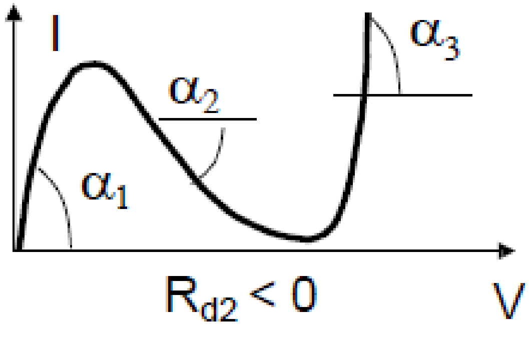
For many semiconductor devices, R ≠ R_d:



Diode



Zener Diode



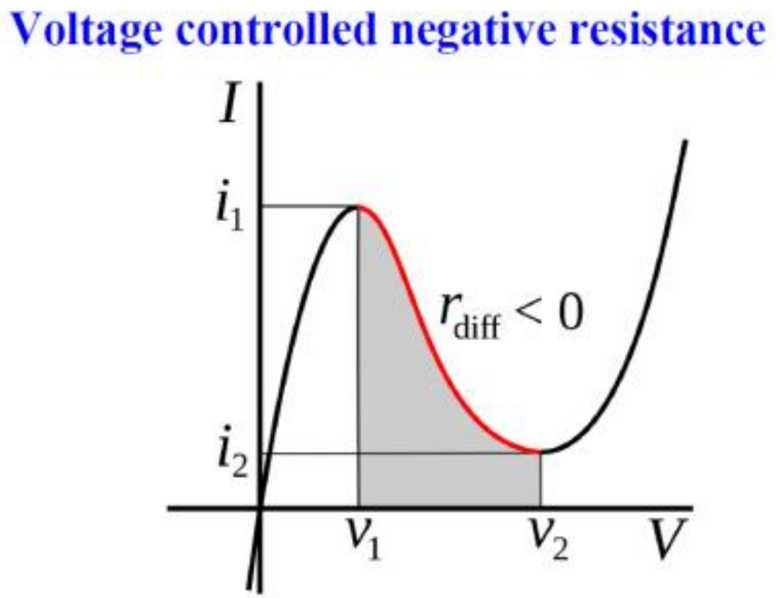
TD

Negative differential resistances

- **Voltage controlled negative resistance (VCNR, short-circuit stable, or "N" type)**
- **Current controlled negative resistance (CCNR, open-circuit stable, or “S" type)**

Voltage controlled negative resistance

- VCNR, short-circuit stable, or "**N**" type:
  - The current is a single valued,
  - Continuous function of the voltage,
  - The voltage is a multivalued function of the current.
- In the most common type there is only one negative resistance region,
- The graph is a curve shaped generally like the letter "N".



Voltage controlled negative resistance

- As the voltage is increased, the current increases (positive resistance) until it reaches a maximum (i_1),

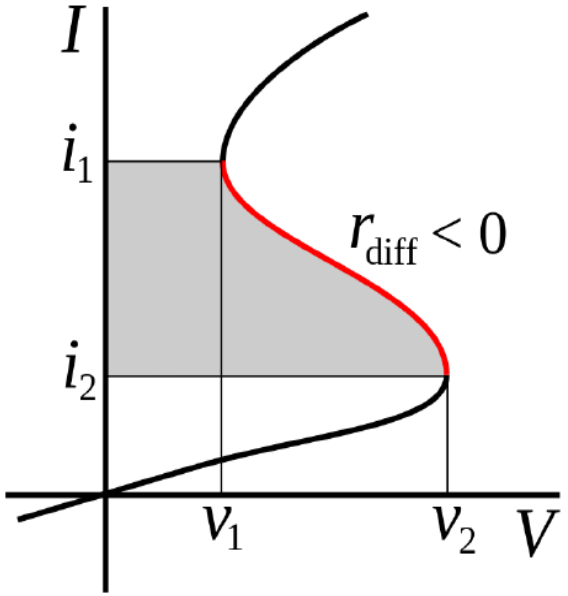
- then decreases in the region of negative resistance to a minimum (i_2), then increases again.

- Devices with this type of negative resistance include
    - the tunnel diode,
    - resonant tunneling diode,
    - lambda diode,
    - Gunn diode,
    - and dynatron oscillators.

Current controlled negative resistance

- CCNR, open-circuit stable, or "S" type:
  - The dual of the VCNR,
  - The voltage is a single valued function of the current,
  - The current is a multivalued function of the voltage.
- In the most common type, with one negative resistance region.
- The graph is a curve shaped like the letter "S".

Current controlled negative resistance



Current controlled negative resistance

- Devices with this type of negative resistance include
  - IMPATT diode,
  - UJT,
  - SCRs
  - Thyristors,
  - electric arc, and gas discharge tubes.
- Most devices have a single negative resistance region.
- However devices with multiple separate negative resistance regions can also be fabricated.
- These can have more than two stable states, and are of interest for use in digital circuits to implement multivalued logic.

VCNR Vs CCNR

- VCNRs require a low impedance bias ($R < r$), such as a voltage source.
- CCNRs require a high impedance bias ($R > r$) such as a current source, or voltage source in series with a high resistance.

- VCNRs are stable when ($R < r$)
- CCNRs are stable when ($R > r$)

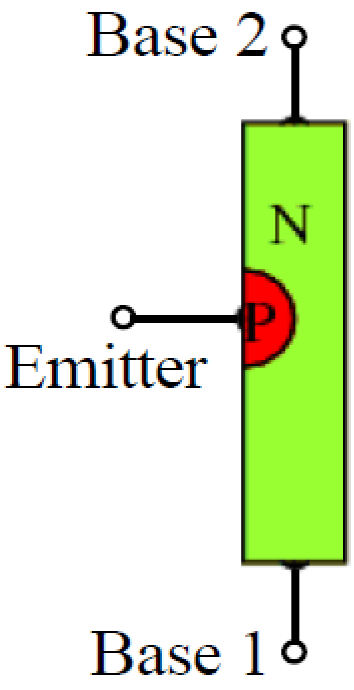
- VCNRs can be bistable when ($R > r$)
- CCNRs can be bistable when ($R < r$)

- Unstable point: When ($R = r$)

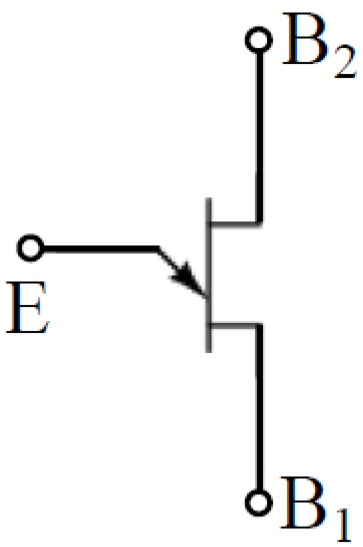
Unijunction Transistor (UJT)

Unijunction Transistor (UJT)

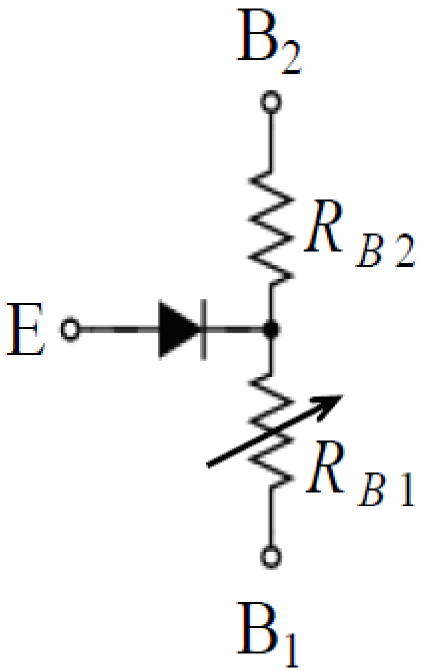
- The uni-junction transistor is a three-terminal single-junction device.
- The switching voltage of the UJT can be easily varied.



Basic Structure



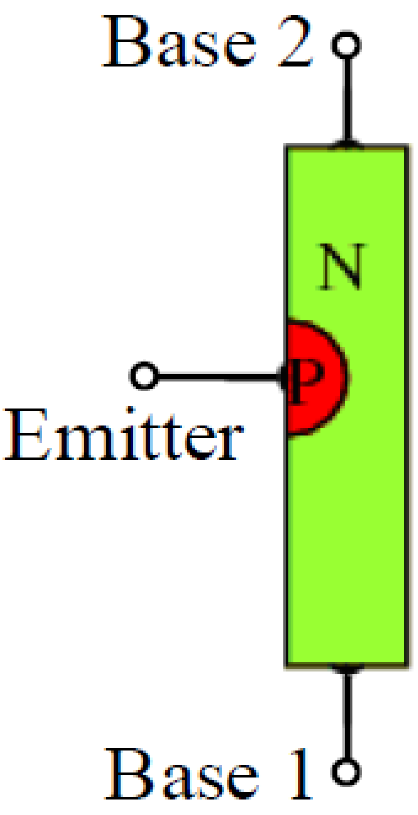
Schematic Symbol

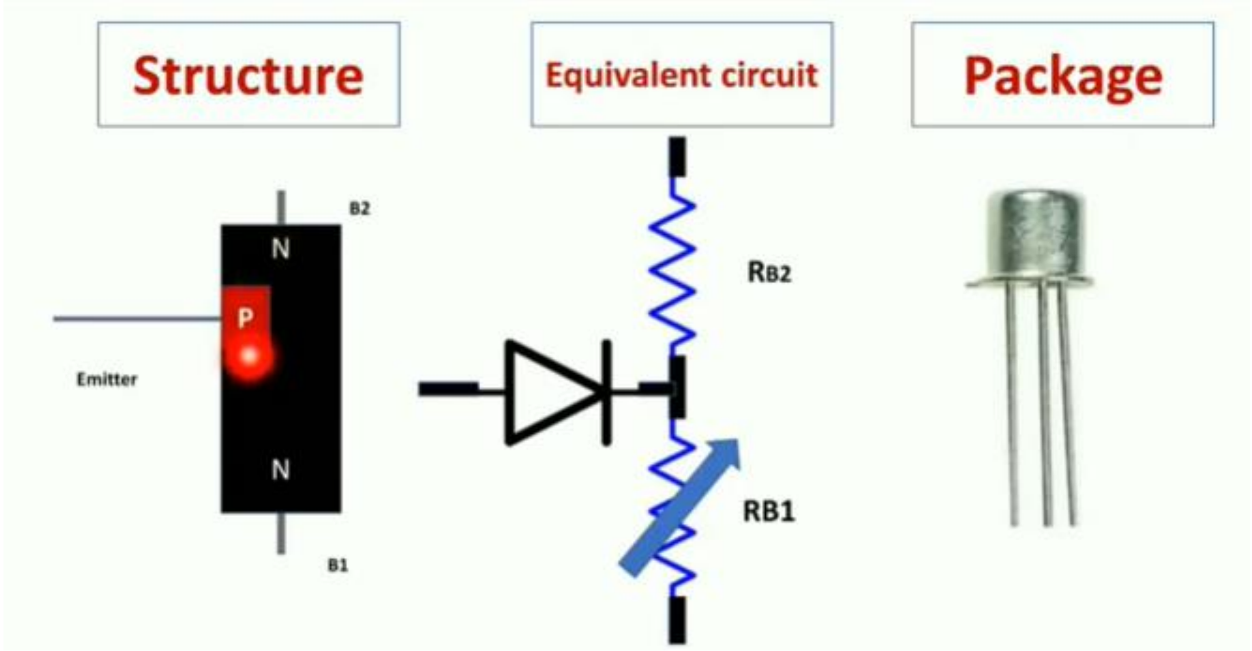


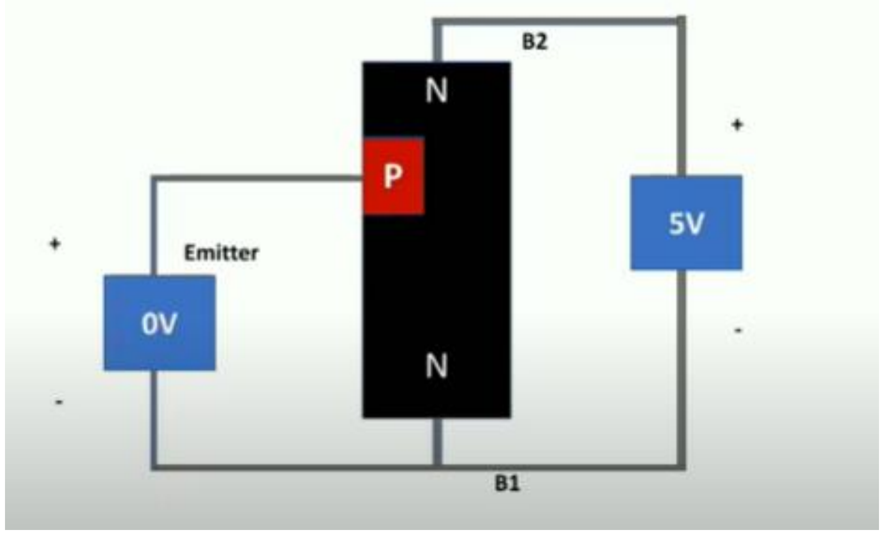
Equivalent Circuit

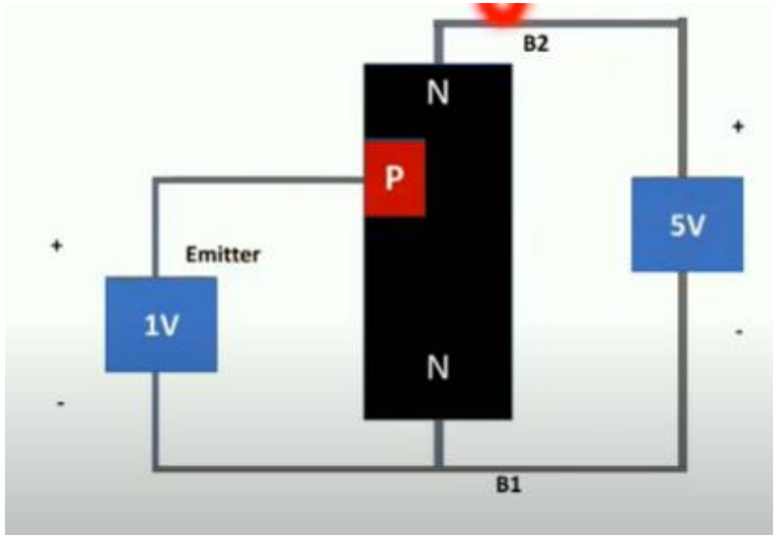
Unijunction Transistor (UJT)

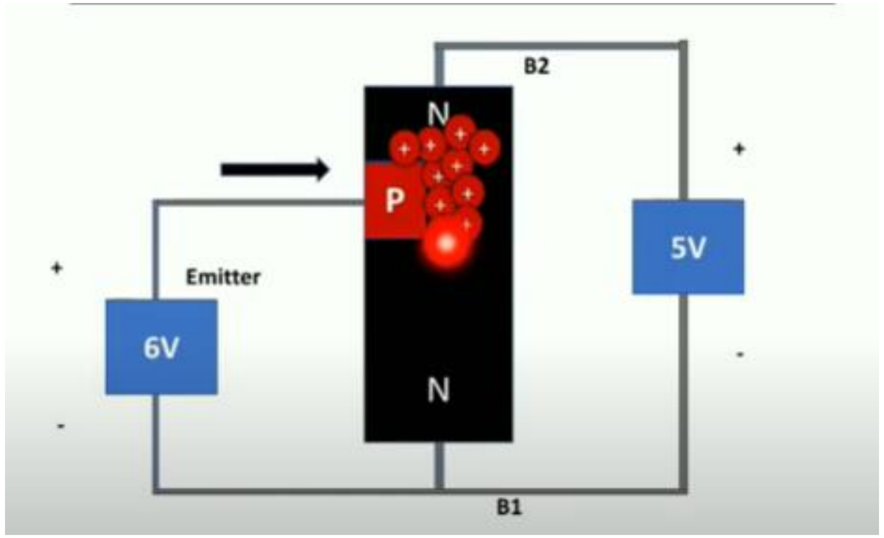
- The UJT structure consists of a **lightly doped n-type silicon** bar provided with **ohmic contacts** on either side.
- The two end connections are called **base B1 and base B2**.
- A small **heavily doped** p-region is alloyed into one side of the bar.
- This p-region is the UJT emitter (E) that forms a p–n junction with the bar.

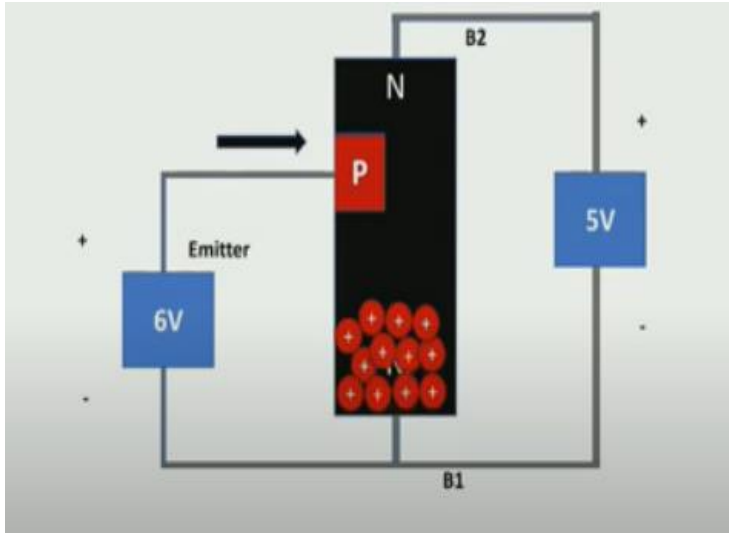



Structure
Equivalent circuit
Package
B2
N
P
Emitter
N
B1
RB2
RB1

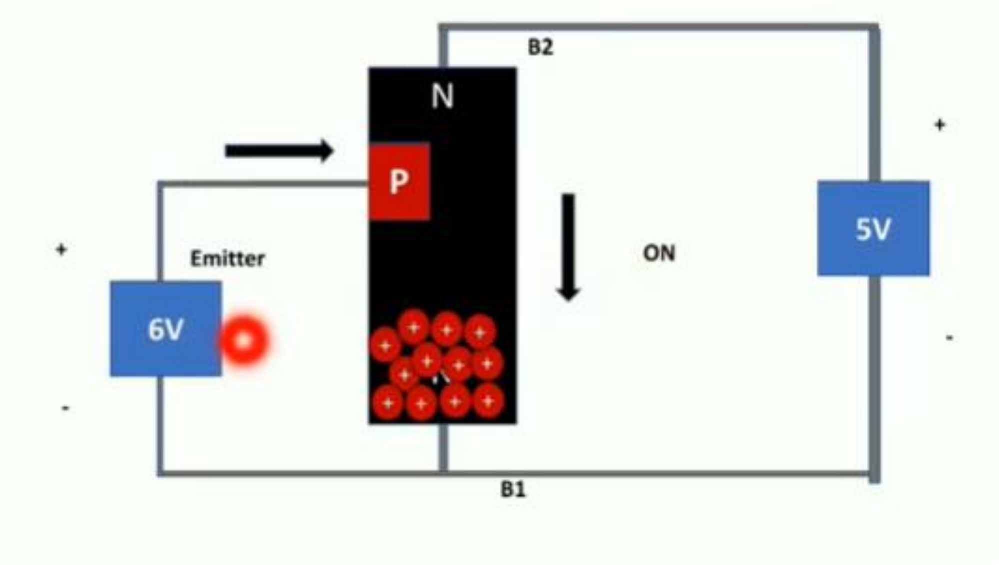

B2
N
P
Emitter
0V
N
5V
B1

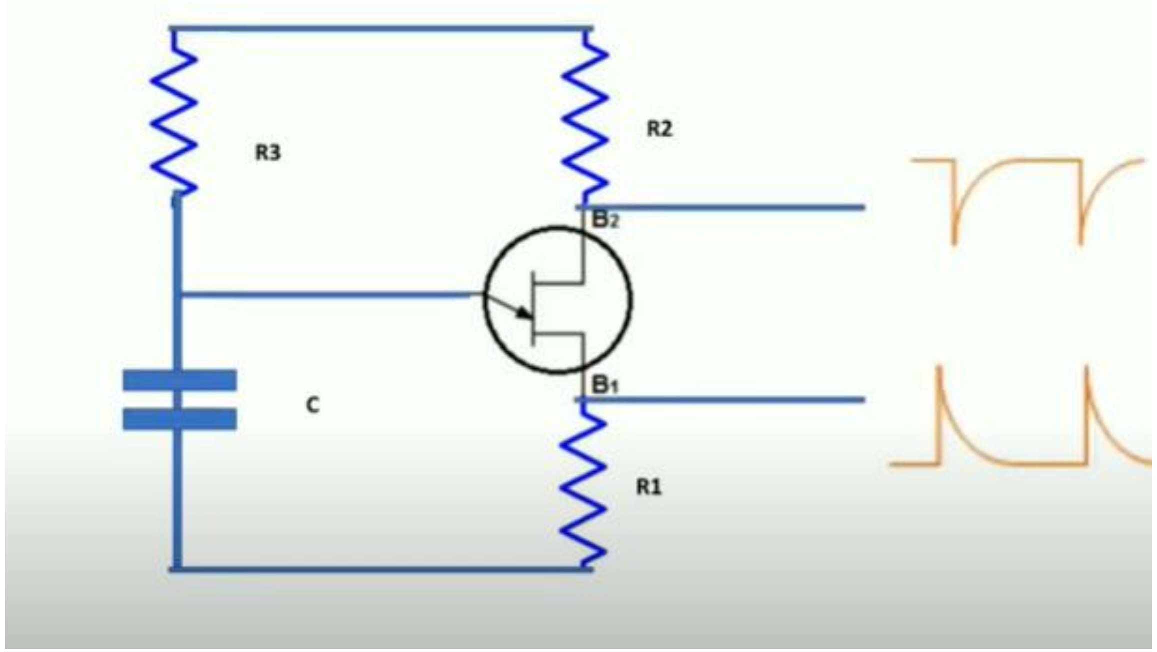

B2
N
P
Emitter
1V
N
5V
B1


B2
N
P
Emitter
6V
N
5V
B1

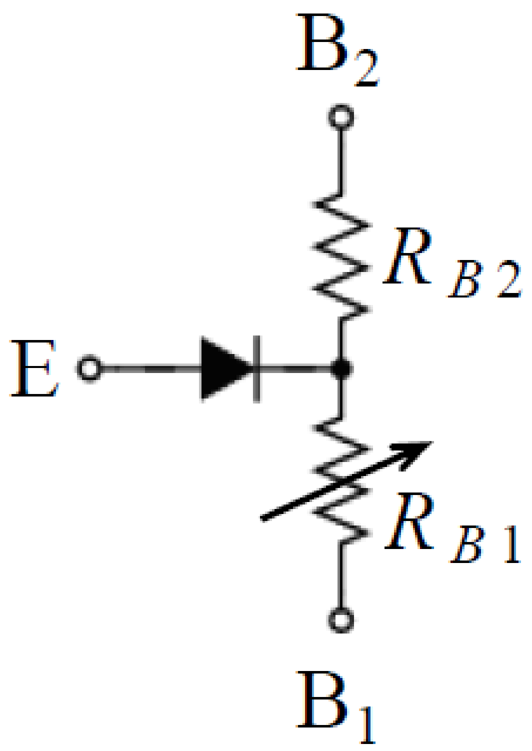

B2
N
P
Emitter
6V
5V
B1


B2
N
P
Emitter
N
B1
RB2
RB1


B2
N
P
+
Emitter
6V
-
ON
+
5V
-
B1


R3
R2
B2
C
B1
R1

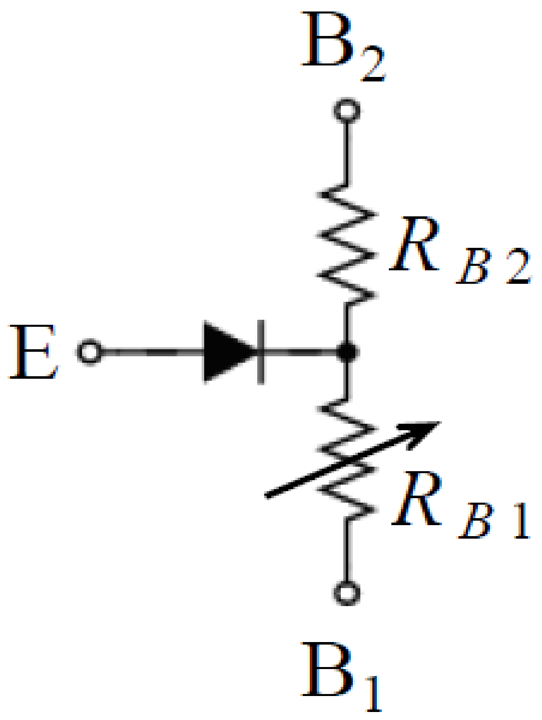
Unijunction Transistor (UJT)



Equivalent Circuit

- R_{B1} = dynamic resistance of the silicon bar between the emitter and base 1.
- R_{B1} varies inversely with emitter current I_E, and therefore it is shown as a variable resistor.
- Range of R_{B1}: several thousand ohms down to tens of ohms

Unijunction Transistor (UJT)



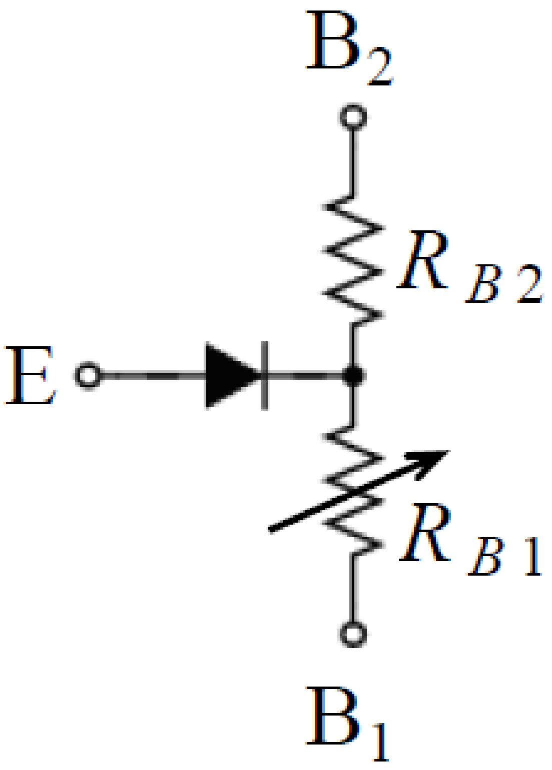
Equivalent Circuit

R_{B2} = dynamic resistance between the emitter and base 2

The total resistance between the base terminals is known as **inter-base resistance R_{BBO}**

$$R_{BBO} = R_{B1} + R_{B2}$$

Unijunction Transistor (UJT)



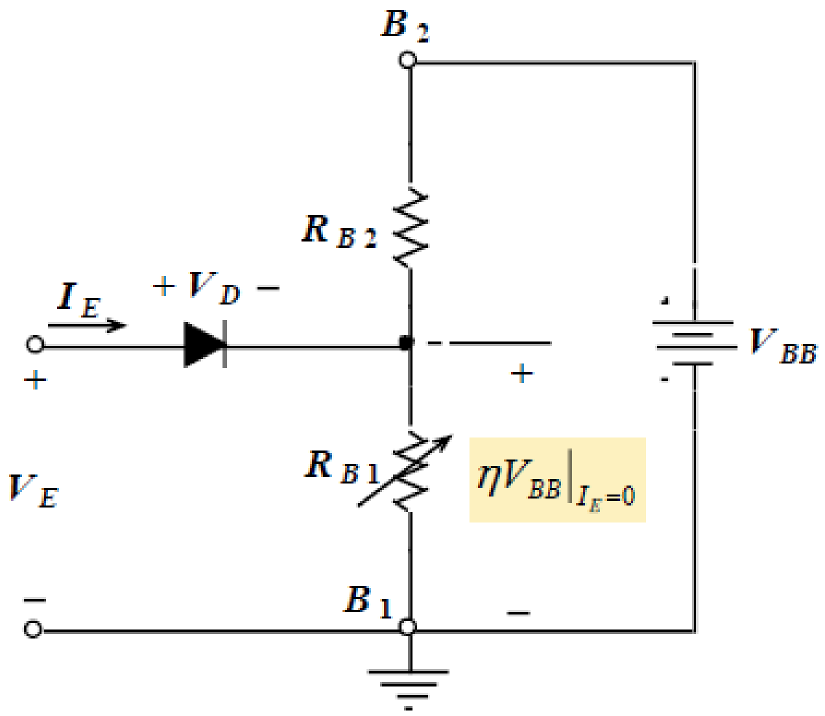
Equivalent Circuit

The ratio of R_{B1} to the inter-base resistance is called the **standoff ratio**, $\boldsymbol{\eta}$.

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} = \frac{R_{B1}}{R_{BBO}}$$

Equivalent circuit for UJT

- The V_{BB} source is generally fixed and provides a constant voltage from B2 to B1.
- The UJT is normally operated with both B2 and VE positive biased relative to B1.
- B1 is always the UJT reference terminal and all voltages are measured relative to B1.
- V_{EE} is a variable voltage source.

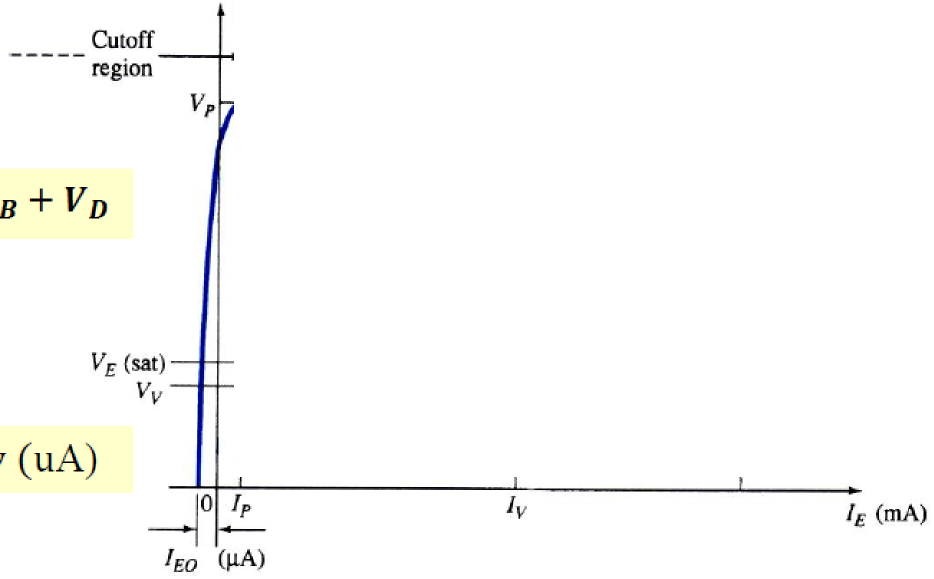


Step 1:

- As long as V_E is less than $\eta V_{BB} + V_D$, there is no emitter current (except a very small leakage current in µA known as I_{EO}) because the pn junction is not forward-biased.

$$V_E < \eta V_{BB} + V_D$$

$$I_{E0} = \text{few (uA)}$$

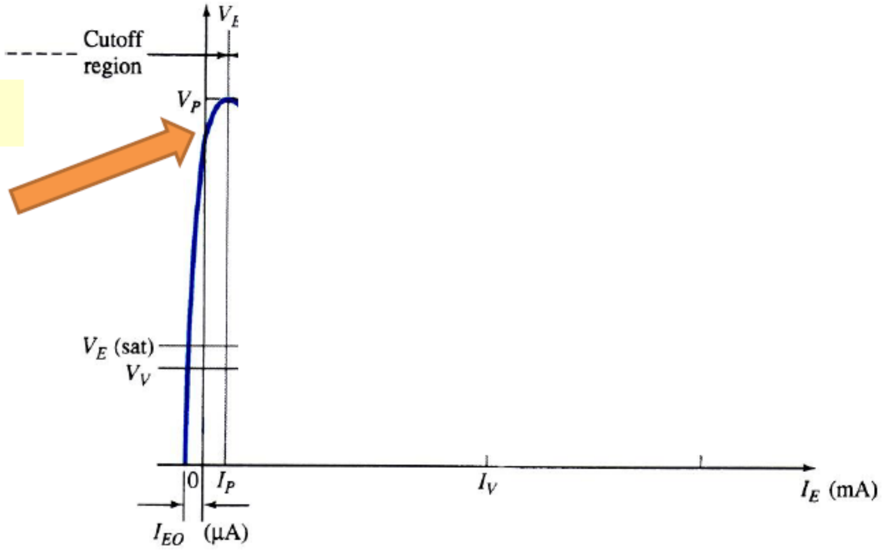


Step 2:

- The level of emitter voltage that causes the pn junction to become forward-biased is called V_P (peak-point-voltage)

$$V_E = \eta V_{BB}$$

$$I_E = 0$$

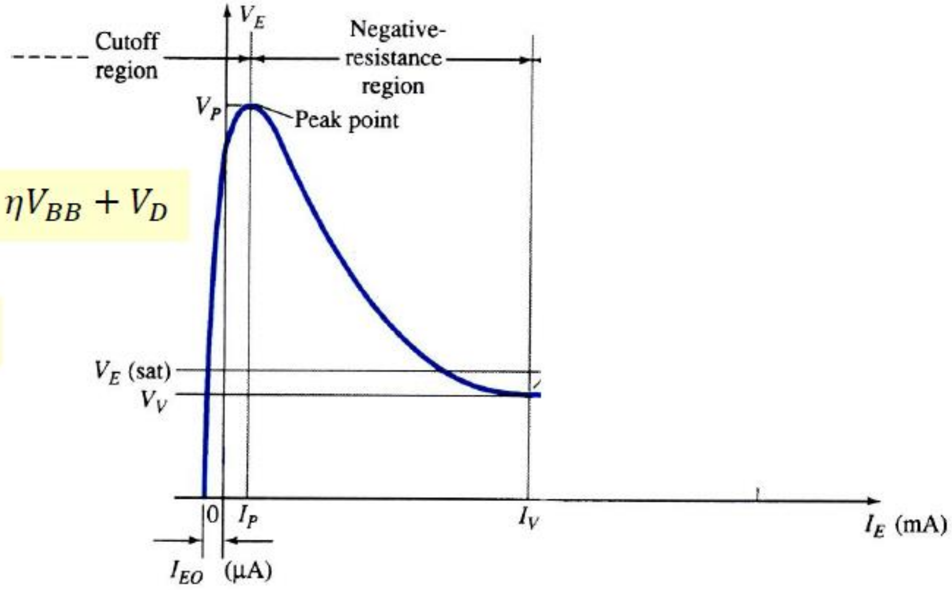


Step 3:

- Once V_E reaches V_P, I_E begins to flow (UJT turns on) – conductivity increases and R_{B1} decreases.
- After turn-on, the UJT operates in a negative resistance region (V_E decreases as I_E increases) up to a certain level of I_E .

$$V_E = V_P = \eta V_{BB} + V_D$$

$$I_E = I_P$$

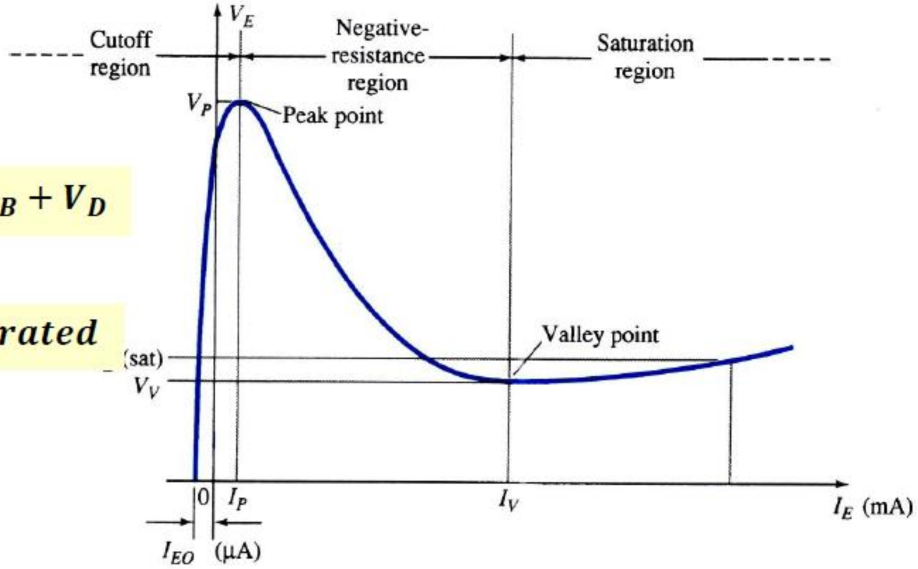


Step 4:

- Beyond this level, V_E begin to increase again. The minimum level of V_E is known as valley point (V_V , I_V). Beyond this point, the device enters its saturation region.

$$V_E > \eta V_{BB} + V_D$$

$$I_E = Saturated$$



UJT Ratings

- Maximum peak emitter current: This represents the maximum allowable value of a pulse of emitter current.

- Maximum reverse emitter voltage: This is the maximum reverse-bias that the emitter base junction *B2* can tolerate before breakdown occurs.

- Maximum inter base voltage: This limit is caused by the maxi mum power that the *n-type base bar can* safely dissipate.

- Emitter leakage current: This is the emitter current which flows when *VE is less than Vp and the UJT is* in the OFF state.

Applications

- The UJT is very popular today mainly due to its high switching speed.

- A few select applications of the UJT are as follows:

  (i) It is used to trigger SCRs and TRIACs

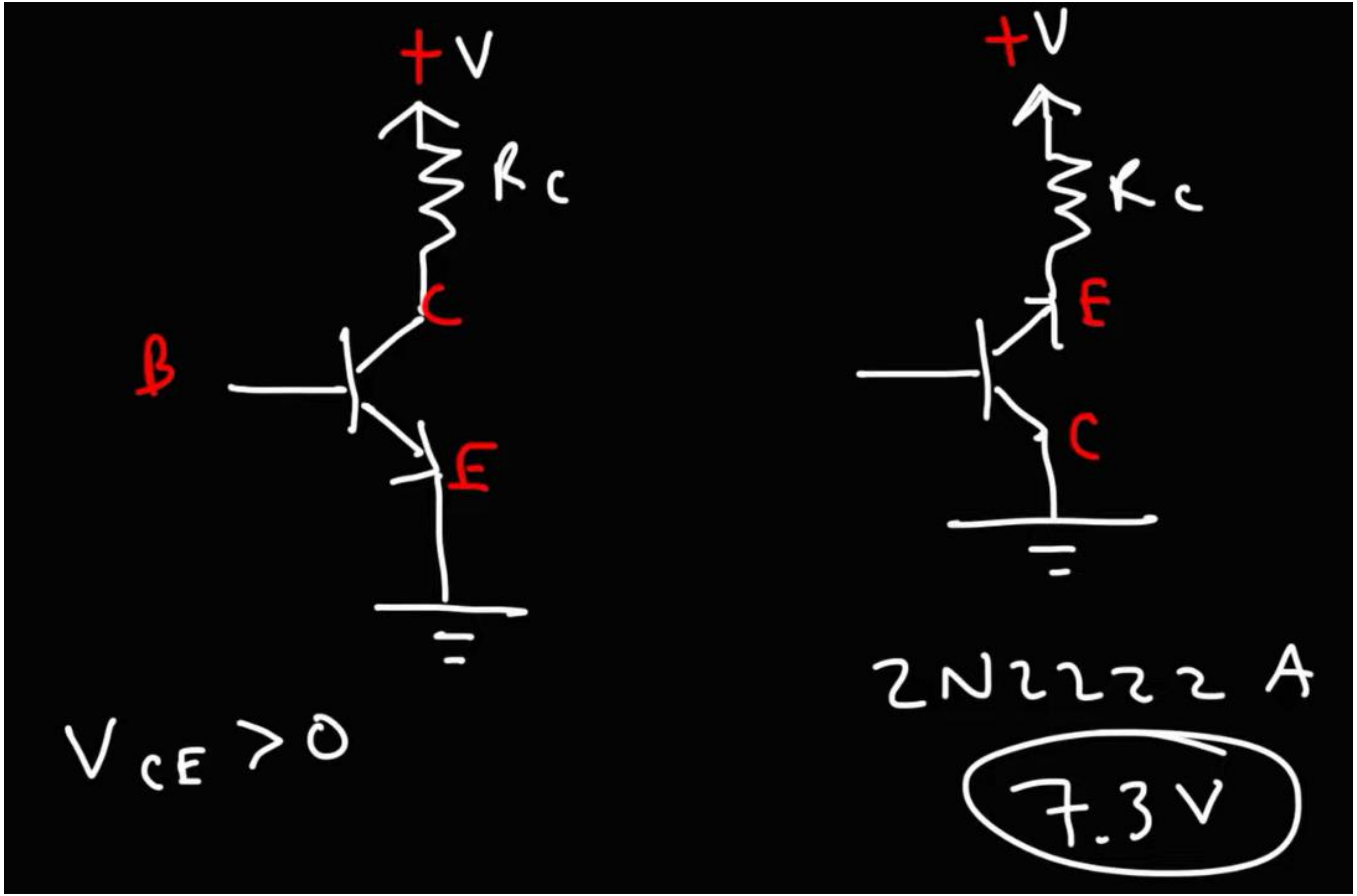
  (ii) It is used in non-sinusoidal oscillators

  (iii) It is used in phase control and timing circuits

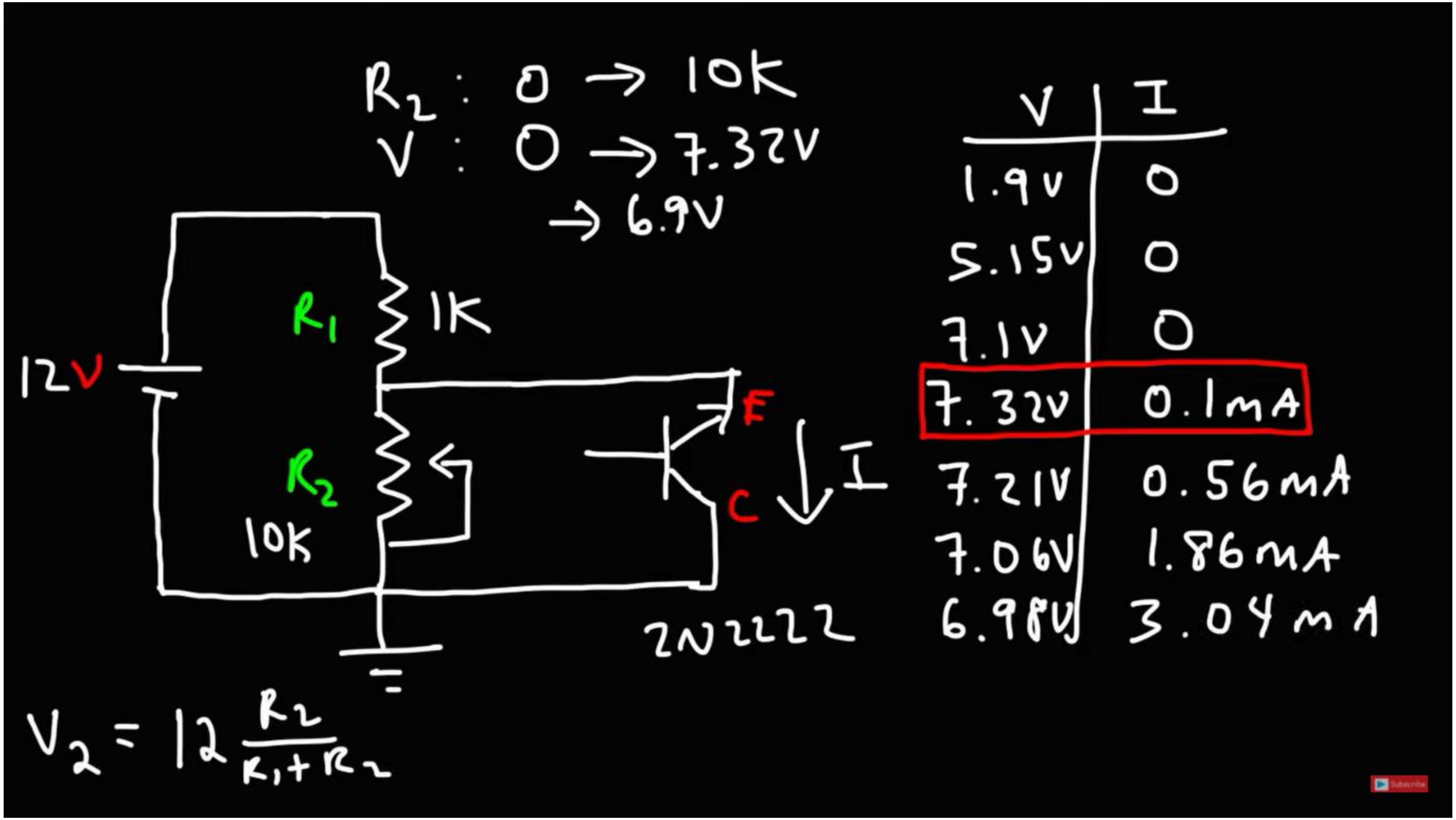
  (iv) It is used in saw tooth generators

  (v) It is used in oscillator circuit design

Negative Resistance



Negative Resistance



Negative Resistance