II B.Tech I-Sem (E.C.E)

(15A04301) ELECTRONIC DEVICES AND CIRCUITS

UNIT- I

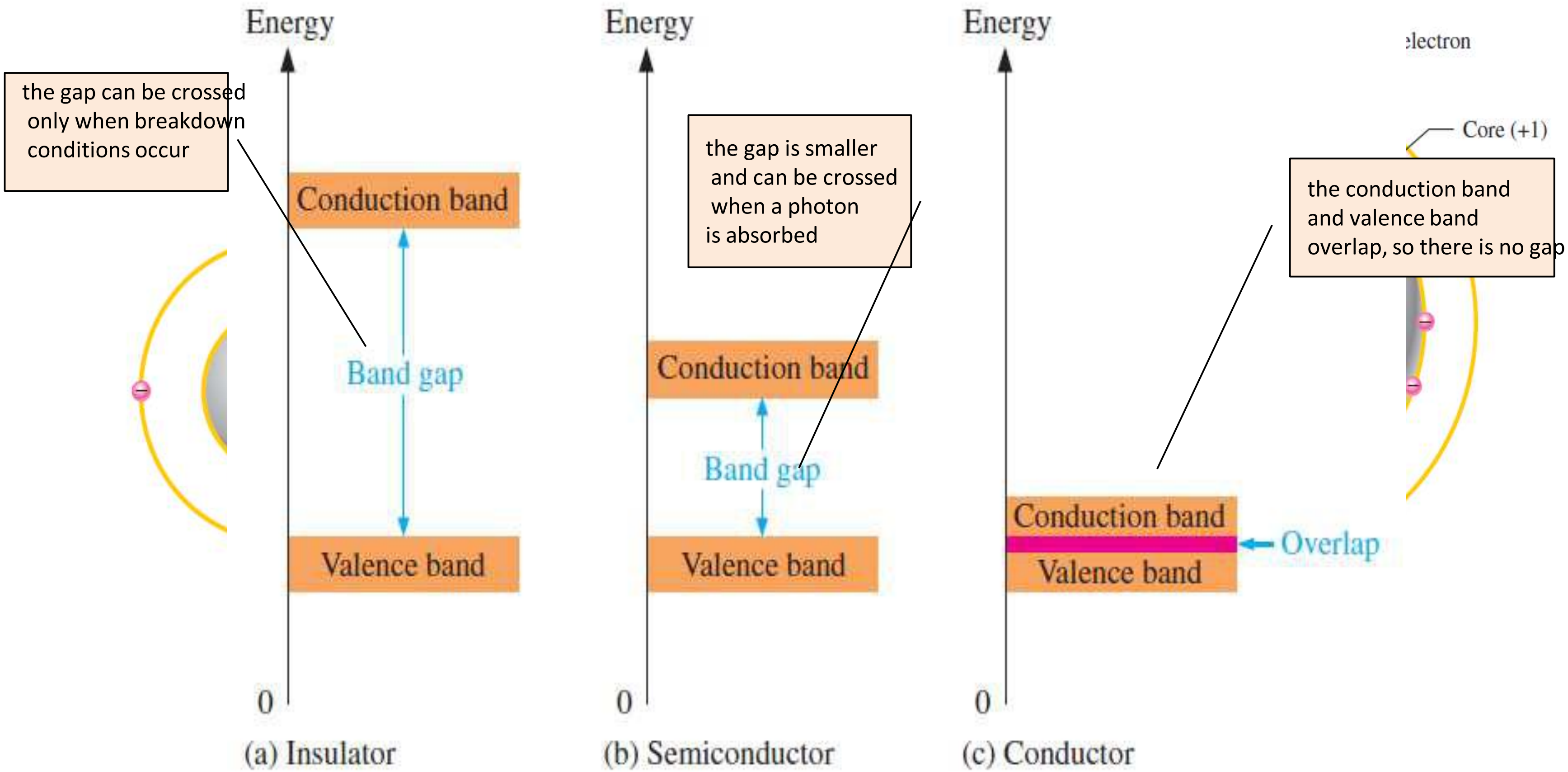
- **Junction Diode Characteristics :** Open circuited p-njunction, Biased p-n junction,p-n junction diode, current components in PN junction Diode, diode equation,V-I Characteristics, temperature dependence on V-I characteristics, Diode resistance, Diode capacitance, energy band diagram of PN junction Diode.
- **Special Semiconductor Diodes**: Zener Diode, Breakdown mechanisms, Zener diode applications, LED, LCD, Photo diode, Varactor diode, Tunnel Diode, DIAC, TRIAC, SCR, UJT. Construction, operation and characteristics of all the diodes is required to be considered.

Discrete Semiconductor Devices

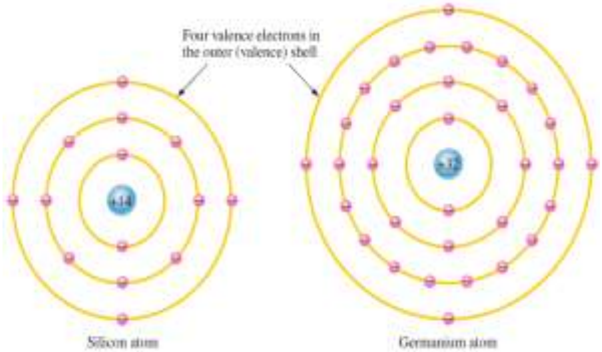
- Semiconductor Materials
  - Conductor and Insulators.
  - N-type, P-Type, electron, and hole current
  - PN junction, depletion region, potential barrier.
- Diodes
  - Forward Bias, reverse bias
  - Diode applications
  - Light Emitting Diodes
  - Zener Diodes
  - Photo Diodes

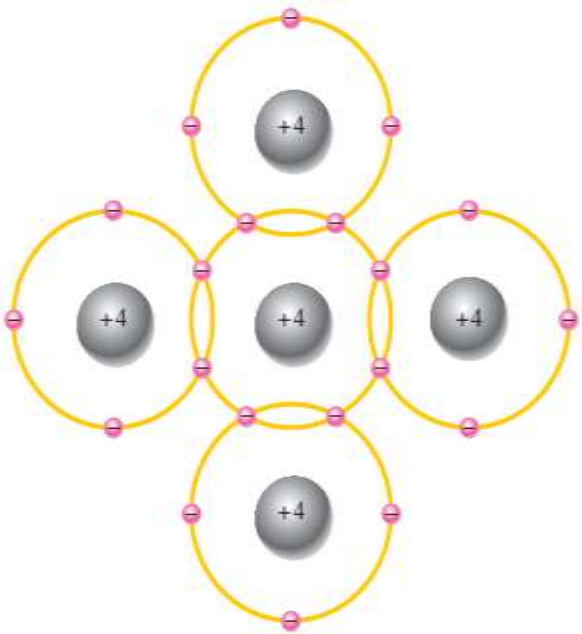
Conductor and Insulators.

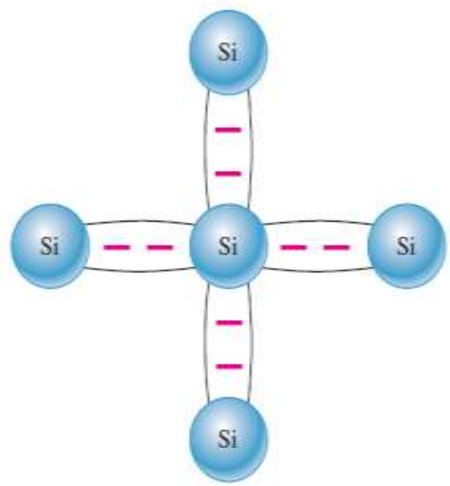
Atomic Model



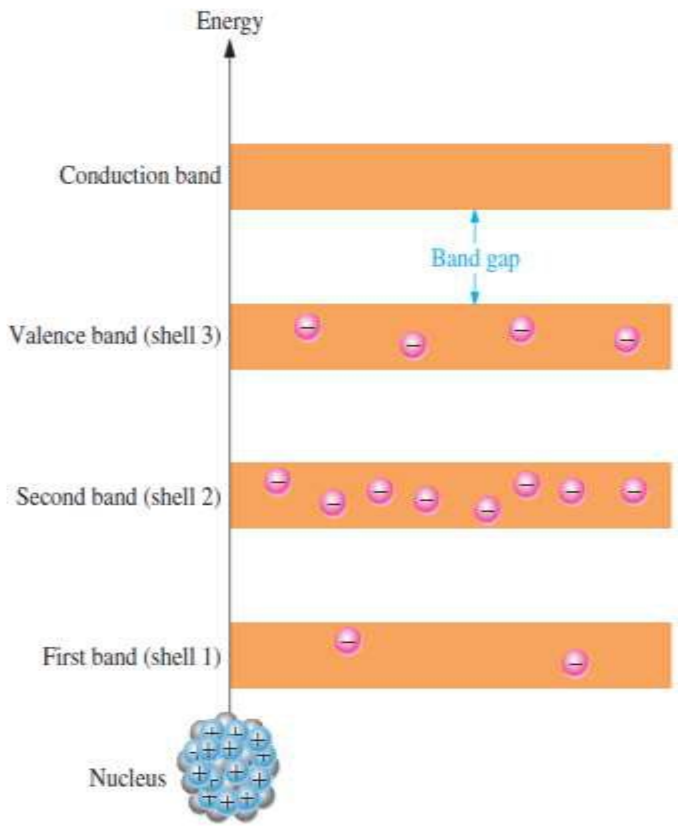
Silicon and Germanium

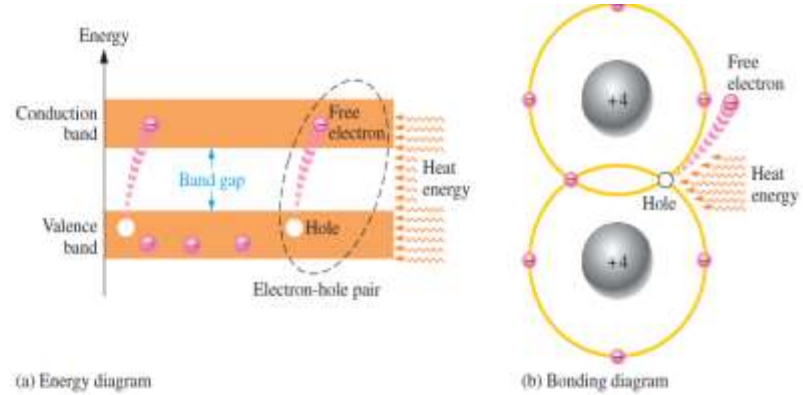






Conduction Electron and Holes.





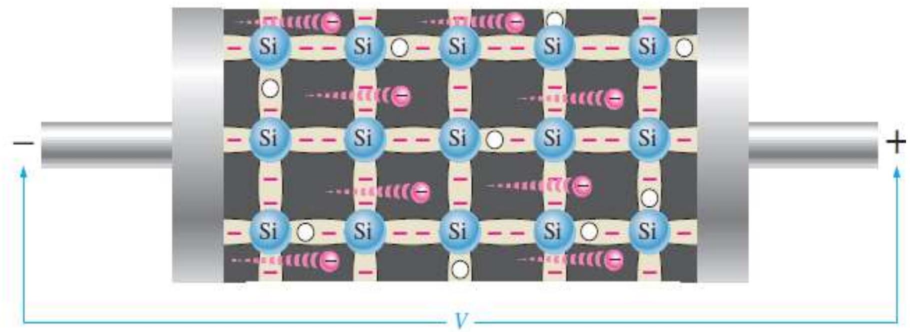
An intrinsic (pure) silicon crystal at room temperature has sufficient heat energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electron called '**Conduction Electron**'

It leaves a vacancy in valance band, called **hole**.

Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

Electron Hole Current.

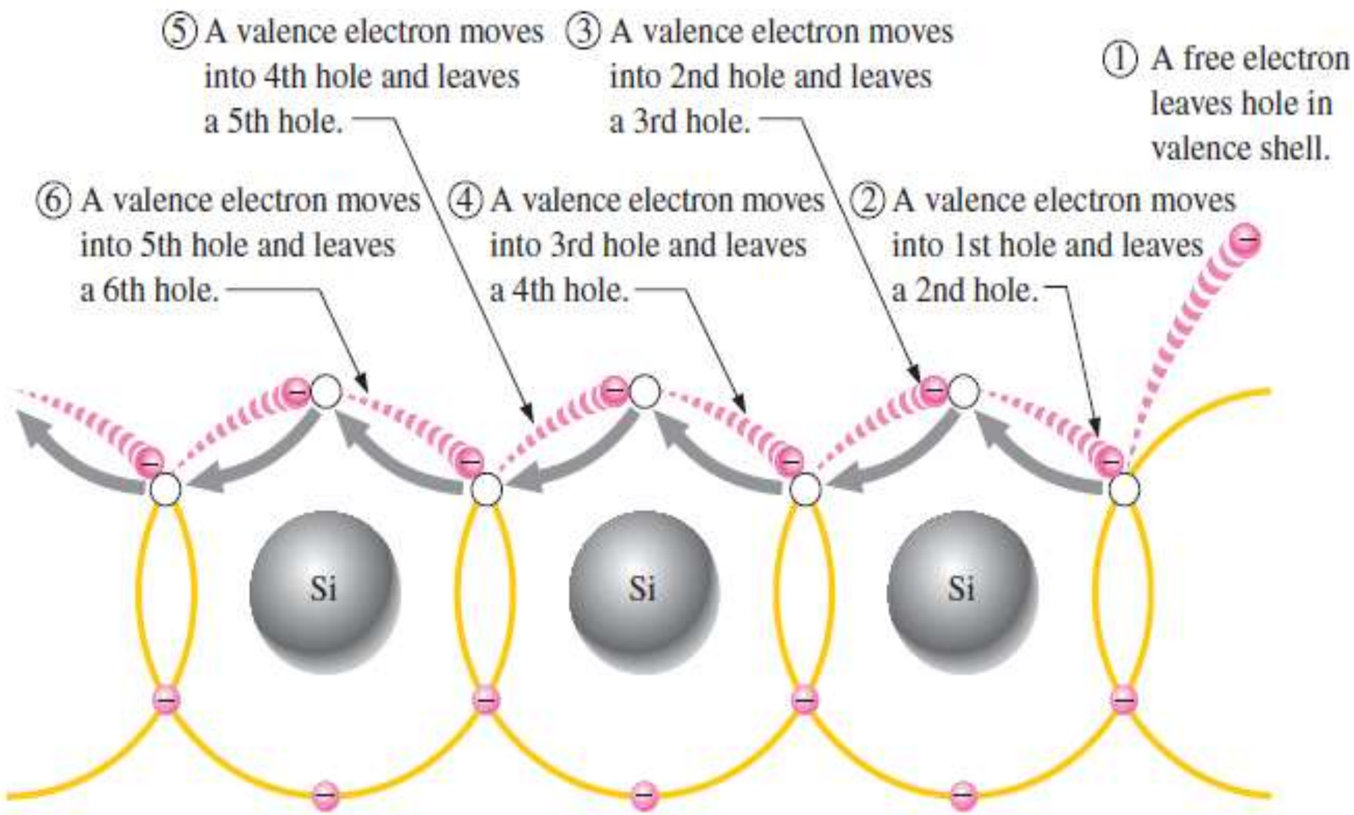
In conduction band : When a voltage is applied across a piece of intrinsic silicon, the thermally generated free electrons in the conduction band, are now easily attracted toward the positive end.



This movement of free electrons is one type of current in a semiconductive material and is called ***electron current.***

In valance band: In valance band holes generated due to free electrons. Electrons in the valance band are although still attached with atom and not free to move, however they can move into nearby hole with a little change in energy, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure. It is called ***hole current.***

Electron Hole Current.



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

N-type semiconductor

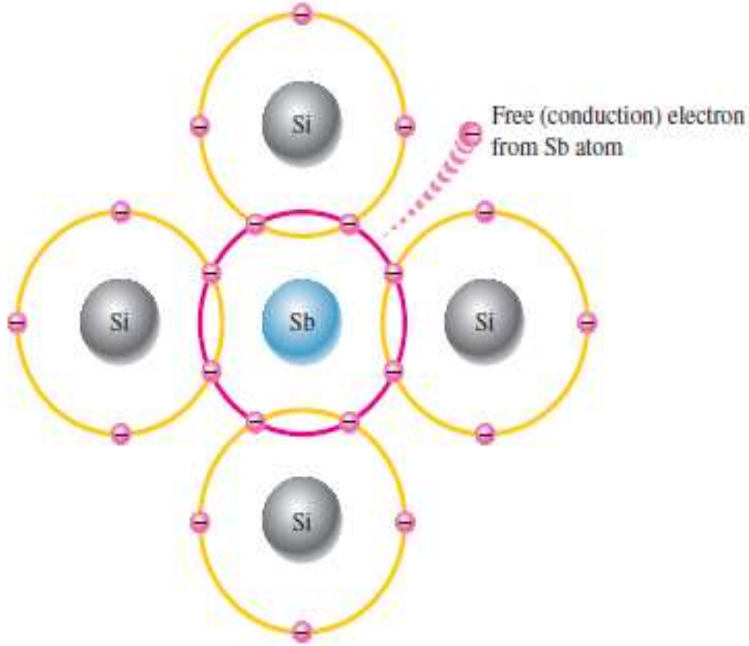
Electrons in the conduction band and holes in the valence band make the semiconductive material to conduct but they are too limited to make it a very good conductor..

Adding impurities in materials like Si or Ge can drastically increase the conductivity of material. The process is called ***doping.***

Addition of a penta-valent material icnreases the number of conduction electrons.

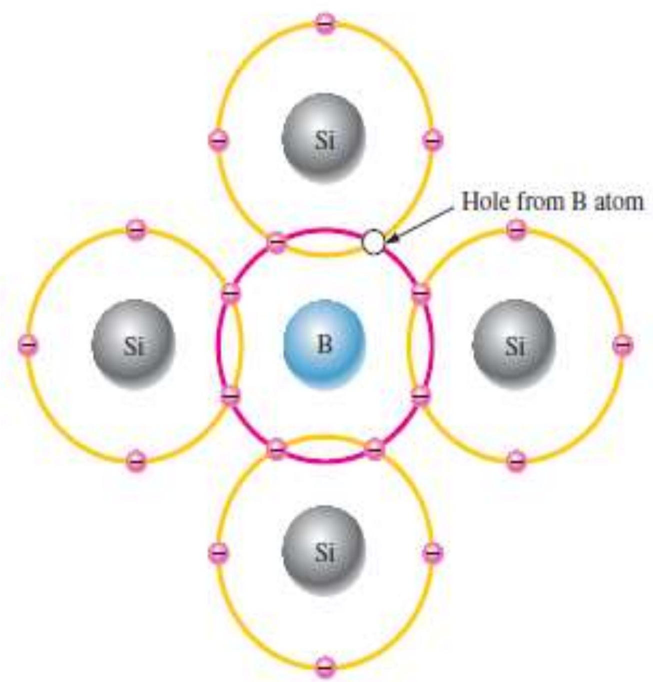
Majority carrier: electrons
Minority carriers: holes

Material is called ***N-type*** semiconductor



An antimony
(Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

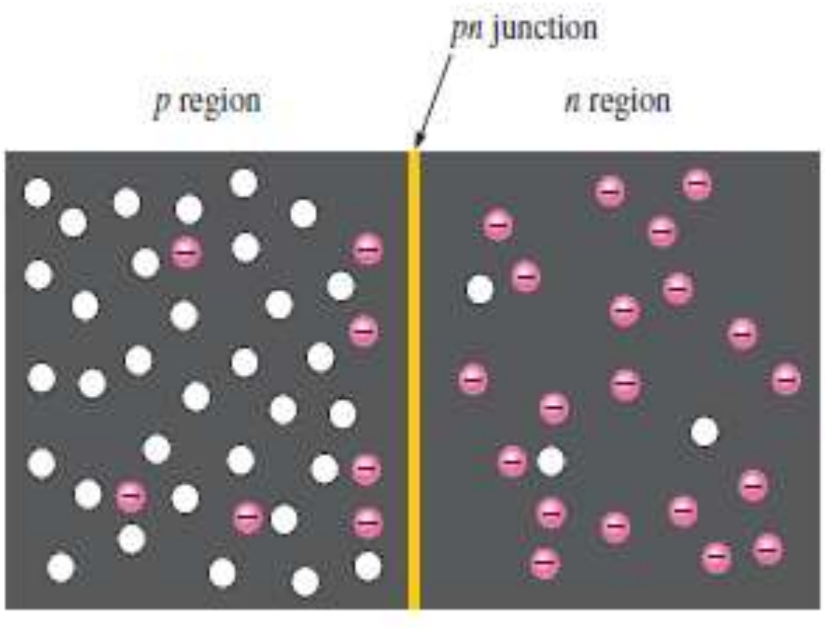
P-type semiconductor.



Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

PN Junction

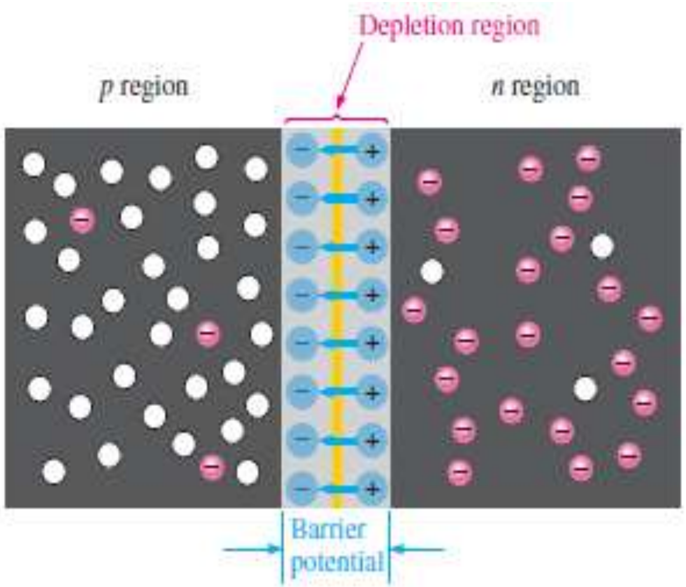
Although P-type material has holes in excess and N-type material has a number of free conduction electron however the net number of proton and electron are equal in each individual material keeping it just neutral.



The basic silicon structure at the instant of junction formation showing only the majority and minority carriers.

Free electrons in the *n region near the pn junction begin to diffuse across the* junction and fall into holes near the junction in the *p region.*

PN Junction

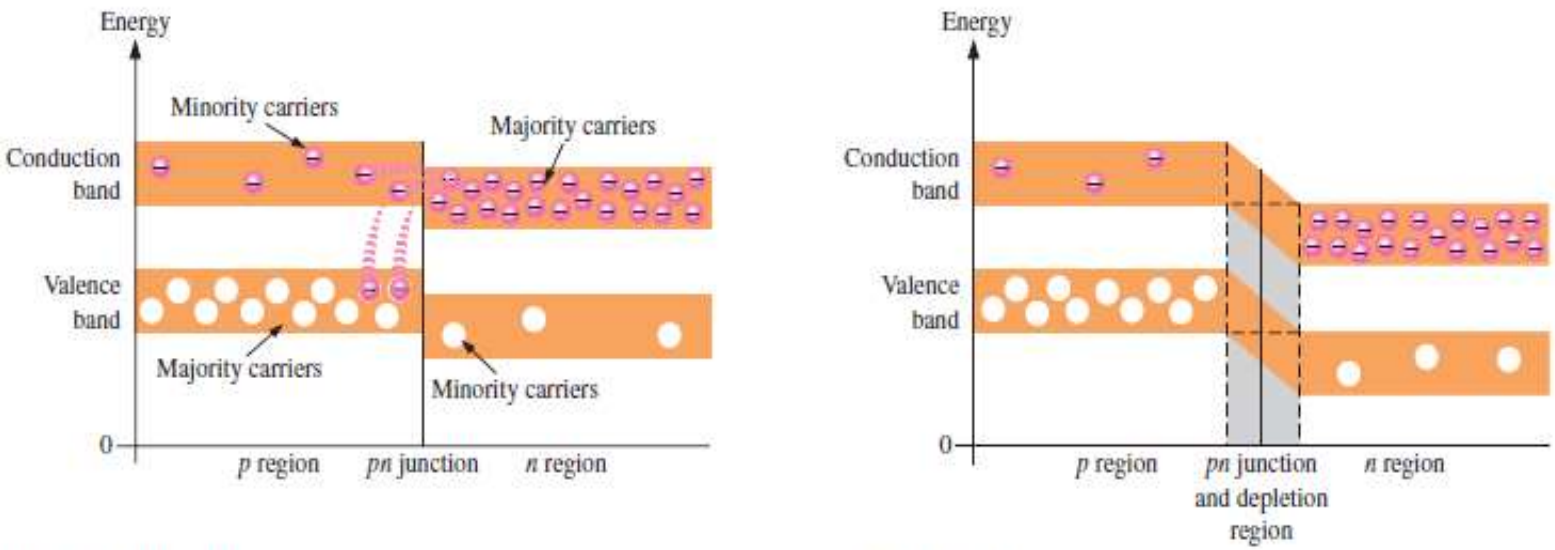


For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n region* and a negative charge is created in the *p region, forming a* barrier potential.

This action continues until the voltage of the barrier repels further diffusion.

The blue arrows between the positive and negative charges in the depletion region represent the electric field.

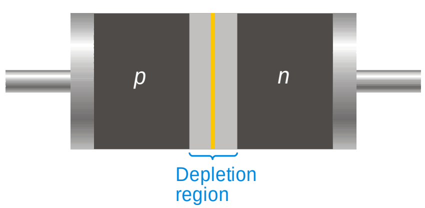
Energy band and potential barrier

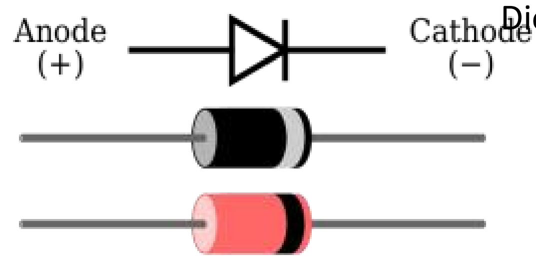


Diodes

- Diode, semiconductor material, such as silicon, in which half is doped as p-region and half is doped as n-region with a pn-junction in between.

- The p region is called **anode** and n type region is called **cathode.**





Diode symbol

Diodes

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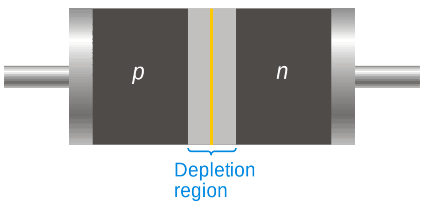
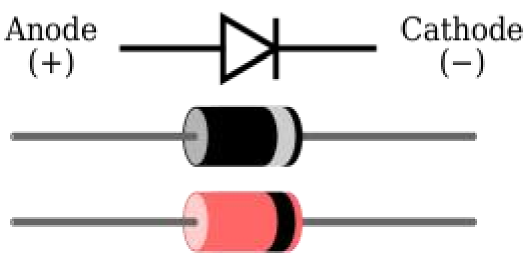


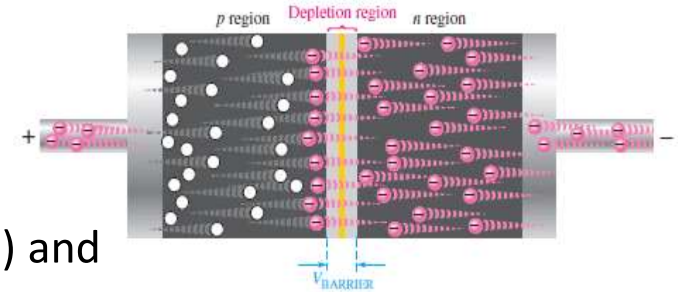


Diode symbol

- It conducts current in one direction and offers high (ideally infinite) resistance in other direction.

Forward Biased

❖ Forward bias is a condition that allows current through pn junction.



❖ A dc voltage (V_{bais}) is applied to bias a diode.

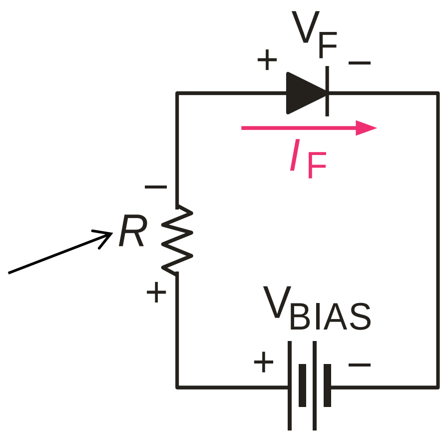
❖ Positive side is connected to p-region (anode) and negative side is connected with n-region.

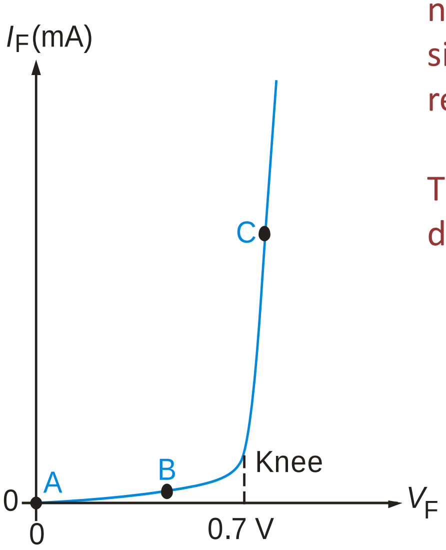
❖ V_{bais} must be greater than 'barrier potential'

As more electrons flow into the depletion region reducing the number of positive ions and similarly more holes move in reducing the positive ions.

This reduces the width of depletion region.

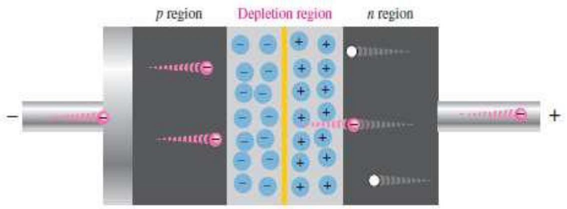
Current limiting resistance





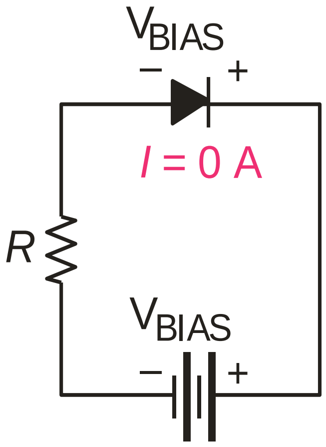
Reverse Biased

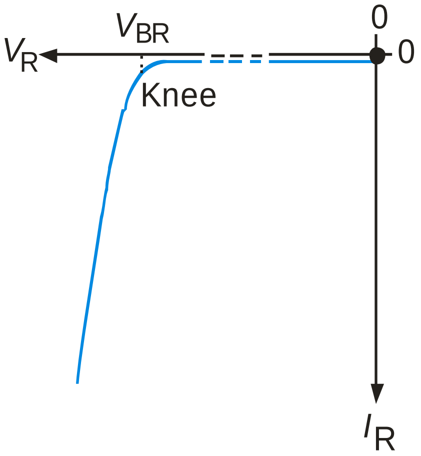
- Reverse bias is a condition that prevents current through junction.
- Positive side of V_{bias} is connected to the n-region whereas the negative side is connected with p-region.
- Depletion region get wider with this configuration.



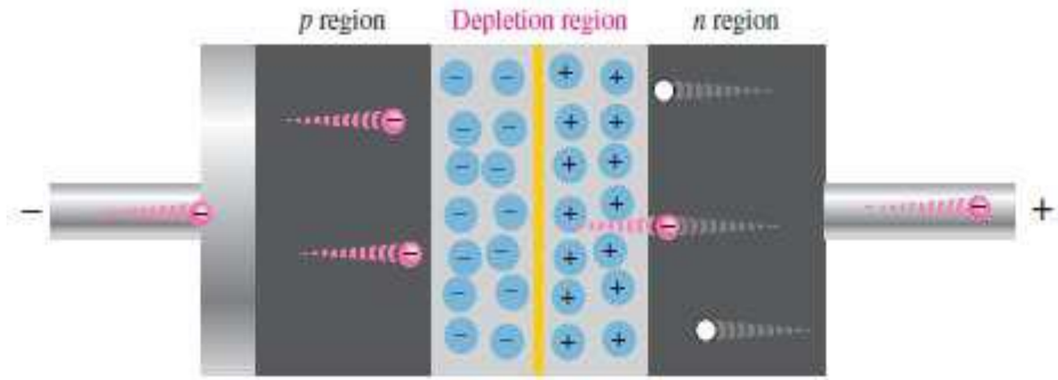
The positive side of bias voltage attracts the majority carriers of n-type creating more positive ions at the junction.

This widens the depletion region.



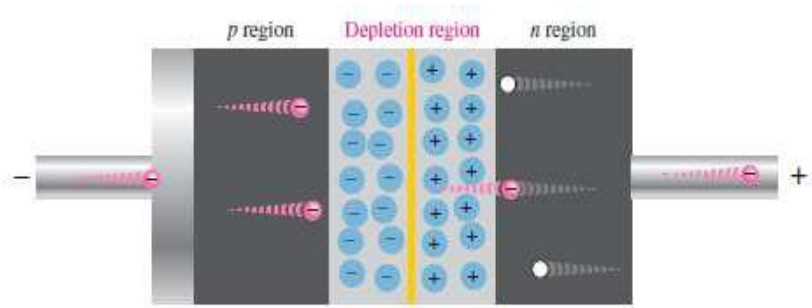


Reverse Current



- A small amount current is generated due to the minority carriers in p and n regions.
- These minority carriers are produced due to thermally generated hole-electron pairs.
- Minority electrons in p-region pushed towards +ve bias voltage, cross junction and then fall in the holes in n-region and still travel in valance band generating a hole current.

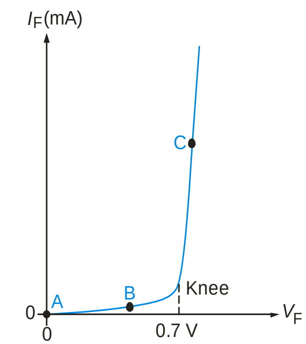
Reverse Breakdown

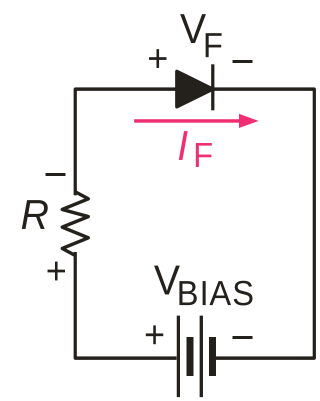


- If the external bias voltage is increased to a value call *breakdown voltage* the reverse current can increase drastically.
- Free minority electrons get enough energy to knock valance electron into the conduction band.
- The newly released electron can further strike with other atoms.
- The process is called ***avalanche effect.***

Diode V-I Characteristic

- **VI Characteristic for forward bias.**
  - The current in forward biased called *forward current* and is designated I_{f}.
  - At 0V (V_{bias}) across the diode, there is no forward current.
  - With gradual increase of V_{bias}, the forward voltage and forward current increases.
  - A resistor in series will limit the forward current in order to protect the diode from overheating and permanent damage.
  - A portion of forward-bias voltage drops across the limiting resistor.
  - Continuing increase of V_f causes rapid increase of forward current but only a gradual increase in voltage across diode.

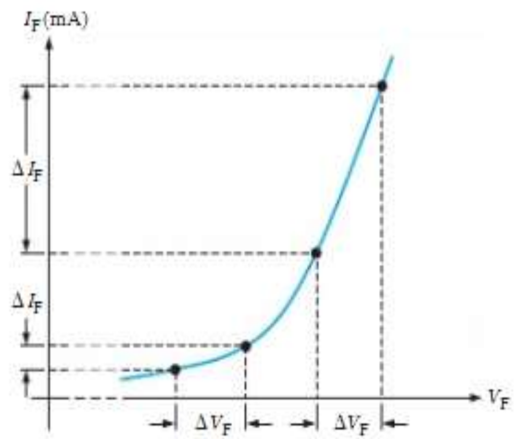




Diode V-I Characteristic

❖ **Dynamic Resistance:**

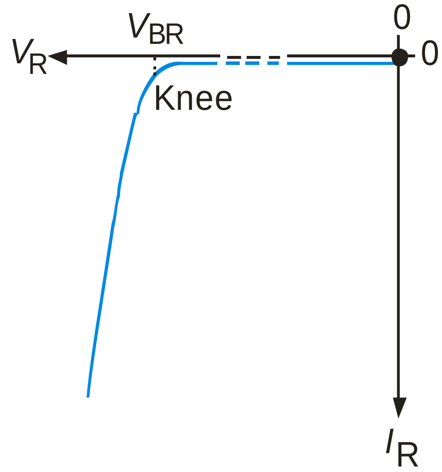
- The resistance of diode is not constant but it changes over the entire curve. So it is called dynamic resistance.



The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F / \Delta I_F$.

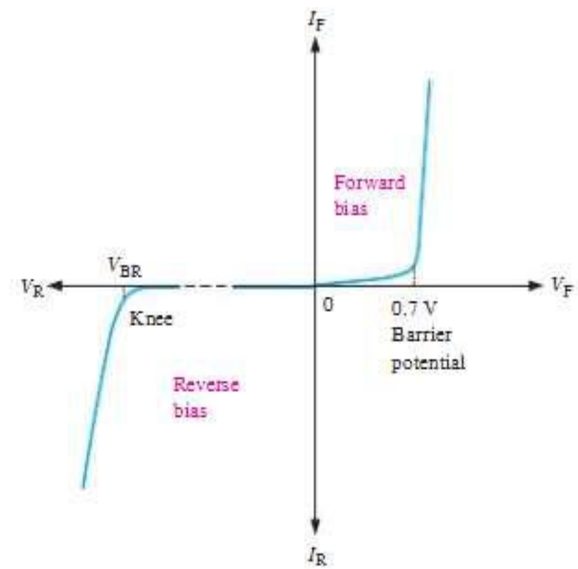
Diode V-I Characteristic

- **VI Characteristic for reverse bias.**
  - With 0V reverse voltage there is no reverse current.
  - There is only a small current through the junction as the reverse voltage increases.
  - At a point, reverse current shoots up with the break down of diode. The voltage called break down voltage. This is not normal mode of operation.
  - After this point the reverse voltage remains at approximately V_{BR} but I_R increase very rapidly.
  - Break down voltage depends on doping level, set by manufacturer.



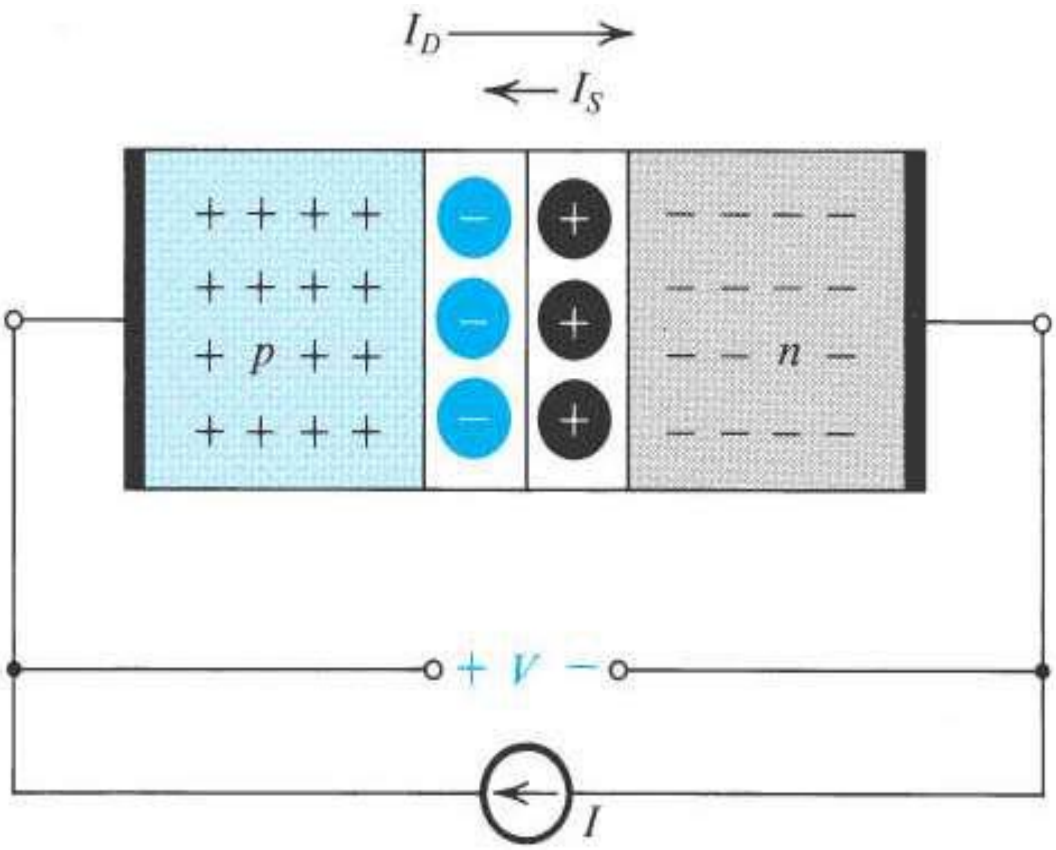
Diode V-I Characteristic

- ❖ The complete V-I characteristic curve



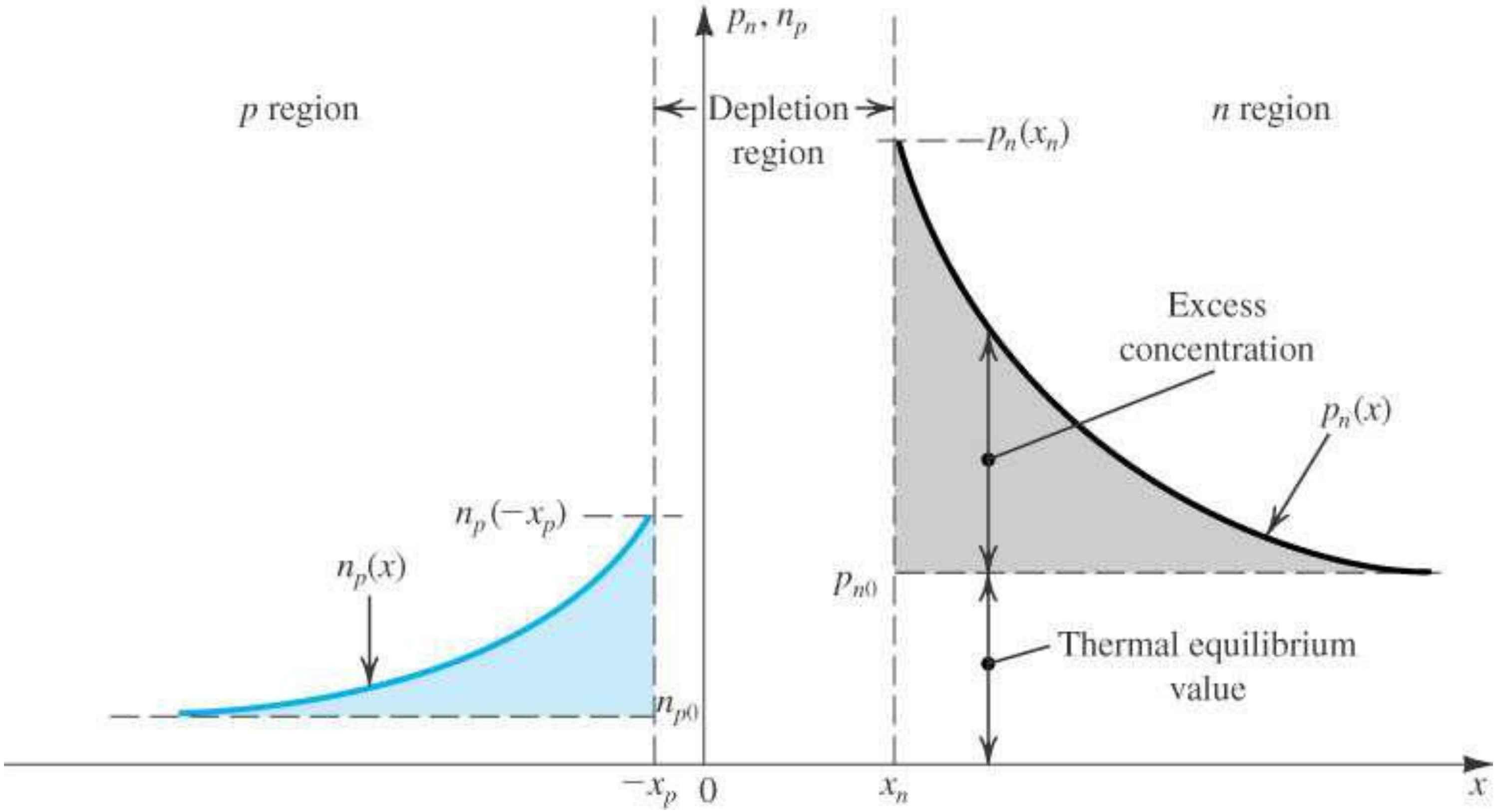
The complete *V-I* characteristic curve for a diode.

The *pn* Junction Under Forward-Bias Conditions



- The *pn* junction excited by a constant-current source supplying a current *I* in the forward direction.
- The depletion layer narrows and the barrier voltage decreases by *V* volts, which appears as an external voltage in the forward direction.

Current Components of PN Junction Diode



Minority-carrier distribution in a forward-biased *pn* junction. It is assumed that the *p* region is more heavily doped than the *n* region; $N_A >> N_D$.

The *pn* Junction Under Forward-Bias Conditions

Excess minority carrier concentration:

$$p_n(x_n) = p_{n0} e^{v/V_T}$$

$$n_p(-x_p) = n_{p0} e^{v/V_T}$$

- Exponential relationship
- Small voltage incremental give rise to great incremental of excess minority carrier concentration.

The *pn* Junction Under Forward-Bias Conditions

Distribution of excess minority concentration:

$$p_n(x) = p_{no} + [p_n(x_n) - p_{n0}]e^{-(x-x_n)/L_p}$$

$$n_p(x) = n_{p0} + [n_p(-x_p) - n_{p0}]e^{(x+x_p)/L_n}$$

Where

$$L_p = \sqrt{D_p \tau_p}$$

$$L_n = \sqrt{D_n \tau_n}$$

τ_n, τ_p are called excess-minority-carrier lifetime.

The *pn* Junction Under Forward-Bias Conditions

The total current can be obtained by the diffusion current of majority carriers.

$$
\begin{aligned}
I &= I_{pD} + I_{nD} \\
&= A(J_{pD} + J_{nD}) \\
&= A\left(-q \left.\frac{dp(x)}{dx}\right|_{x=x_n} + q \left.\frac{dn(x)}{dx}\right|_{x=-x_p}\right) \\
&= Aq\left(\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n}\right)\left(e^{V/V_T} - 1\right)
\end{aligned}
$$

The *pn* Junction Under Forward-Bias Conditions

The saturation current is given by :

$$I_s = qA(\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n})$$

$$= qAn_i^2(\frac{D_p}{L_p n_D} + \frac{D_n}{L_n n_A})$$

The *pn* Junction Under Forward-Bias Conditions

I-V characteristic equation:

$$i = I_s(e^{v/nV_T} - 1)$$

- Exponential relationship, nonlinear.
- I_s is called saturation current, strongly depends on temperature.
- $n = 1$ or 2， in general $n = 1$
- V_T is thermal voltage.

The *pn* Junction Under Forward-Bias Conditions

assuming V_1 at I_1 and V_2 at I_2

then:

$$V_2 - V_1 = nV_T \ln {I_2}/{I_1} = 2.3nV_T \lg {I_2}/{I_1}$$

** For a decade changes in current, the diode voltage drop changes by 60mv (for n=1) or 120mv (for n=2).*

The *pn* Junction Under Forward-Bias Conditions

- Turn-on voltage

  A conduction diode has approximately a constant voltage drop across it. It's called turn-on voltage.

  $$V_{D(on)} = 0.7V$$ For silicon

  $$V_{D(on)} = 0.25V$$ For germanium

- Diodes with different current rating will exhibit the turn-on voltage at different currents.
- Negative TC,

  $$TC = -2mv/^\circ C$$

Junction Capacitance

- Diffusion Capacitance
  - Charge stored in bulk region changes with the change of voltage across *pn* junction gives rise to capacitive effect.
  - Small-signal diffusion capacitance
- Depletion capacitance
  - Charge stored in depletion layer changes with the change of voltage across *pn* junction gives rise to capacitive effect.
  - Small-signal depletion capacitance

Diffusion Capacitance

According to the definition:

$$C_d = \left. {dQ}\middle/{dV} \right|_Q$$

The charge stored in bulk region is obtained from below equations:

$$Q_p = Aq \times \int_{x_n}^{\infty} [p_n(x) - p_{no}]dx$$

$$= Aq \times [p_n(x_n) - p_{no}] \cdot L_p$$

$$= \tau_p I_p$$

$$Q_n = \tau_n I_n$$

Diffusion Capacitance

The expression for diffusion capacitance:

$$C_d = \frac{d}{dV}[\tau_T I_s e^{V/V_T}]$$

$$= (\frac{\tau_T}{V_T}) I_Q$$

$$\approx \begin{cases} (\frac{\tau_T}{V_T}) I_Q \\ 0 \end{cases}$$

Forward-bias, linear relationship

Reverse-bias, almost inexistence

Depletion Capacitance

According to the definition: $C_j = {dQ}/{dV_R}\Big|_{V_R=V_Q}$

Actually this capacitance is similar to parallel plate capacitance.

$$C_j = \frac{\varepsilon A}{W_{dep}} = \frac{\varepsilon A}{\sqrt{[\frac{2\varepsilon}{q}(\frac{1}{N_A}+\frac{1}{N_B})(V_0+v_R)}}$$

$$= \frac{C_{j0}}{\sqrt{(1+{V_R}/{V_o})}}$$

Depletion Capacitance

- A more general formula for depletion capacitance is :

$$C_j = \frac{C_{j0}}{(1+{V_R}/{V_0})^m}$$

- Where m is called grading coefficient. $m = \frac{1}{3} \sim \frac{1}{2}$
- If the concentration changes sharply, $m = \frac{1}{2}$
- Forward-bias condition, $C_j \approx 2C_{j0}$
- Reverse-bias condition, $C_j << C_d$

Junction Capacitance

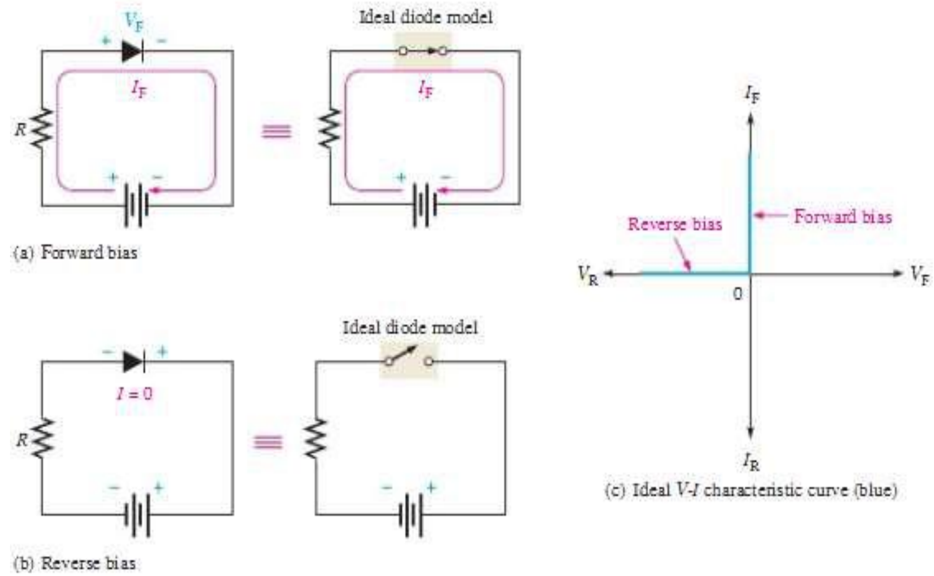
Remember:

a) Diffusion and depletion capacitances are incremental capacitances, only are applied under the small-signal circuit condition.

b) They are not constants, they have relationship with the voltage across the pn junction.

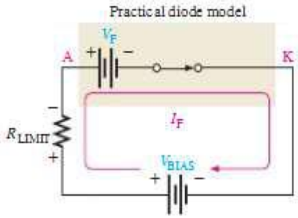
Diode models

- **Ideal Diode Model**



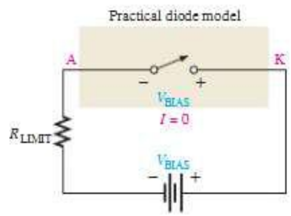
- Barrier potential, the forward dynamic resistance and reverse current all are neglected.

Diode models



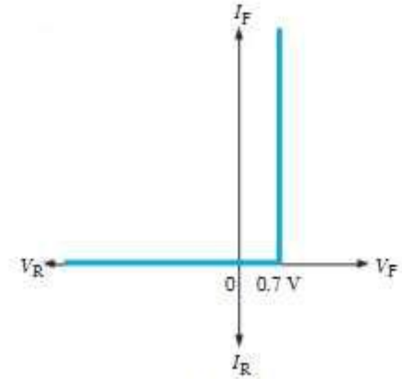
(a) Forward bias

$V_F = 0.7V$



(b) Reverse bias

- **Practical Diode Model**
- Barrier potential, the forward dyr resistance and reverse current all neglected.



(c) Characteristic curve (silicon)

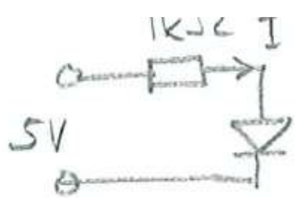
- Forward current I_F is determined using Kirchhoff's voltage as follows:

$$V_{BIAS} - V_F - V_{R_{LIMIT}} = 0$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT}$$

Substituting and solving for I_F, $$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

Ex)

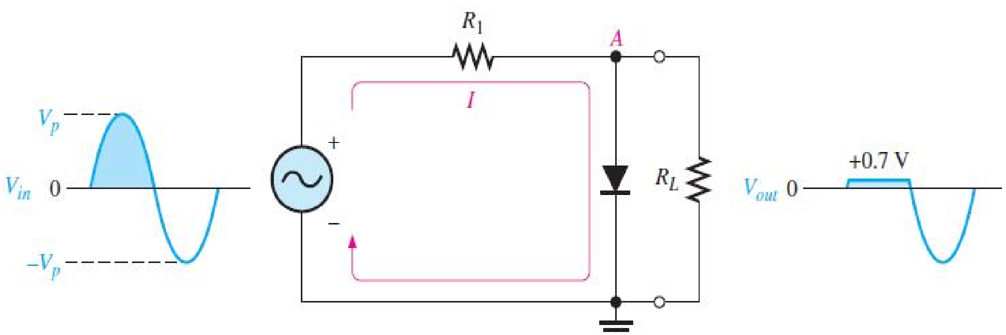


$V > 0,7V \rightarrow$ Diode conducts $\rightarrow V_0 = 0,7V$

$$I = \frac{V_R}{R} = \frac{5-0,7}{1k} = \frac{4,3}{1k} = 4,3\,mA$$

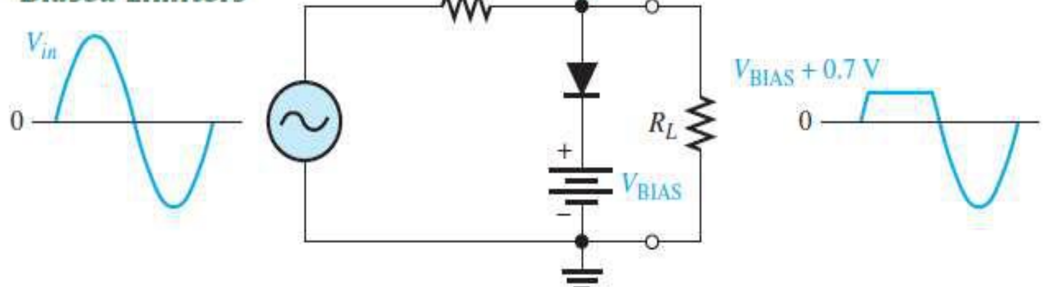
Diode Limiters

- Diode circuits, called limiters or clippers, are used to clip off portions of signal voltages above or below certain levels.

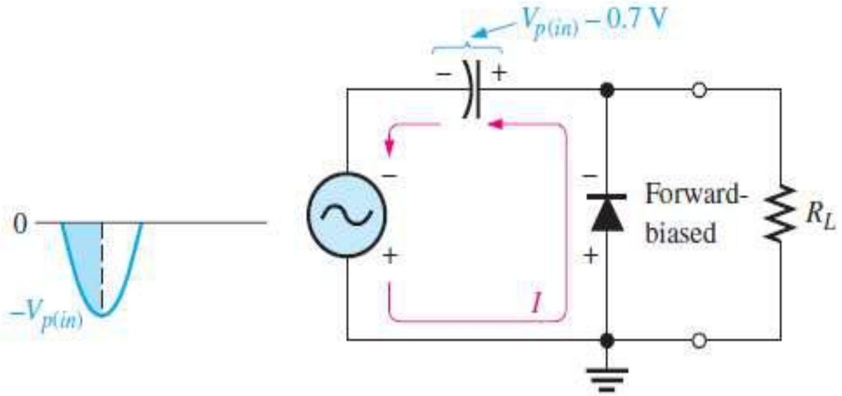


$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right)V_{in}$$

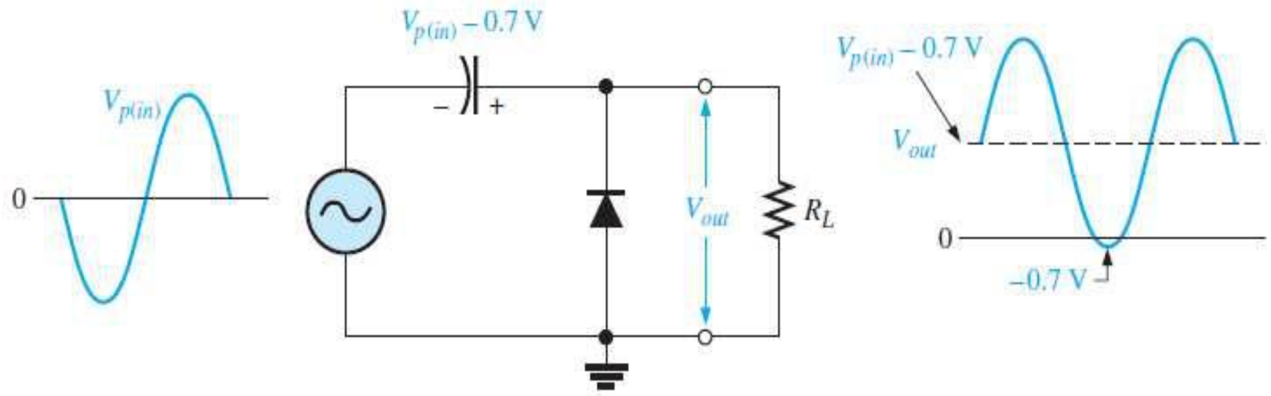
Biased Limiters



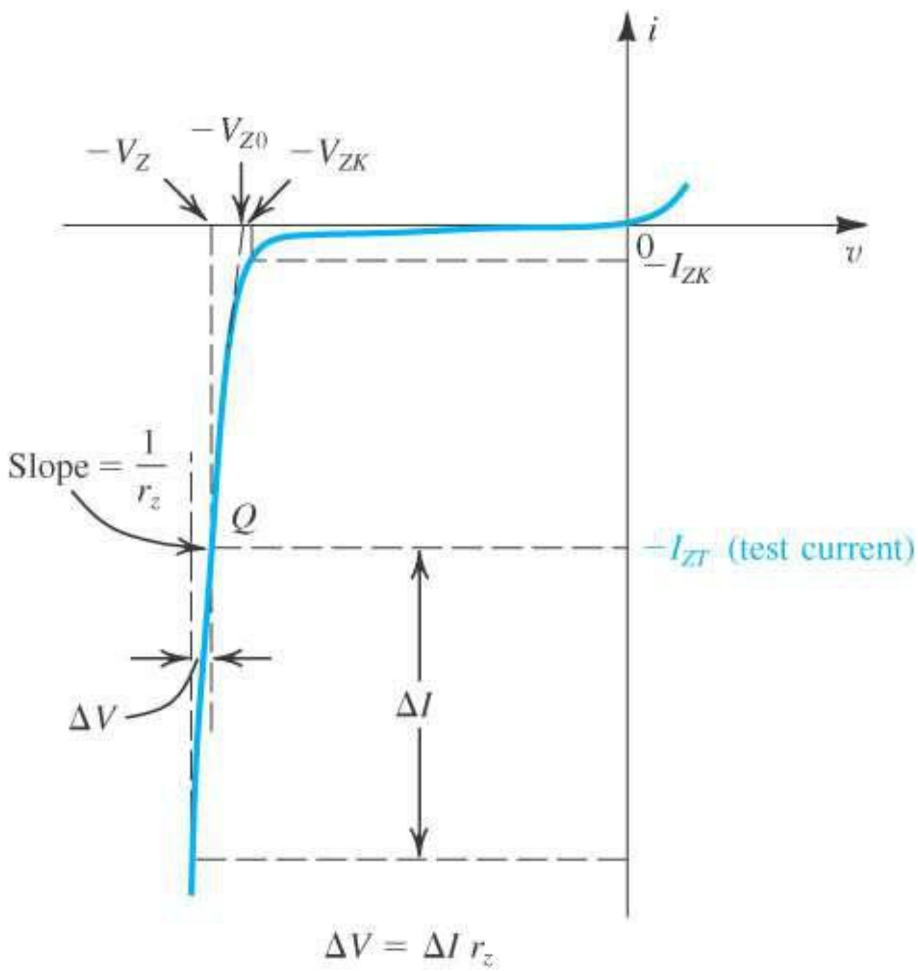
Diode Clampers

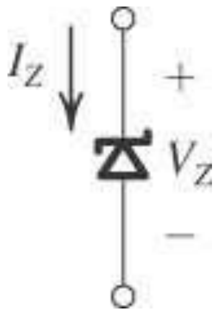


(a)



Zener Diode





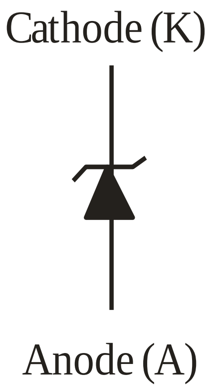
Circuit symbol

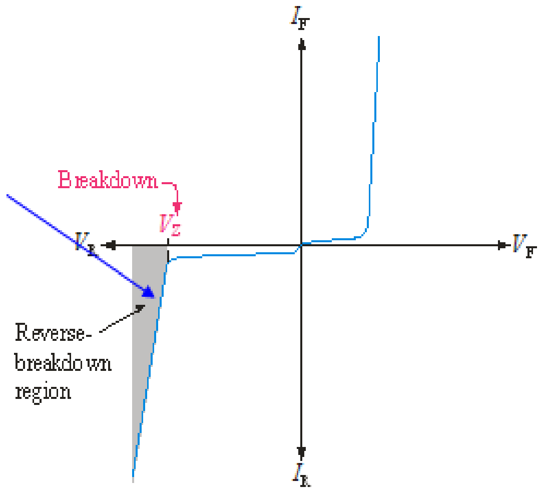
The diode *i*–*v* characteristic with the breakdown region shown in some detail.

Zener Diodes

❖ A Zener diode is a silicon pn junction that is designed for operation in reverse-breakdown region

❖ When a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is key to the Zener diode operation.





Characteristic curve

Zener Breakdown Characteristic

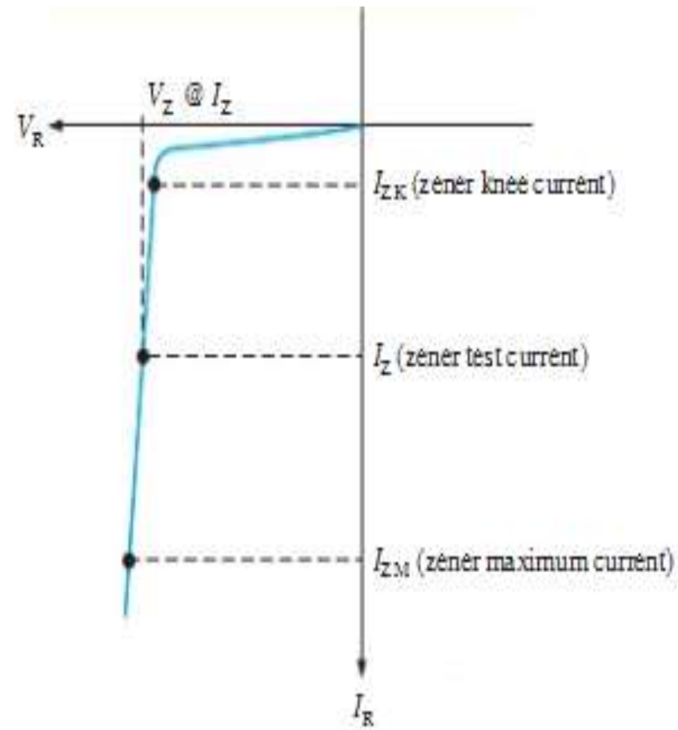
- As the reverse voltage (V_R) increases, the reverse current(I_R) remains extremely small up to the knee of the curve.

- Reverse current is also called Zener current(I_z).

- At knee point the breakdown effect begins, the internal Zener resistance (Z_Z) begins to decrease.

- The reverse current increase rapidly.

- The Zener breakdown (V_Z) voltage remains nearly constant.

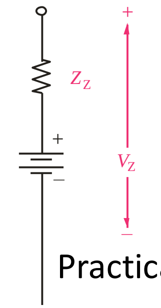


Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

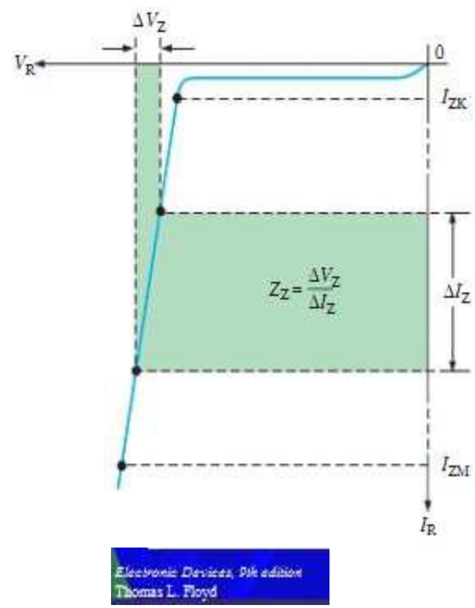
Zener Diode Impedence

- The zener impedance, Z_Z, is the ratio of a change in voltage in the breakdown region to the corresponding change in current:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$



Practical model



What is the zener impedance if the zener diode voltage changes from 4.79 V to 4.94 V when the current changes from 5.00 mA to 10.0 mA?

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{0.15\text{ V}}{5.0\text{ mA}} = \quad 30\ \Omega$$

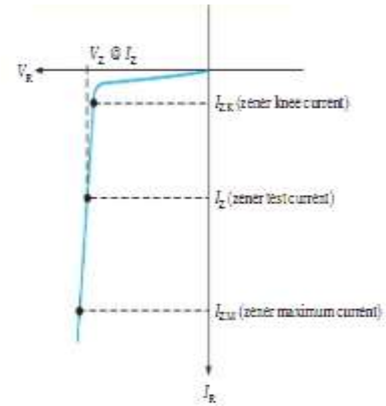
Zener Regulation

❖ The ability to keep the reverse voltage constant across its terminal is the key feature of the Zener diode.

❖ It maintains constant voltage over a range of reverse current values.

❖ A minimum reverse current I_{ZK} must be maintained in order to keep diode in regulation mode. Voltage decreases drastically if the current is reduced below the knee of the curve.

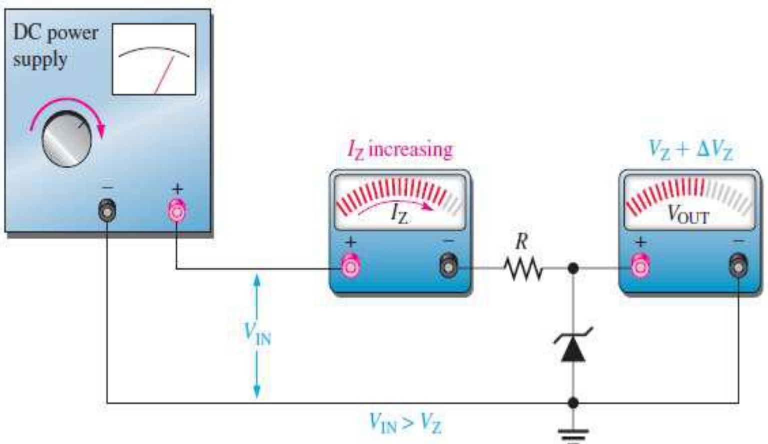
❖ Above I_{ZM}, max current, the Zener may get damaged permanently.

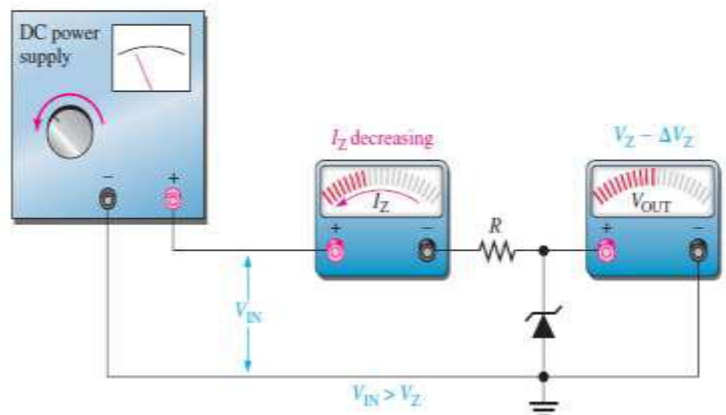


Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

Zener Regulation

❖ Zener Regulation with variable input voltage:



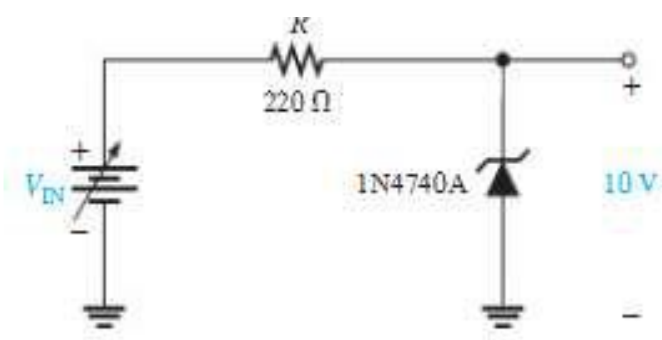


As the input voltage changes, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

Zener Regulation

❖ Zener Regulation with variable input voltage

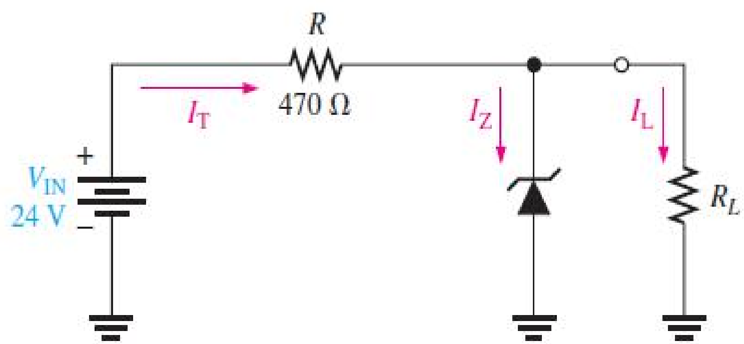
- Ideal model of IN4047A
- I_{ZK} = 0.25mA
- V_Z = 10V
- $P_{D(max)}$ = 1W



Vin(min) = 10.55V
Vin(max) = 32V

Zener Regulation

- Zener Regulation with variable load



It maintains voltage a nearly constant across RL as long as Zener current is within IZK and IZM.

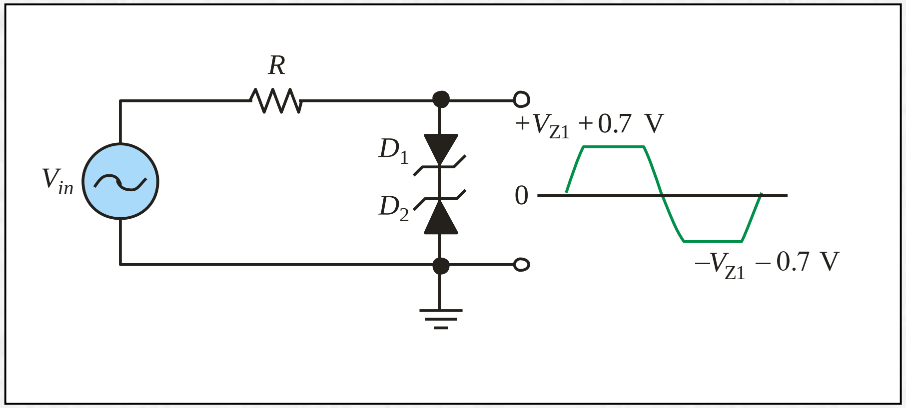
$V_Z = 12$ V,
$I_{ZK} = 1$ mA,
$I_{ZM} = 50$ mA.

Zener Diode Applications

Zeners can also be used as limiters. The back-to-back zeners in this circuit limit the output to the breakdown voltage plus one diode drop.

Question:

What are the maximum positive and negative voltages if the zener breakdown voltage is 5.6 V?



± 6.3 V

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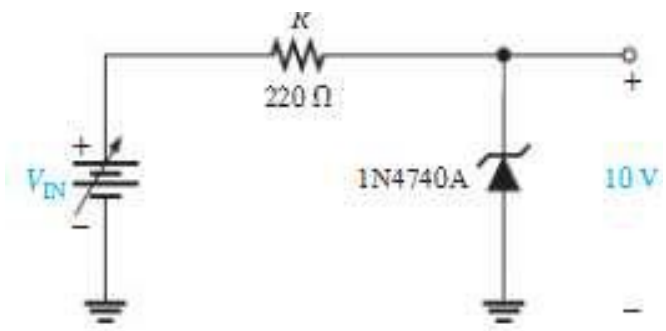
Zener Regulation

❖ Zener Regulation with variable input voltage

- Ideal model of IN4047A
- I_{ZK} = 0.25mA
- V_Z = 10V
- $P_{D(max)}$ = 1W, I_{ZM} = 1W / 10V = 100mA



For the minimum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZK}R = (0.25\text{ mA})(220\ \Omega) = 55\text{ mV}$$

Since $V_R = V_{IN} - V_Z$,

$$V_{IN(min)} = V_R + V_Z = 55\text{ mV} + 10\text{ V} = 10.055\text{ V}$$

For the maximum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZM}R = (100\text{ mA})(220\ \Omega) = 22\text{ V}$$

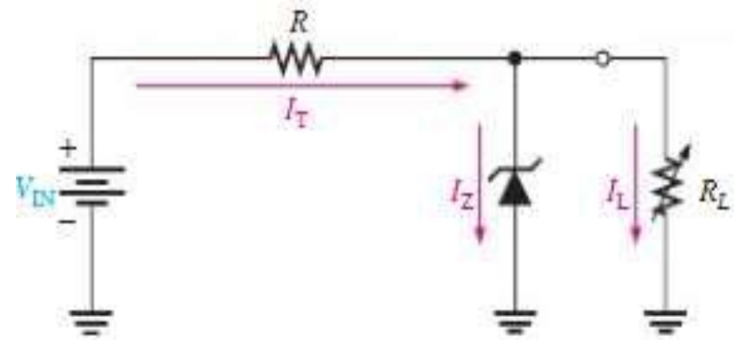
Therefore,

$$V_{IN(max)} = 22\text{ V} + 10\text{ V} = 32\text{ V}$$

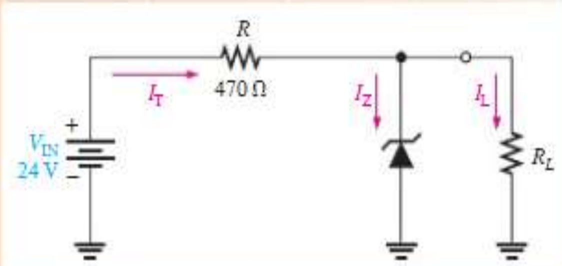
This shows that this zener diode can ideally regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output. The output will vary slightly because of the zener impedance, which has been neglected in these calculations.

Zener Regulation

- Zener Regulation with variable load
  - It maintains voltage a nearly constant across RL as long as Zener current is within IZK and IZM.



Determine the minimum and the maximum load currents for which the zener diode in Figure 3–14 will maintain regulation. What is the minimum value of R_L that can be used? $V_Z = 12$ V, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ mA. Assume an ideal zener diode where $Z_Z = 0\ \Omega$ and V_Z remains a constant 12 V over the range of current values, for simplicity.



When $I_L = 0$ A ($R_L = \infty$), I_Z is maximum and equal to the total circuit current I_T.

$$I_{Z(max)} = I_T = \frac{V_{IN} - V_Z}{R} = \frac{24\text{ V} - 12\text{ V}}{470\ \Omega} = 25.5\text{ mA}$$

If R_L is removed from the circuit, the load current is 0 A. Since $I_{Z(max)}$ is less than I_{ZM}, 0 A is an acceptable minimum value for I_L because the zener can handle all of the 25.5 mA.

$$I_{L(min)} = \mathbf{0\ A}$$

The maximum value of I_L occurs when I_Z is minimum ($I_Z = I_{ZK}$), so

$$I_{L(max)} = I_T - I_{ZK} = 25.5\text{ mA} - 1\text{ mA} = \mathbf{24.5\ mA}$$

The minimum value of R_L is

$$R_{L(min)} = \frac{V_Z}{I_{L(max)}} = \frac{12\text{ V}}{24.5\text{ mA}} = \mathbf{490\ \Omega}$$

Therefore, if R_L is less than 490 Ω, R_L will draw more of the total current away from the zener and I_Z will be reduced below I_{ZK}. This will cause the zener to lose regulation. Regulation is maintained for any value of R_L between 490 Ω and infinity.

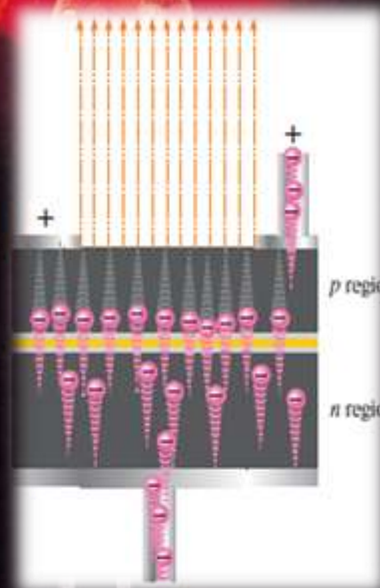
Optical Diodes

- ***Light Emitting Diodes*** **(LEDs): Diodes can be made to emit light electroluminescence) or sense light.**

- **When forward biased electrons form n-region cross the junction and recombines to holes with the emission of photons.**

- **Various impurities are added during the doping process to establish the wavelength of the emitted light.**

- **The process is called electroluminescence.**



Light Emitting Diodes

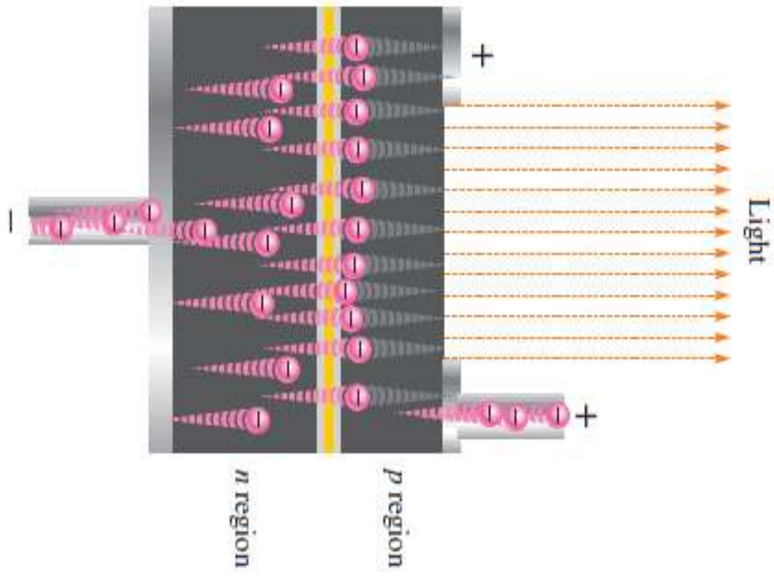
❖ LEDs vary widely in size and brightness – from small indicating lights and displays to high-intensity LEDs that are used in traffic signals, outdoor signs, and general illumination.

❖ LEDs are very efficient light emitters, and extremely reliable, so domain of uses getting wider.

Light Emitting Diodes

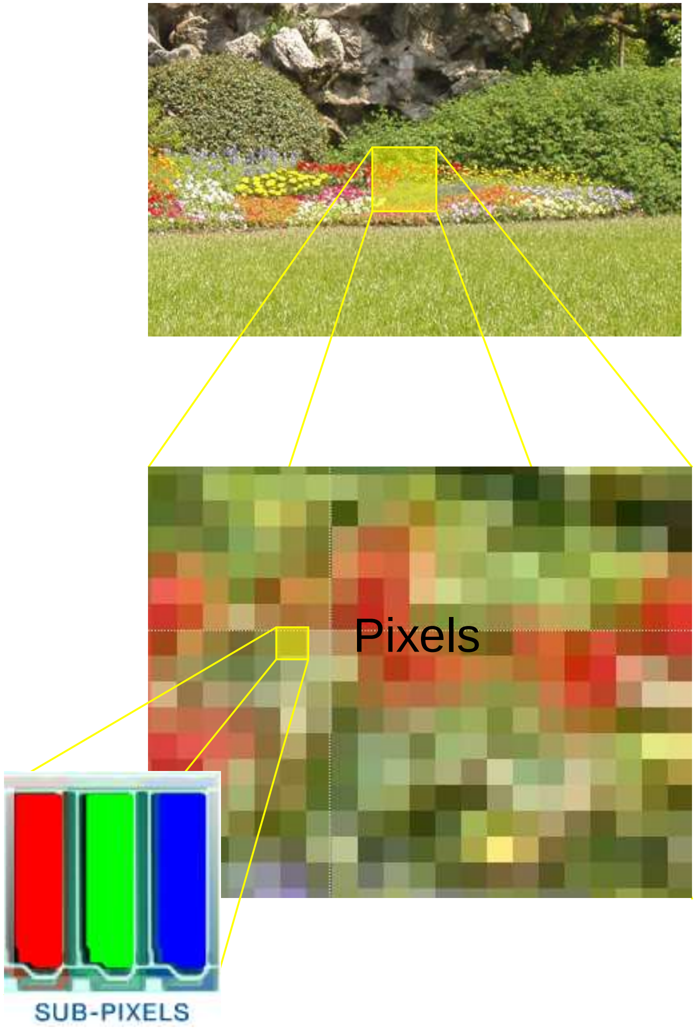
- When the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material.

- The difference in energy between the electrons and the holes corresponds to the energy of visible light.



Digital Images and Pixels

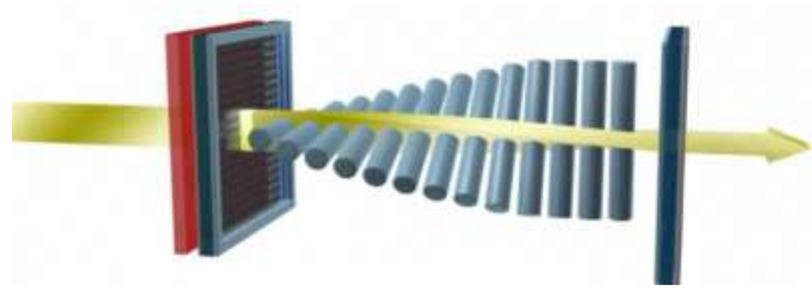
- A digital image is a binary (digital) representation of a two-dimensional pictorial data.
- Digital images may have a raster or vector representation.
- Raster Images defined over a 2D grid of picture elements, called pixels.
- A pixel is the basic items of a raster image and include intensity or color value.

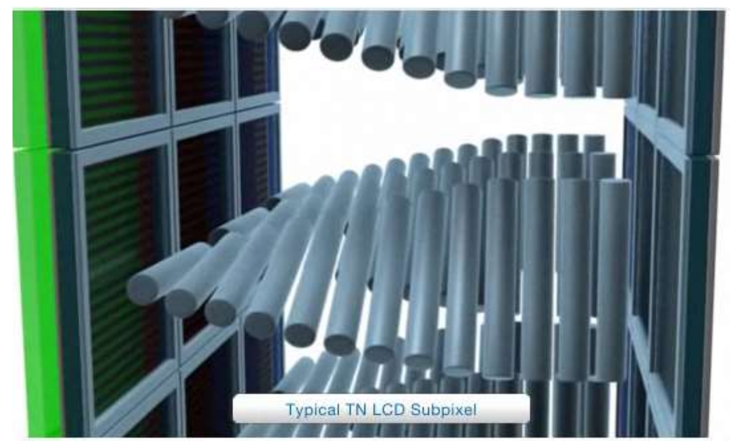


Figures are curtsy of 3M

LCD (Liquid Crystal Display)

- LCD Panel is based on
  - A light valve for each pixel that turn the light on, off, or an intermediate level.
- Grid of such light valve for the LCD display panel.
- A back light and display enhancement films create the illumination.





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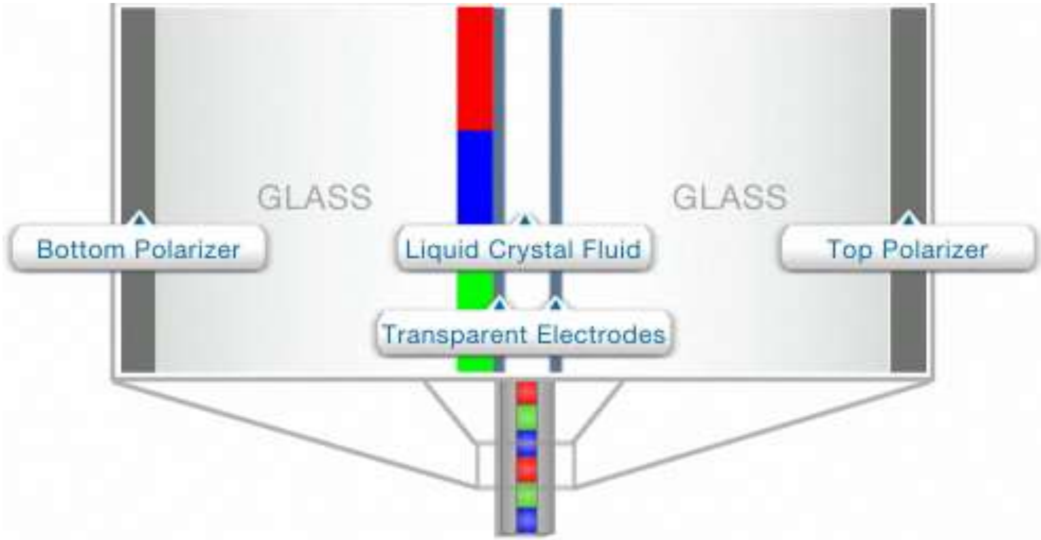
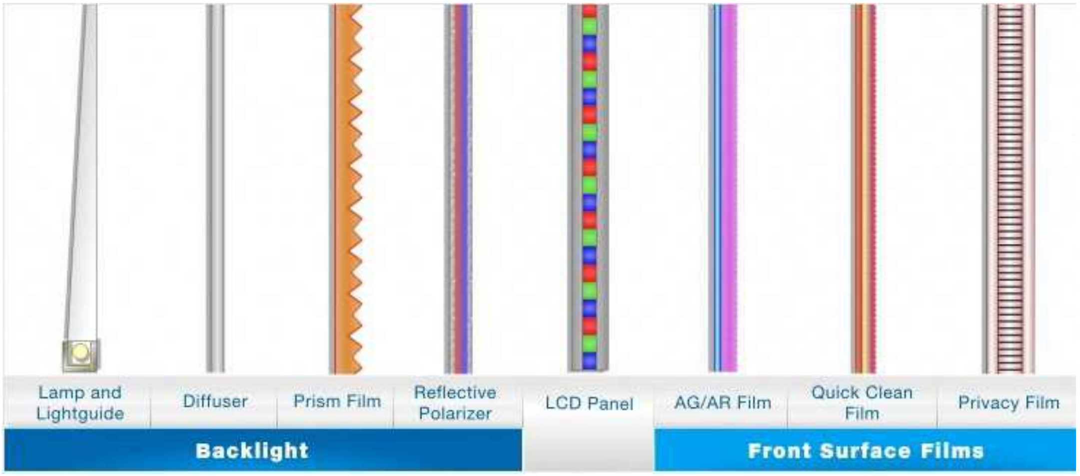
LCD-Display

- Applying voltage to the electrodes changes the level of illumination in each sub-pixel
- The panel is sandwiched between
  - Front surface films to enhance display property





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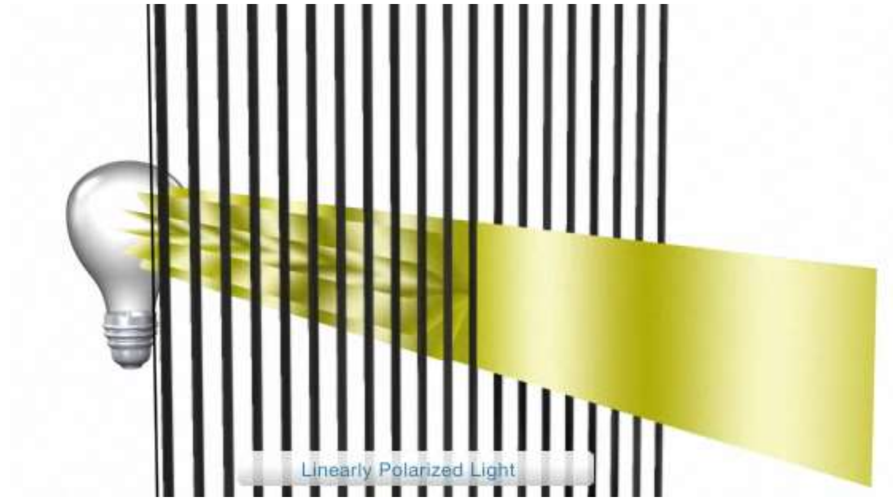
Linear Polarized Light

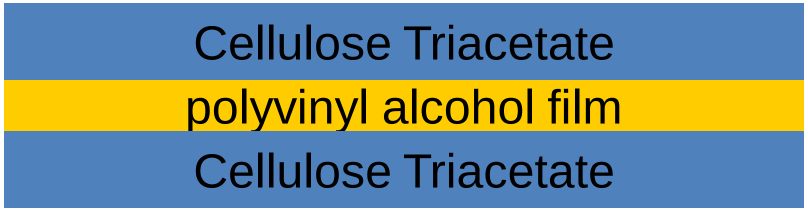


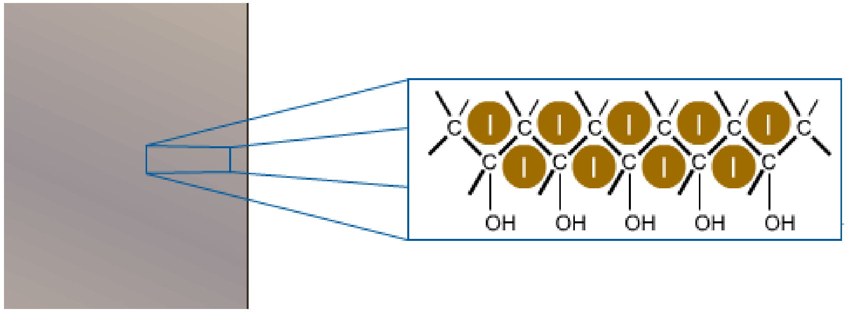
- Light usually vibrates in all direction
- A linear polarized light limit the vibration to one direction
- It absorbs the component of light that vibrate in all

Figures are curtsy of 3M

Iodine Based Polarizer

- Is the most common polarizer
- It is made by
  - Stretching a cast polyvinyl alcohol film (PVA) to align the iodine in turn.
  - Staining it with iodine
  - The stained PVA laminated between two slices of cellulose triacetate.



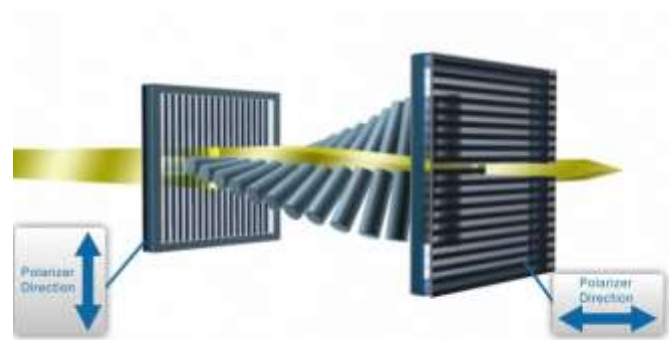


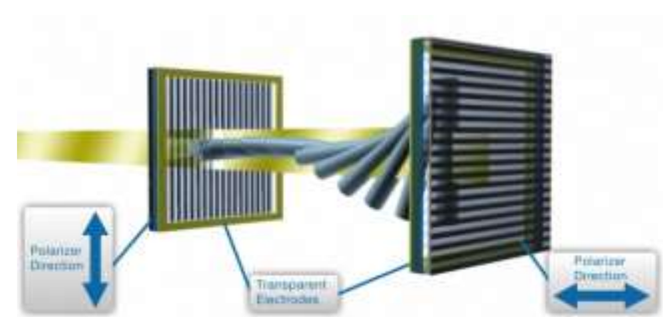
polyvinyl alcohol film

Figures are curtsy of 3M.

About Liquid Crystal

- Liquid crystal molecules can move freely while maintaining their orientation.
- It align itself to a polyimide film to the inside of a panel glass.
- When the two glass panels are not aligned

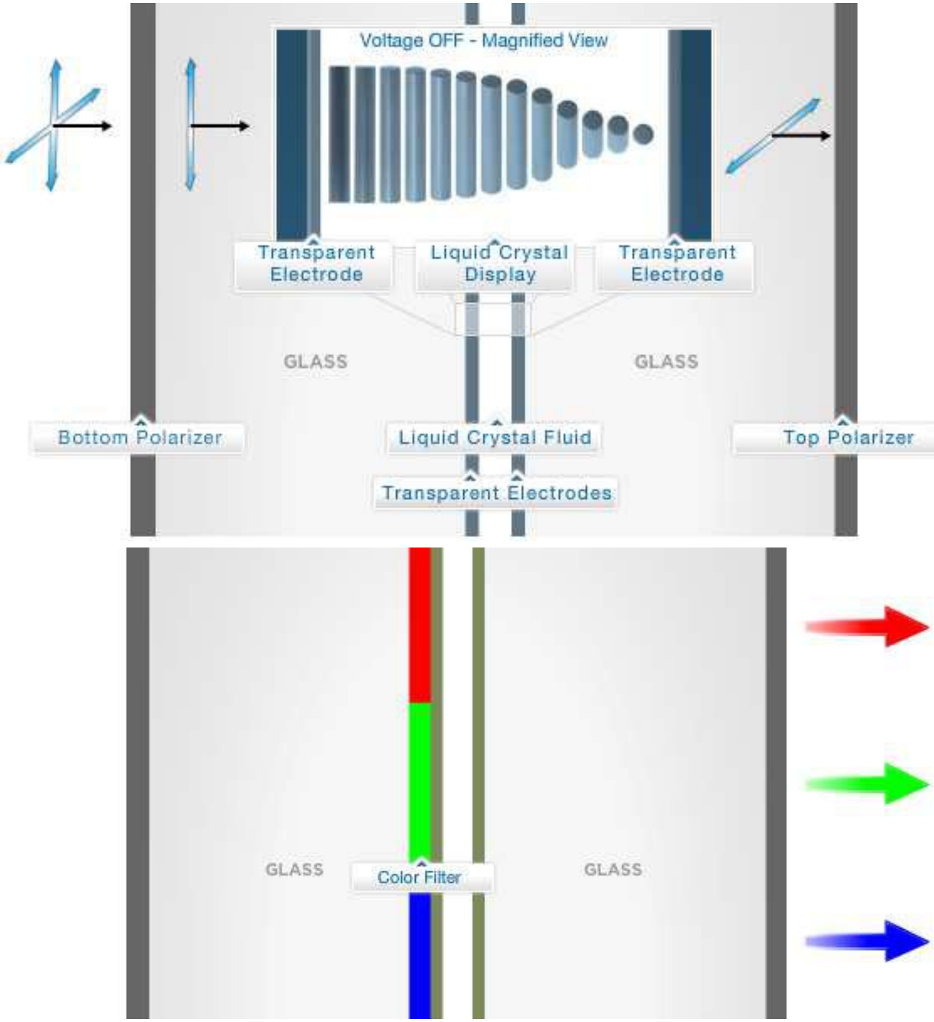




Figures are curtsy of 3M

Light Path

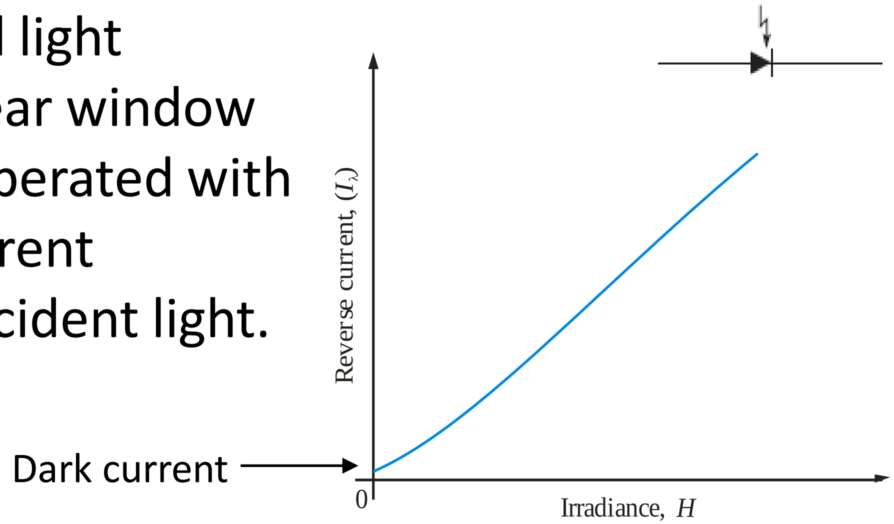
- The light passes through the polarizer.
- The voltage applied tc the electrodes controls the liquid crystal orientation
- The liquid crystal orientation controls the rotation of the incoming polarized light.



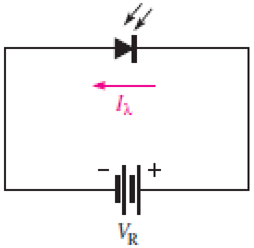
Figures are curtsy of 3M

Photo Diode

- A **photodiode** is a special light sensitive diode with a clear window to the *pn* junction. It is operated with reverse bias. Reverse current increases with greater incident light.



- The tiny current that is present when the diode is not exposed to light is called **dark current**



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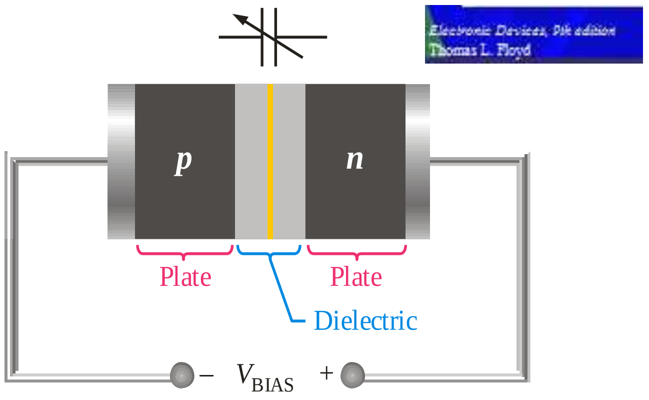
Varactor Diode

- A **varactor diode** is a special purpose diode operated in reverse-bias to form a voltage-controlled capacitor. The width of the depletion region increases with reverse-bias.

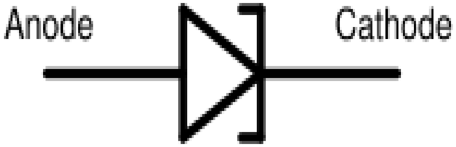
- Varactor diodes are used in tuning applications. The applied voltage controls the capacitance and hence the resonant frequency.



$$C = \frac{A\epsilon}{d}$$

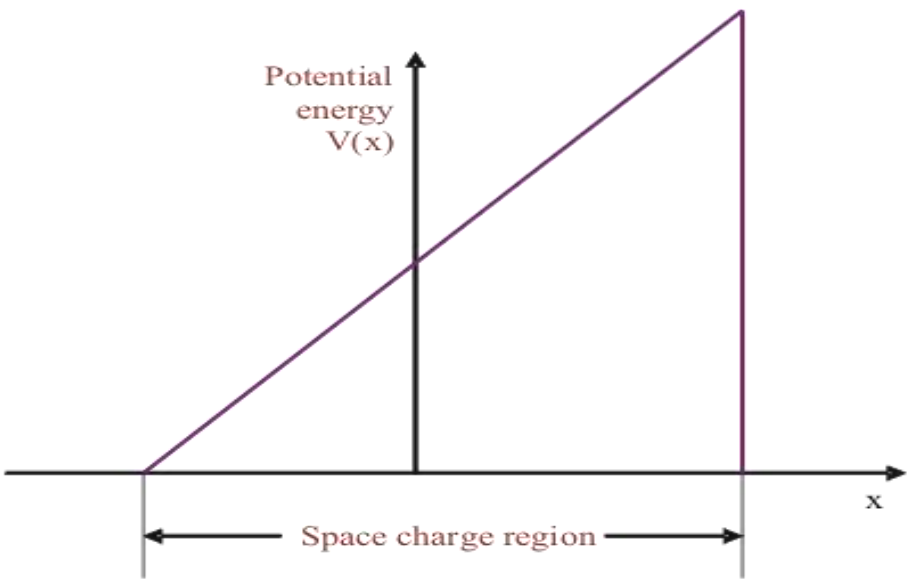
TUNNEL DIODE (Esaki Diode)

- It was introduced by Leo Esaki in 1958.
- Heavily-doped p-n junction
  - Impurity concentration is 1 part in 10^3 as compared to 1 part in 10^8 in p-n junction diode
- Width of the depletion layer is very small (about 100 A).
- It is generally made up of Ge and GaAs.
- It shows tunneling phenomenon.
- Circuit symbol of tunnel diode is :



WHAT IS TUNNELING

- **Classically**, carrier must have energy at least equal to potential-barrier height to cross the junction .
- But according to **Quantum mechanics** there is finite probability that it can penetrate through the barrier for a thin width.
- This phenomenon is called **tunneling** and hence the Esaki Diode is know as **Tunnel Diode**.



Triangular potential barrier approximation of the potential barrier in the tunnel diode.

CHARACTERISTIC OF TUNNEL DIODE

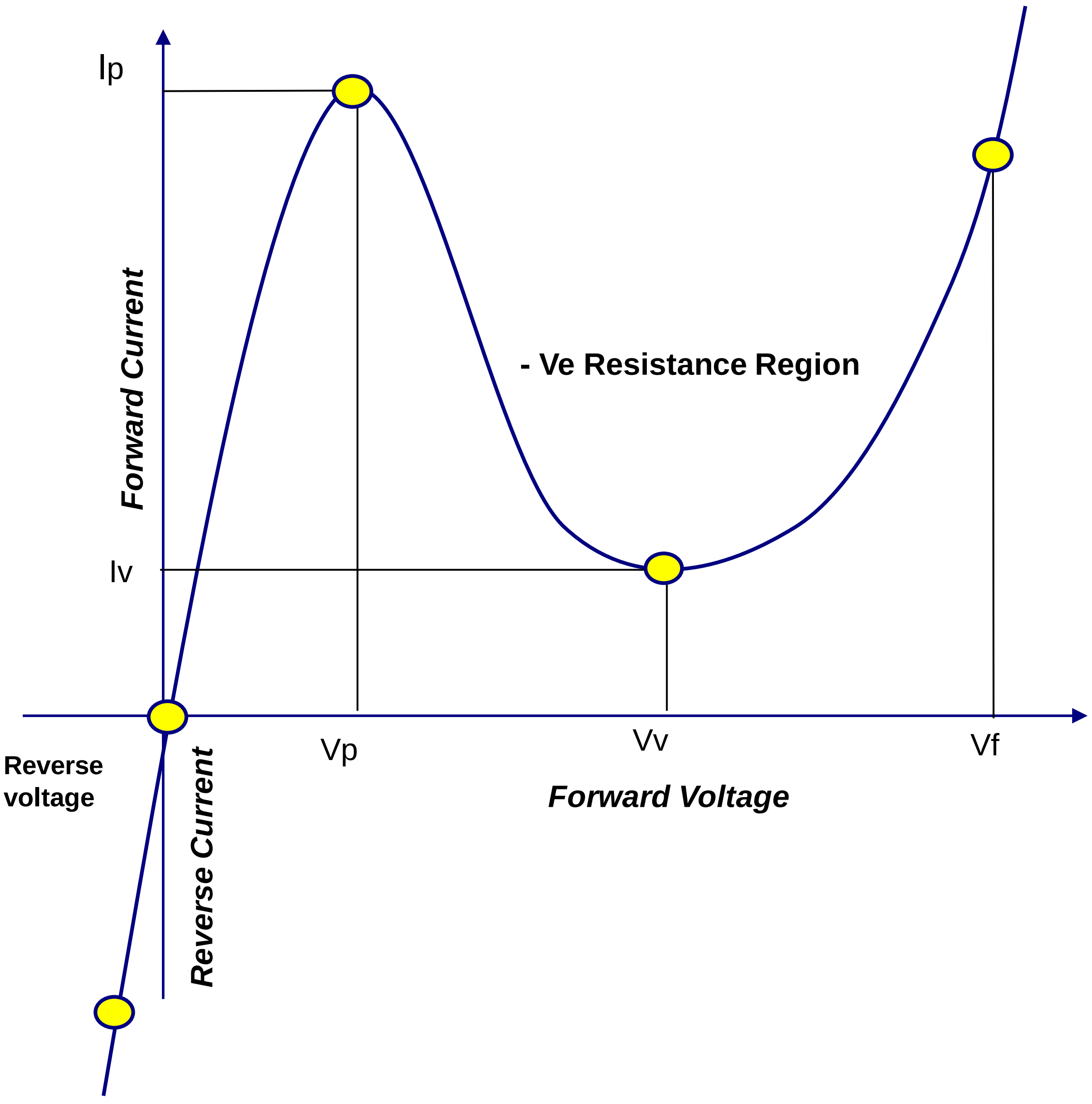
Ip:- Peak Current

Iv :- Valley Current

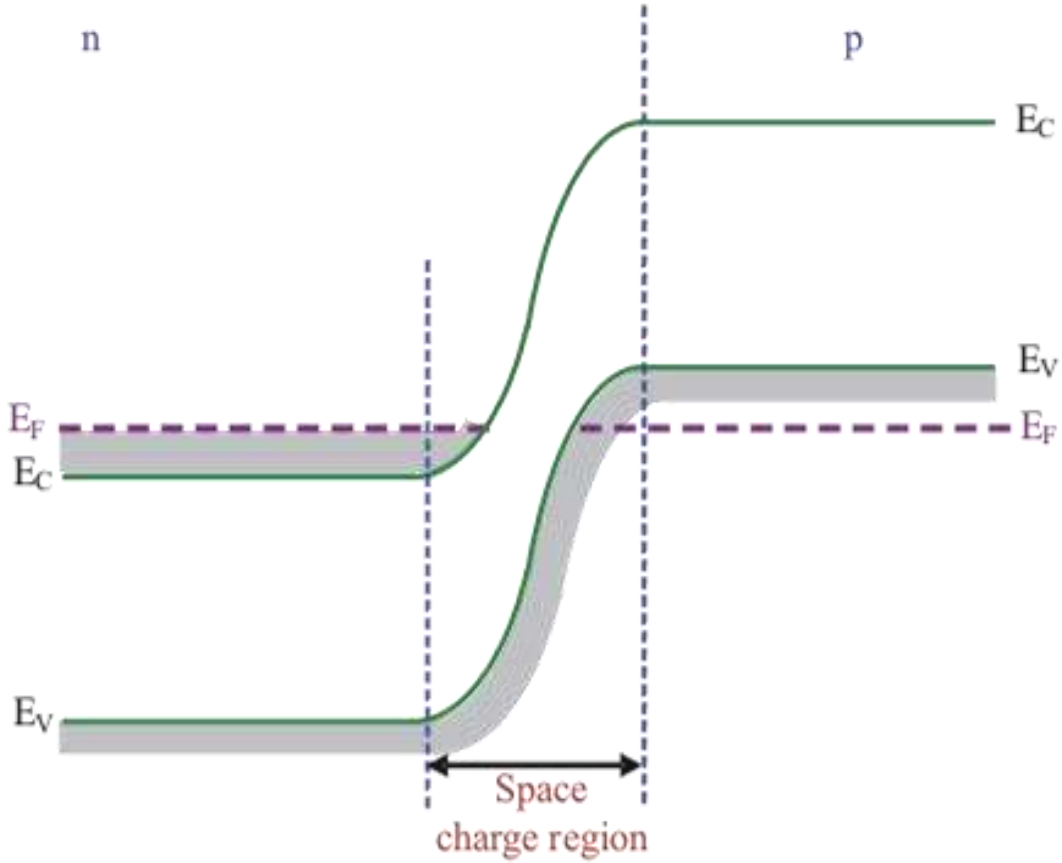
Vp:- Peak Voltage

Vv:- Valley Voltage

Vf:- Peak Forward Voltage

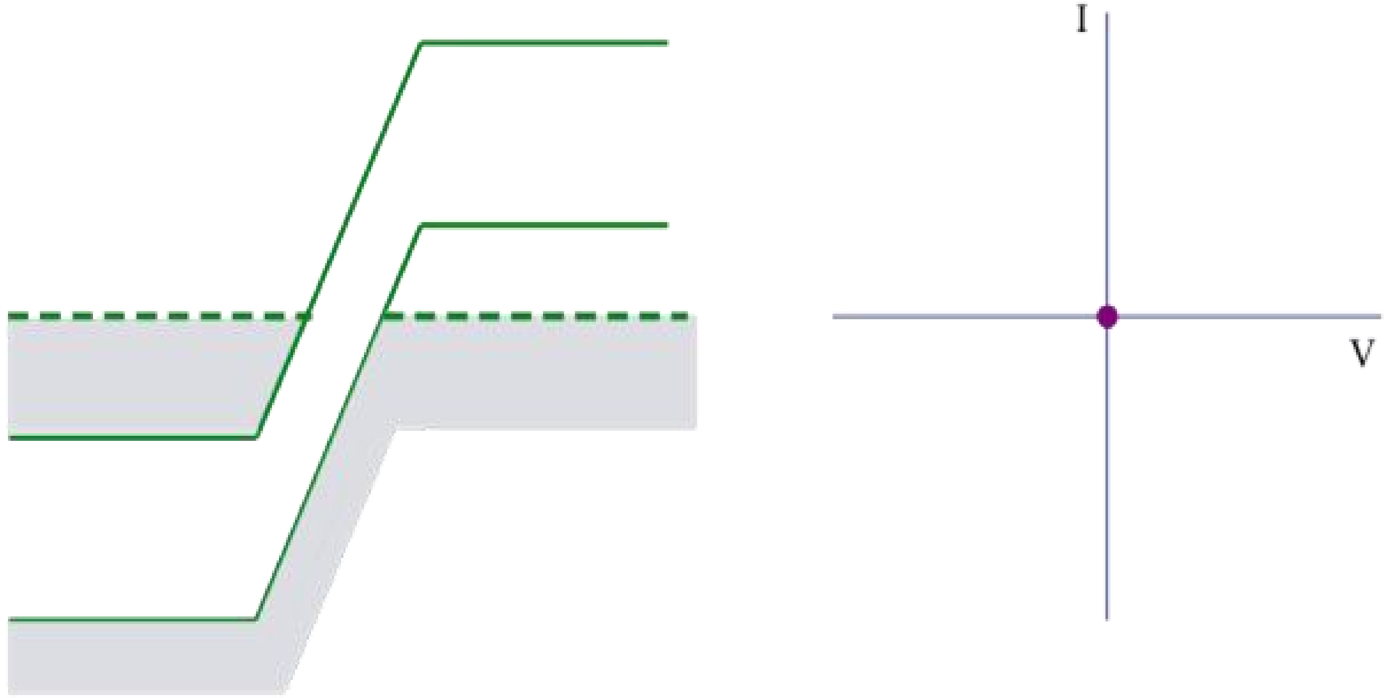


ENERGY BAND DIAGRAM



Energy-band diagram of pn junction in thermal equilibrium in which both the n and p region are degenerately doped.

AT ZERO BIAS

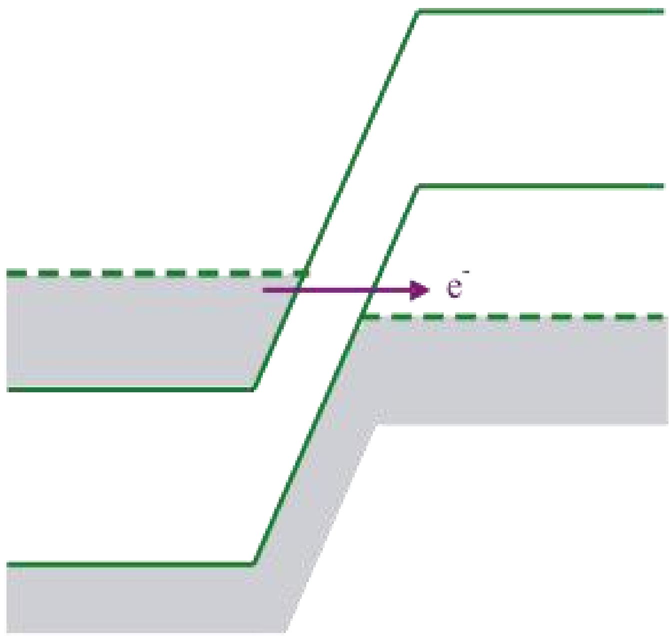


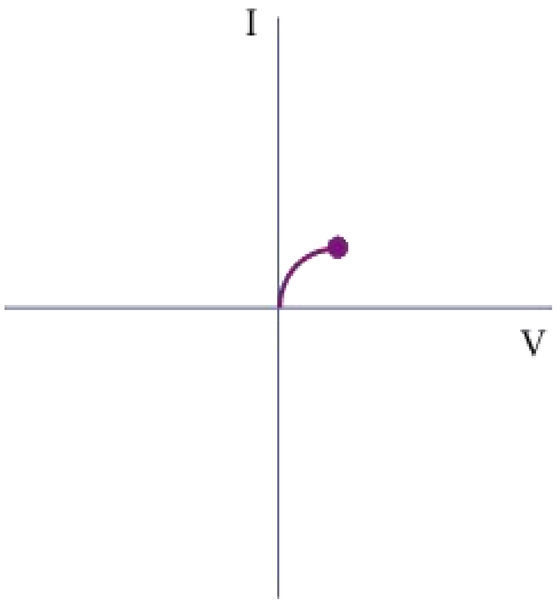
Simplified energy-band diagram and I-V characteristics of the tunnel diode at zero bias.

-Zero current on the I-V diagram;

-All energy states are filled below E_F on both sides of the junction;

AT SMALL FORWARD VOLTAGE



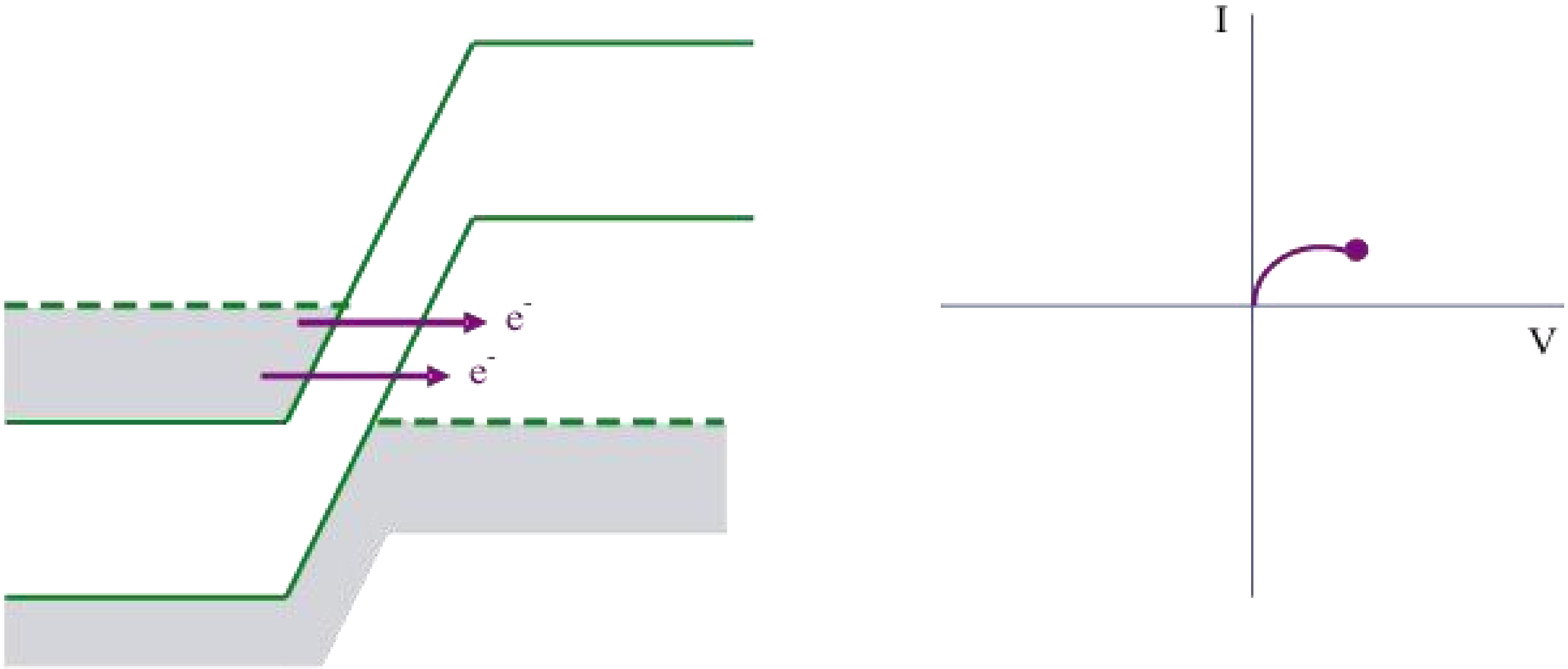


Simplified energy-band diagram and I-V characteristics of the tunnel diode at a slight forward bias.

-Electrons in the conduction band of the n region are directly opposite to the empty states in the valence band of the p region.

-So a finite probability that some electrons tunnel directly into the empty states resulting in forward-bias tunneling current.

AT MAXIMUM TUNNELING CURENT

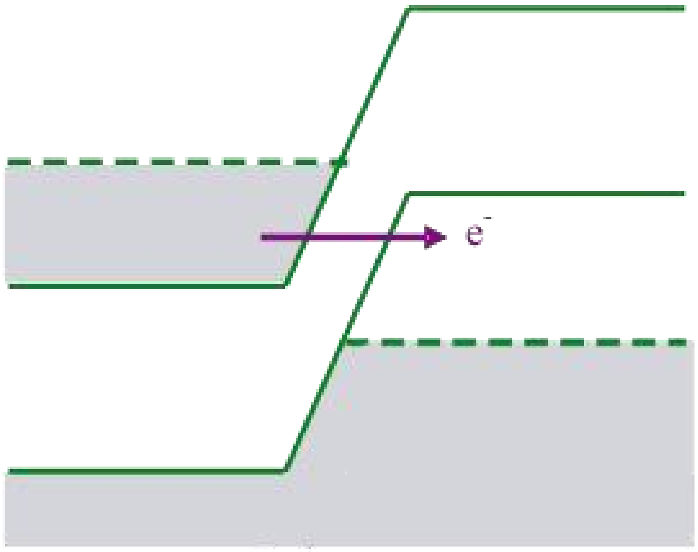


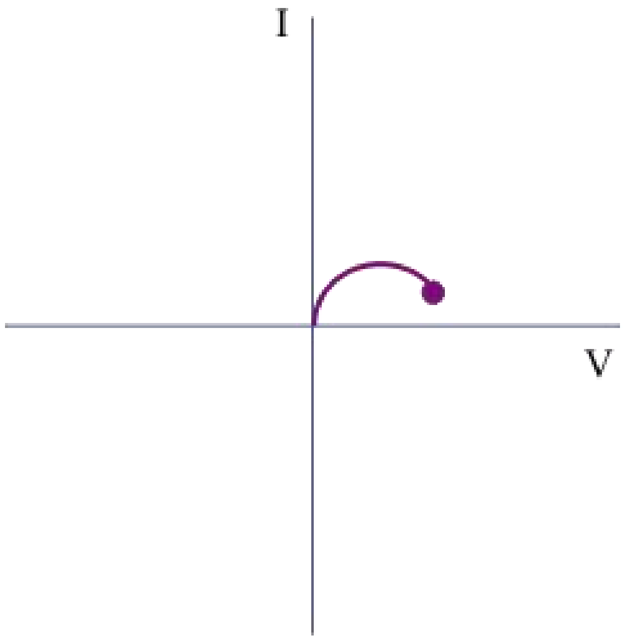
Simplified energy-band diagraam and I-V characteristics of the tunnel diode at a forward bias producing maximum tunneling current.

-The maximum number of electrons in the n region are opposite to the maximum number of empty states in the p region.

- Hence tunneling current is maximum.

AT DECREASING CURRENT REGION



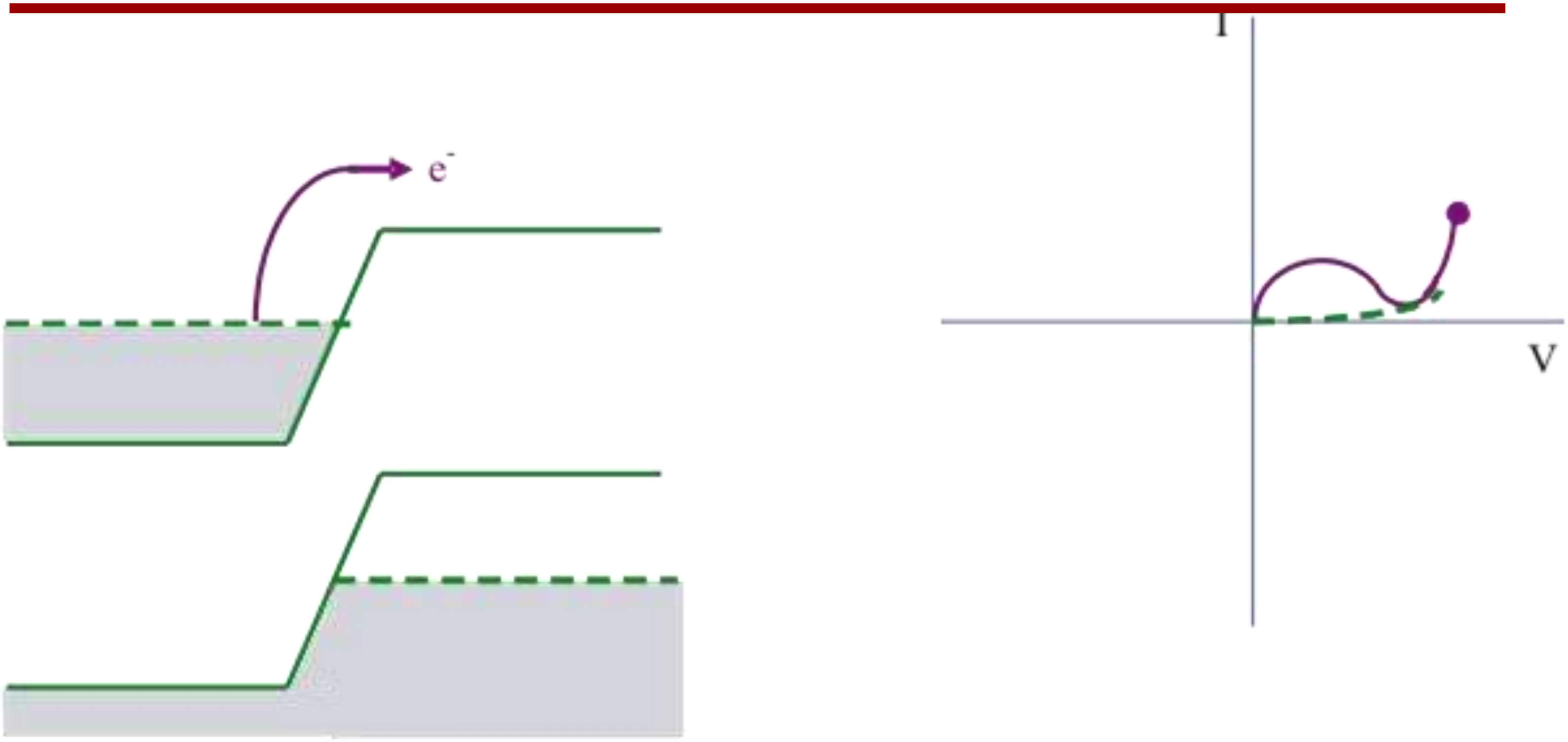


Simplified energy-band diagram and I-V characteristics of the tunnel diode at a higher forward bias producing less tunneling current.

-The forward-bias voltage increases so the number of electrons on the n side, directly opposite empty states on the p side decreases.

- Hence the tunneling current decreases.

AT HIGHER FORWARD VOLTAGE



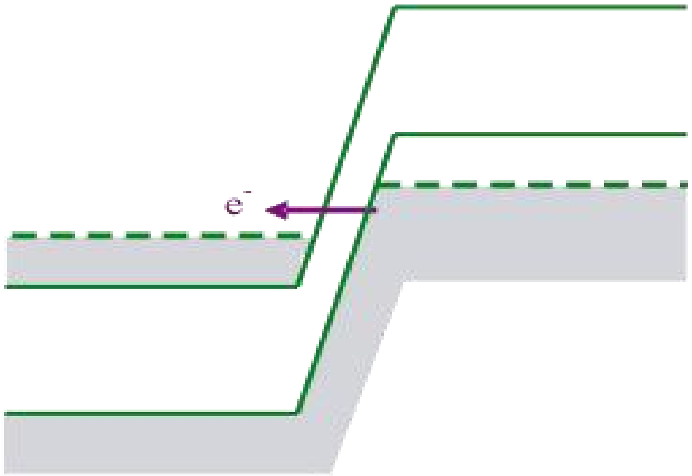
Simplified energy-band diagram and I-V characteristics of the tunnel diode at a forward bias for which the diffusion current dominates.

-No electrons on the n side are directly opposite to the empty states on the p side.

- The tunneling current is zero.

-The normal ideal diffusion current exists in the device.

AT REVERSE BIAS VOLTAGE



A simplified energy-band diagram of a tunnel diode with a reverse bias voltage

I-V characteristic of a tunnel diode with a reverse-bias voltage.

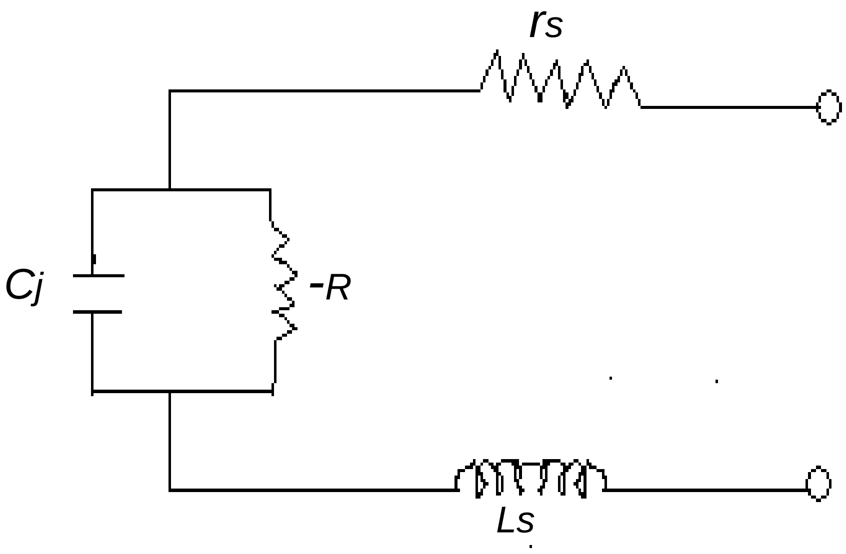
- Electrons in the valence band on the p side are directly opposite to empty states in the conduction band on the n side.

-Electrons tunnel directly from the p region into the n region.

- The reverse-bias current increases monotonically and rapidly with reverse-bias voltage.

TUNNEL DIODE EQUIVALENT CIRCUIT

- This is the equivalent circuit of tunnel diode when biased in negative resistance region.



- At higher frequencies the series R and L can be ignored.

- Hence equivalent circuit can be reduced to parallel combination of junction capacitance and negative resistance.

INTRODUCTION:

The SCR is the most important special semiconductor device. This device is popular for its ***Forward-Conducting*** and ***Reverse-blocking characteristics.***

SCR can be used in ***high-power devices***. For example, in the central processing unit of the computer, the SCR is used in ***switch mode power supply (SMPS).***

The ***DIAC***, a combination of two ***Shockley Diodes***, and the ***TRIAC***, a combination of two ***SCR***s connected

anti-parallelly are important power-control devices. The ***UJT*** is also used as an ***efficient switching device***.

SILICON-CONTROLLED RECTIFIER (SCR)

The ***silicon-controlled rectifier or semiconductor controlled rectifier*** is a two-state device used for efficient power control.

SCR is the parent member of the ***thyristor family*** and is used in ***high-power electronics***.Its constructional features, physical operation and characteristics are explained in the following sections.

Constructional Features

The SCR is a ***four-layer structure***, either ***p–n–p–n or n–p–n–p****, that effectively blocks current through two* terminals until it is turned ***ON*** by a small-signal at a third terminal.

The SCR has ***two states***: a ***high-current low-impedance ON state*** and ***a low-current high-impedance OFF state.***

The basic transistor action in a ***four-layer p–n–p–n structure*** *is analysed first with only two terminals,* and then the third control input is introduced.

Physical Operation and Characteristics:

- The physical operation of the SCR can be explained clearly with reference to the current–voltage characteristics.
- The forward-bias condition and reverse-bias condition illustrate the conducting state and the reverse blocking state respectively. Based on these two states a typical I –V characteristic of the SCR is shown in Fig. 8-2.

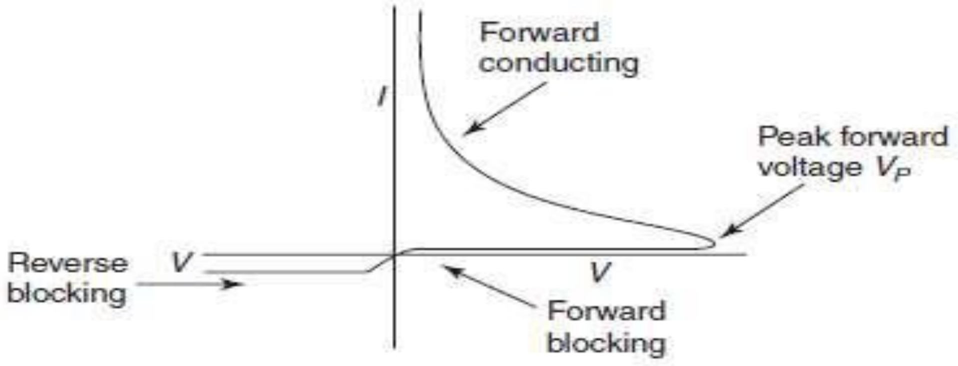


Figure 8-2 I–V characteristics of a two terminal *p–n–p–n* device

SCR in Forward Bias:

- There are two different states in which we can examine the SCR in the forward-biased condition:

  (i) The high- impedance or forward-blocking state

  (ii) The low-impedance or forward-conducting state

  At a critical peak forward voltage *Vp, the SCR switches from the blocking state to the conducting state, as* shown in Fig. 8-2.
- A positive voltage places junction *j1 and j3 under forward-bias, and the centre junction j2 under reverse-bias.*
- The for ward voltage in the blocking state appears across the reverse-biased junc tion *j2 as the applied voltage V is increased. The voltage from the anode A to cathode C, as shown in Fig. 8-1, is very small after switching* to the forward-conducting state, and all three junctions are forward-biased. The junction *j2 switches from* reverse-bias to forward-bias..

SCR in Reverse Bias:

- In the reverse-blocking state the junctions *j1 and j3 are reverse-biased, and j2 is forward-biased.*
- The supply of electrons and holes to junction *j2 is restricted, and due to the thermal generation of* electron–hole pairs near junctions *j1 and j2 the device current is a small saturation current.*
- *In the reverse blocking* condition the current remains small until avalanche breakdown occurs at a large reverse-bias of several thousand volts.
- An SCR *p–n–p–n structure is equivalent to* one *p–n–p transistor and one n–p–n transistor sharing some common terminals.*

- Collector current $I_{C1} = \alpha_1 i + I_{CO1}$ *having a transfer ratio* α_1 *for the p–n–p.*
- Collector current $I_{C2} = \alpha_2 i + I_{CO2}$ *having a transfer ratio a2 for the n–p–n.*
- I_{CO1} *and* I_{CO2} *stand for the respective* collector-saturation currents.

$$I_{C1} = \alpha_1 i + I_{CO1} = I_{B2} \qquad \text{..................}(8\text{-}1)$$

$$I_{C2} = \alpha_2 i + I_{CO2} = I_{B1} \qquad \text{.................}(8\text{-}2)$$

SCR in Reverse Bias:

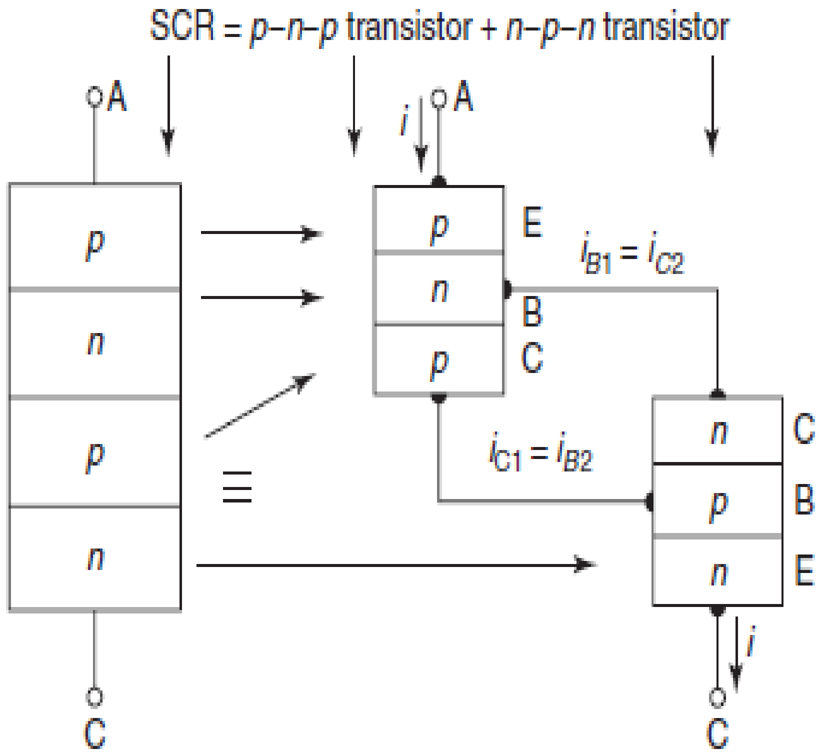


Figure 8-3 An SCR *p–n–p–n*: a combination of one *p–n–p* transistor and one *n–p–n* transistor

SCR in Reverse Bias:

- The total current through the SCR is the sum of *iC1 and iC2:*
- $I_{C1} + I_{=} \; i$ ....(8-3)
- Substituting the values of collector current from Eqs. (8-1) and (8-2) in Eq. (8-3) we get:
- $i\,(\alpha 1 + \alpha 2) + I_{CO1} + I_{CO2} = i$
- $i = (I_{CO1} + I_{CO2})/(1 - \alpha 1 + \alpha 2)$ ....(8-4)
- **Case I: When** *(α1 + α2)* **→ *1, then the SCR current i → infinite.***
- As the sum of the values of alphas tends to unity, the SCR current *i increases rapidly. The derivation is no*
- longer valid as *(α1 + α2) equals unity.*
- **Case II: When** *(α1 + α2* **→ *0, i.e., when the summation value of alphas goes to zero, the SCR resultant current*** can be expressed as:
- $i = I_{CO1} + I_{CO2}$ ....(8-5)
- The current, *i, passing through the SCR is very small. It is the combined collector-saturation currents of the* two equivalent transistors as long as the sum *(α1 + α2) is very small or almost near zero.*

I–V Characteristics of the SCR:

- **Forward-Blocking State:**
- When the device is biased in the forward-blocking state, as shown in Fig. 8-4(a), the applied voltage appears primarily across the reverse-biased junction *j2. Al though the junctions j1 and j3 are forward-biased, the current* is small.

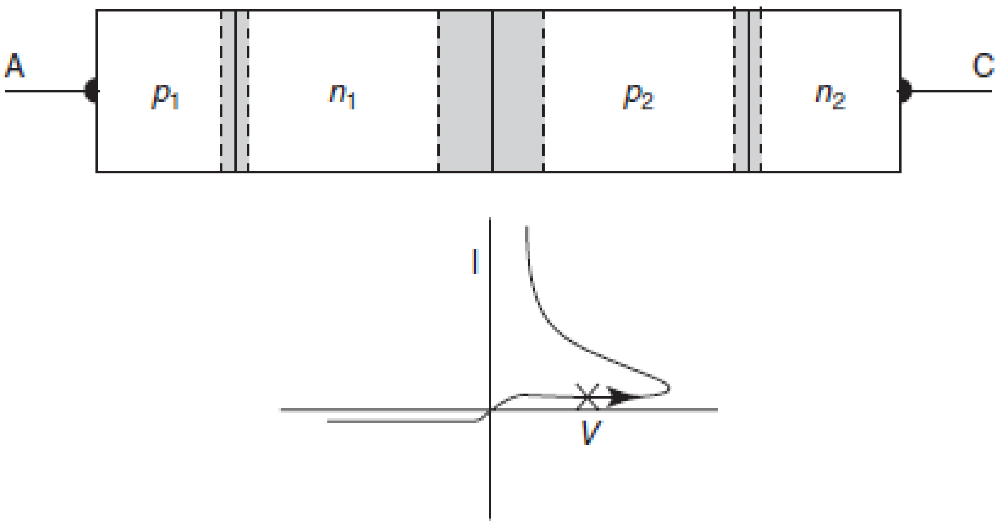


Figure 8-4 (a) The forward-blocking state of the SCR

I–V Characteristics of the SCR:

- **Forward-Conducting State of the SCR:**

As the value of ($\alpha 1 + \alpha 2$) *approaches unity through one of the mechanisms ,many holes* injected at *j1 survive to be swept across j2 into p2.*

- *This process helps feed the recombination in p2 and support* the injection of holes into *n2. In a similar manner, the transistor action of electrons injected at j3 and collected* at *j2 supplies electrons for n1.*
- *The current through the device can be much **larger.***

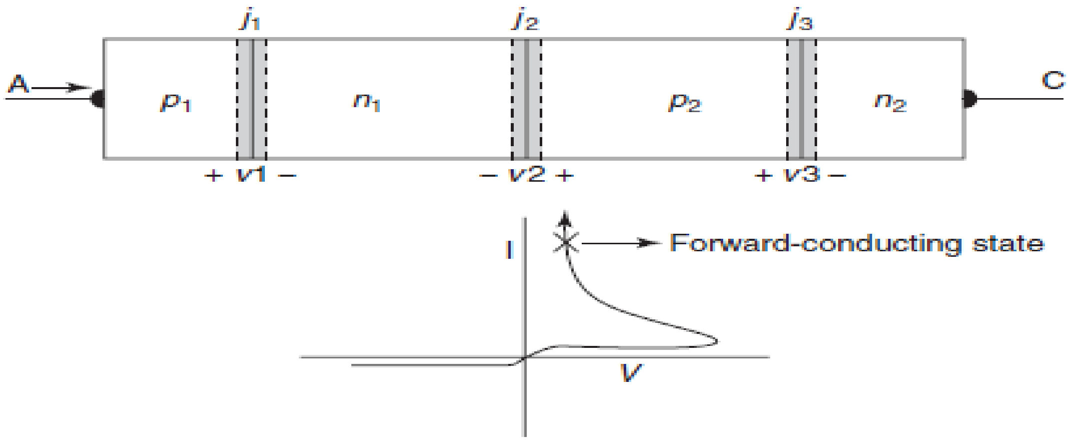


Figure 8-4 (b) Forward-conducting state of the SCR

Reverse-Blocking State of the SCR:

- The SCR in reverse-biased condition allows almost negligible current to flow through it. This is shown in Fig. 8-4(c).
- In the reverse-blocking state of the SCR, a small saturation current flows from anode to cathode. Holes will flow from the gate into *p2, the base of the n–p–n transistor, due to positive gate* current.
- The required gate current for turn-on is only a few milli-amperes, therefore, the SCR can be turned on by a very small amount of power in the gate.

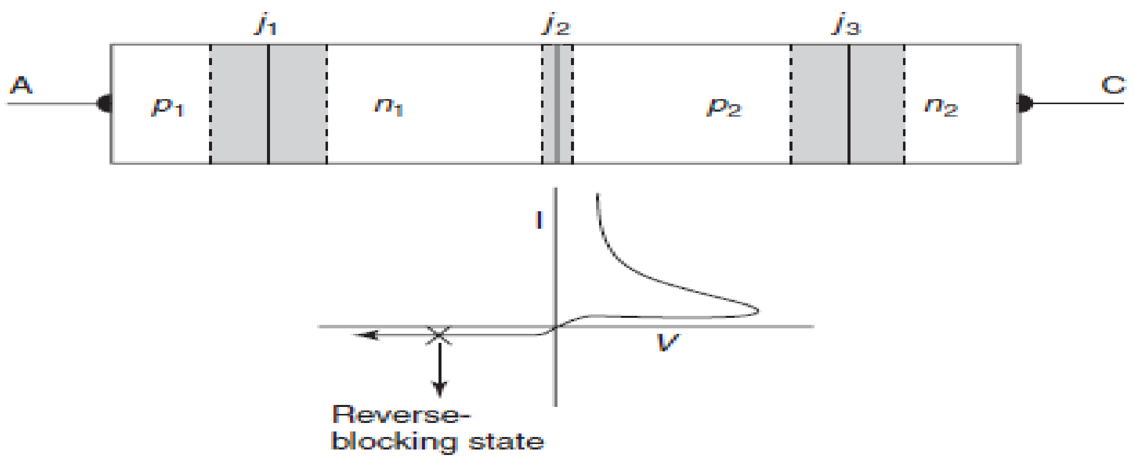


Figure 8-4 (c) Reverse-blocking state of the SCR

I–V Characteristics of the SCR:

- As shown in Fig. 8-5, if the gate current is 0 mA, the critical voltage is higher, i.e., the SCR requires more voltage to switch to the conducting state.
- But as the value of gate current increases, the critical voltage becomes lower, and the SCR switches to the conducting state at a lower voltage.

I–V Characteristics of the SCR:

- At the higher gate current *IG2, the SCR switches faster than at the lower gate current IG1,*

because *IG2 > IG1.*

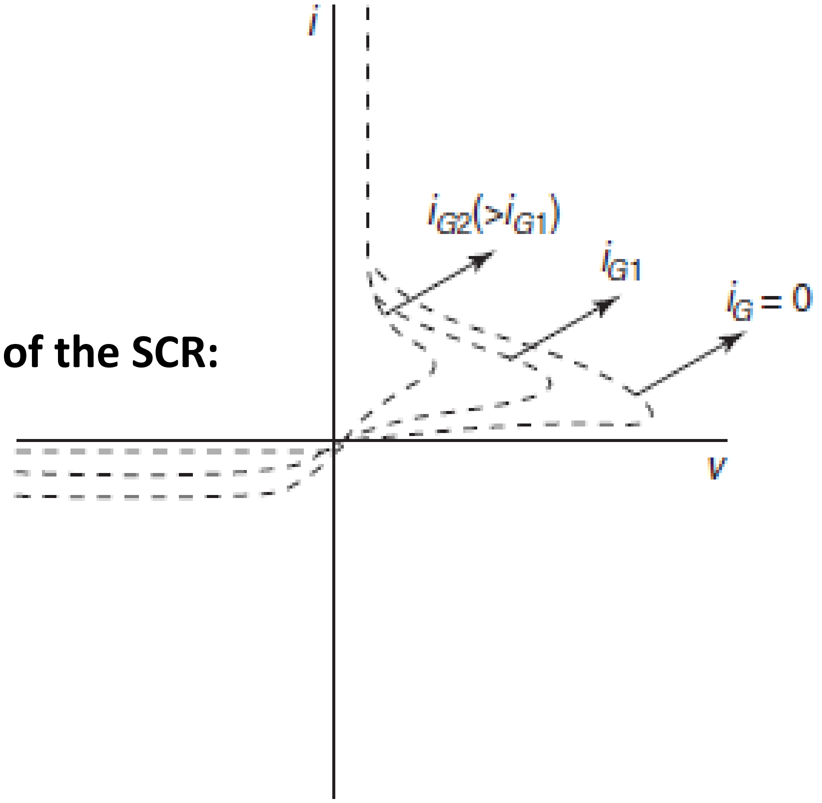


Figure 8-5 I–V characteristics of SCR

Semiconductor-controlled switch (SCS):

- Few SCRs have two gate leads, *G2 attached to p2 and G1*
attached to *n1, as shown in Fig. 8-6. This configuration is called the* semiconductor-controlled switch (SCS).
- The SCS, biased in the forward-blocking state, can be switched to the conducting state by a negative pulse at the anode gate *n1 or by a positive current pulse applied to the* cathode gate at *p2.*

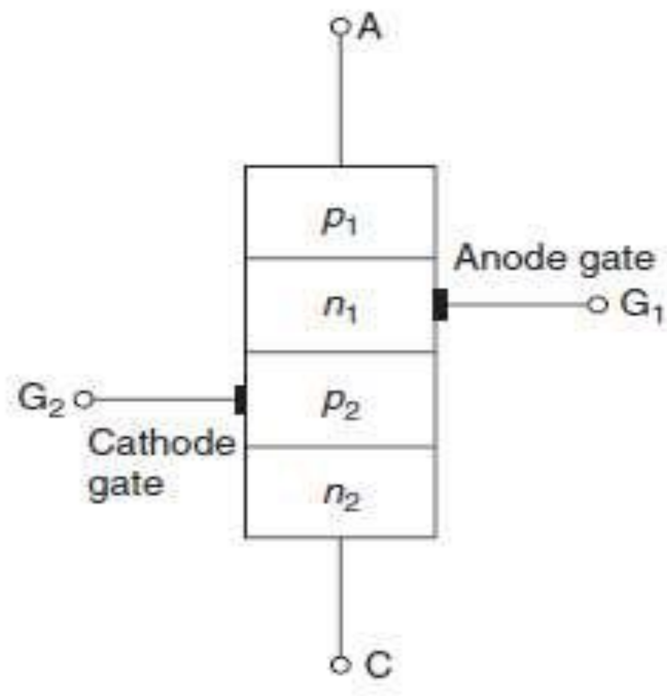


Figure 8-6 Schematic diagram for a semiconductor-controlled switch

Simple Applications:

- The SCR is the most important member of the thyristor family. The SCR is a capable power device as it can handle thousands of amperes and volts.
- Generally the SCR is used in many applications such as in high power electronics, switches, power-control and conversion mode.
- It is also used as surge protector.
- **Static Switch:** The SCR is used as a switch for power-switching in various control circuits.
- **Power Control:** Since the SCR can be turned on externally, it can be used to regulate the amount of power delivered to a load.
- **Surge Protection:** In an SCR circuit, when the voltage rises beyond the threshold value, the SCR is turned on to dissipate the charge or voltage quickly.
- **Power Conversion:** The SCR is also used for high-power conversion and regulation. This includes conversion of power source from ac to ac, ac to dc and dc to ac.

TRIODE AC SWITCH (TRIAC):

- The term TRIAC is derived by combining the first three letters of the word "TRIODE" and the word "AC".
- A TRIAC is capable of conducting in both the directions. The TRIAC, is thus, a bidirectional thyristor with three terminals. It is widely used for the control of power in ac circuits.

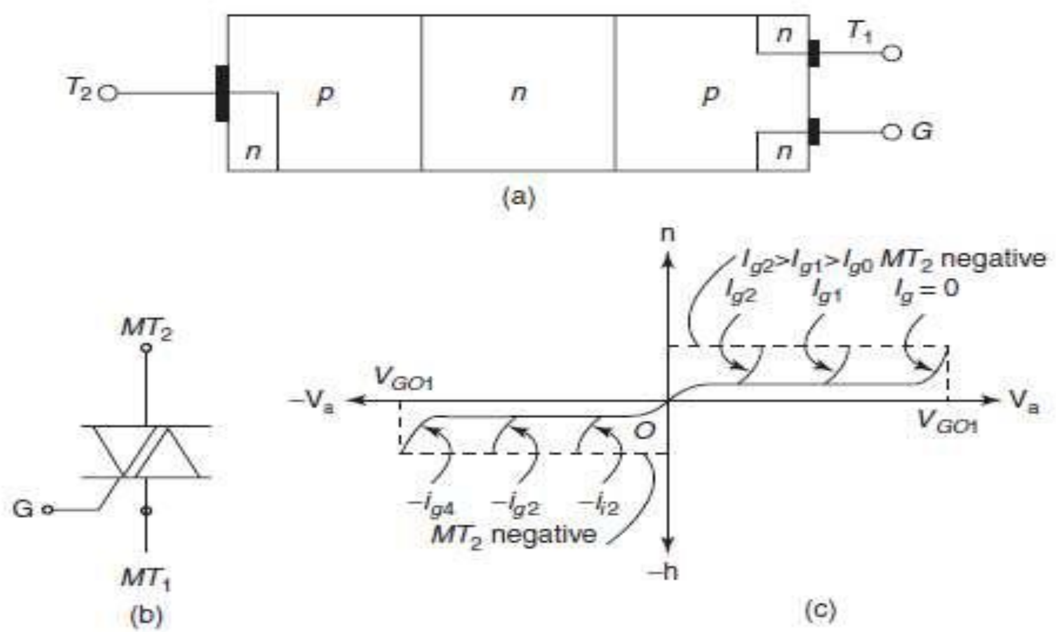


Figure 8-7 (a) Structure of TRIAC (b) Circuit symbol (c) Static I—V characteristics

Constructional Features:

Depending upon the polarity of the gate pulse and the biasing conditions, the main four-layer structure that turns ON by a regenerative process could be one of *p1 n1, p2 n2, p1 n1 p2 n3, or p2 n1 p1 n4, as shown in Fig. 8-8.*

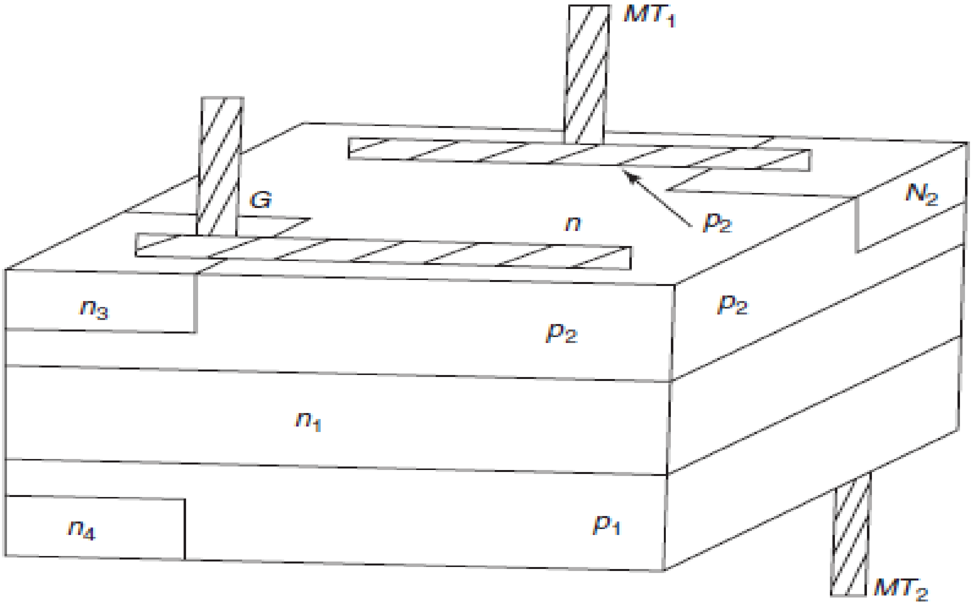


Figure 8-8 Cross-sectional view of the TRIAC

Advantages of the TRIAC:

- *The TRIAC has the following advantages:*

(i) They can be triggered with positive- or negative-polarity voltage.

(ii) They need a single heat sink of slightly larger size.

(iii) They need a single fuse for protection, which simplifies their construction.

(iv) In some dc applications, the SCR has to be connected with a parallel diode for protection against reverse voltage, whereas a TRIAC may work without a diode, as safe breakdown in either direction is possible.

Disadvantages of the TRIAC:

- *The TRIAC has the following disadvantages:*

(i) TRIACs have low *dv/dt ratings compared to SCRs.*

(ii) Since TRIACs can be triggered in either direction, the trigger circuits with TRIACs needs careful consideration.

(iii) Reliability of TRIACs is less than that of SCRs.

Simple Applications of the TRIAC:

- *The TRIAC as a bidirectional thyristor has various applications. Some of the popular applications of the TRIAC are as follows:*

(i) In speed control of single-phase ac series or universal motors.

(ii) In food mixers and portable drills.

(iii) In lamp dimming and heating control.

(iv) In zero-voltage switched ac relay.

DIODE AC SWITCH (DIAC):

- The DIAC is a combination of two diodes. Diodes being unidirectional devices, conduct current only in one direction.
- If bidirectional (ac) operation is desired, two Shockley diodes may be joined in parallel facing different directions to form the DIAC.

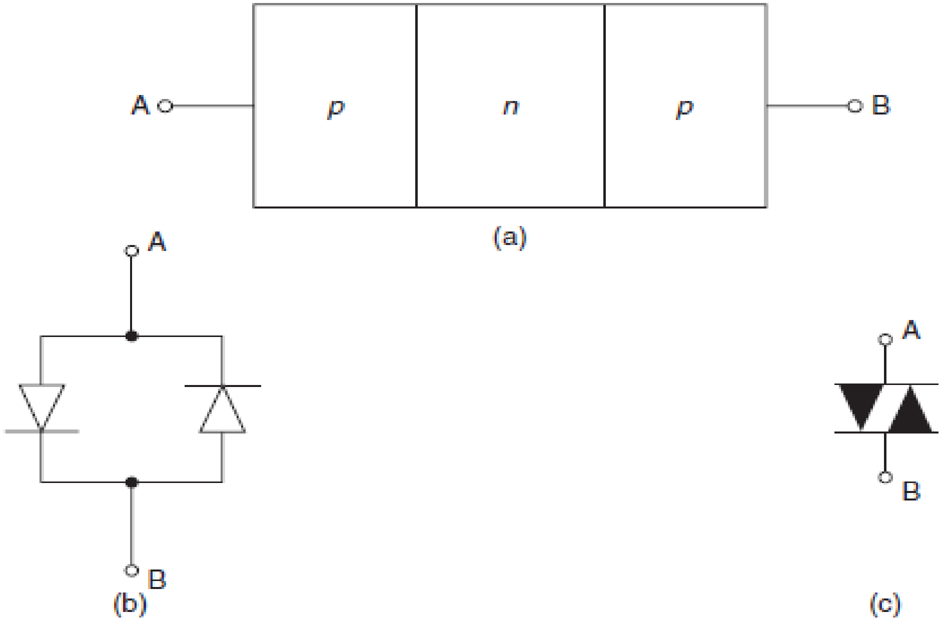


Figure 8-13 (a) Basic structure of the DIAC (b) Equivalent circuit of the DIAC (c) Symbol of the DIAC

Constructional Features:

- The construction of DIAC looks like a transistor but there are major differences.
- **<u>They are as follows:</u>**

 (i) All the three layers, *p–n–p or n–p–n, are equally doped in the DIAC, whereas in the BJT there is a gradation* of doping. The emitter is highly doped, the collector is lightly doped, and the base is moderately doped.

- (ii) The DIAC is a two-terminal diode as opposed to the BJT, which is a three-terminal device.

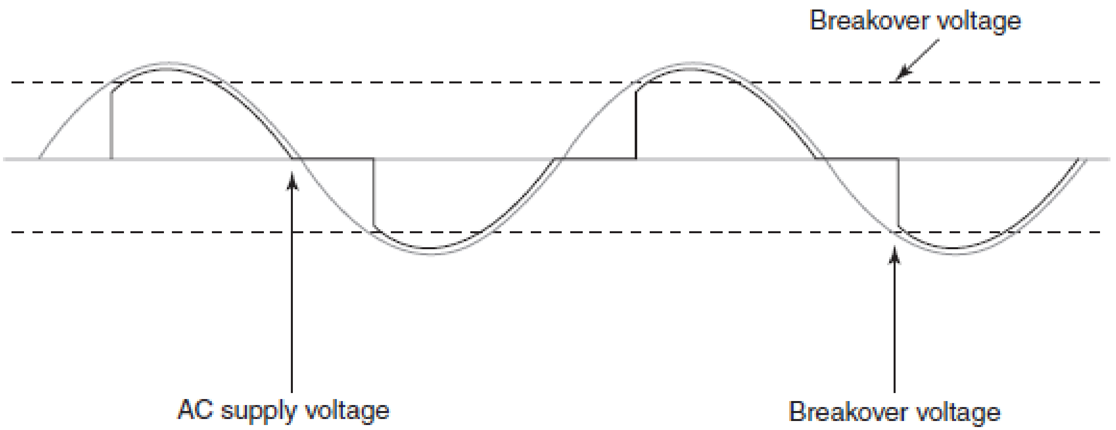


Figure 8-14 Current waveform in the DIAC

Physical Operation and Characteristics:

- **<u>The main characteristics are of the DIAC are as follows:</u>**

  (i) Break over voltage

  (ii) Voltage symmetry

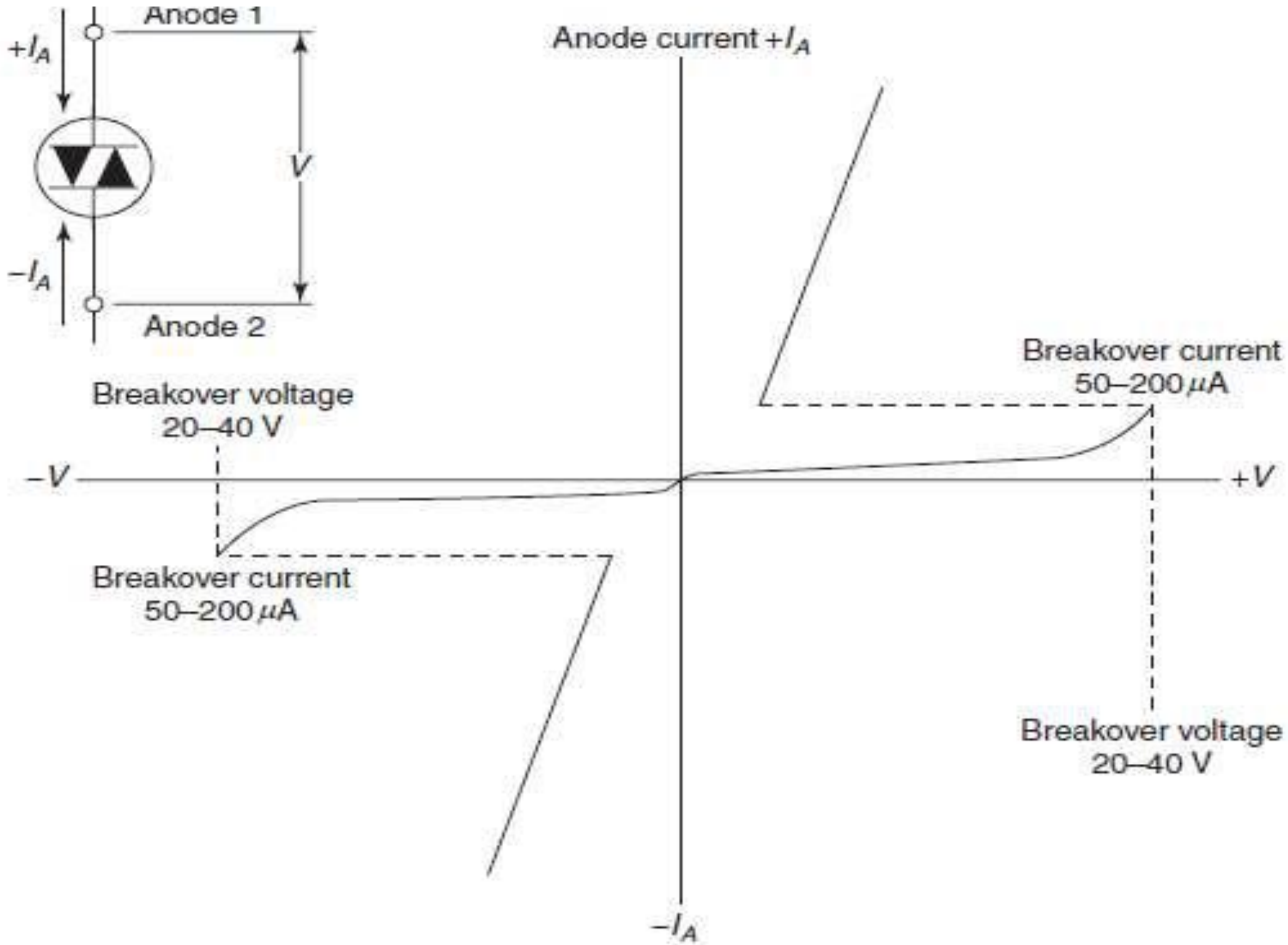
  (iii) Break-back voltage

  (iv) Break over current

  (v) Lower power dissipation

- Although most DIACs have symmetric switching voltages, asymmetric DIACs are also available. Typical DIACs have a power dissipations ranging from 1/2 to 1 watt.

I-V characteristics of the DIAC:



UNIJUNCTION TRANSISTOR (UJT):

- The uni-junction transistor is a three-terminal single-junction device. The switching voltage of the UJT can be easily varied.
- The UJT is always operated as a switch in oscillators, timing circuits and in SCR/TRIAC trigger circuits.

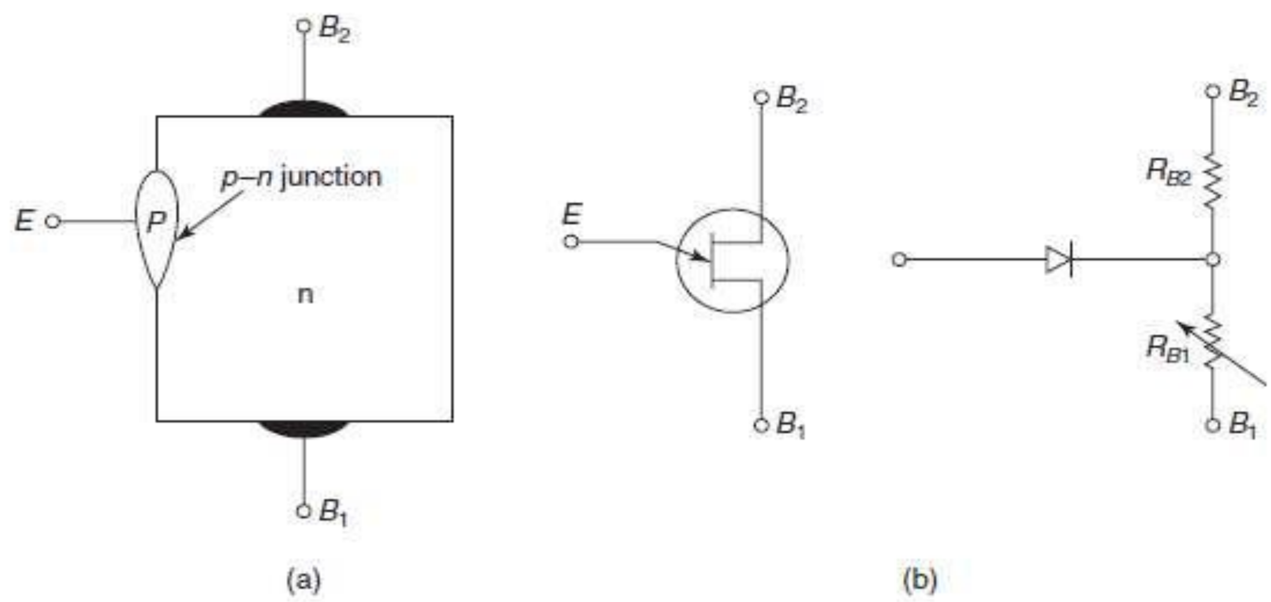


Figure 8-16 (a) Basic UJT structure (b) UJT symbol and equivalent circuit

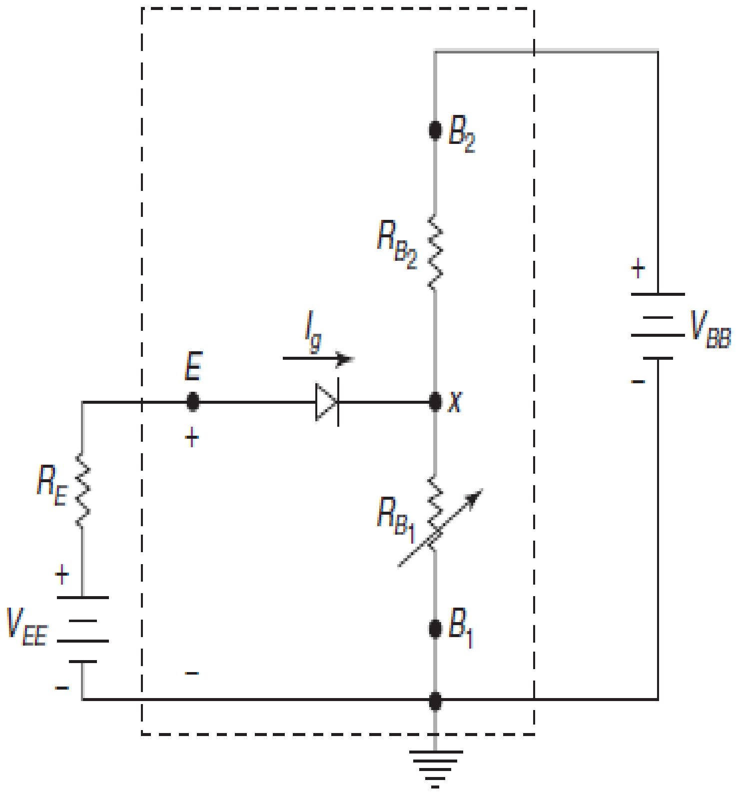
Constructional Features:

- 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.
- Between base *B1 and base B2, the resistance of the n-type bar called inter-base resistance (RB) and is in* the order of a few kilo ohm.
- This inter-base resistance can be broken up into two resistances—the resistance from *B1 to the emitter is RB1 and the resistance from B2 to the emitter is RB 2.*
- *Since the emitter is closer to B2* the value of *RB1is greater than RB2.*
- <u>Total resistance is given by:</u>

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

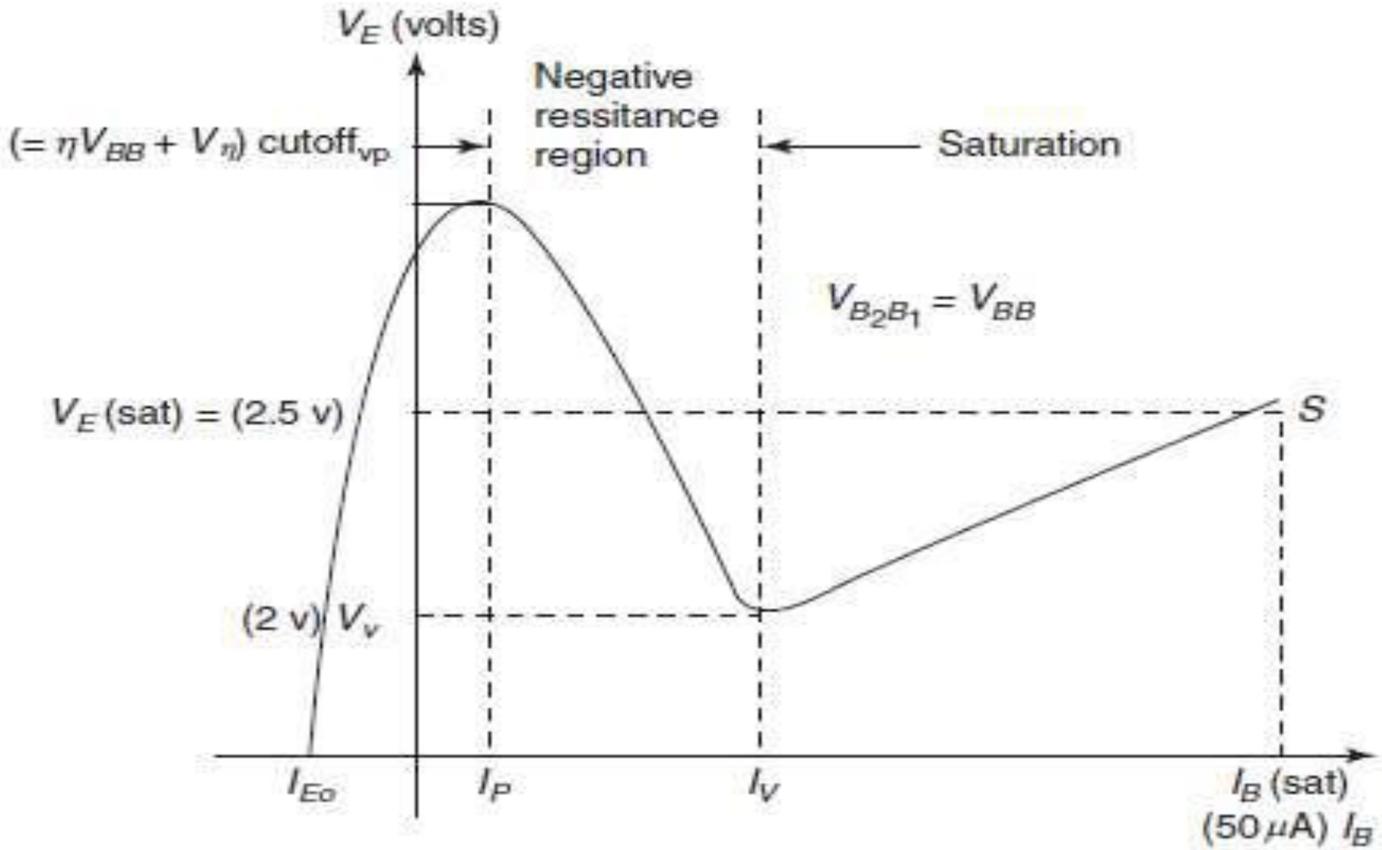
Equivalent circuit for UJT:

- 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 E 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.*



Equivalent circuit for UJT analysis

UJT V–I characteristic curves:



Typical UJT V–I characteristic curves

ON State of the UJT Circuit:

- As V_{EE} *increases, the UJT stays in the OFF state until* V_E *approaches the peak point value* V_P*. As* V_E *approaches* V_P *the p–n junction becomes forward-biased and begins to conduct in the opposite direction.*
- *As a result* I_E becomes positive near the peak point *P on the* V_E - I_E *curve. When* V_E *exactly equals* V_P *the emitter current* equals *IP .*

- *At this point holes from the heavily doped emitter are injected into the n-type bar, especially* into the *B1 region. The bar, which is lightly doped, offers very little chance for these holes to recombine.*

- The lower half of the bar becomes replete with additional current carriers (holes) and its resistance *RB is* drastically reduced; the decrease in *BB1 causes Vx to drop.*
- *This drop, in turn, causes the diode to become more* forward-biased and *IE increases even further.*

OFF State of the UJT Circuit:

- When a voltage *VBB is applied across the two base terminals B1 and B2, the potential of point p with respect* to *B1 is given by:*

  *VP =[VBB/ (RB1 +RB2)]*RB1=η*RB1*
- *η is called the intrinsic stand off ratio with its typical value lying between 0.5 and 0.8.*

- The V_{EE} *source is applied to the emitter which is the p-side. Thus, the emitter diode will be reverse-biased* as long as V_{EE} *is less than Vx. This is OFF state and is shown on the VE - IE curve as being a very low current* region.

- In the OFF the UJT has a very high resistance between E and *B1, and IE is usually a negligible reverse* leakage current. With no *IE, the drop across RE is zero and the emitter voltage equals the source voltage.*

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 maxi mum 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.
- **<u>A few select applications of the UJT are as follows:</u>**

  (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

POINTS TO REMEMBER:

- 1. A thyristor is a multilayer *p–n terminal electronic* device used for bi-stable switching.
- 2. The SCR has two states:
  - (a) High-current low-impedance ON state
  - (b) Low-current OFF state
- 3. Latching current is defined as a minimum value of anode current which is a must in order to attain the turn-on process required to maintain conduction when the gate signal is removed.
- 4. Holding current is defined as a minimum value of anode current below which it must fall for turning off the thyristor..
- 5. The TRIAC is a bidirectional thyristor with three terminals. It is used extensively for the control of power in ac circuits.
- 6. The DIAC is an *n–p–n or p–n–p structure with a* uniformly doped layer.

POINTS TO REMEMBER:

- 7. Applications of the UJT:

    (a) As trigger mechanism in the SCR and the TRIAC

    (b) As non-sinusoidal oscillators

    (c) In saw-tooth generators

    (d) In phase control and timing circuits

- 8. The UJT operation can be stated as follows:

    (a) When the emitter diode is reverse-biased, only a very small emitter current flows. Under this condition *RB1 is at its normal* high-value. This is the OFF state of the UJT.

    (b) When the emitter diode becomes forward-biased *RB1 drops to a very low value so* that the total resistance between *E and B1* becomes very low, allowing emitter current to flow readily. This is the ON state.

UNIT- II

Rectifiers and Filters

- Basic Rectifier setup, half wave rectifier, full wave rectifier, bridge rectifier, derivations of characteristics of rectifiers, rectifier circuits-operation, input and output waveforms,Filters, Inductor filter, Capacitor filter, L- section filter, Π- section filter, Multiple L- section and Multiple Π section filter ,comparison of various filter circuits in terms of ripple factors.

Outline…

- What is Power supply?
- Need for Power supply
- Elements of Power supply
- Filters
- Voltage Regulators
- A basic Power supply

Why we go for power supply studies?

- All electronic circuits need smooth DC power supply in order to function correctly.
- The DC power supplied either from battery or power pack units

Contd…

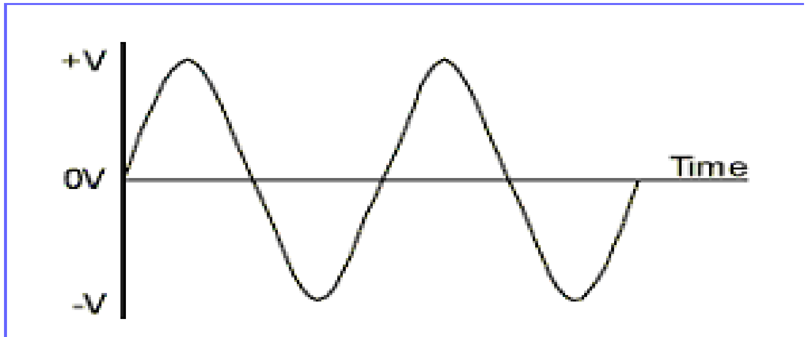
- The battery power supply may not be economical
- Some other circuits, those using digital ICs, also need their power supply to be regulated.

What is a Power Supply?

- A device, which converts, regulates, and transmits the required power to the circuit to be operated

What is AC

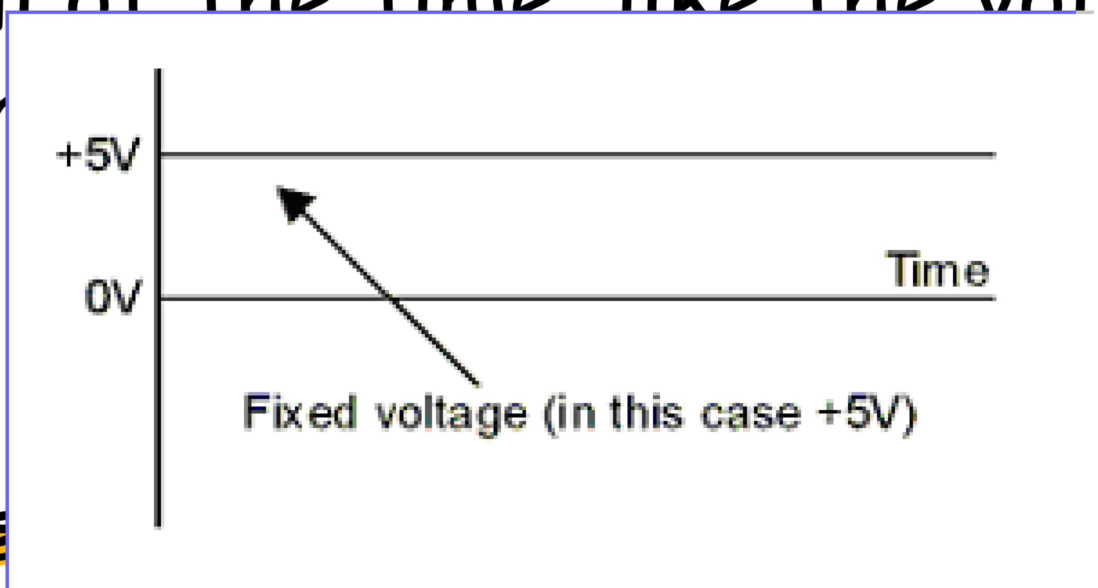
- The voltage (and current) alternates between positive and negative over time and the resulting waveform shape is a sine



An AC Waveform

What is DC?

- A Direct Current (DC) supply stays at a fixed, regular, voltage all of the time, like the voltage fr



A DC Waveform

Elements of a Power Supply

- Transformer
- Rectifier
- Filter
- Regulator

TRANSFORMER

- The AC line voltage available for commercial purpose is not suitable for electronic circuits.
- Most of the electronic circuits require a considerably lower voltage

Contd…..

- The transformer is a device used to convert the ac line voltage to a voltage level more appropriate to the needs of the circuit to be operated
- At the same time, the transformer provides electrical isolation between the ac line and the circuit to be operated.
- This is an important safety consideration.

Contd….

- The output of the transformer is still an ac voltage, but now of an appropriate magnitude for the circuit to be powered.

Rectifiers

- Rectifier is a device which convert AC voltage in to pulsating DC
- A rectifier utilizes unidirectional conducting device Ex : P-N junction diodes

Important points to be studied while analyzing the various rectifiers

- Rectifier efficiency
- Peak value of the current
- Peak value of the voltage
- Ripple factor

Types

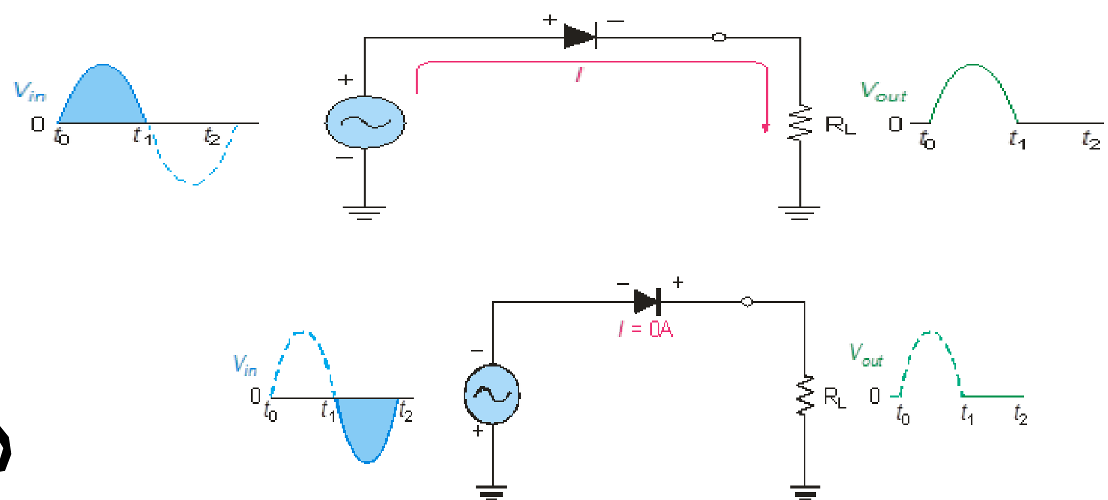
- Depending up on the period of conduction
  - ❖ Half wave rectifier
  - ❖ Full wave rectifier
- Depending up on the connection procedure
  - ❖ Bridge rectifier

Half wave rectifier

- The ripple factor is quite high(1.21)
- Rectifier efficiency is very low(40%)
- TUF is low(0.21)
- The half wave rectifier circuit is normally not used as a power rectifier circuit

Half wave Rectifiers

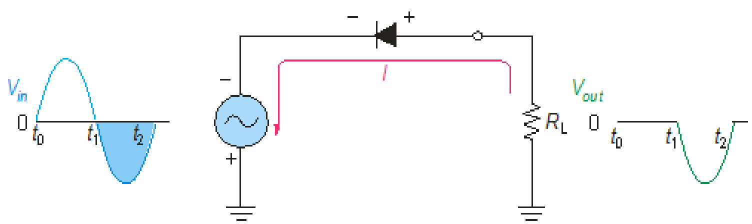
- As diodes conduct current in one direction and block in other.
- When connected with ac voltage, diode only allows half cycle passing through it and hence convert ac into dc.
- As the half of the wave get rectified, the process called half wave rectification.



- A diode is connected to an ac source and a load resistor forming a half wave rectifier.
- Positive half cycle causes current through diode, that causes voltage drop across resistor.

Diode as Rectifiers

- Reversing diode.



- Average value of Half wave output voltage:

$$V_{AVG} = V_P / \pi$$

- V_{AVG} is approx 31.8% of V_p

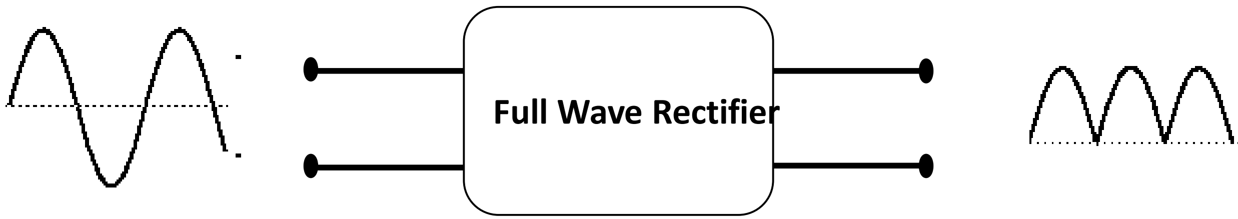
- PIV: Peak Inverse Voltage = V_p

Full wave rectifier

- Ripple factor is (0.48)
- Rectifier efficiency is high(81.2%)
- TUF is high(0.693)

Full wave rectifiers

- A full wave rectifier allows unidirectional current through the load during the entire 360 degree of input cycle.



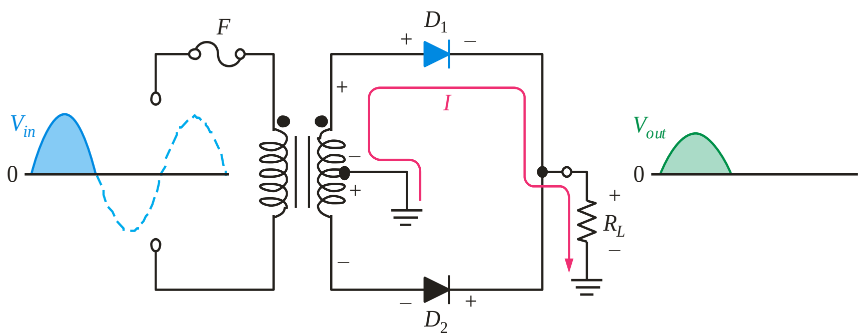
- The output voltage have twice the input frequency.

$$V_{AVG} = 2V_P / pi$$

- V_{AVG} is 63.7% of Vp

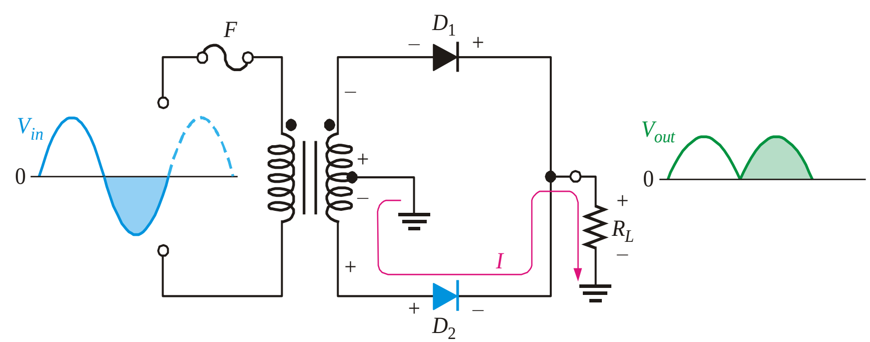
The Center-Tapped Full wave rectifiers

- A center-tapped transformer is used with two diodes that conduct on alternating half-cycles.



During the positive half-cycle, the upper diode is forward-biased and the lower diode is reverse-biased.

During the negative half-cycle, the lower diode is forward-biased and the upper diode is reverse-biased.

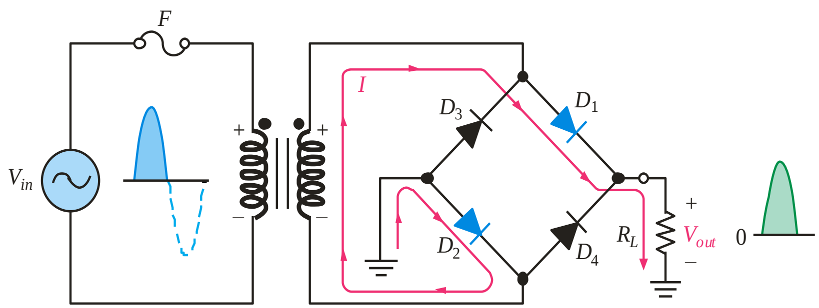


Bridge Rectifier

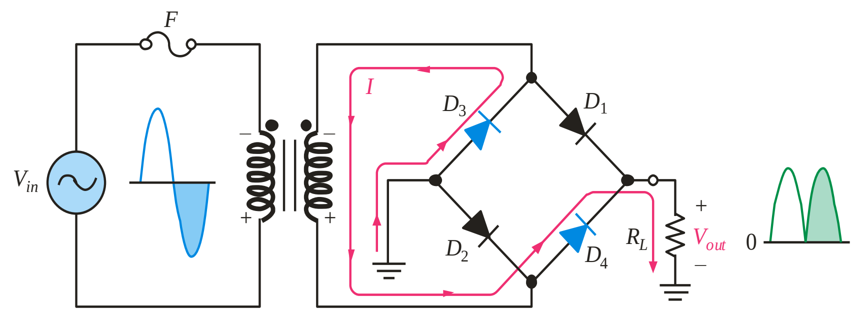
- Suitable for applications where large powers are required

The Bridge Full-wave rectifiers

- The Bridge Full-Wave rectifier uses four diodes connected across the entire secondary as shown.



Conduction path for the positive half-cycle.



Conduction path for the negative half-cycle.

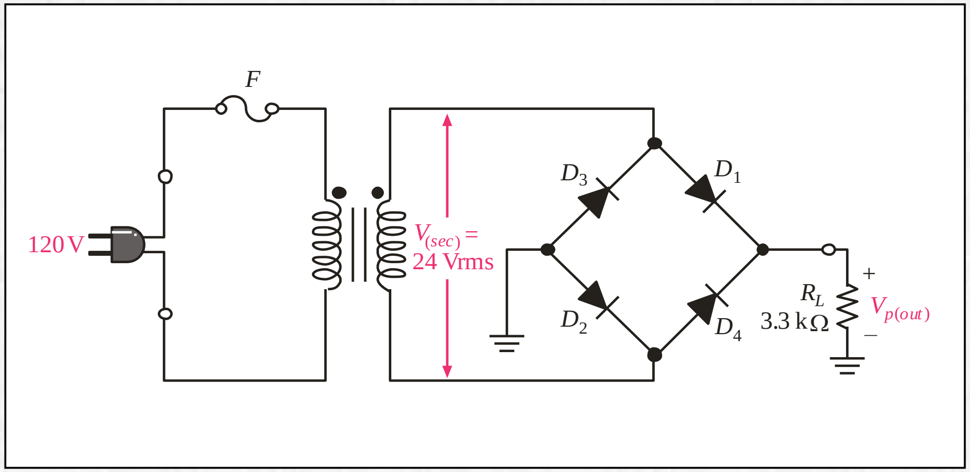
The Bridge Full-Wave Rectifier

Example:

Determine the peak output voltage and current in the 3.3 kΩ load resistor if $V_{sec} = 24\ V_{rms}$. Use the practical diode model.

Solution:

The peak output voltage is:



$$V_{p(sec)} = 1.41V_{rms} = 33.9\ V$$

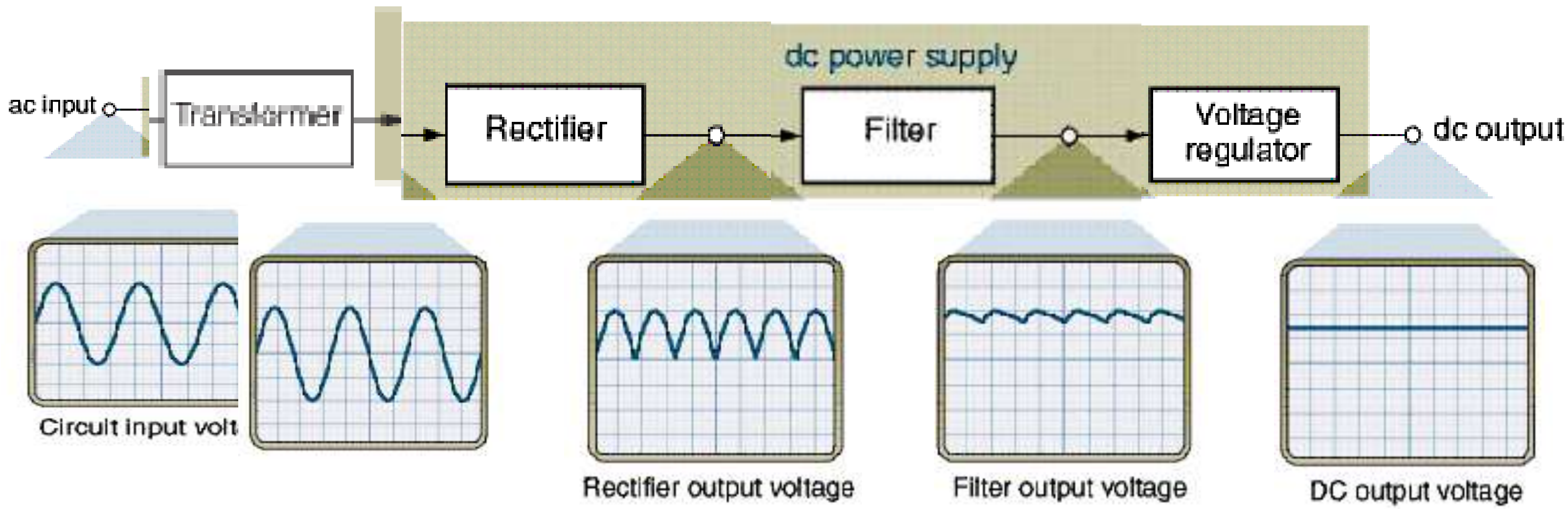
$$V_{p(out)} = V_{p(sec)} - 1.4\ V$$

$$= 32.5\ V$$

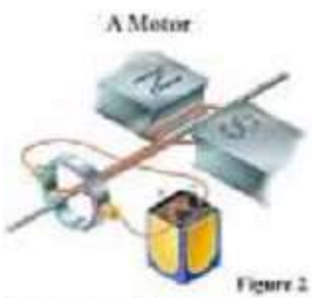
Applying Ohm's law,

$I_{p(out)}$ = 9.8 mA

Block diagram of a Power Supply



Fields?



Points to note…

- The most important consideration in designing a power supply is the DC voltage at the output
- It should be able to furnish the maximum current needed ,maintaining the voltage at constatnt level

Contd…

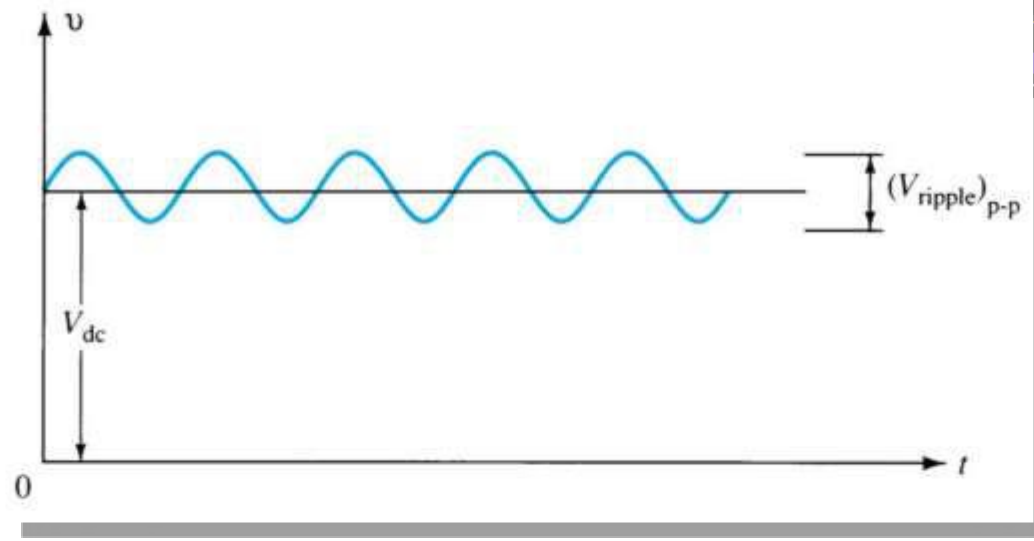
- The AC ripple should be low
- The power supply should be protect in the event of short circuit on the load side
- The response of the power supply to temperature changes should be minimum

Filter Circuits

- The output from the rectifier section is a pulsating DC.
- The filter circuit reduces the peak-to-peak pulses to a small ripple voltage.

Ripple Factor

After the filter circuit a small amount of AC is still remaining. The amount of ripple voltage can be rated in terms of ripple factor (r).



$$\%r = \frac{\text{ripple voltage (rms)}}{\text{dc voltage}} = \frac{V_{r(rms)}}{V_{dc}} \times 100$$

Rectifier Ripple Factor

Half-Wave

DC output:

$$V_{dc} = 0.318V_m$$

AC ripple output:

$$V_{r(rms)} = 0.385V_m$$

Ripple factor:

$$\%r = \frac{V_{r(rms)}}{V_{dc}} \times 100$$

$$= \frac{0.385V_m}{0.318V_m} \times 100 = 121\%$$

Full-Wave

DC output:

$$V_{dc} = 0.636V_m$$

AC ripple output:

$$V_{r(rms)} = 0.308V_m$$

Ripple factor:

$$\%r = \frac{V_{r(rms)}}{V_{dc}} \times 100$$

$$= \frac{0.308V_m}{0.636V_m} \times 100 = 48\%$$

Types of Filter Circuits

Capacitor Filter

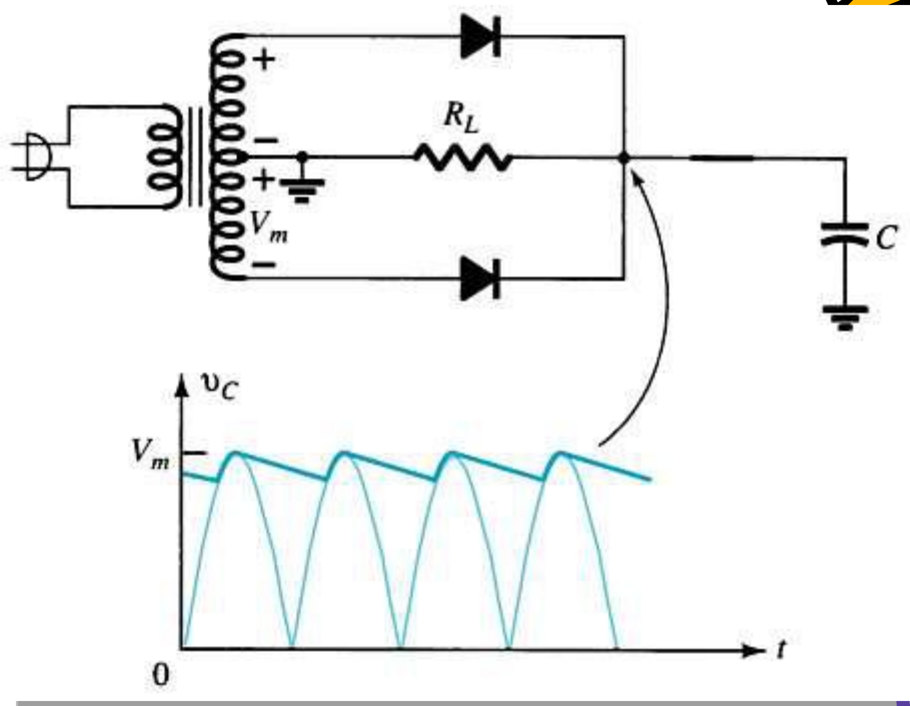
RC Filter

Capacitor Filter

Ripple voltage

$$V_{r(rms)} = \frac{I_{dc}}{4\sqrt{3}fC} = \frac{2.4 I_{dc}}{C} = \frac{2.4 V_{dc}}{R_L C}$$

The larger the capacitor the smaller the ripple voltage.



DC output

$$V_{dc} = V_m - \frac{I_{dc}}{4fC} = V_m - \frac{4.17 I_{dc}}{C}$$

Ripple factor

$$\%r = \frac{V_{r(rms)}}{V_{dc}} \times 100 = \frac{2.4 I_{dc}}{C V_{dc}} \times 100 = \frac{2.4}{R_L C} \times 100$$

Diode Ratings with Capacitor Filter

The size of the capacitor increases the current drawn through the diodes—the larger the capacitance, the greater the amount of current.

Peak Current vs. Capacitance:

$$I = \frac{CV}{t}$$

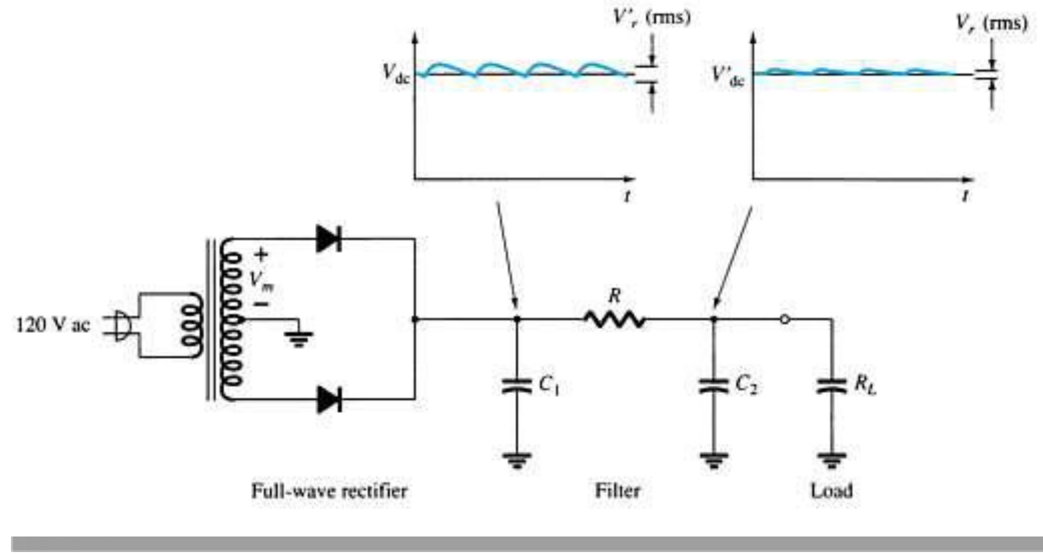
where

C = capacitance

V = change in capacitor voltage during charge/discharge

t = the charge/discharge time

RC Filter Circuit



Adding an RC section further reduces the ripple voltage and decrease the surge current through the diodes.

$$V'_{r(rms)} \approx \frac{X_C}{R} V_{r(rms)}$$

$V'_{r(rms)}$ = ripple voltage after the RC filter
$V_{r(rms)}$ = ripple voltage before the RC filter
R = resistor in the added RC filter
X_C = reactance of the capacitor in the added RC filter

$$\%V_R = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

V_{NL} = no-load voltage
V_{FL} = full-load voltage

Voltage Regulation Circuits

There are two common types of circuitry for voltage regulation:

- Discrete Transistors
- IC's

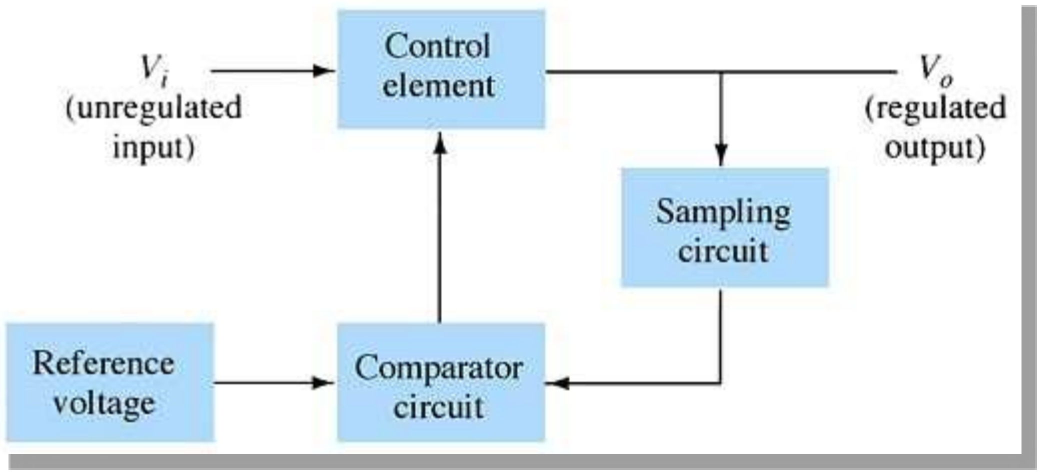
Discrete-Transistor Regulators

Series voltage regulator

Current-limiting circuit

Shunt voltage regulator

Series Voltage Regulator Circuit

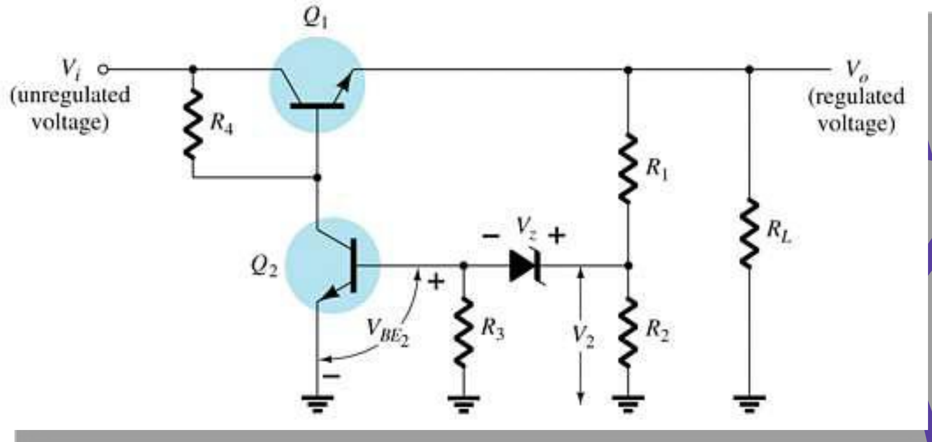


The series element controls the amount of the input voltage that gets to the output.

If the output voltage increases (or decreases), the comparator circuit provides a control signal to cause the series control element to decrease (or increase) the amount of the output voltage.

Series Voltage Regulator Circuit

- R_1 and R_2 act as the sampling circuit
- Zener provides the reference voltage
- Q_2 controls the base current to Q_1
- Q_1 maintains the constant output voltage



When the output increases:

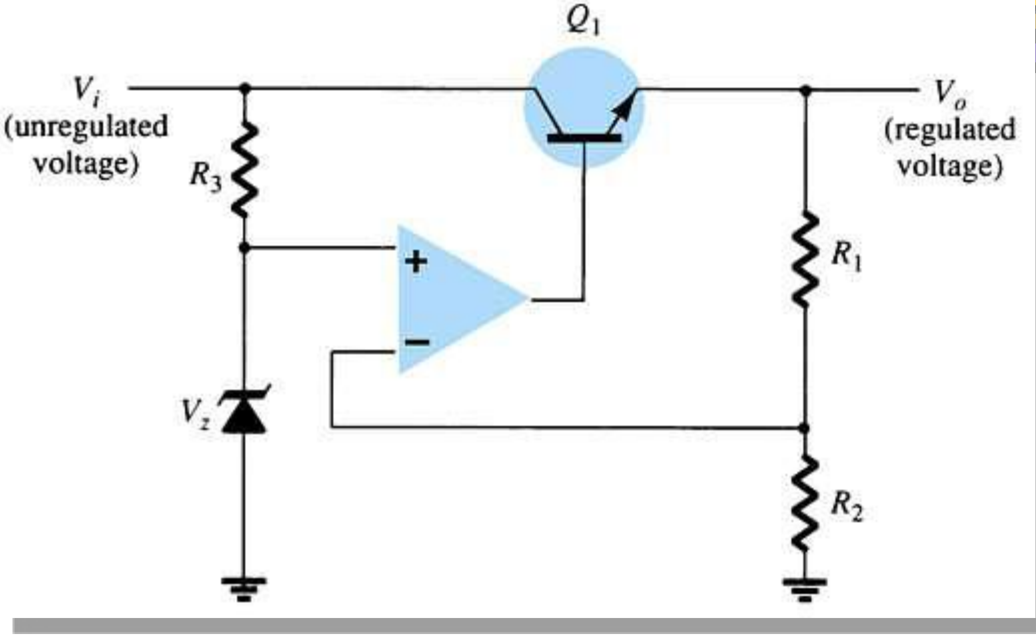
1. The voltage at V_2 and V_{BE} of Q_2 increases
2. The conduction of Q_2 increases
3. The conduction of Q_1 decreases
4. The output voltage decreases

When the output decreases:

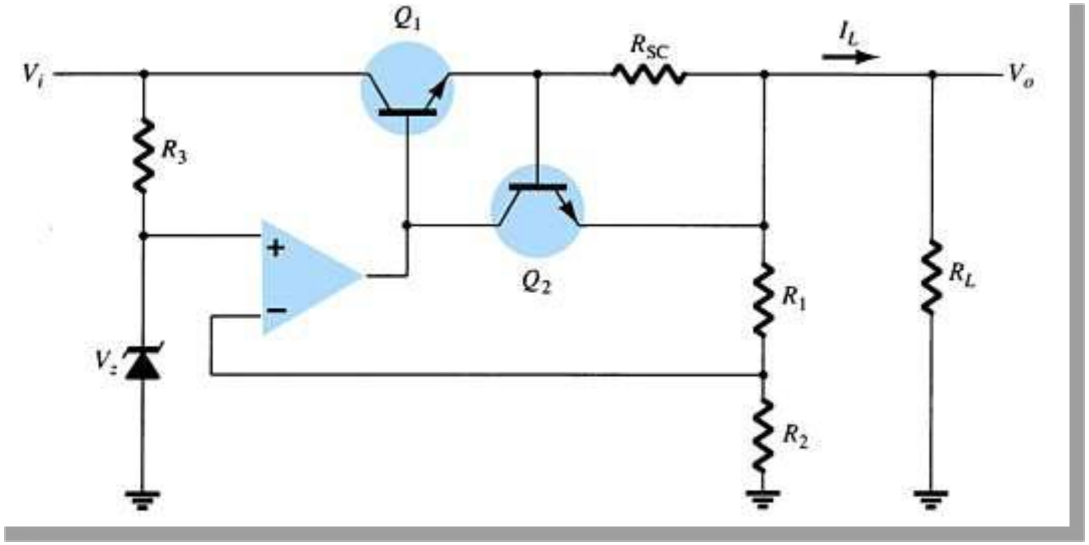
1. The voltage at V_2 and V_{BE} of Q_2 decreases
2. The conduction of Q_2 decreases
3. The conduction of Q_1 increases
4. The output voltage increases

Series Voltage Regulator Circuit

The op-amp compares the Zener diode voltage with the output voltage (at R_1 and R_2) and controls the conduction of Q_1.



Current-Limiting Circuit

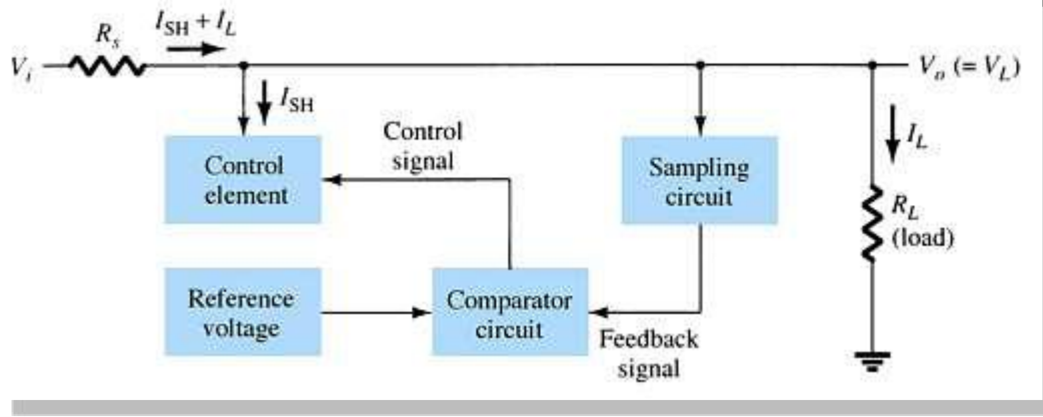


When I_L increases:

- **The voltage across R_{SC} increases**
- **The increasing voltage across R_{SC} drives Q_2 on**
- **Conduction of Q_2 reduces current for Q_1 and the load**

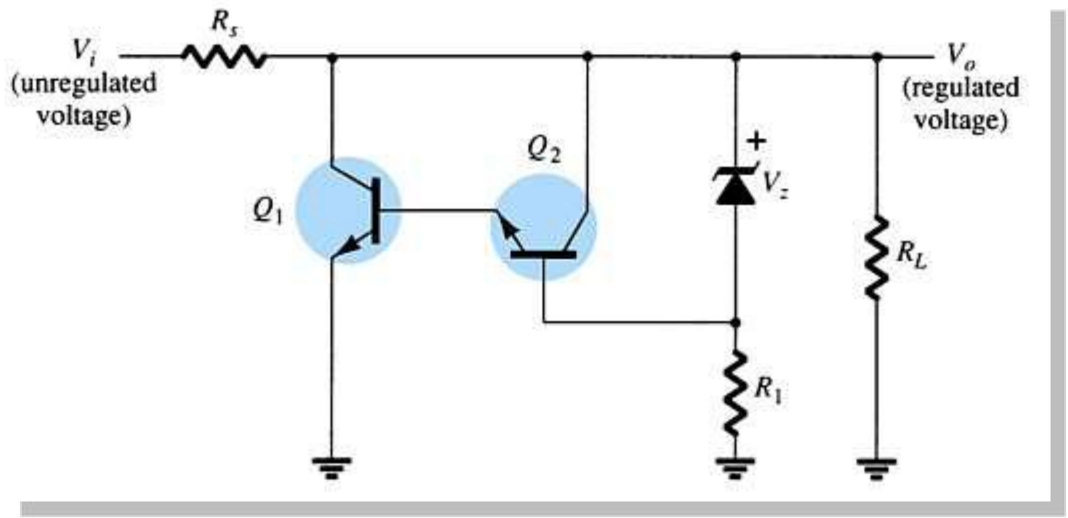
Shunt Voltage Regulator Circuit

The shunt voltage regulator shunts current away from the load.



The load voltage is sampled and fed back to a comparator circuit. If the load voltage is too high, control circuitry shunts more current away from the load.

Shunt Voltage Regulator Circuit



When the output voltage increases:

- The Zener current increases
- The conduction of Q_2 increases
- The voltage drop at R_s increases
- The output voltage decreases

When the output voltage decreases:

- The Zener current decreases
- The conduction of Q_2 decreases
- The voltage drop at R_s decreases
- The output voltage increases

IC Voltage Regulators

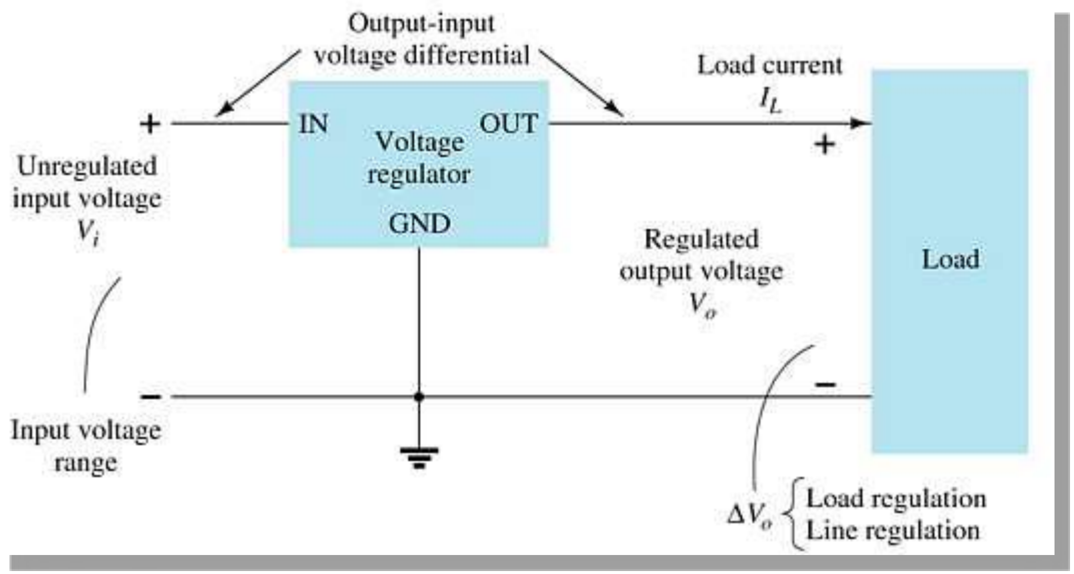
Regulator ICs contain:

- **Comparator circuit**
- **Reference voltage**
- **Control circuitry**
- **Overload protection**

Types of three-terminal IC voltage regulators

- **Fixed positive voltage regulator**
- **Fixed negative voltage regulator**
- **Adjustable voltage regulator**

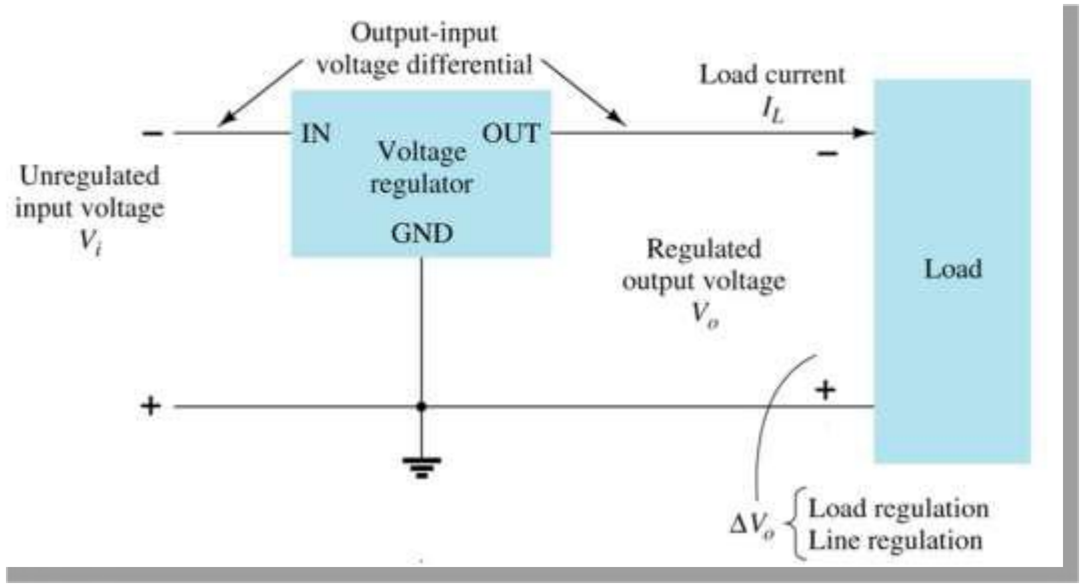
Three-Terminal Voltage Regulators



The specifications for this IC indicate:

- **The range of input voltages that can be regulated for a specific range of output voltage and load current**
- **Load regulation—variation in output voltage with variations in load current**
- **Line regulation—variation in output voltage with variations in input voltage**

Fixed Negative Voltage Regulator

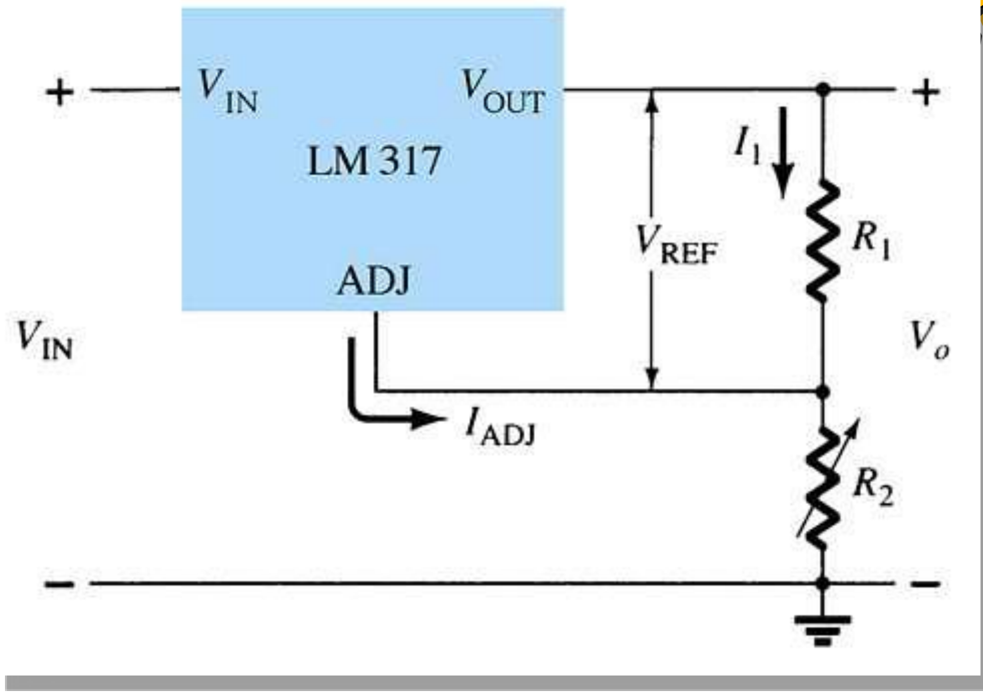


These ICs output a fixed negative output voltage.

Adjustable Voltage Regulator

These regulators have adjustable output voltages.

The output voltage is commonly selected using a potentiometer.



Practical Power Supplies

DC supply (linear power supplies)

Chopper supply (switching power supplies)

TV horizontal high voltage supply

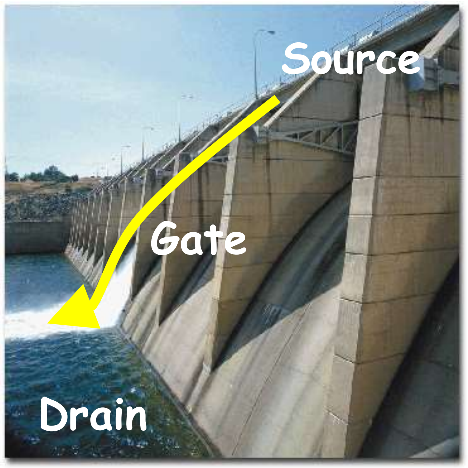
Battery chargers

»THANK YOU

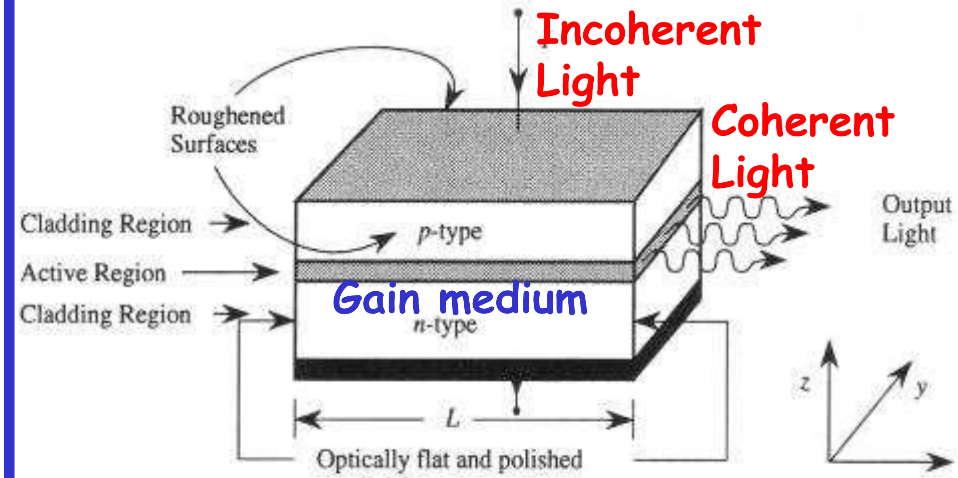
UNIT- III
Transistor Characteristics

- **BJT:** Junction transistor, transistor current components, transistor equation, transistor configurations, transistor as an amplifier, characteristics of transistor in Common Base, Common Emitter and Common Collector configurations, Ebers-Moll model of a transistor, punch through/ reach through, Photo transistor, typical transistor junction voltage values.
- **FET:** FETtypes, construction, operation, characteristics, parameters, MOSFET-types, construction, operation, characteristics, comparison between JFET and MOSFET.

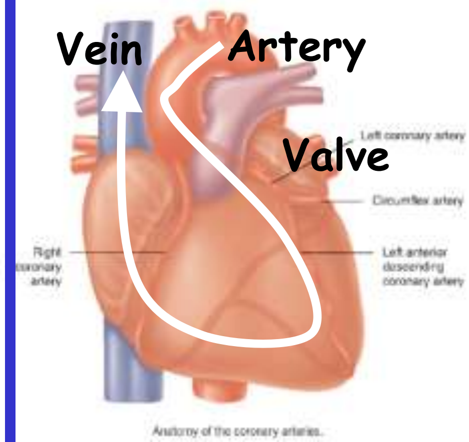
Transistor/switch/amplifier – a 3 terminal device



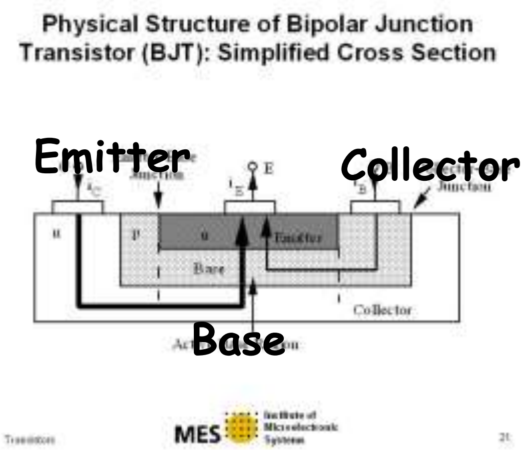
Dam



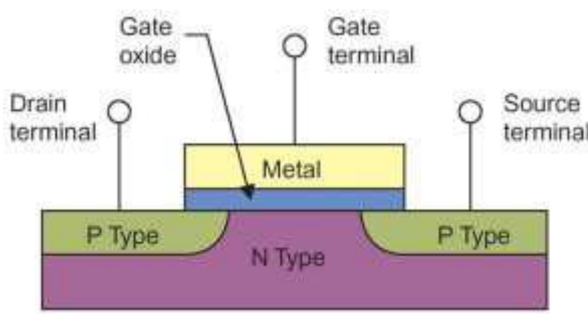
Laser



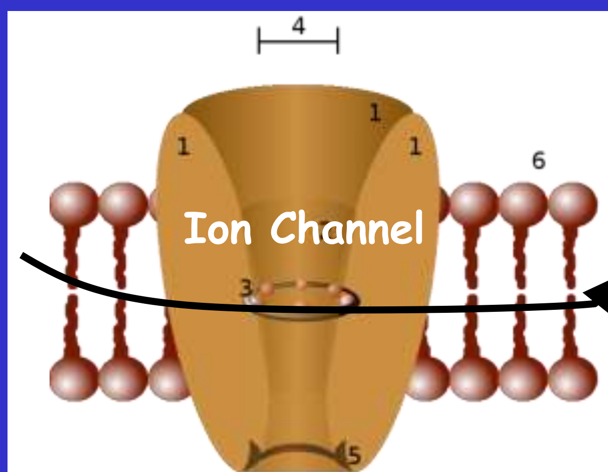
Heart



BJT



MOSFET



Axonal conduction

All of these share a feature with…

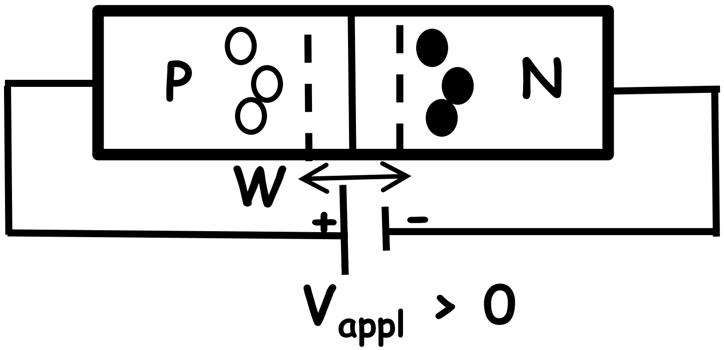
- Output current can toggle between large and small

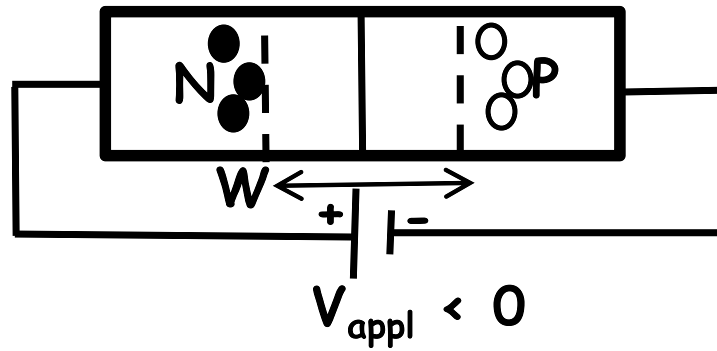
  (Switching → Digital logic; create 0s and 1s)

- Small change in 'valve' (3rd terminal) creates Large change in output between 1st and 2nd terminal

  (Amplification → Analog applications; Turn 0.5 → 50)

Recall p-n junction



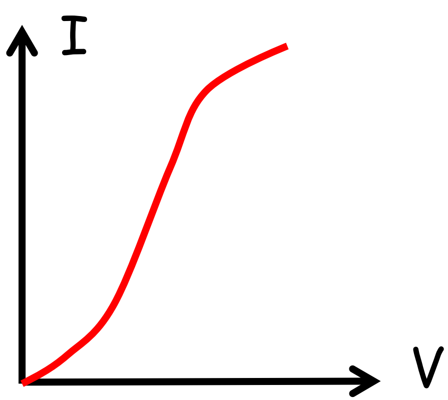


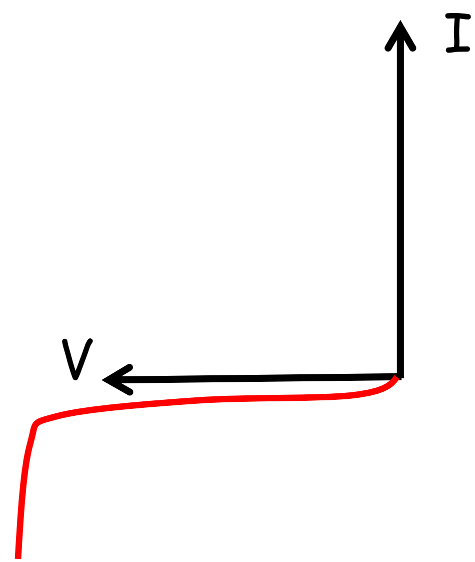
Forward bias, + on P, - on N
(Shrink W, V_{bi})

Allow holes to jump over barrier
into N region as minority carriers

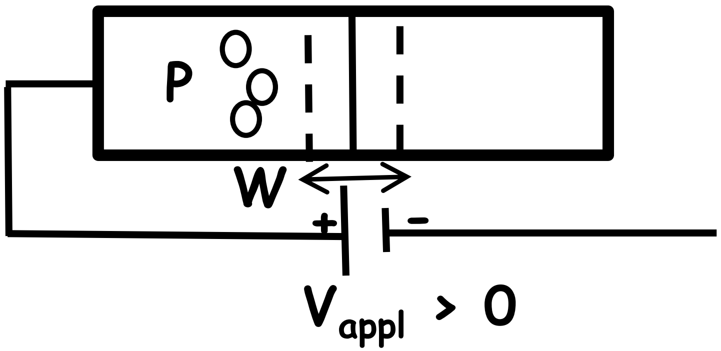
Reverse bias, + on N, - on P
(Expand W, V_{bi})

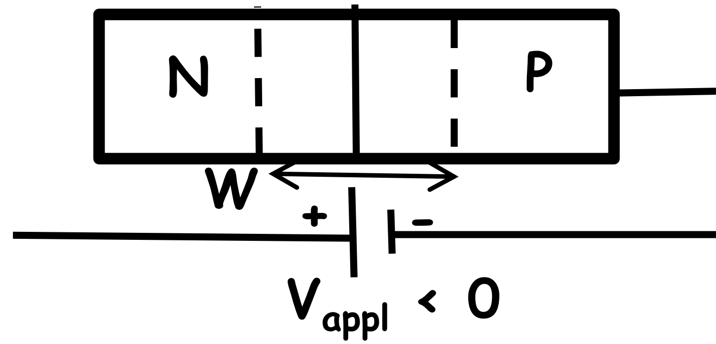
Remove holes and electrons away
from depletion region





So if we combine these by fusing their terminals…



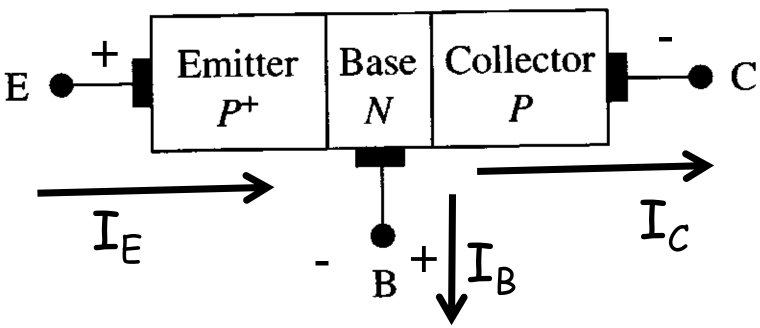


Holes from P region ("Emitter") of 1st PN junction driven by FB of 1st PN junction into central N region ("Base")

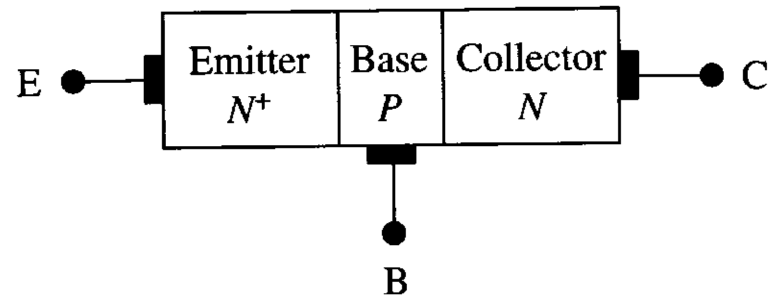
Driven by RB of 2nd PN junction from Base into P region of 2nd junction ("Collector")

- 1st region FB, 2nd RB
- If we want to worry about holes alone, need P+ on 1st region
- For holes to be removed by collector, base region must be thin

Bipolar Junction Transistors: Basics



(a) *pnp*



(b) *npn*

$$I_E = I_B + I_C \quad \text{.........(KCL)}$$

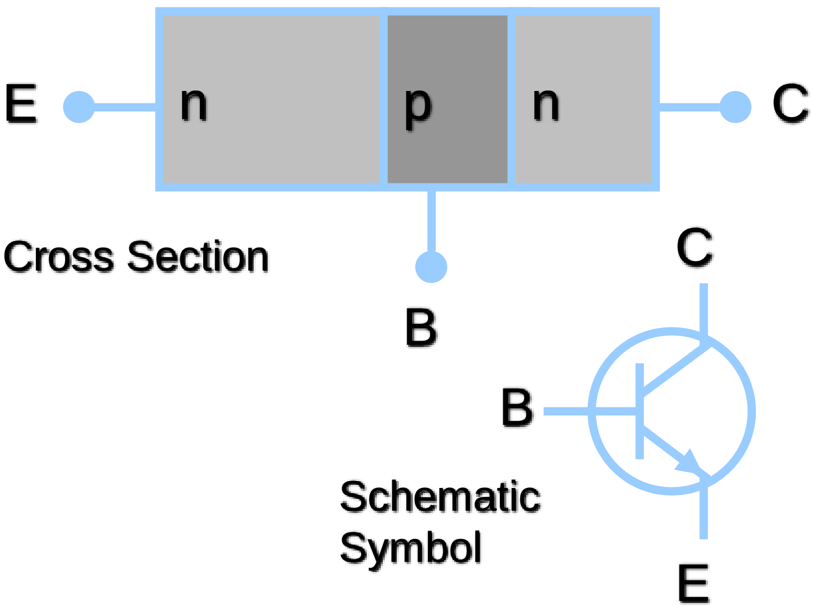
$$V_{EC} = V_{EB} + V_{BC} \quad \text{........ (KVL)}$$

The BJT – Bipolar Junction Transistor

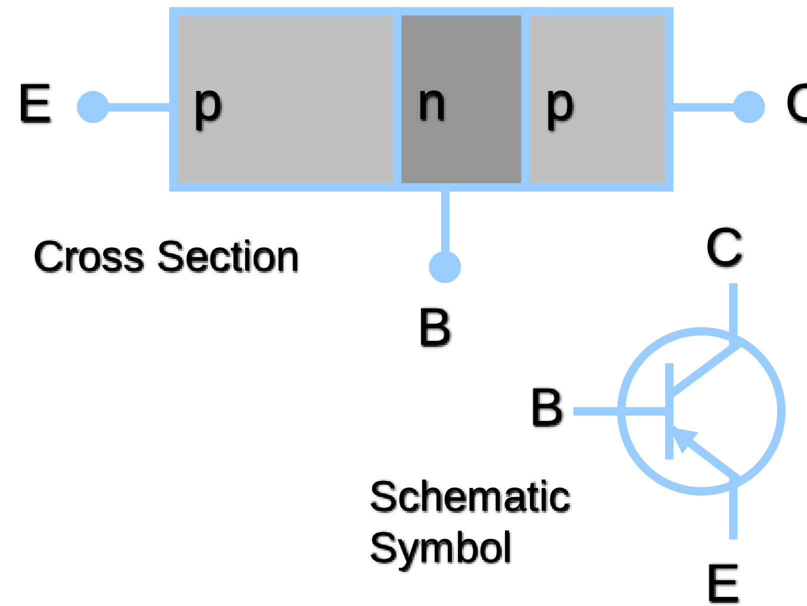
Note: Normally Emitter layer is heavily doped, Base layer is lightly doped and Collector layer has Moderate doping.

The Two Types of BJT Transistors:

npn

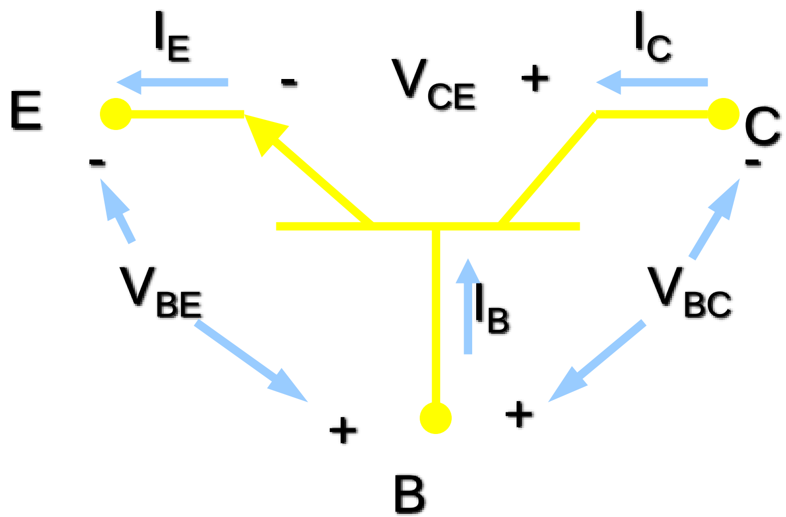


pnp



- Collector doping is usually ~ 10^{9}
- Base doping is slightly higher ~ 10^{10} – 10^{11}
- Emitter doping is much higher ~ 10^{17}

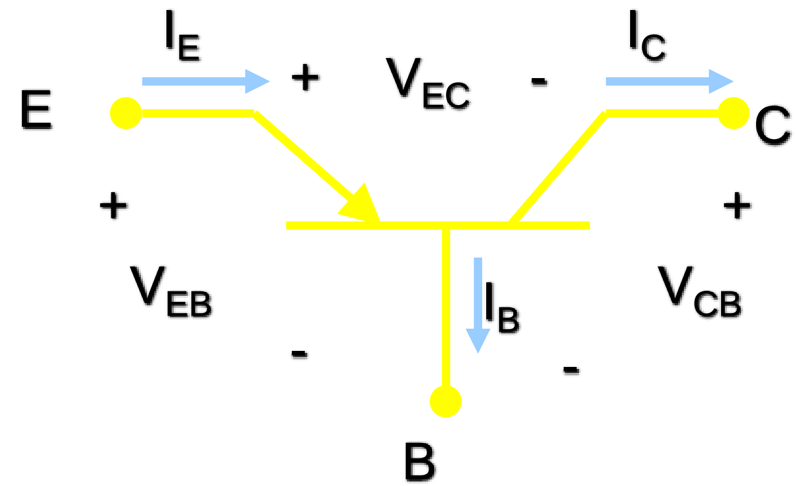
BJT Current & Voltage - Equations



n p n

$I_E = I_B + I_C$

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



p n p

$I_E = I_B + I_C$

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

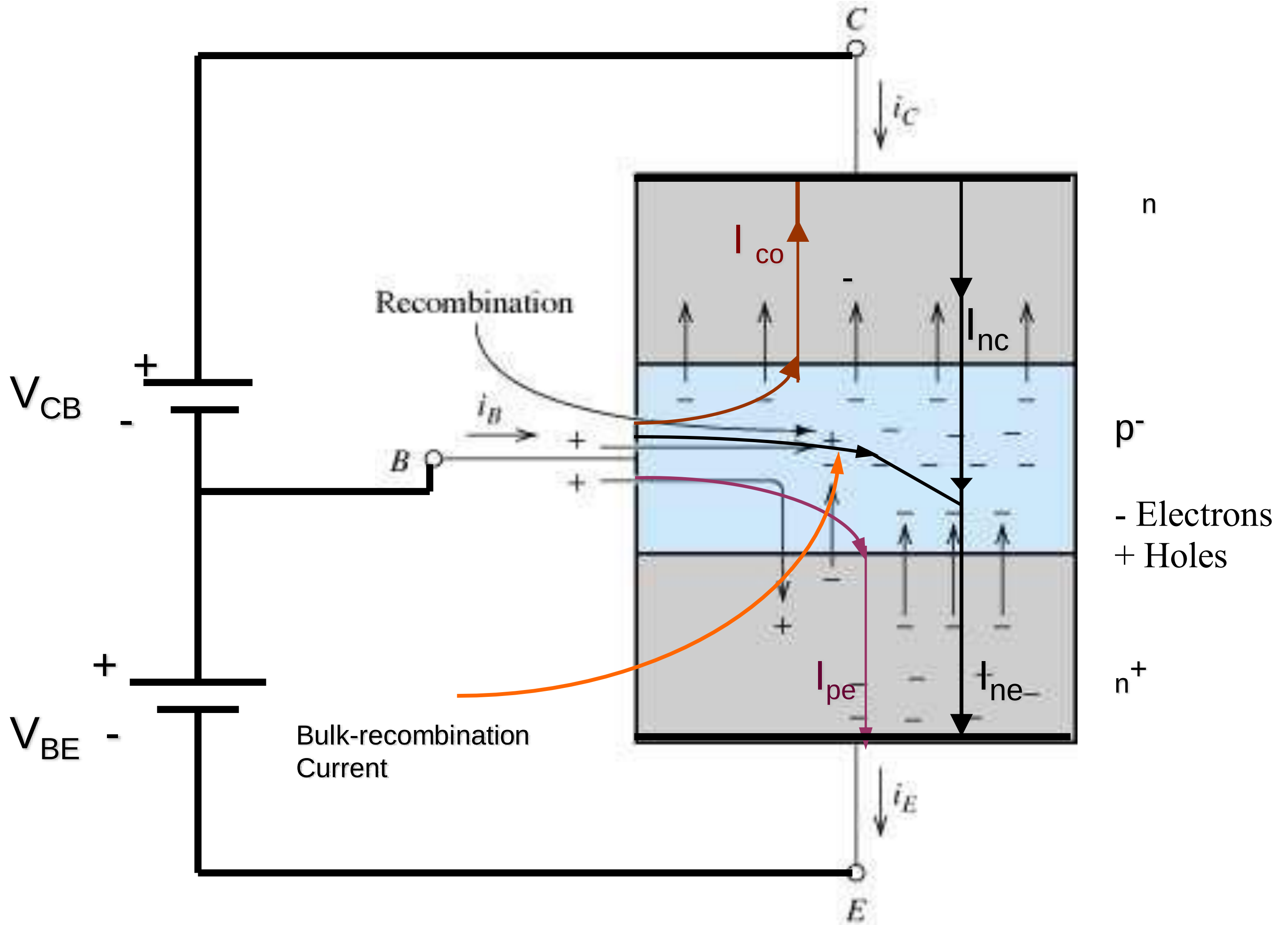
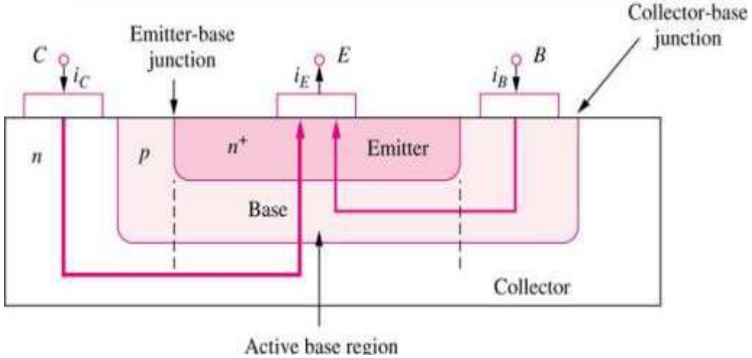
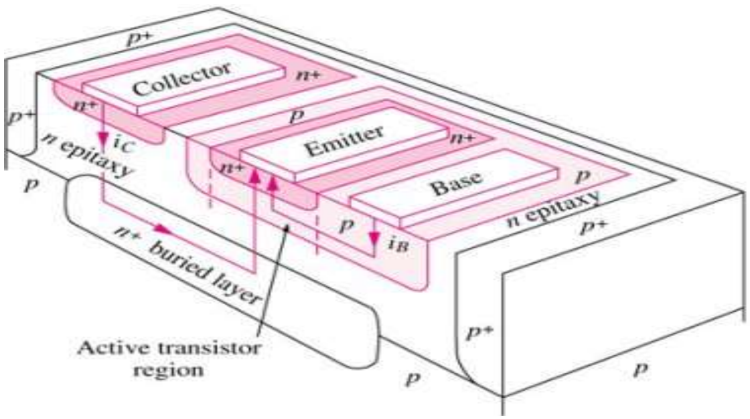


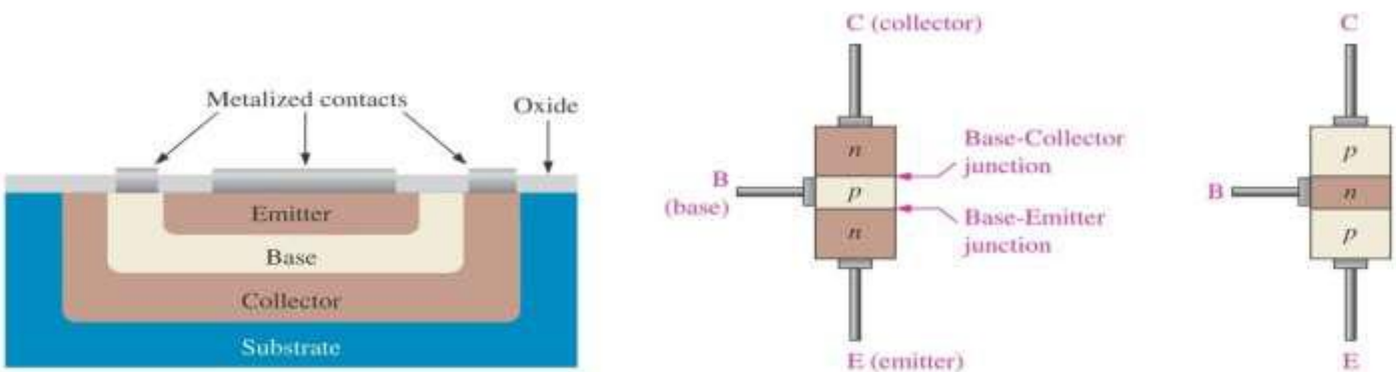
Figure : Current flow (components) for an n-p-n BJT in the active region.

NOTE: Most of the current is due to electrons moving from the emitter through base to the collector. Base current consists of holes crossing from the base into the emitter and of holes that recombine with electrons in the base.

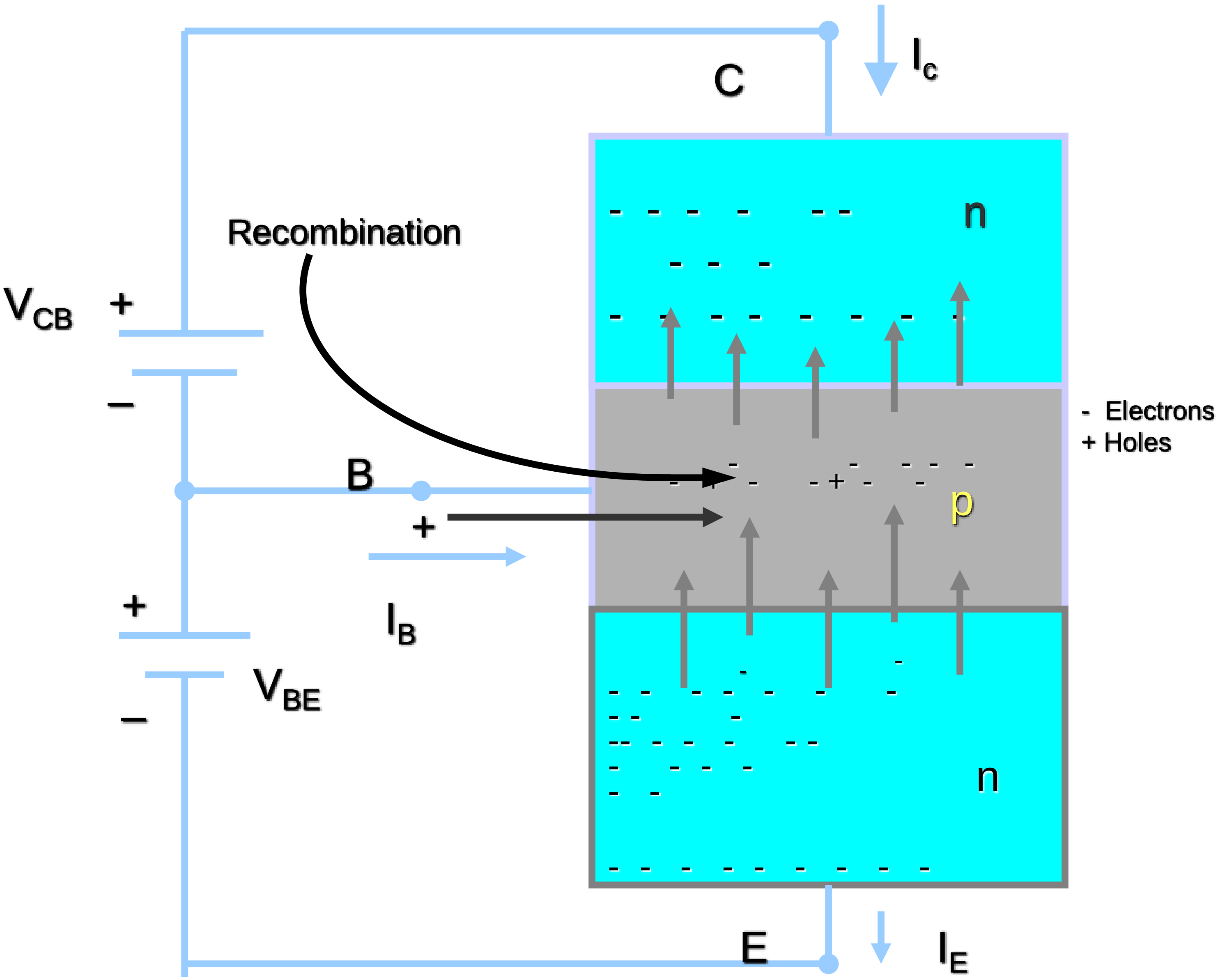
Physical Structure



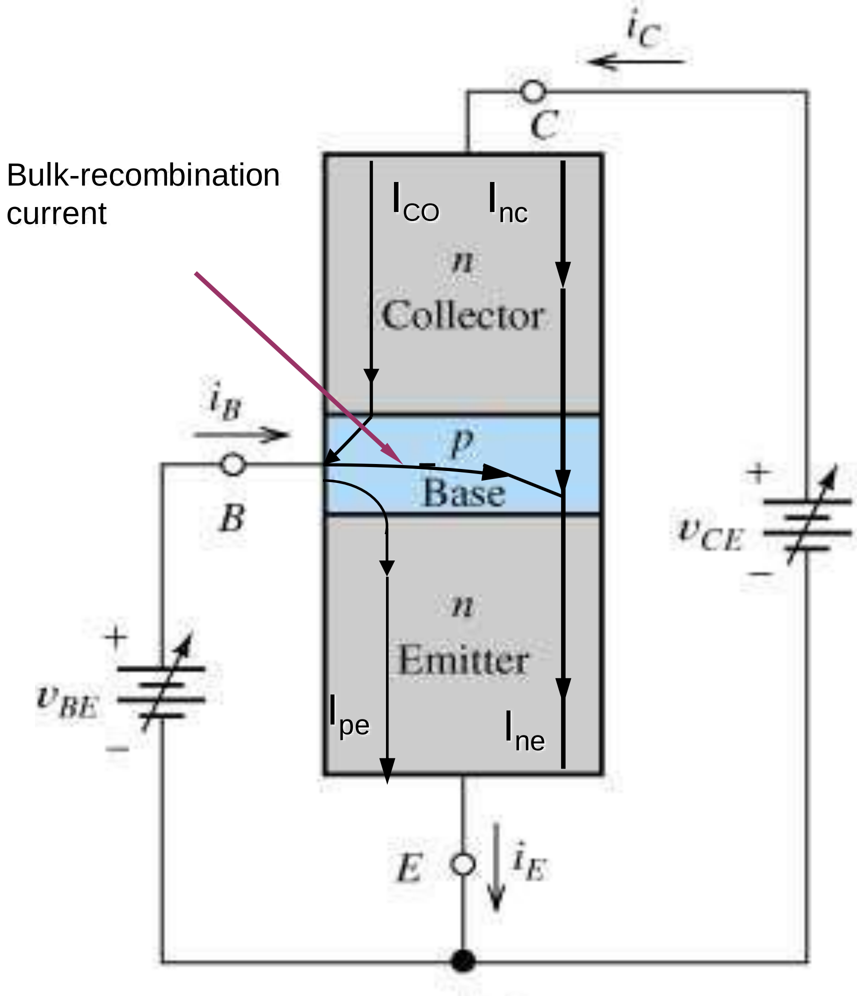




(a) Basic epitaxial planar structure (b) *npn* (c) *pnp*



I_c
C
n
Recombination
V_{CB}
+
–
- Electrons
+ Holes
B
p
+
I_B
+
V_{BE}
–
n
E
I_E



(a)

For CB Transistor $I_E = I_{ne} + I_{pe}$

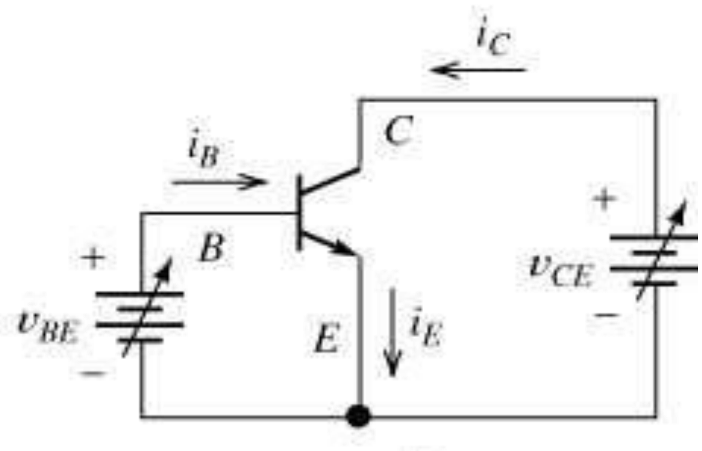
$I_c = I_{nc} - I_{co}$

And $I_c = -\alpha I_E + I_{Co}$

CB Current Gain, $\alpha = \dfrac{(I_c - I_{co})}{(I_E - 0)}$

For CE Trans., $I_C = \beta I_b + (1+\beta) I_{co}$

where $\beta = \dfrac{\alpha}{1-\alpha}$, is CE Gain

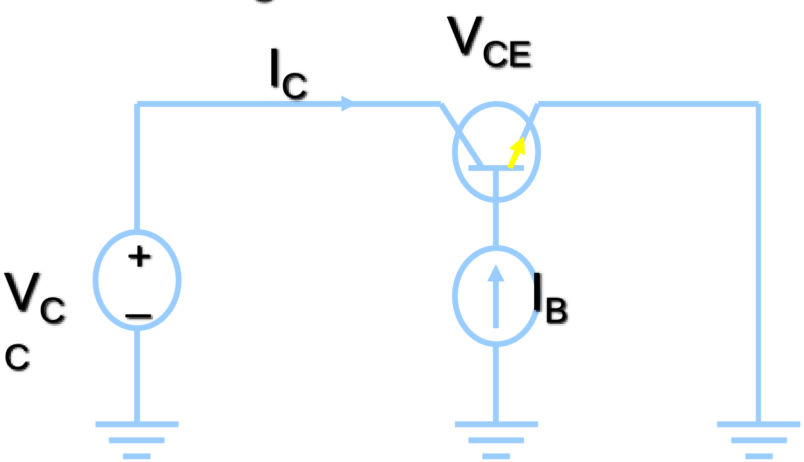


(b)

Figure: An *npn* transistor with variable biasing sources (common-emitter configuration).

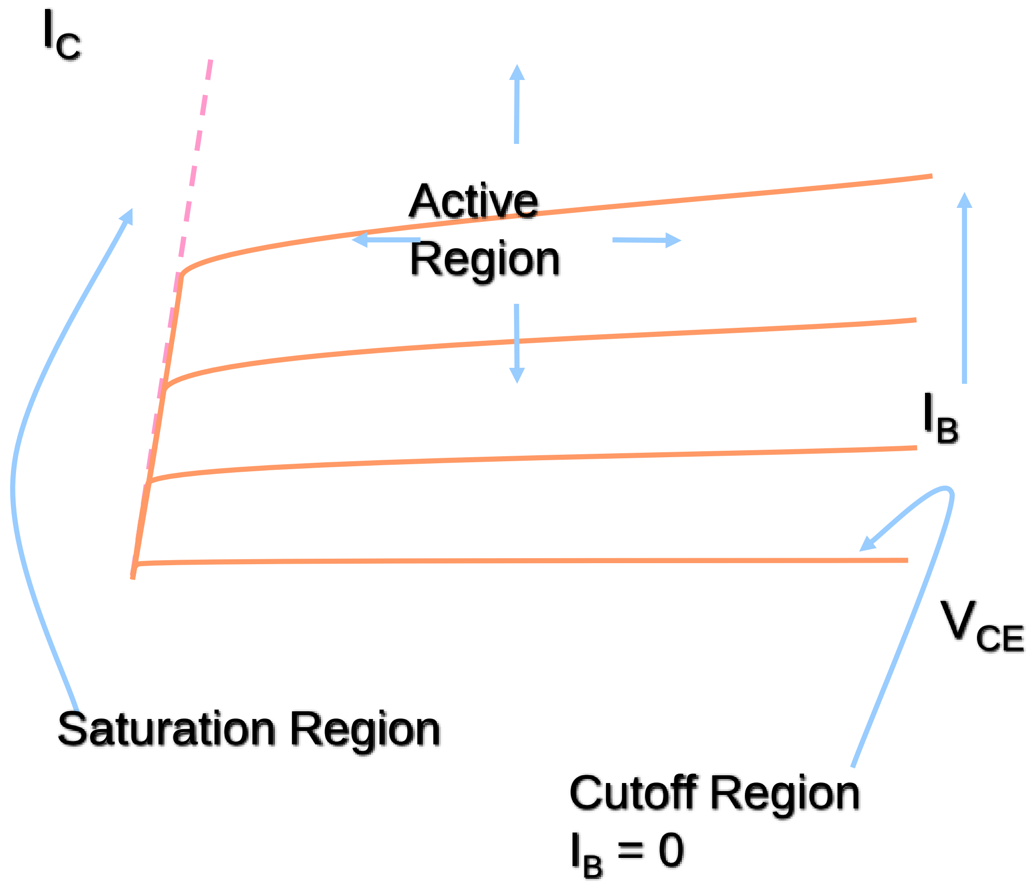
Common-Emitter

Circuit Diagram



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 be equal to 0.**

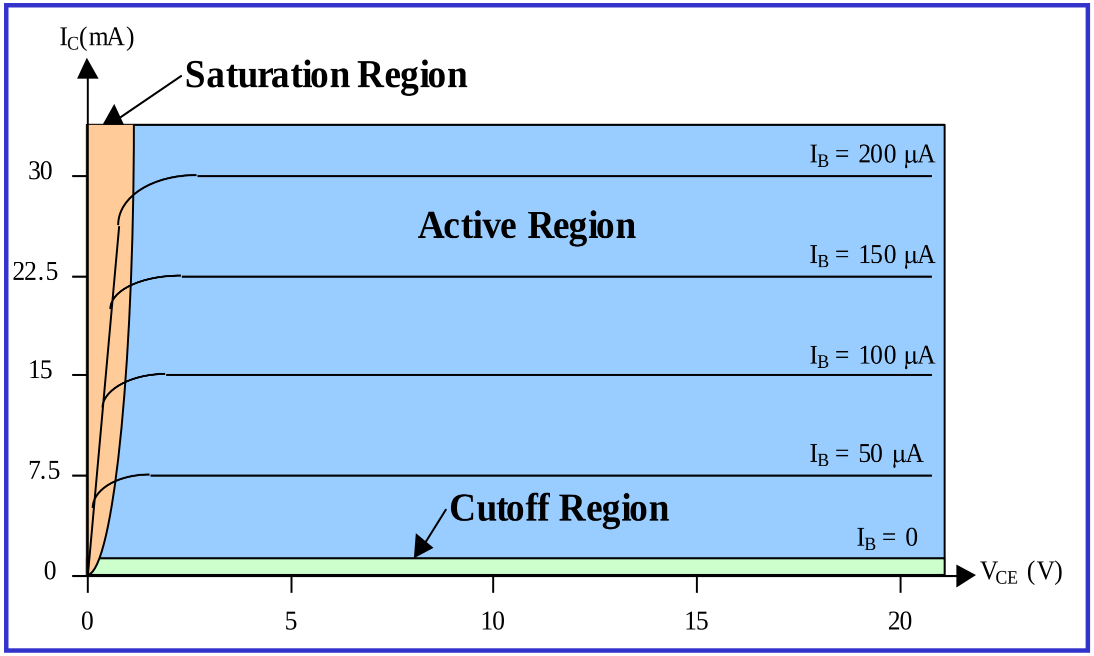
Collector-Current Curves

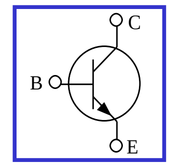


BJT's have three regions of operation:

1) Active - BJT acts like an amplifier (most common use)
2) Saturation - BJT acts like a short circuit
3) Cutoff - BJT acts like an open circuit

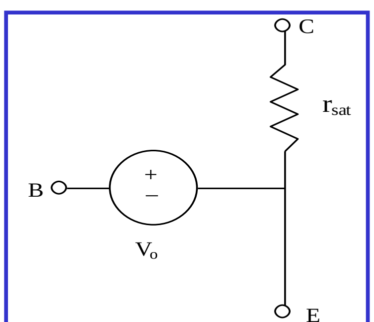
} BJT is used as a switch by switching between these two regions.



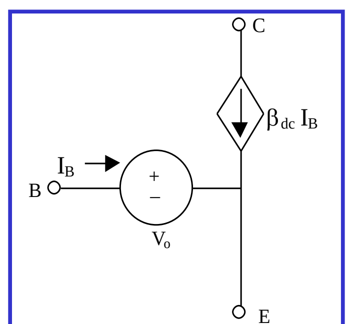


When analyzing a DC BJT circuit, the BJT is replaced by one of the DC circuit models shown below.

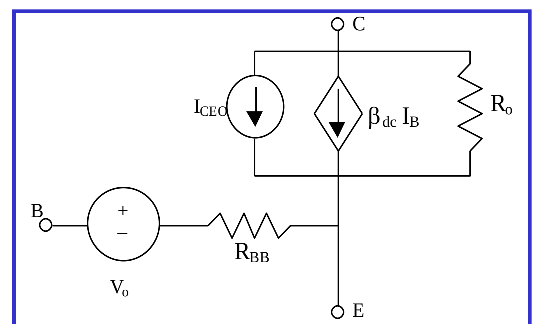
DC Models for a BJT:



Saturation Region Model



Active Region Model #1



Active Region Model #2

DC β and DC α

β = Common-emitter current gain

α = Common-base current gain

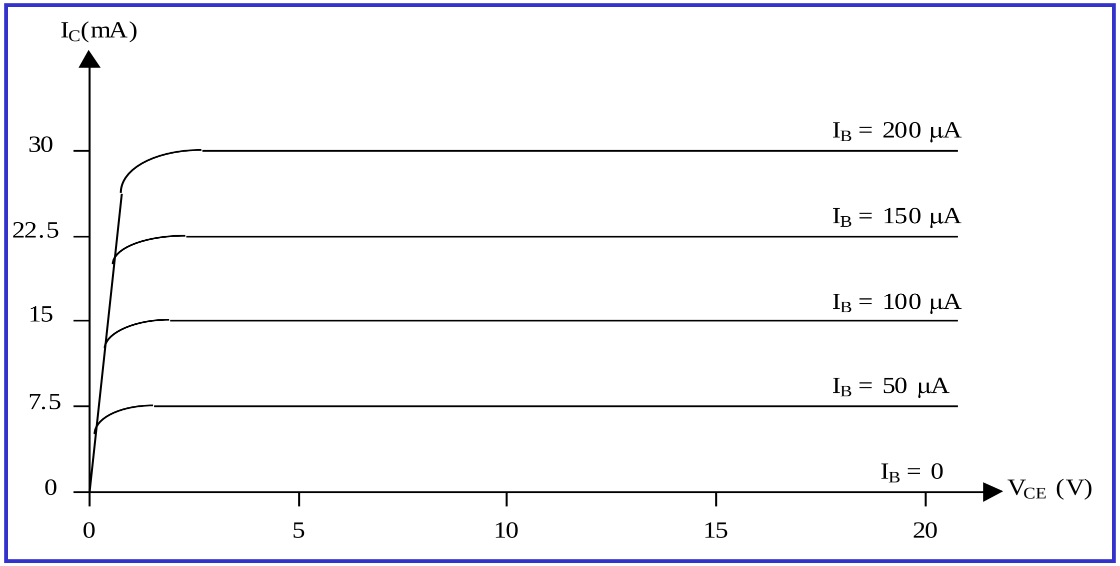
$$\beta = \frac{I_C}{I_B} \qquad \alpha = \frac{I_C}{I_E}$$

The relationships between the two parameters are:

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

Note: α and β are sometimes referred to as α_{dc} and β_{dc} because the relationships being dealt with in the BJT are DC.

Output characteristics: npn BJT (typical)



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

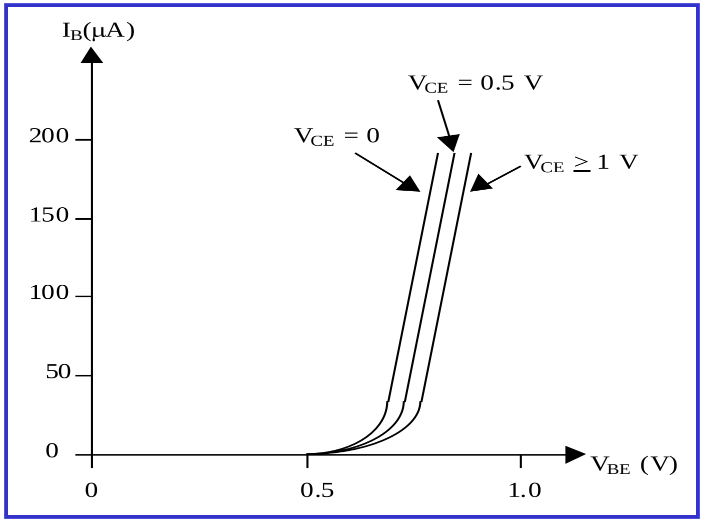
Note: The PE review text sometimes uses α_{dc} instead of β_{dc}. They are related as follows:

$$\alpha_{dc} = \frac{\beta_{dc}}{\beta_{dc} + 1}$$

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

- Find the approximate values of β_{dc} and α_{dc} from the graph.

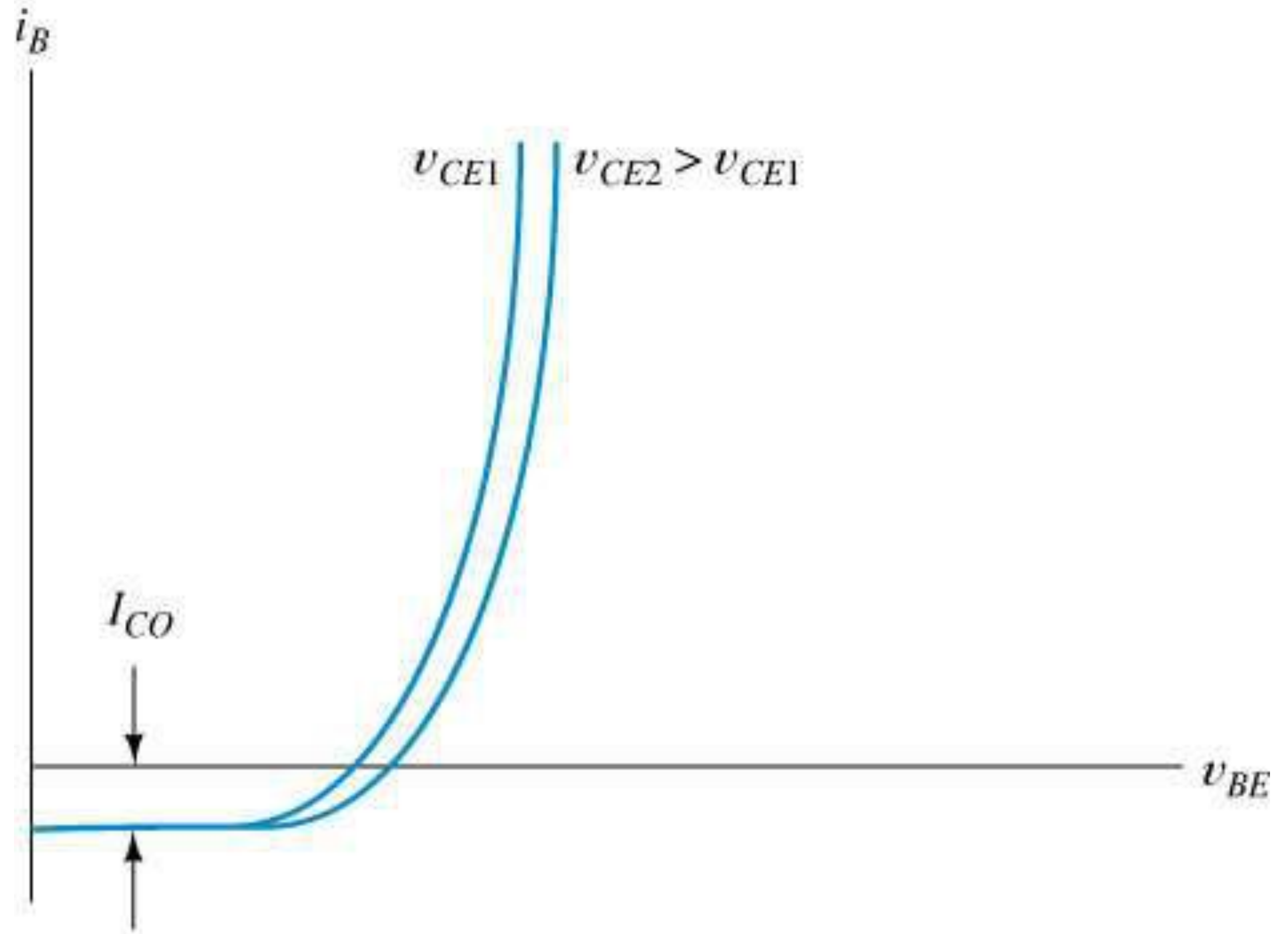
Input characteristics: npn BJT (typical)



The input characteristics look like the characteristics of a forward-biased diode. Note that V_{BE} varies only slightly, so we often ignore these characteristics and assume:

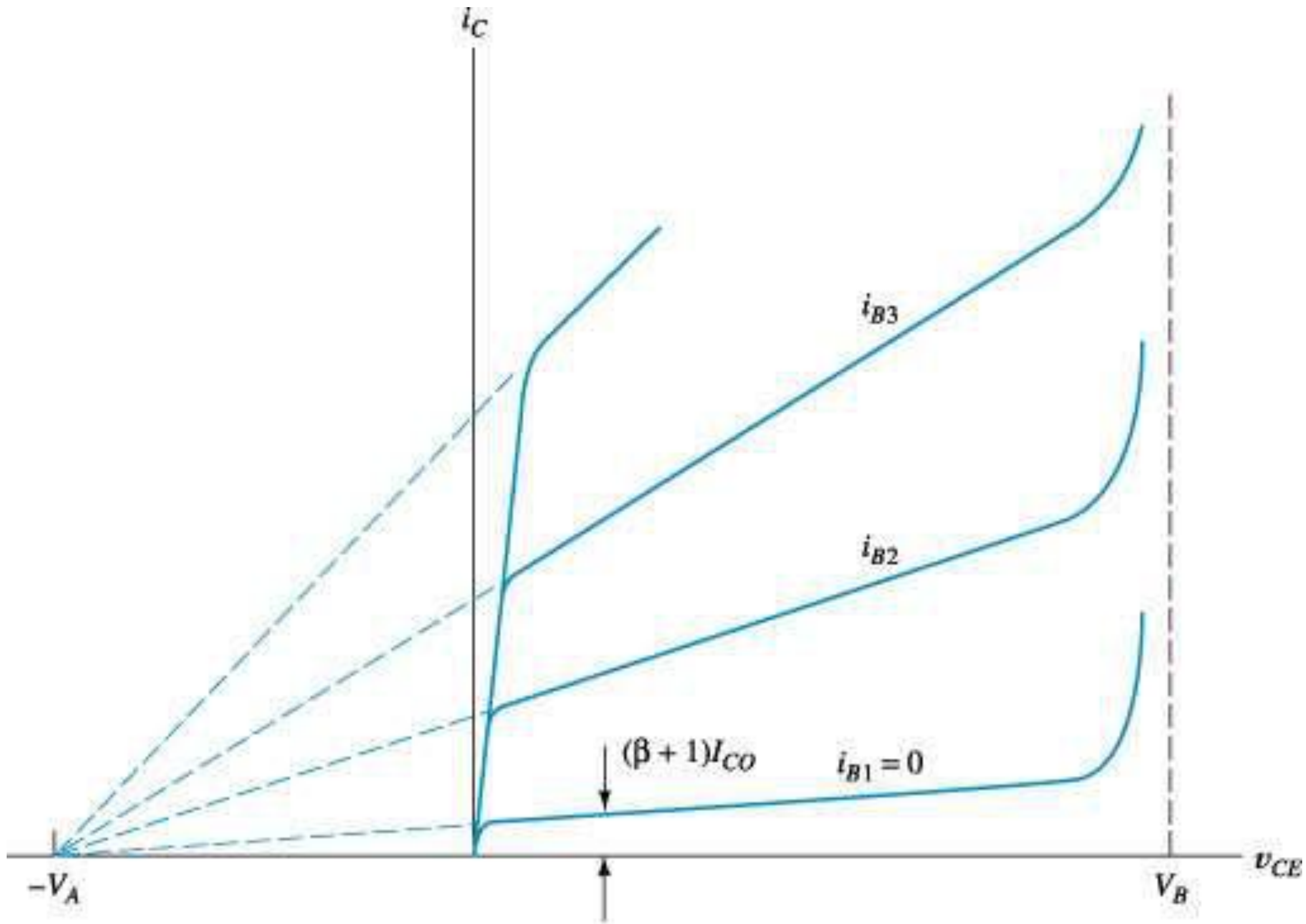
Common approximation: $V_{BE} = V_o$ = 0.65 to 0.7V

Note: Two key specifications for the BJT are B_{dc} and V_o (or assume V_o is about 0.7 V)



(a) Input characteristics

Figure: Common-emitter characteristics displaying exaggerated secondary effects.



(b) Output characteristics

Figure: Common-emitter characteristics displaying exaggerated secondary effects.

Various Regions (Modes) of Operation of BJT

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 (behaves as on state Switch)

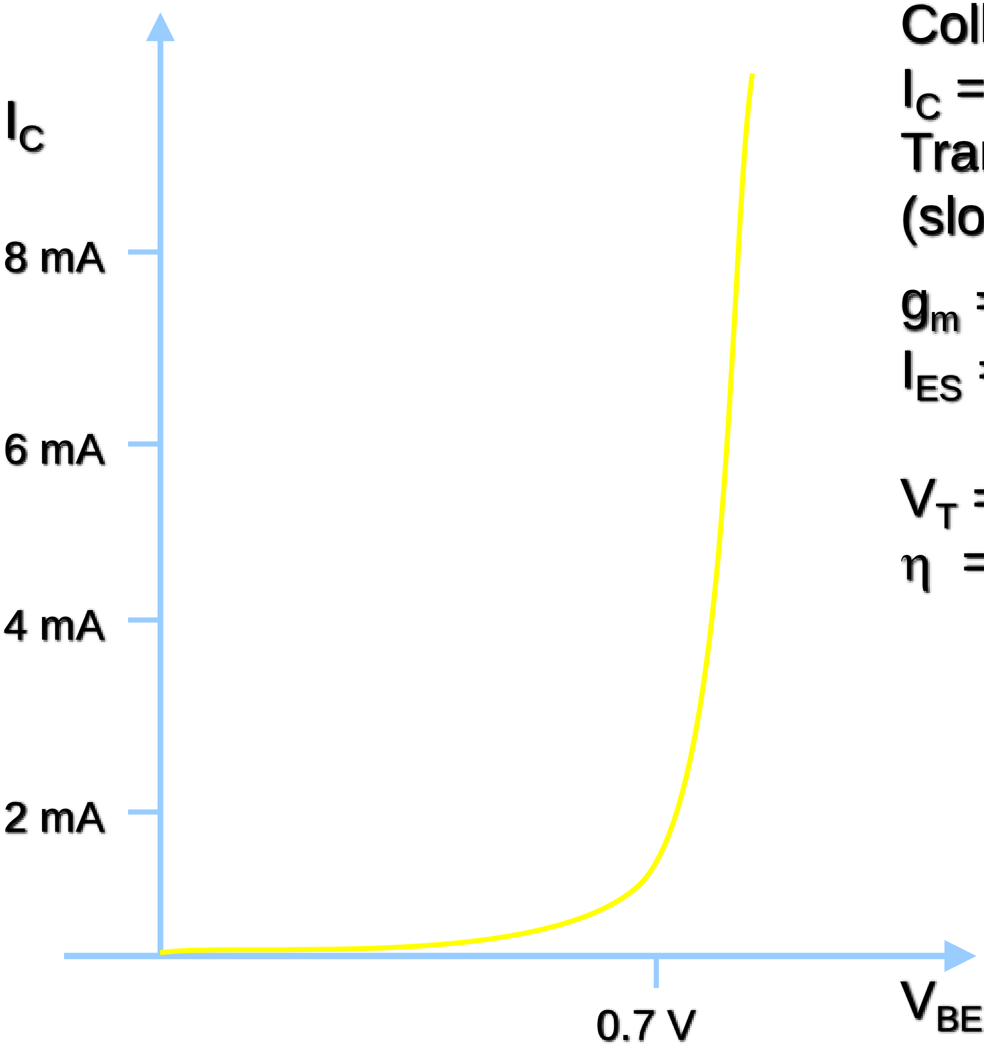
Cutoff:

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

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

BJT Trans-conductance Curve

For 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=300°K)

η = the emission coefficient and is usually ~1

Three Possible Configurations of BJT

Biasing the transistor refers to applying voltages to the transistor to achieve certain operating conditions.

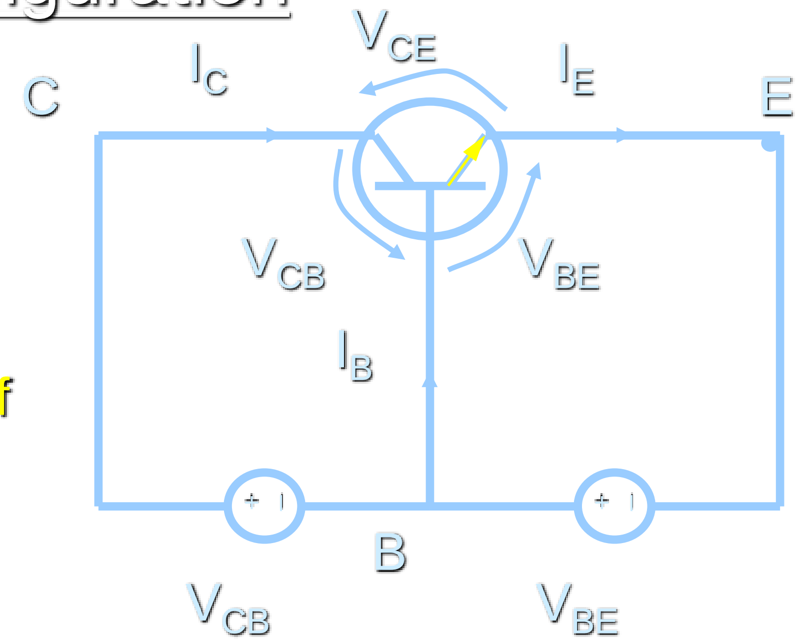
1. Common-Base Configuration (CB) : input = V_{EB} & I_E
   output = V_{CB} & I_C

2. Common-Emitter Configuration (CE): input = V_{BE} & I_B
   output= V_{CE} & I_C

3. Common-Collector Configuration (CC) :input = V_{BC} & I_B
   (Also known as Emitter follower) output = V_{EC} & I_E

Common-Base BJT Configuration

Circuit Diagram: NPN Transistor



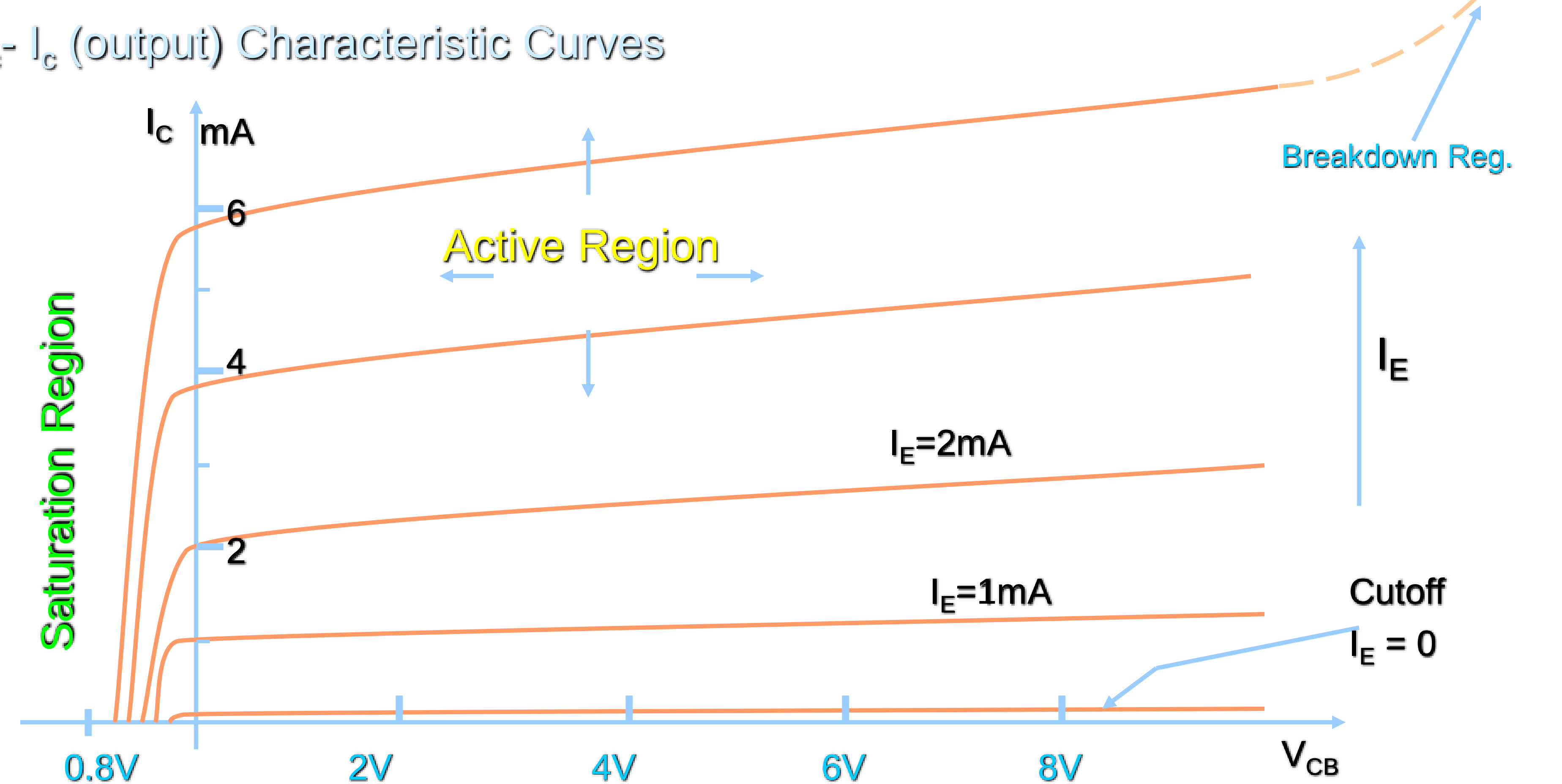
The Table Below lists assumptions that can be made for the attributes of the common-base BJT circuit in the different regions of operation. Given for a Silicon NPN transistor.

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.

Common-Base (CB) Characteristics

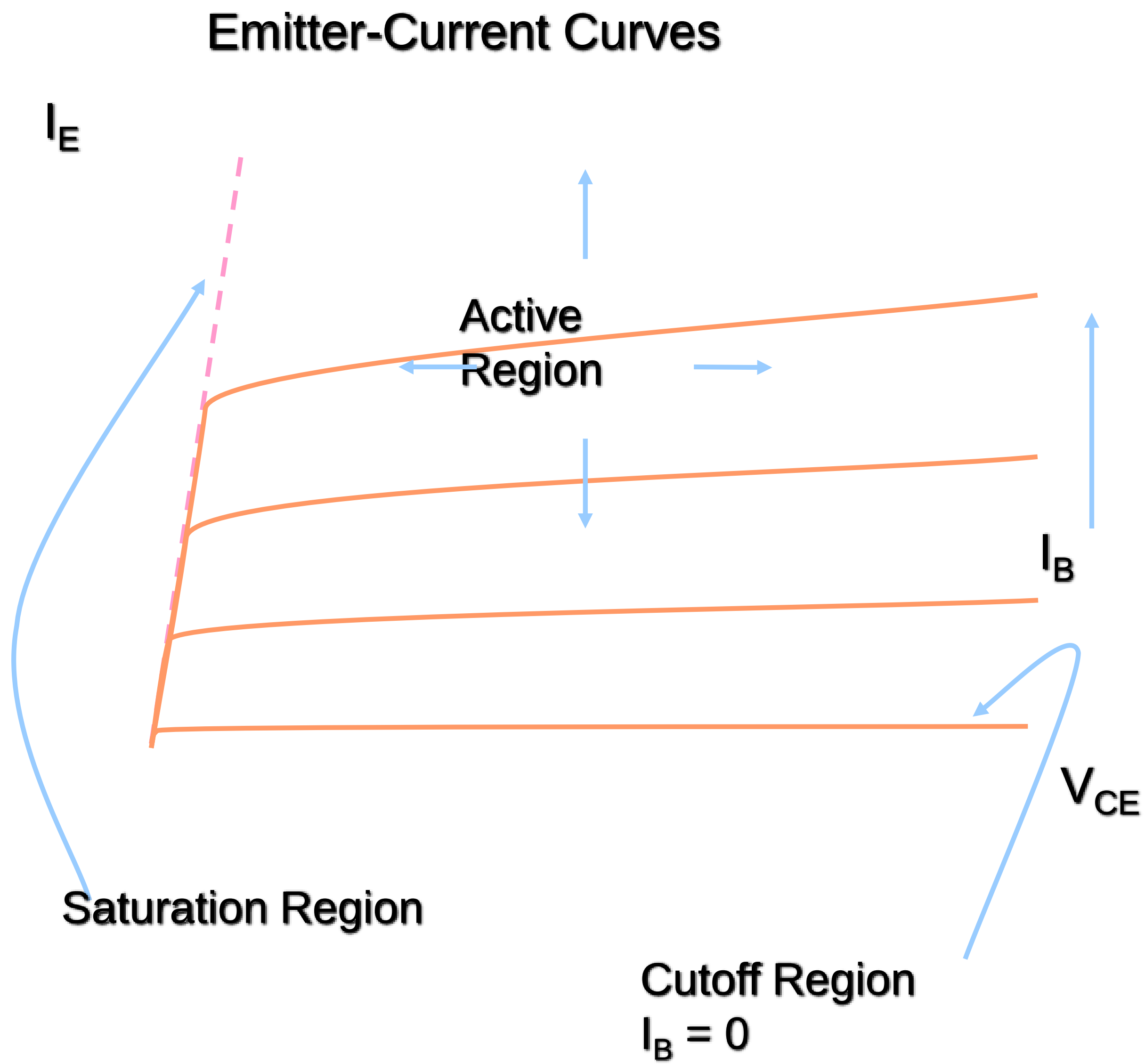
Although the Common-Base configuration is not the most common configuration, it is often helpful in the understanding operation of BJT

V_c- I_c (output) Characteristic Curves

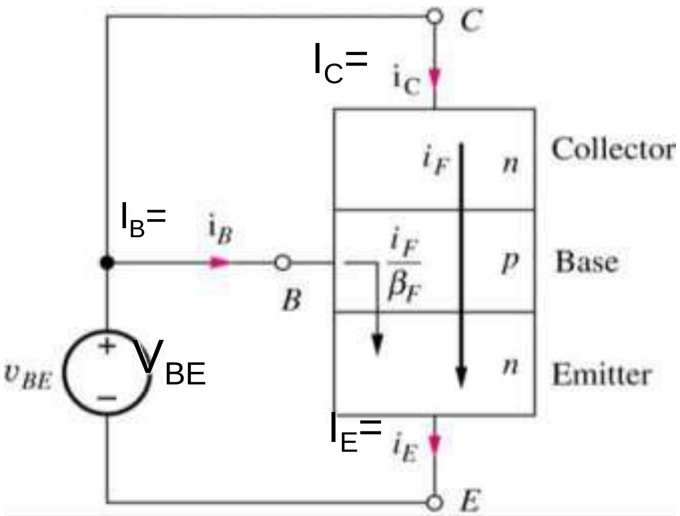


Common-Collector BJT Characteristics

The Common-Collector biasing circuit is basically equivalent to the common-emitter biased circuit except instead of looking at I_C as a function of V_{CE} and I_B we are looking at I_E. Also, since $\alpha \sim 1$, and $\alpha = I_C/I_E$ that means $I_C \sim I_E$



n p n Transistor: Forward Active Mode Currents



Forward Collector current is

$$I_C = I_{co}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

I_{co} is reverse saturation current

$$10^{-18}\text{A} \le I_{co} \le 10^{-9}\text{A}$$

$V_T = kT/q$ =25 mV at room temperature

Base current is given by

$$I_B = \frac{I_C}{\beta_F} = \frac{I_{co}}{\beta_F}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

$20 \le \beta_F \le 500$ is forward common-emitter current gain

Emitter current is given by

$$I_E = I_C + I_B = \frac{I_{co}}{\alpha_F}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

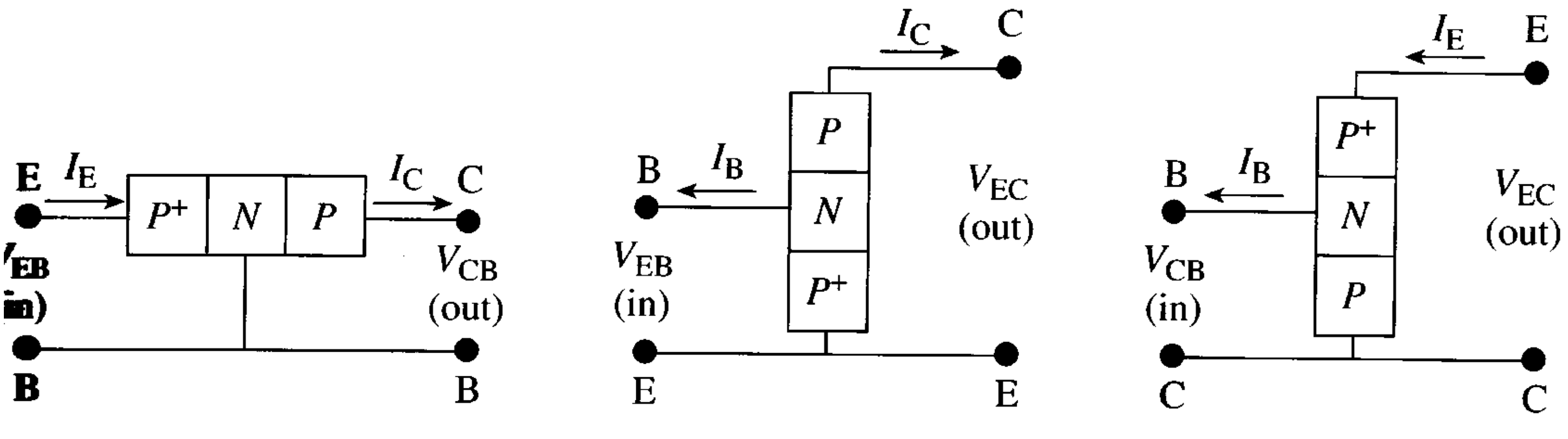
$$0.95 \le \alpha_F = \frac{\beta_F}{\beta_F + 1} \le 1.0$$

is forward common-base current gain

In this forward active operation region,

$$\frac{I_C}{I_B} = \beta_F \qquad \frac{I_C}{I_E} = \alpha_F$$

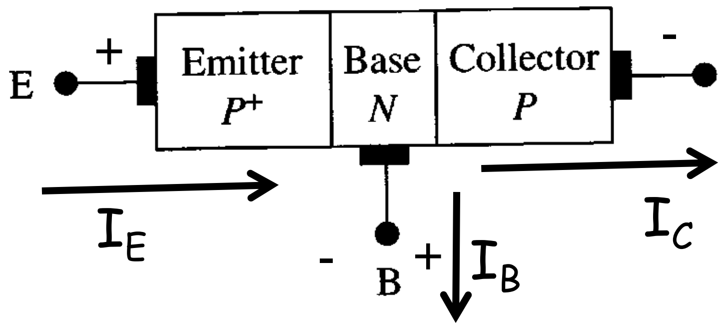
BJT configurations



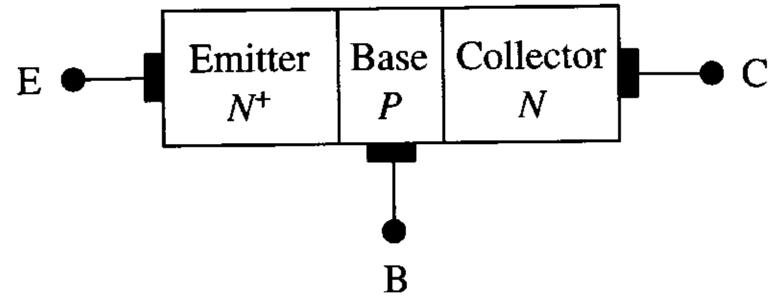
(a) Common base (b) Common emitter (c) Common collector

GAIN
CONFIG

Bipolar Junction Transistors: Basics



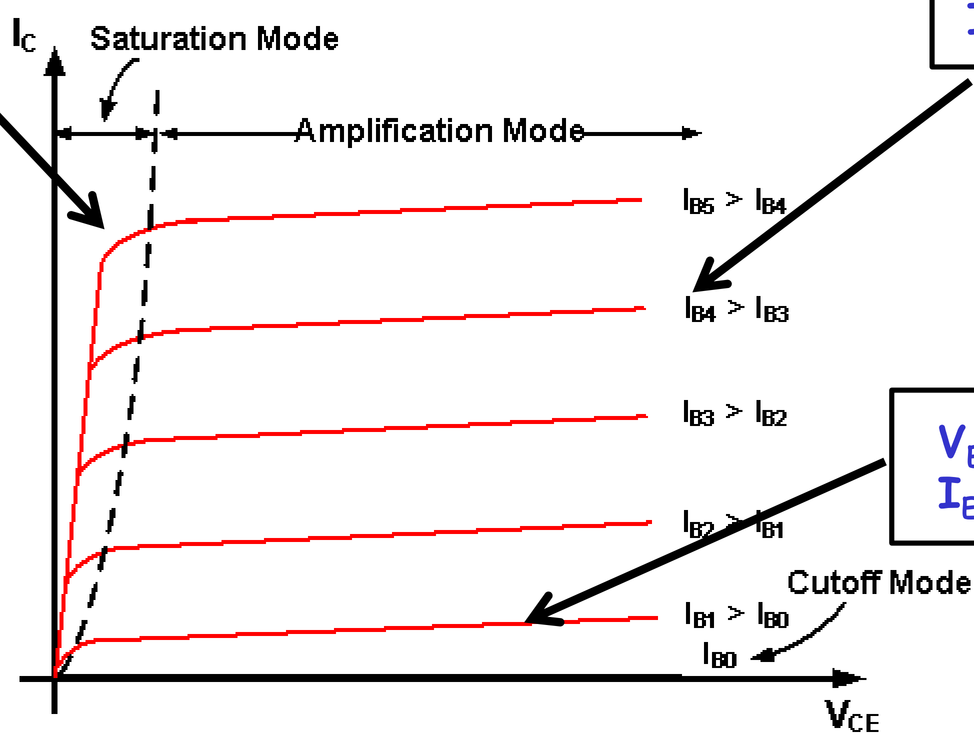
(a) *pnp*



(b) *npn*

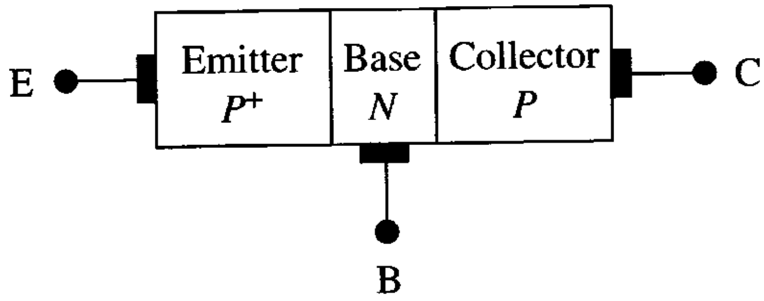
$V_{EB} > -V_{BC} > 0 \rightarrow V_{EC} > 0$ but small
$I_E > -I_C > 0 \rightarrow I_B > 0$

$V_{EB}, V_{BC} > 0 \rightarrow V_{EC} >> 0$
$I_E, I_C > 0 \rightarrow I_B > 0$

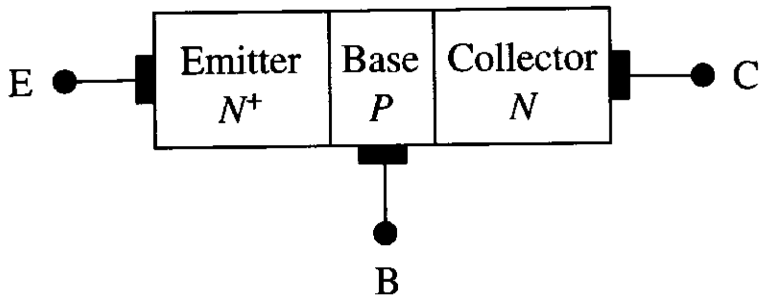


$V_{EB} < 0, V_{BC} > 0 \rightarrow V_{EC} > 0$
$I_E < 0, I_C > 0 \rightarrow I_B > 0$ but small

Bipolar Junction Transistors: Basics



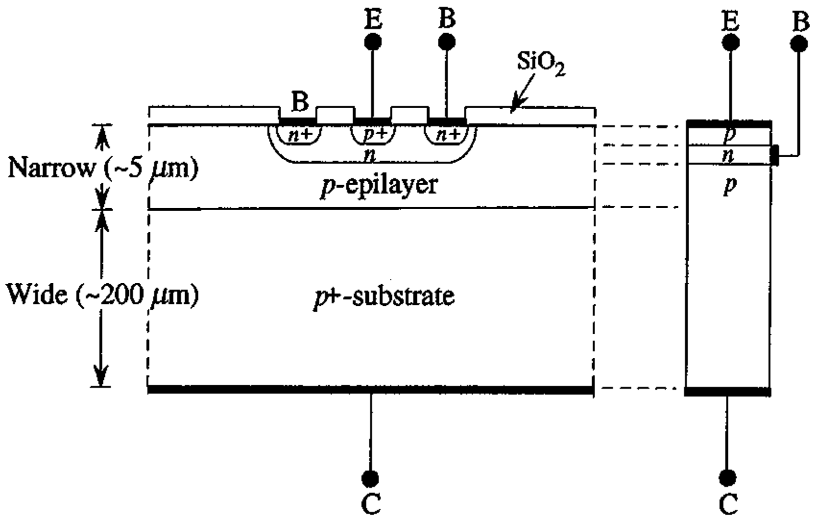
(a) *pnp*

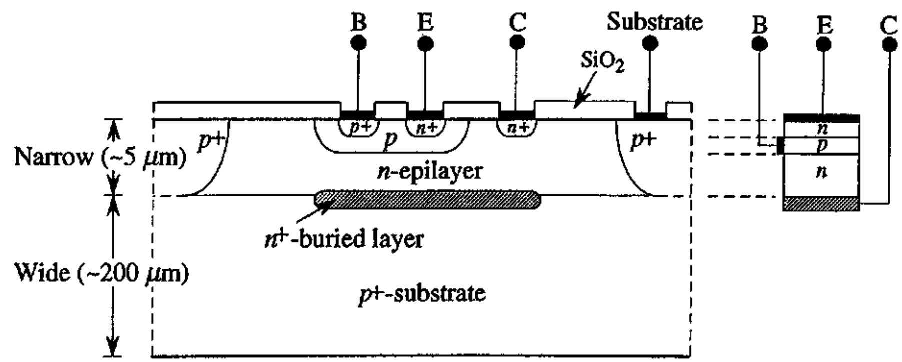


(b) *npn*

Bias Mode	*E-B Junction*	*C-B Junction*
Saturation	Forward	Forward
Active	**Forward**	**Reverse**
Inverted	Reverse	Forward
Cutoff	Reverse	Reverse

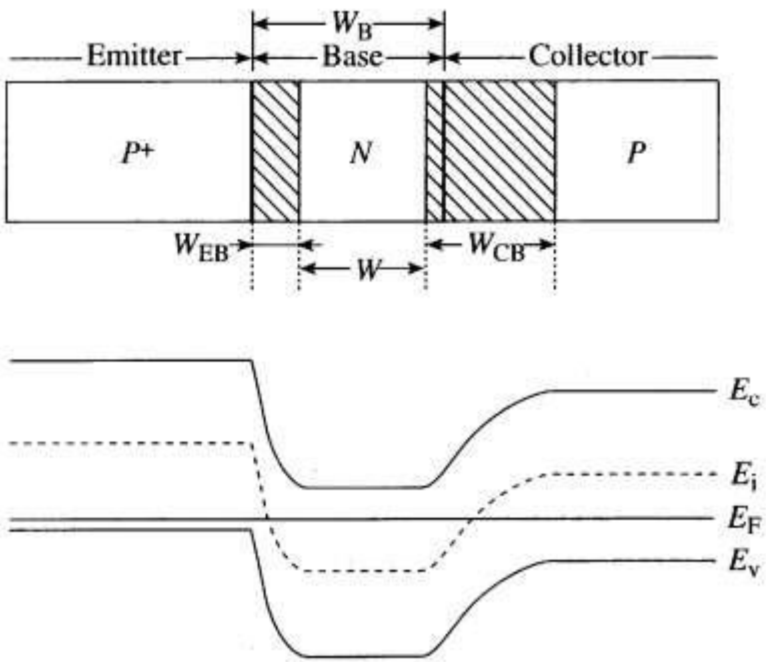
BJT Fabrication





(b)

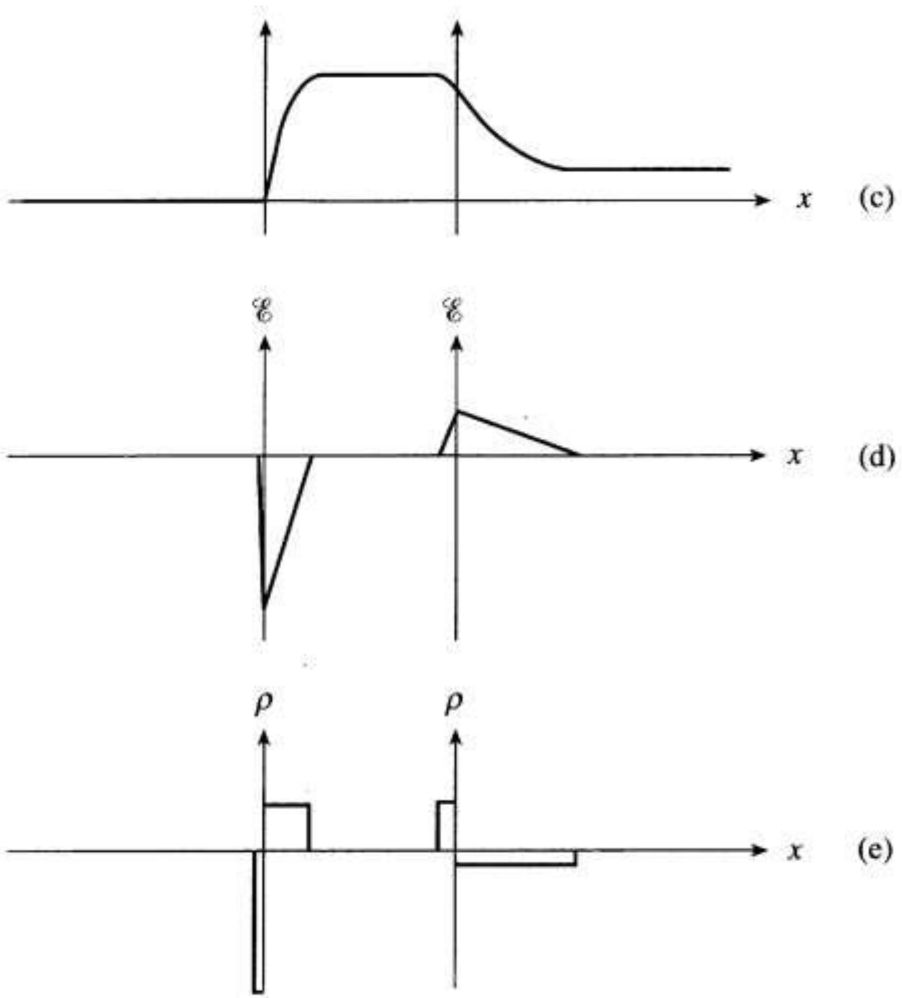
PNP BJT Electrostatics



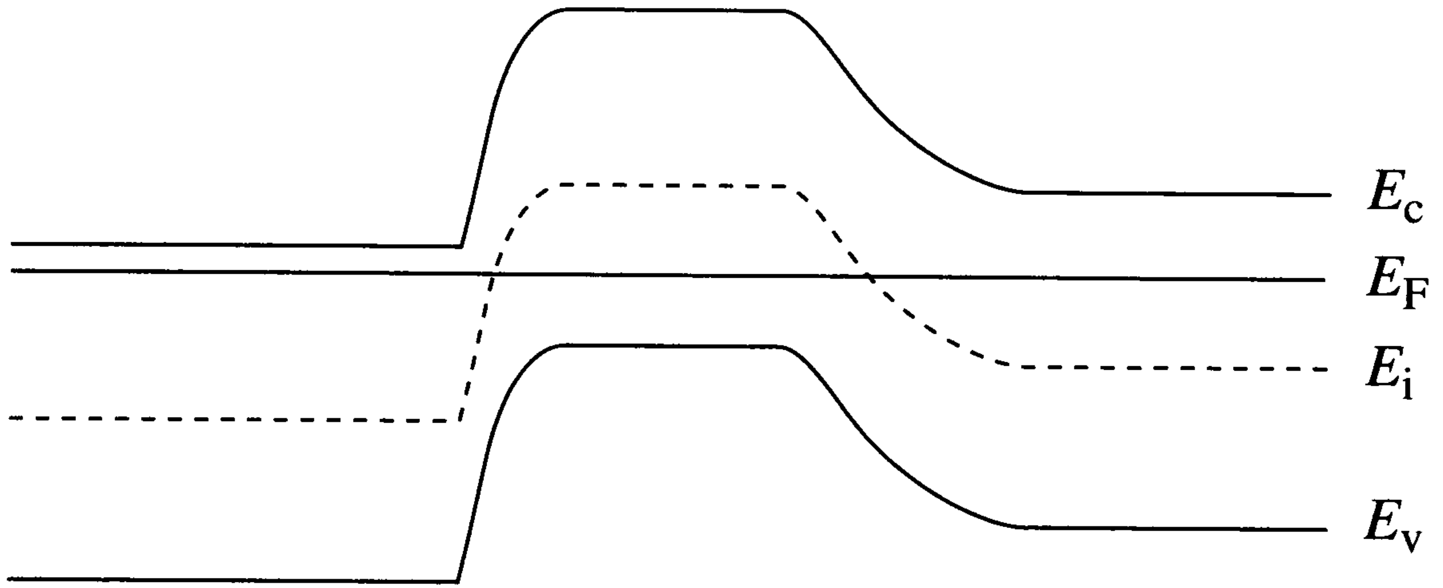
(a)

(b)

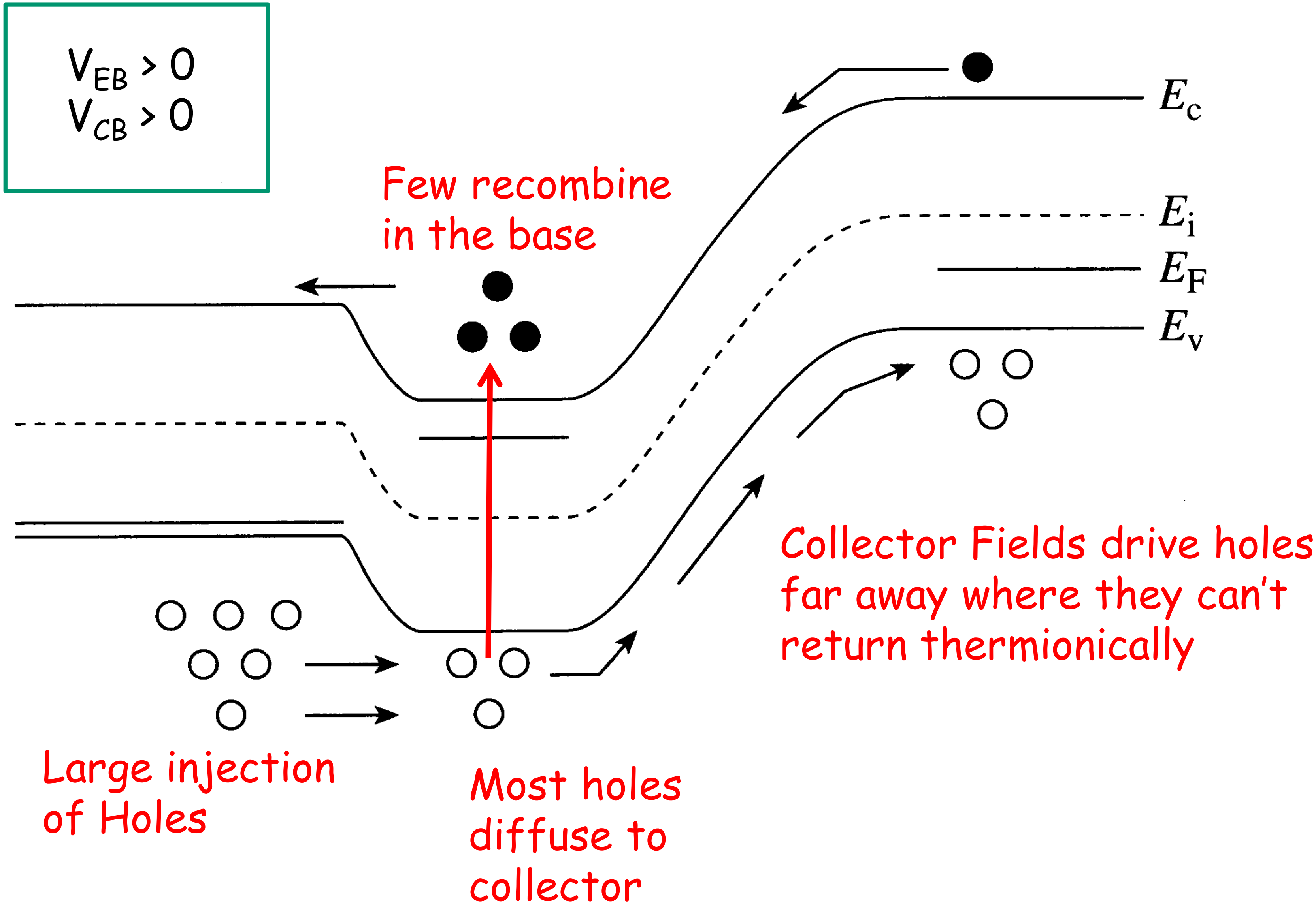
PNP BJT Electrostatics



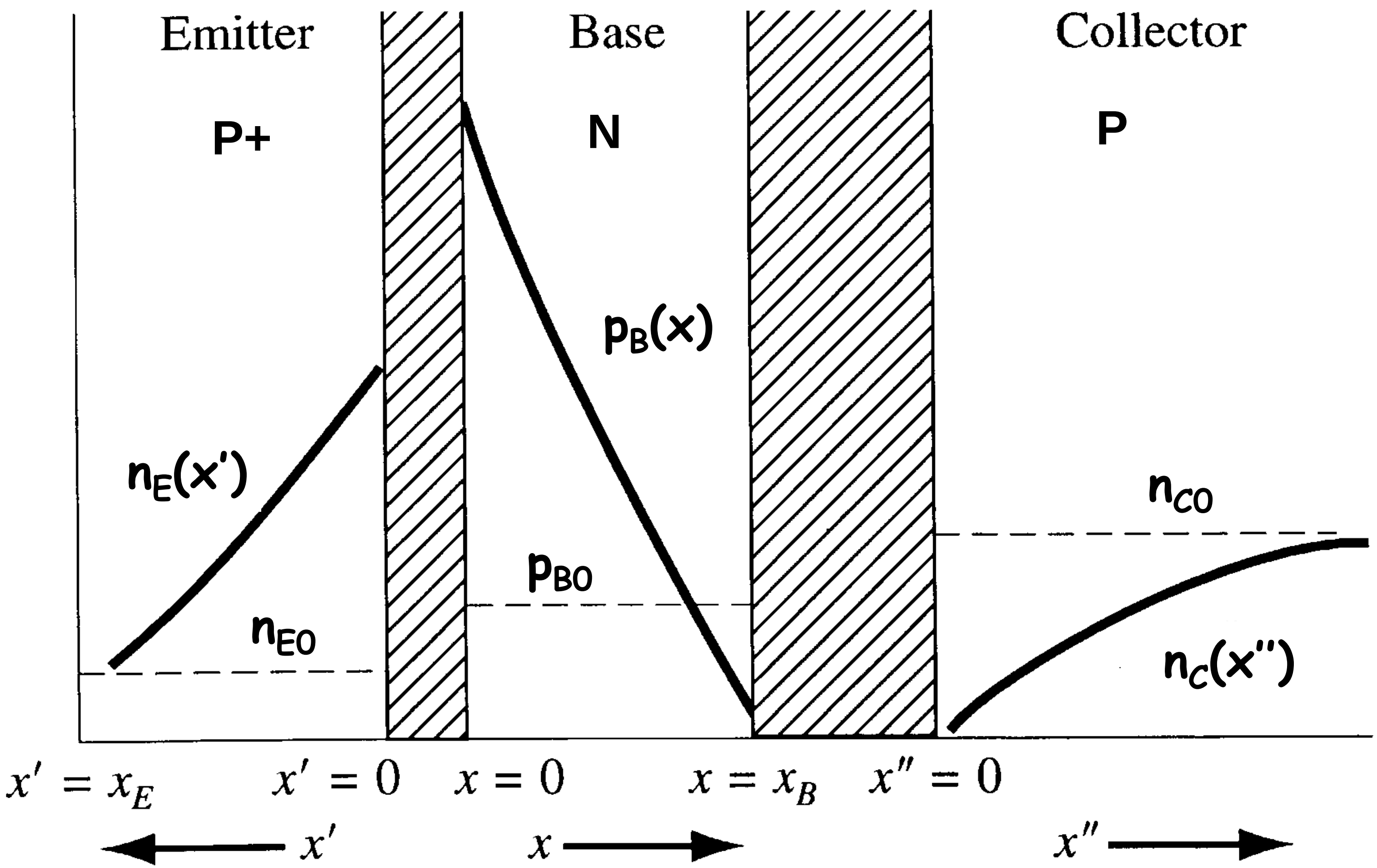
NPN Transistor Band Diagram: Equilibrium



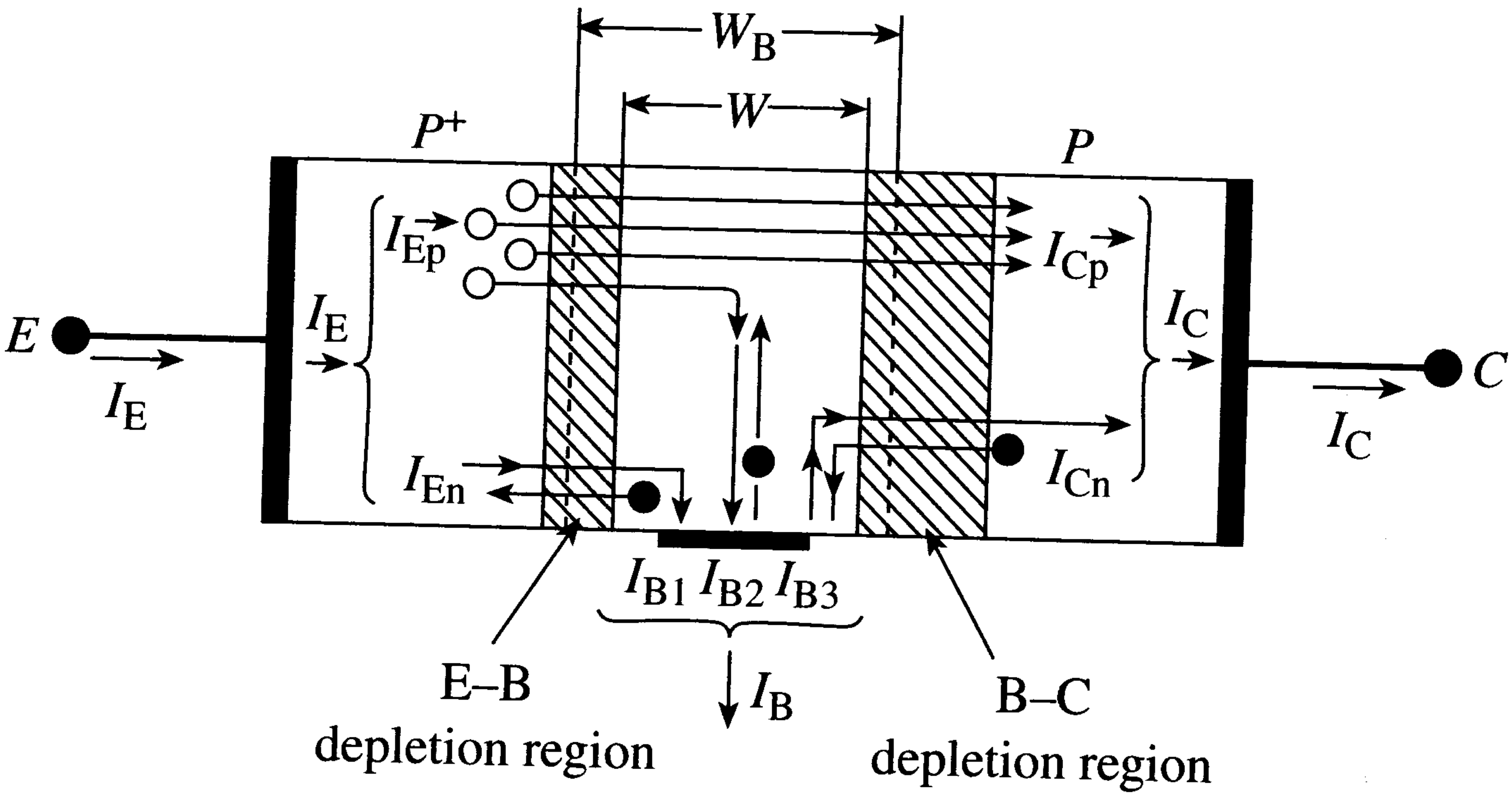
PNP Transistor Active Bias Mode



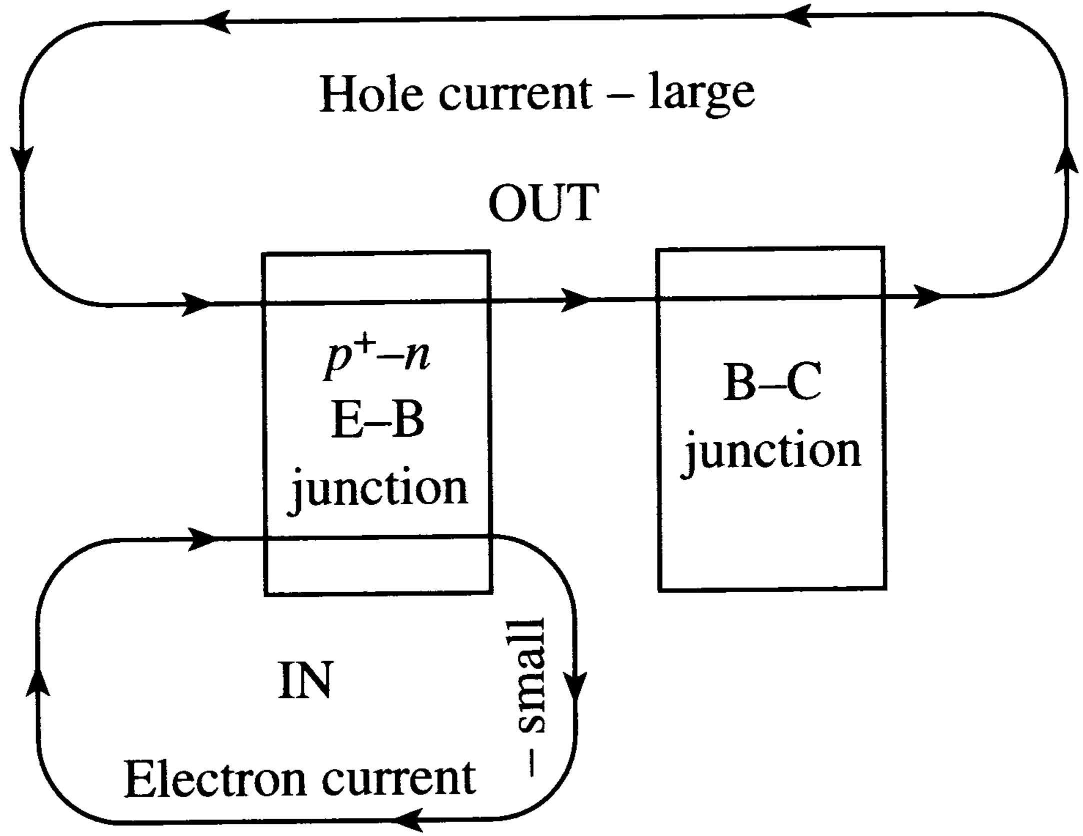
Forward Active minority carrier distribution



PNP Physical Currents

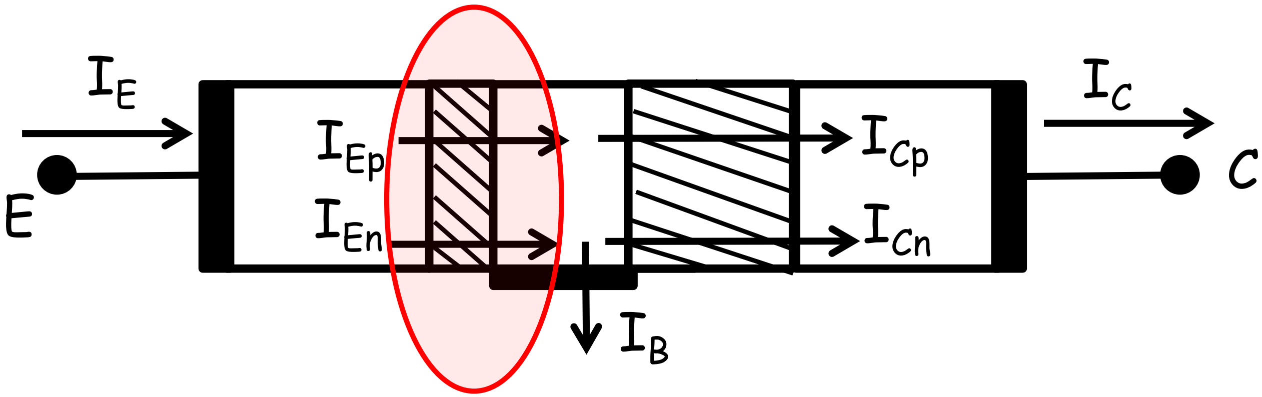


PNP transistor amplifier action



Clearly this works in common emitter configuration

Emitter Injection Efficiency - PNP

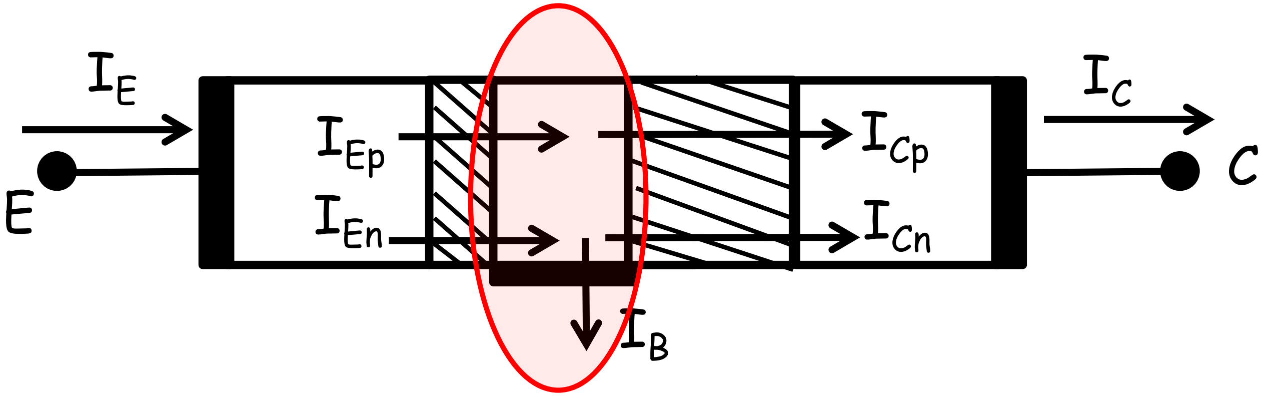


$$\gamma = \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

$$0 \le \gamma \le 1$$

Can we make the emitter see holes alone?

Base Transport Factor



$$\alpha_T = \frac{I_{Cp}}{I_{Ep}}$$

$$0 \leq \alpha_T \leq 1$$

Can all injected holes make it to the collector?

Common Base DC current gain - PNP

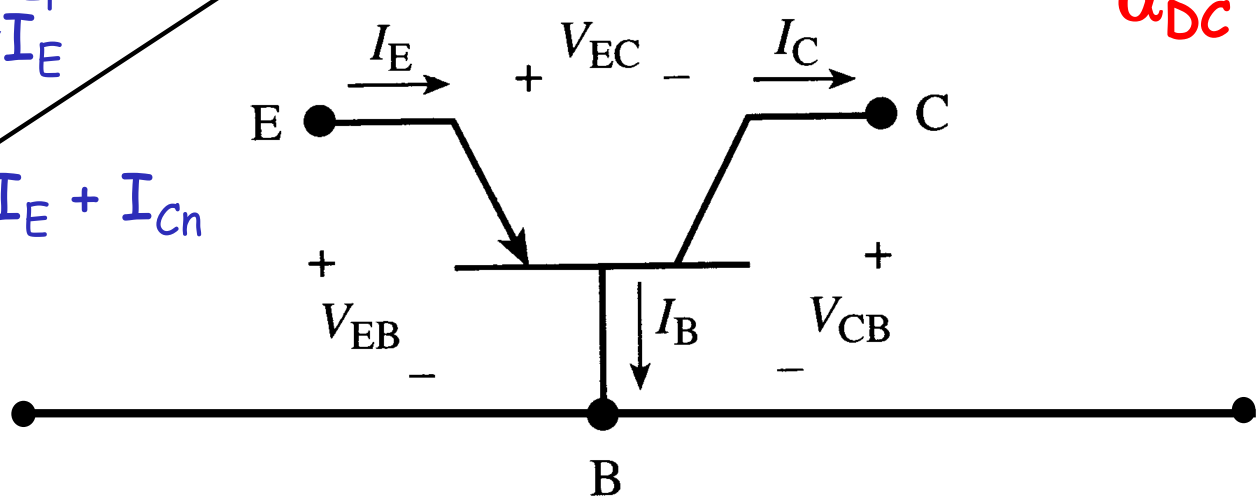
Common Base – Active Bias mode:

$$I_C = \alpha_{DC} I_E + I_{CBO}$$

$$I_{Cp} = \alpha_T I_{Ep}$$
$$= \alpha_T \gamma I_E$$

$$I_C = \alpha_T \gamma I_E + I_{Cn}$$

$$\alpha_{DC} = \alpha_T \gamma$$



Common Emitter DC current gain - PNP

Common Emitter - Active Bias mode:

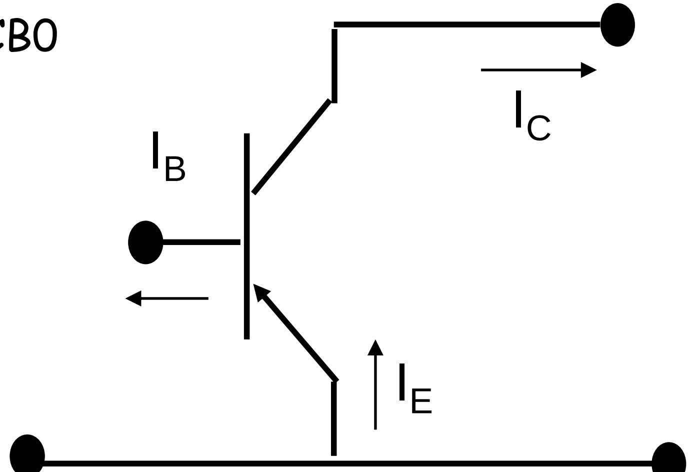
$$I_E = \beta_{DC} I_B + I_{CEO}$$

$$\beta_{DC} = \alpha_{DC}/(1-\alpha_{DC})$$

GAIN !!

$$I_C = \alpha_{DC} I_E + I_{CBO}$$
$$= \alpha_{DC}(I_C + I_B) + I_{CBO}$$

$$I_C = \frac{\alpha_{DC} I_B + I_{CBO}}{1-\alpha_{DC}}$$

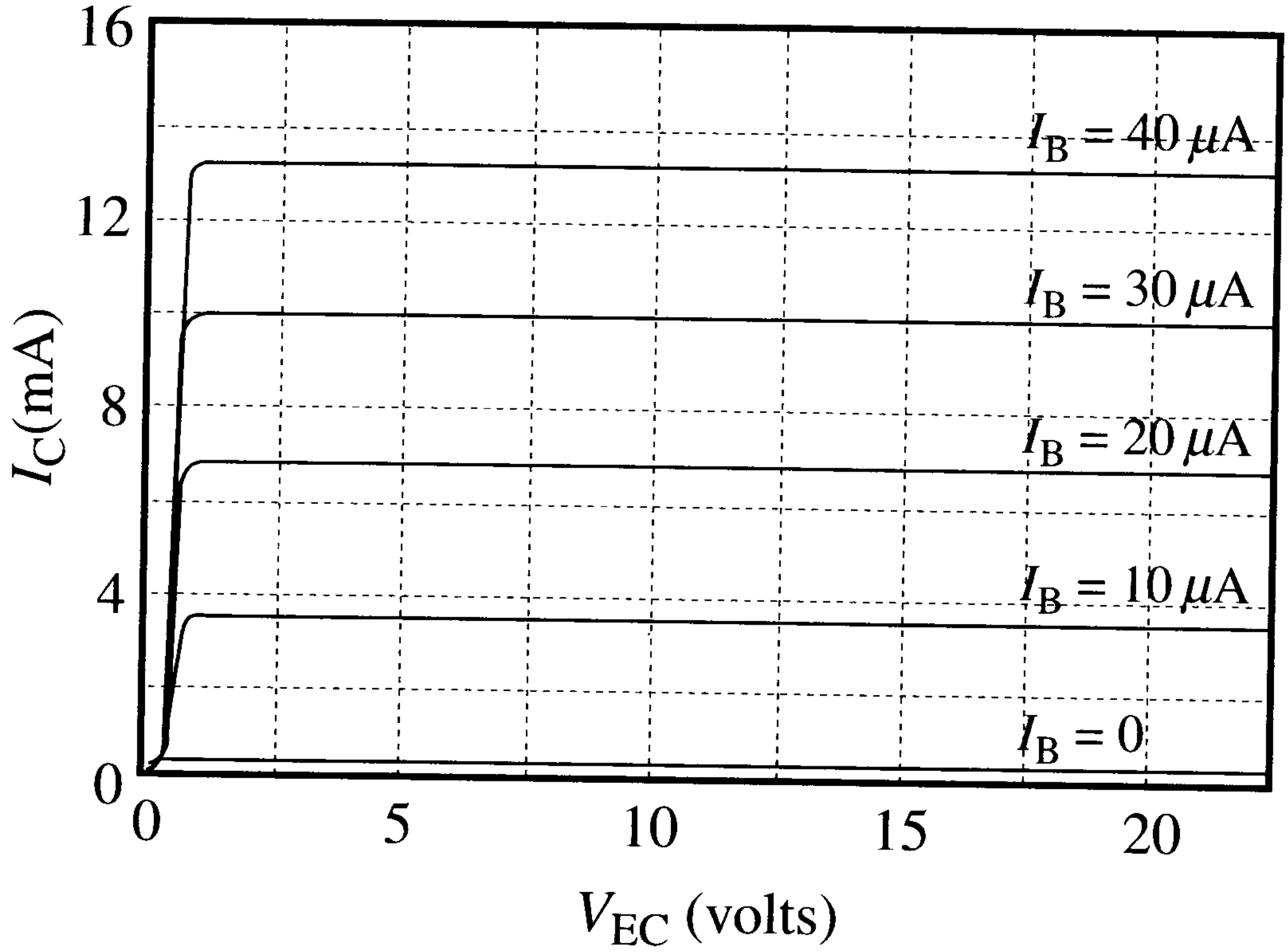


Common Emitter DC current gain - PNP

$$\beta_{dc} = \frac{\gamma\alpha_T}{1-\gamma\alpha_T}$$

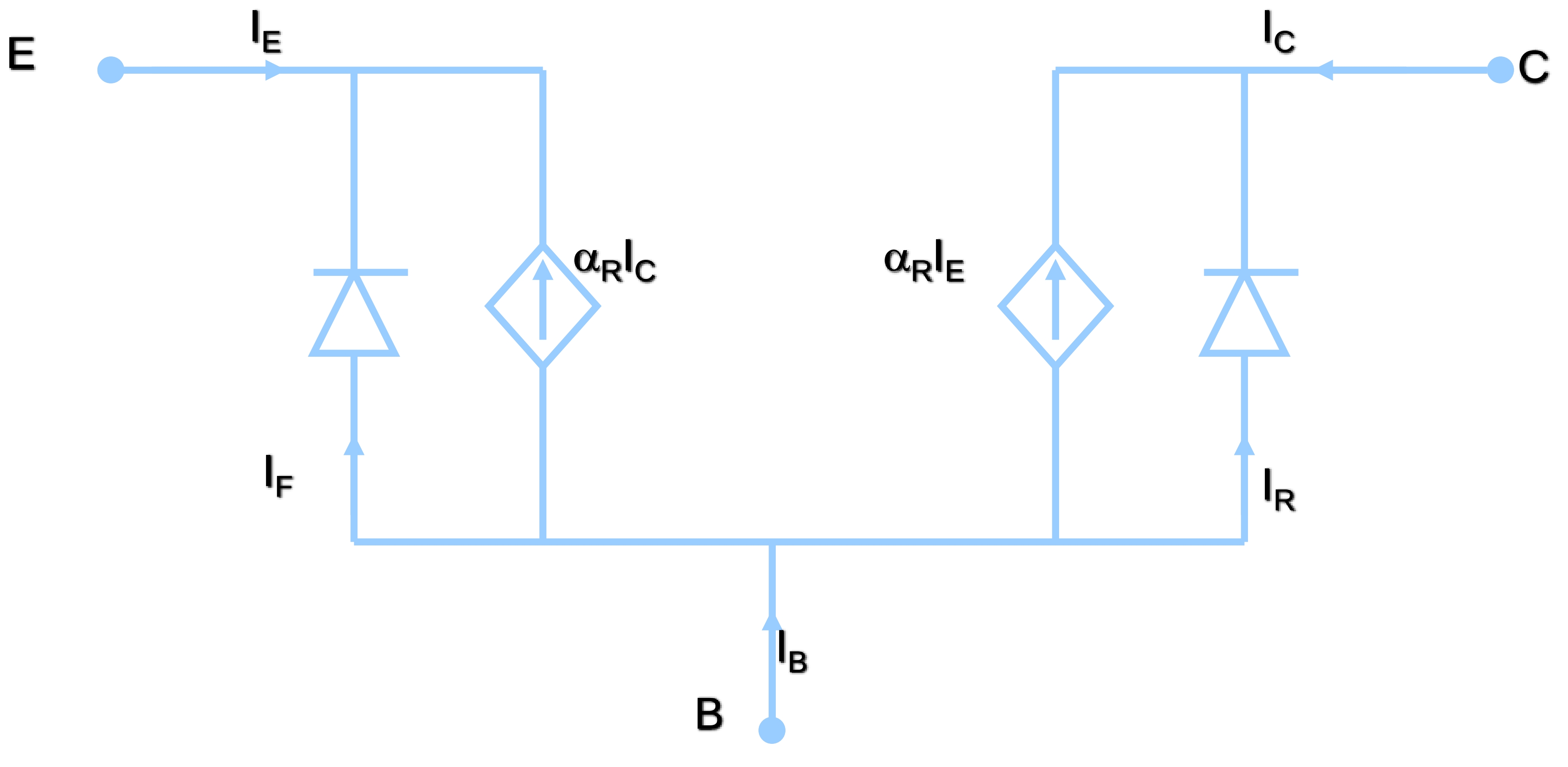
Thin base will make $\alpha_T \rightarrow 1$
Highly doped P region will make $\gamma \rightarrow 1$

PNP BJT Common Emitter Characteristic



Eber-Moll BJT Model

The Eber-Moll Model for BJTs is fairly complex, but it is valid in all regions of BJT operation. The circuit diagram below shows all the components of the Eber-Moll Model:



Eber-Moll BJT Model

α_R = Common-base current gain (in forward active mode)
α_F = Common-base current gain (in inverse active mode)
I_{ES} = Reverse-Saturation Current of B-E Junction
I_{CS} = Reverse-Saturation Current of B-C Junction

$I_C = \alpha_F I_F - I_R$ $\quad$ $I_B = I_E - I_C$
$I_E = I_F - \alpha_R I_R$

$I_F = I_{ES}\,[\exp(qV_{BE}/kT) - 1]$ $\quad$ $I_R = I_C\,[\exp(qV_{BC}/kT) - 1]$

✶ If I_{ES} & I_{CS} are not given, they can be determined using various BJT parameters.

PHOTO TRANSSTOR

- *The phototransistor is a transistor in which base current is produced when light strikes the photosensitive semiconductor base region.*

- *The collector-base P-N junction is exposed to incident light through a lens opening in the transistor package.*

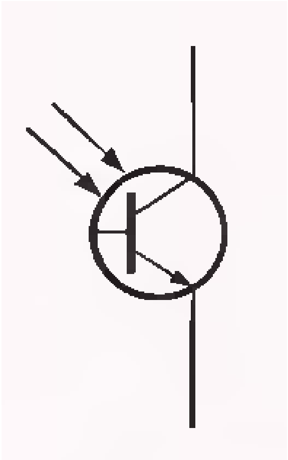
- *When there is no incident light, there is only a small thermally generated collector-to-emitter leakage current i.e. $I_{(CEO)}$, this is called the dark current and is typically in the nA range.*

- When light strikes the collector-base pn junction, a base current is produced that is directly proportional to the light intensity.
- Since the actual photo generation of base current occurs in the collector-base region, the larger the physical area of this region, the more base current is generated.
- A phototransistor does not activated at every type of wave lengths of light.

- The phototransistor is similar to a regular BJT except that the base current is produced and controlled by light instead of a voltage source.
- The phototransistor effectively converts variations in light energy to an electrical signal
- The collector-base pn junction is exposed to incident light through a lens opening in the transistor package.
- The phototransistor is a transistor in which base current is produced when light strikes the photosensitive semiconductor base region.
- When there is no incident light, there is only a small thermally generated collector-to-emitter leakage current i.e. I(CEO), this is called the dark current and is typically in the range of nA.

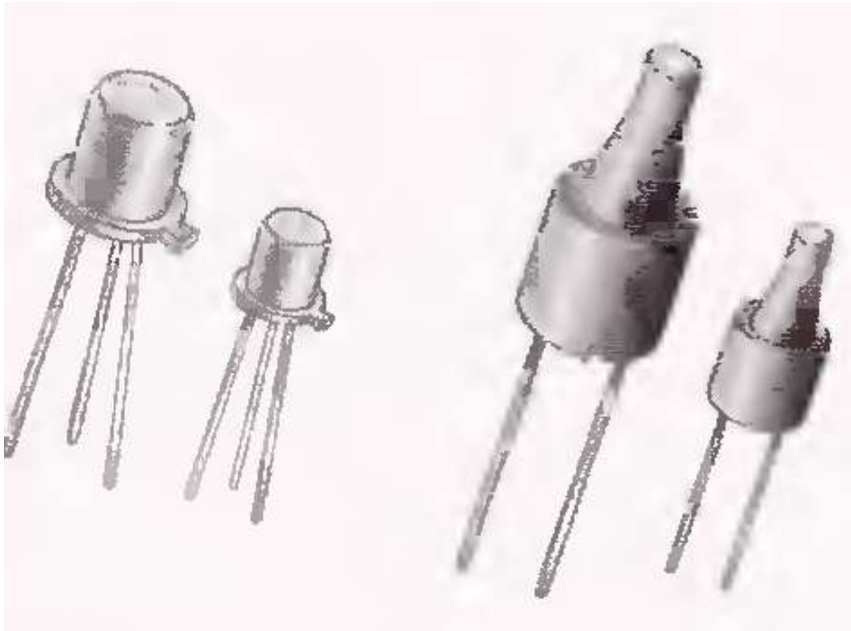
- When light strikes the collector-base pn junction, a base current, I_λ, is produced that is directly proportional to the light intensity.
- This action produces a collector current that increases with I_λ .
- Except for the way base current is generated, the phototransistor behaves as a conventional BJT.
- In many cases there is no electrical connection to the base
- The relationship between the collector current and the light-generated base current in a phototransistor is $I_C = \beta_{DC} * I_\lambda$.

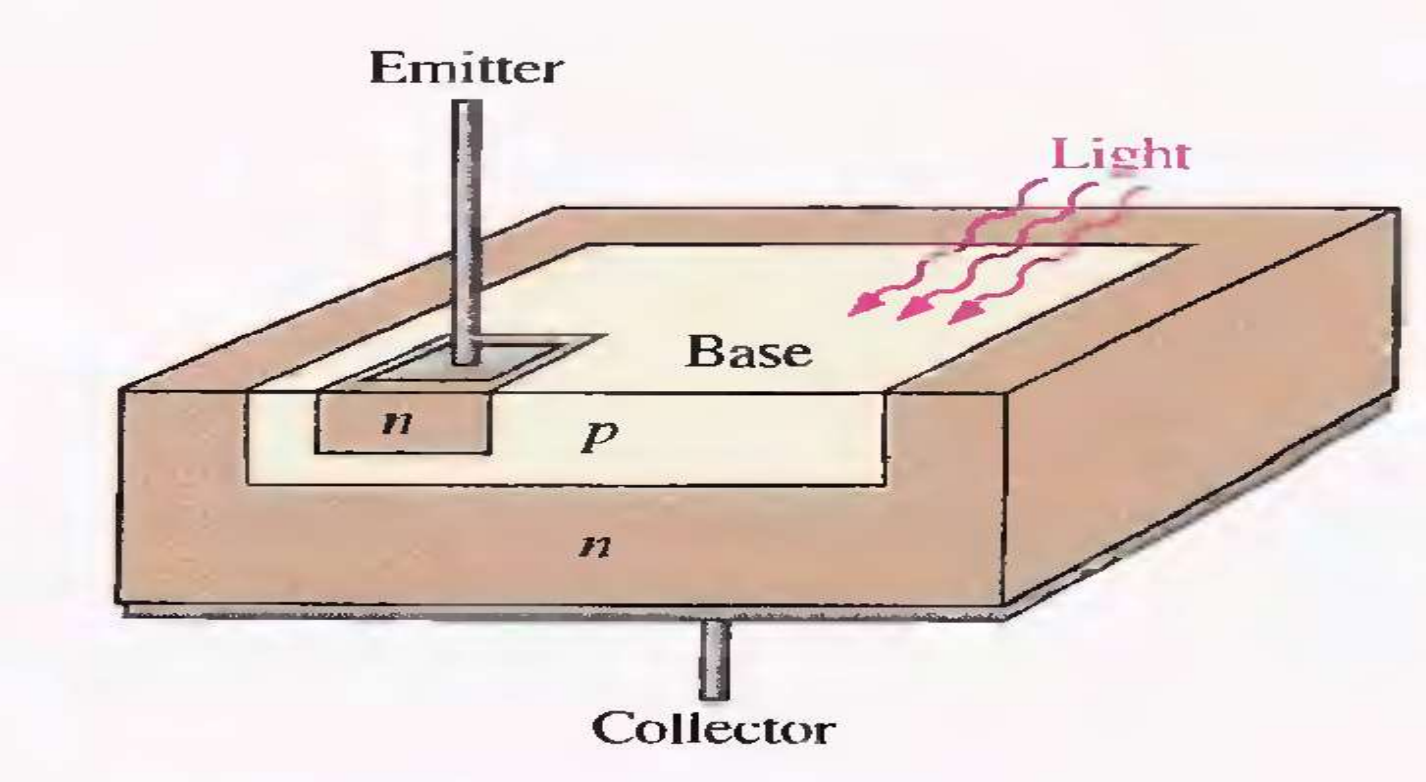
SYMBOL OF PHOTOTRANSISTOR



Schematic symbol

A typical phototransistor is designed to offer a large area to the incident light, as the simplified structure diagram in Figure:





Typical phototransistor chip structure.

Phototransistor are of two types.

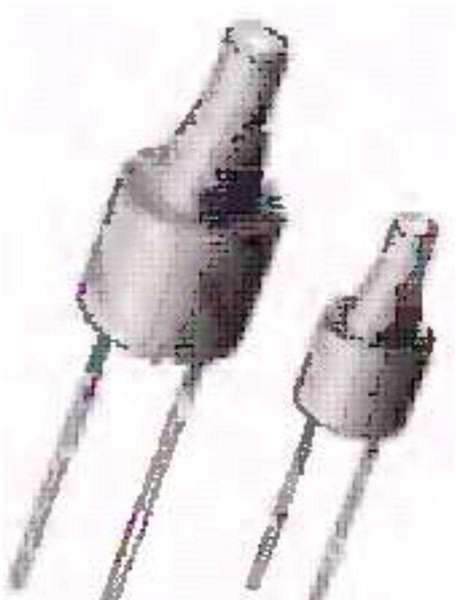
1. Three Lead Phototransistor.
2. Two Lead Phototransistor.

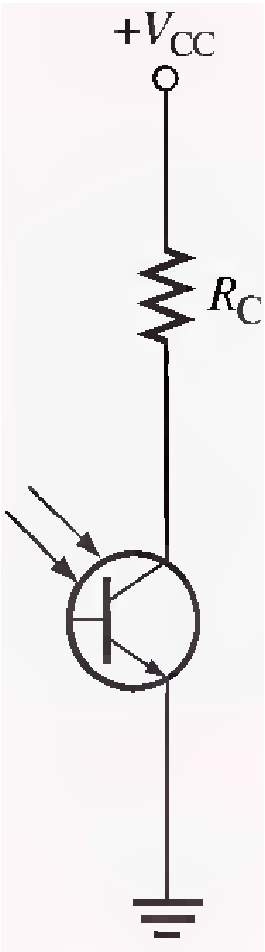
1. Three Lead Phototransistor:

In the three-lead configuration, the base lead is brought out so that the device can be used as a conventional BJT with or without the additional light-sensitivity feature.

2. Two Lead Phototransistor:

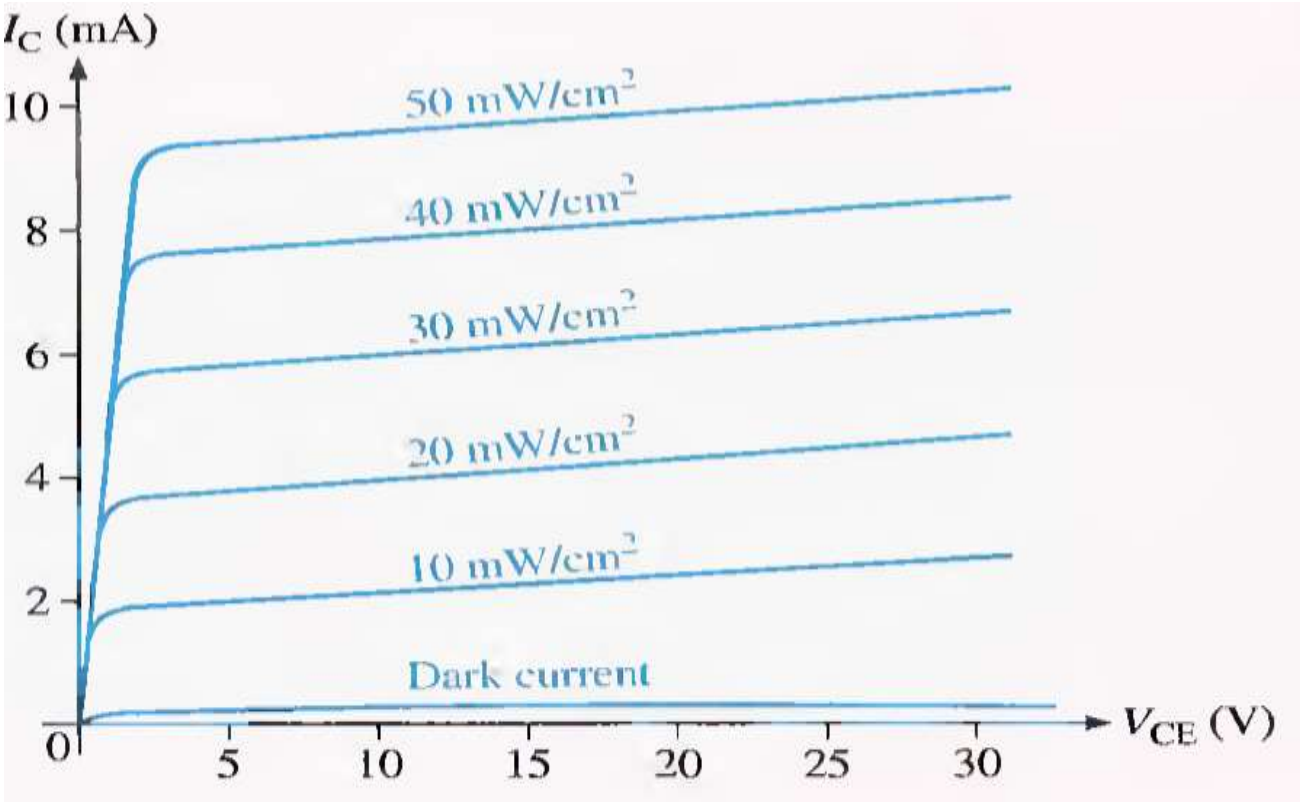
In the two-lead configuration. the base is not electrically available, and the device can be used only with light as the input. In many applications, the phototransistor is used in the two-lead version.

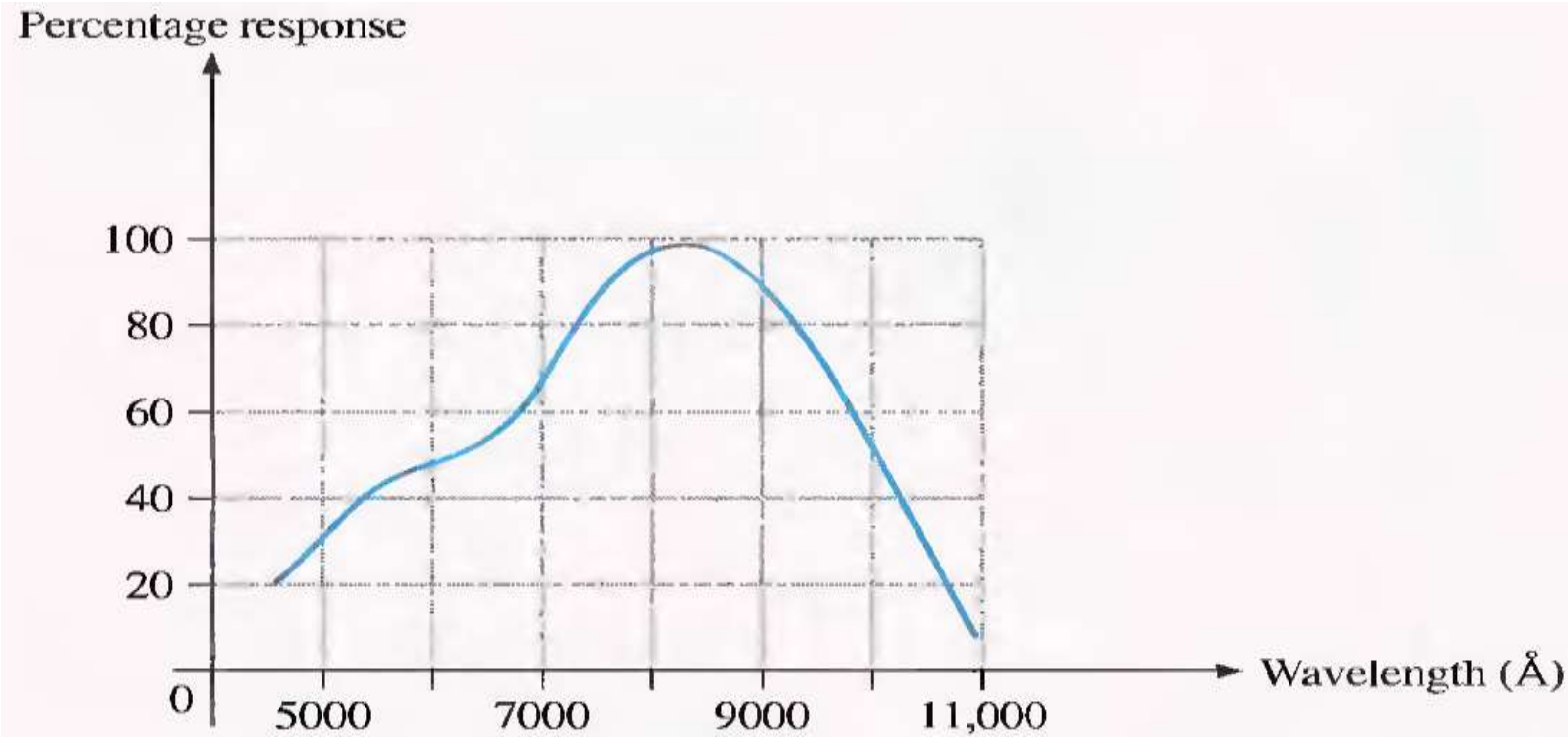




Phototransistor Bias Circuit

Typical collector characteristic curves. Notice that each individual curve on the graph corresponds to a certain value of light intensity (in this case, the units are m W/cm²) and that the collector current increases with light intensity.





Phototransistors are not sensitive to all light but only to light within a certain range of wavelengths. They are most sensitive to particular wavelengths. as shown by the peak of the spectral response curve in Figure.

Key Points

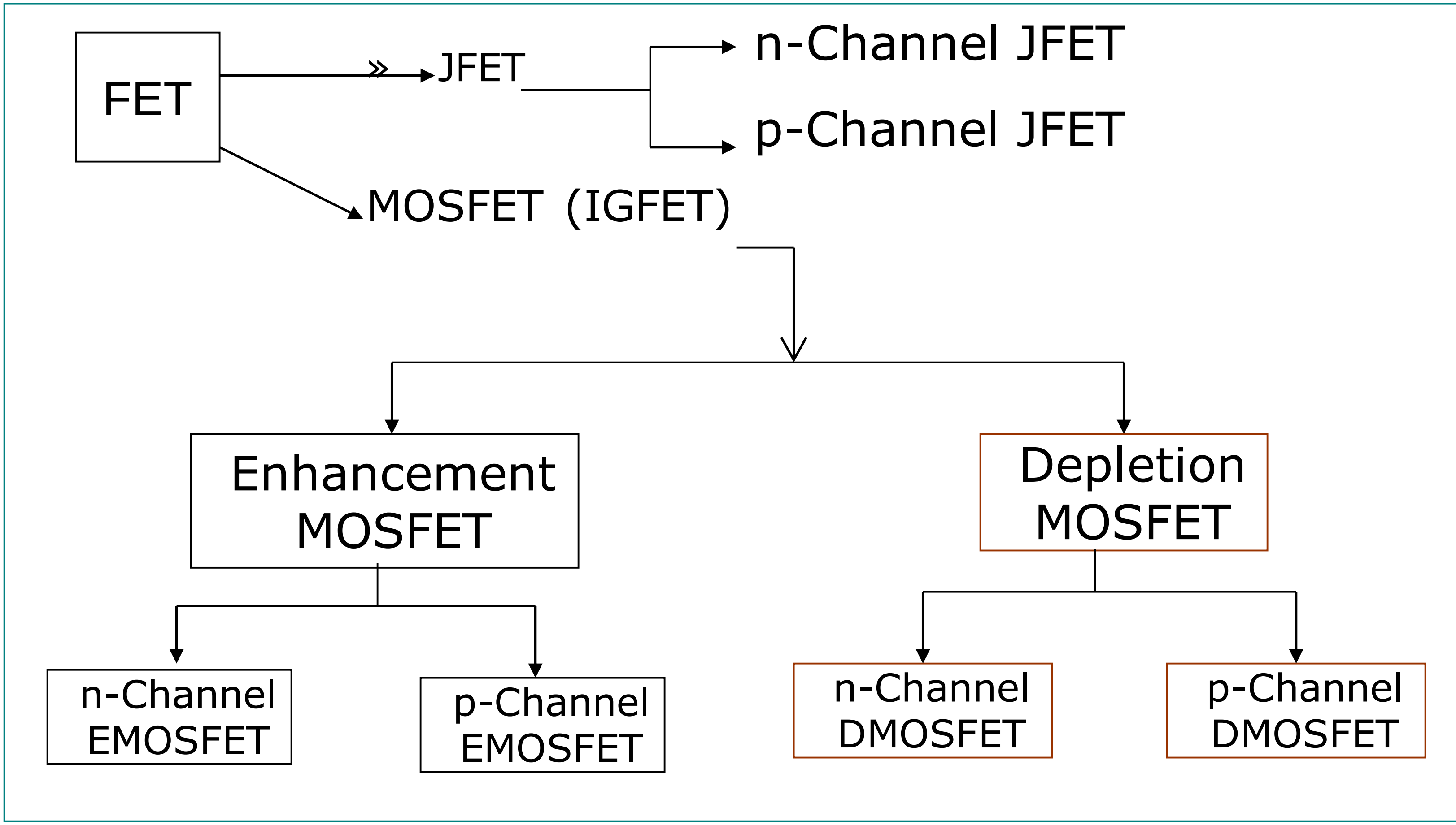
- Bipolar transistors are widely used in both analogue and digital circuits
- They can be considered as either voltage-controlled or current-controlled devices
- Their characteristics may be described by their gain or by their transconductance
- Feedback can be used to overcome problems of variability
- The majority of circuits use transistors in a common-emitter configuration where the input is applied to the base and the output is taken from the collector
- Common-collector circuits make good buffer amplifiers
- Bipolar transistors are used in a wide range of applications

FET (Field Effect Transistor)

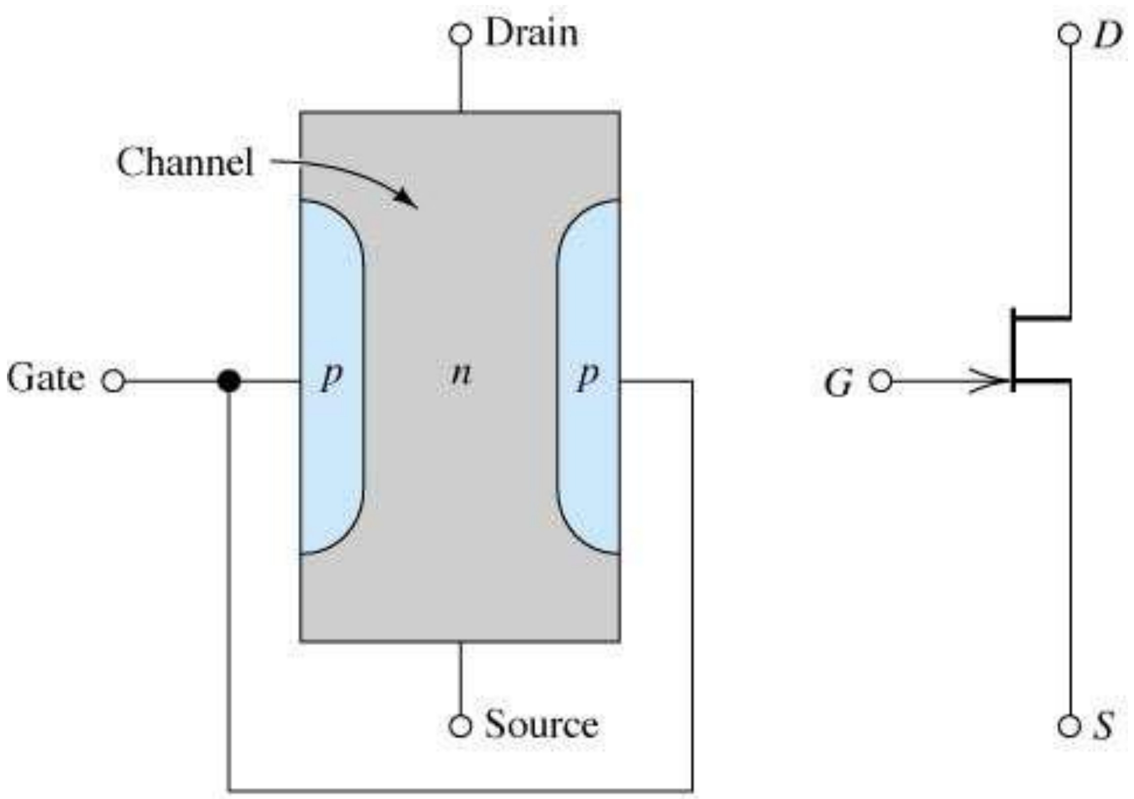
Few important advantages of FET over conventional Transistors

1. Unipolar device i. e. operation depends on only one type of charge carriers (*h* or *e)*
2. Voltage controlled Device (gate voltage controls drain current)
3. Very high input impedance ($\approx 10^9$-$10^{12}\,\Omega$)
4. Source and drain are interchangeable in most Low-frequency applications
5. Low Voltage Low Current Operation is possible (Low-power consumption)
6. Less Noisy as Compared to BJT
7. No minority carrier storage (Turn off is faster)
8. Self limiting device
9. Very small in size, occupies very small space in ICs
10. Low voltage low current operation is possible in MOSFETS
11. Zero temperature drift of out put is possiblek

Types of Field Effect Transistors (The Classification)



The Junction Field Effect Transistor (JFET)

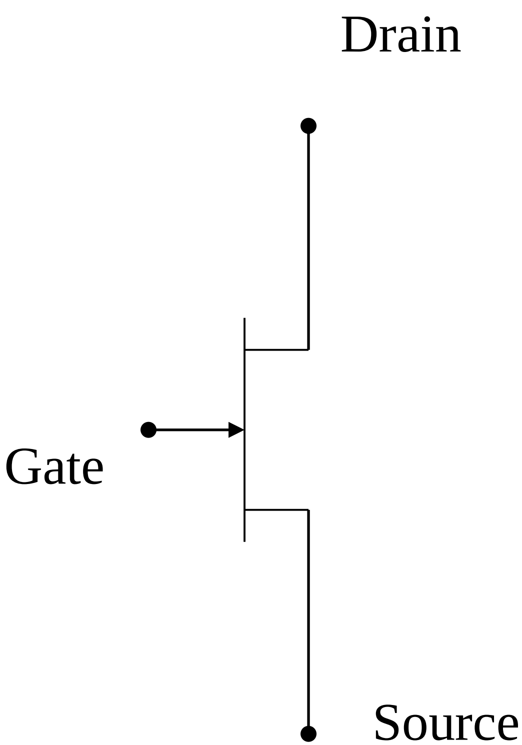


(a) Simplified physical structure

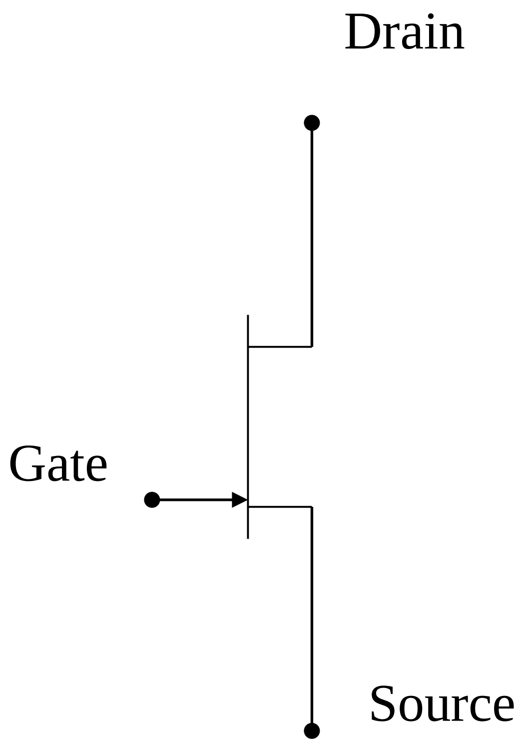
(b) Circuit symbol

Figure: *n*-Channel JFET.

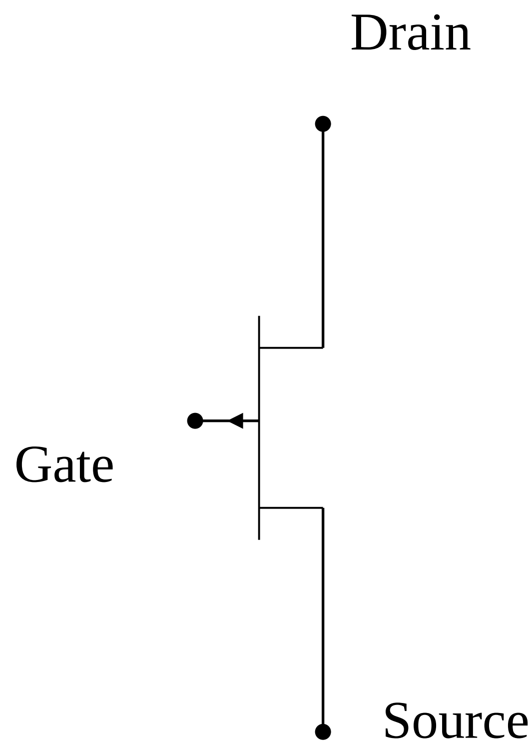
SYMBOLS



n-channel JFET



n-channel JFET
Offset-gate symbol



p-channel JFET

Biasing the JFET

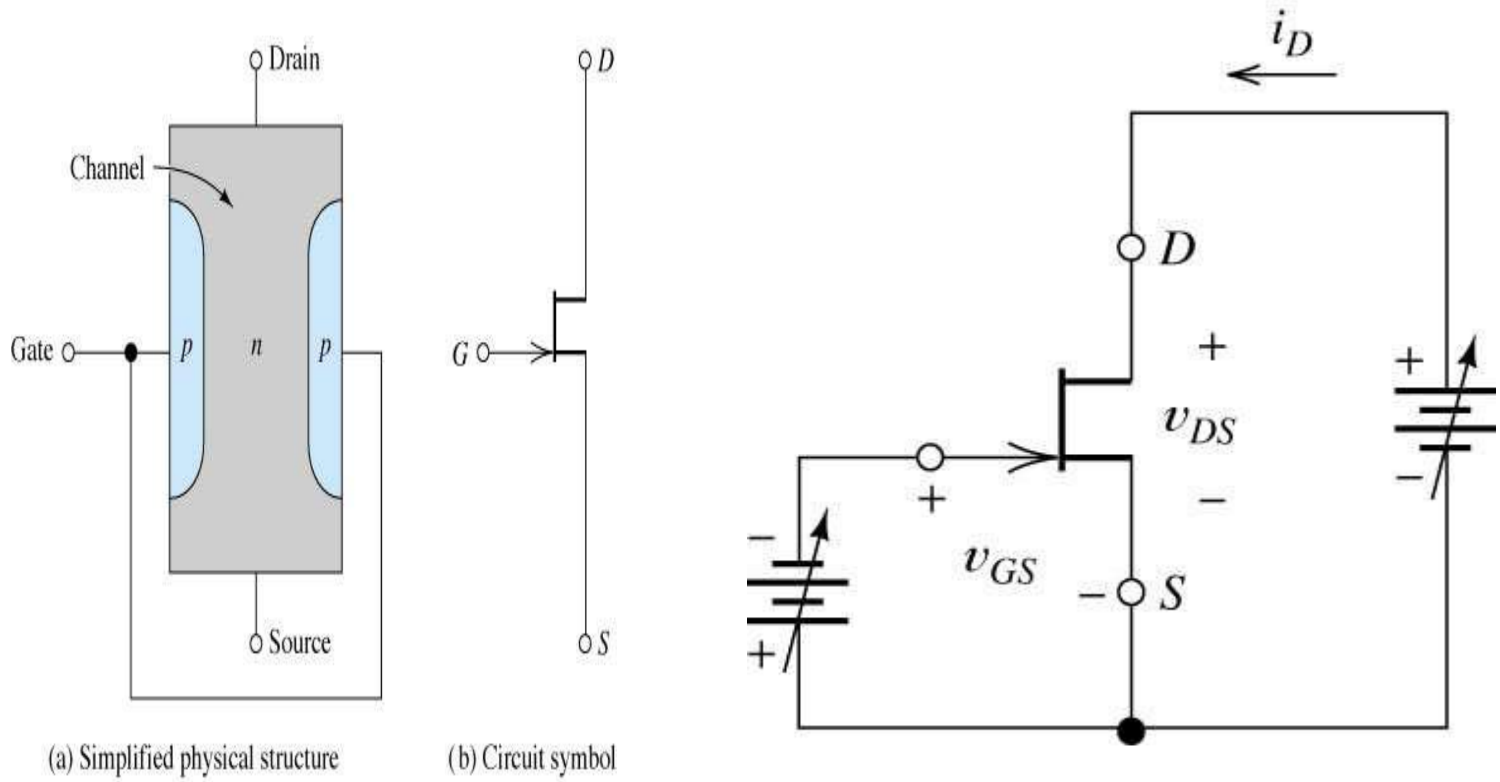


Figure: *n*-Channel JFET and Biasing Circuit.

Operation of JFET at Various Gate Bias Potentials

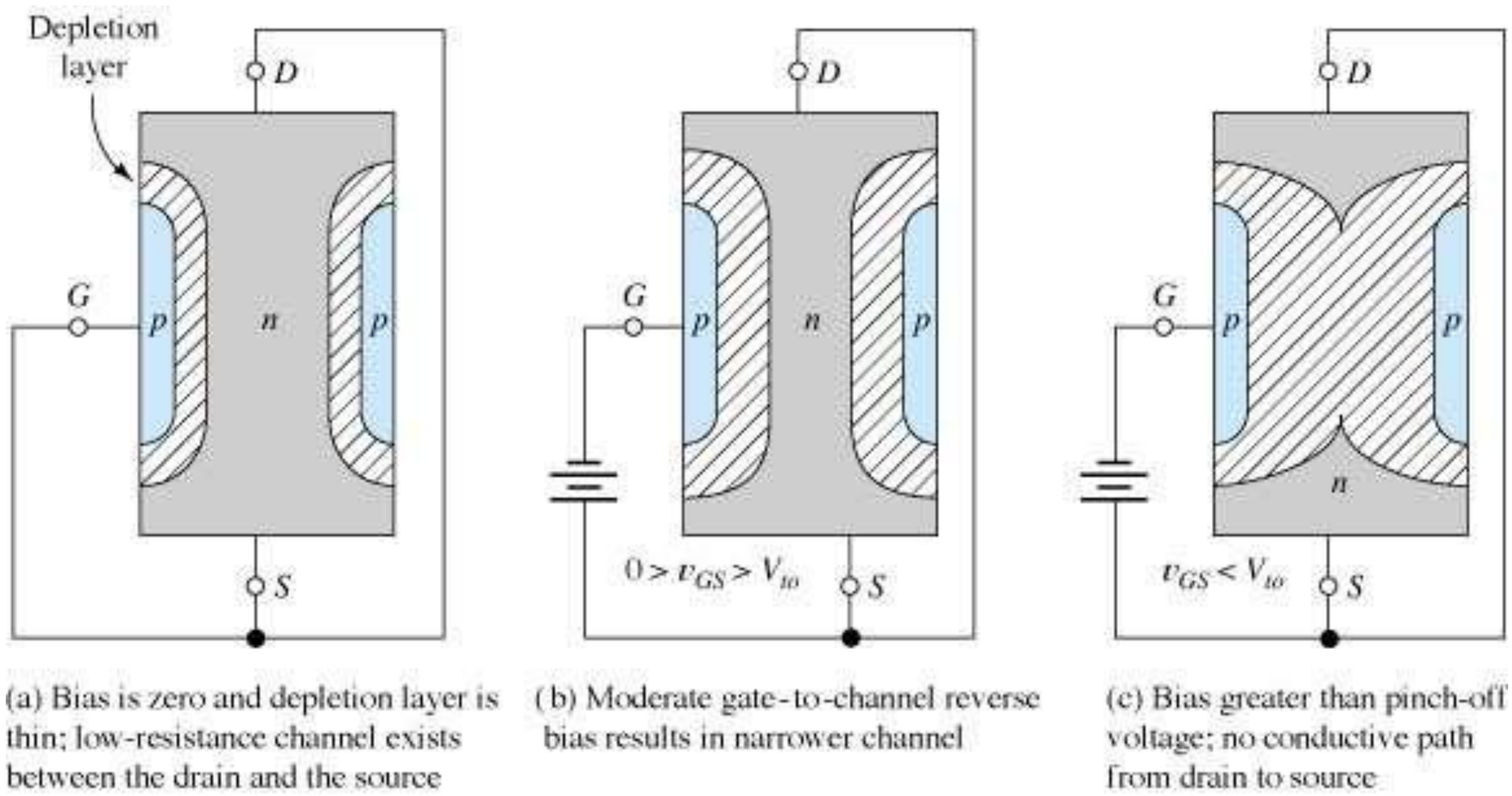
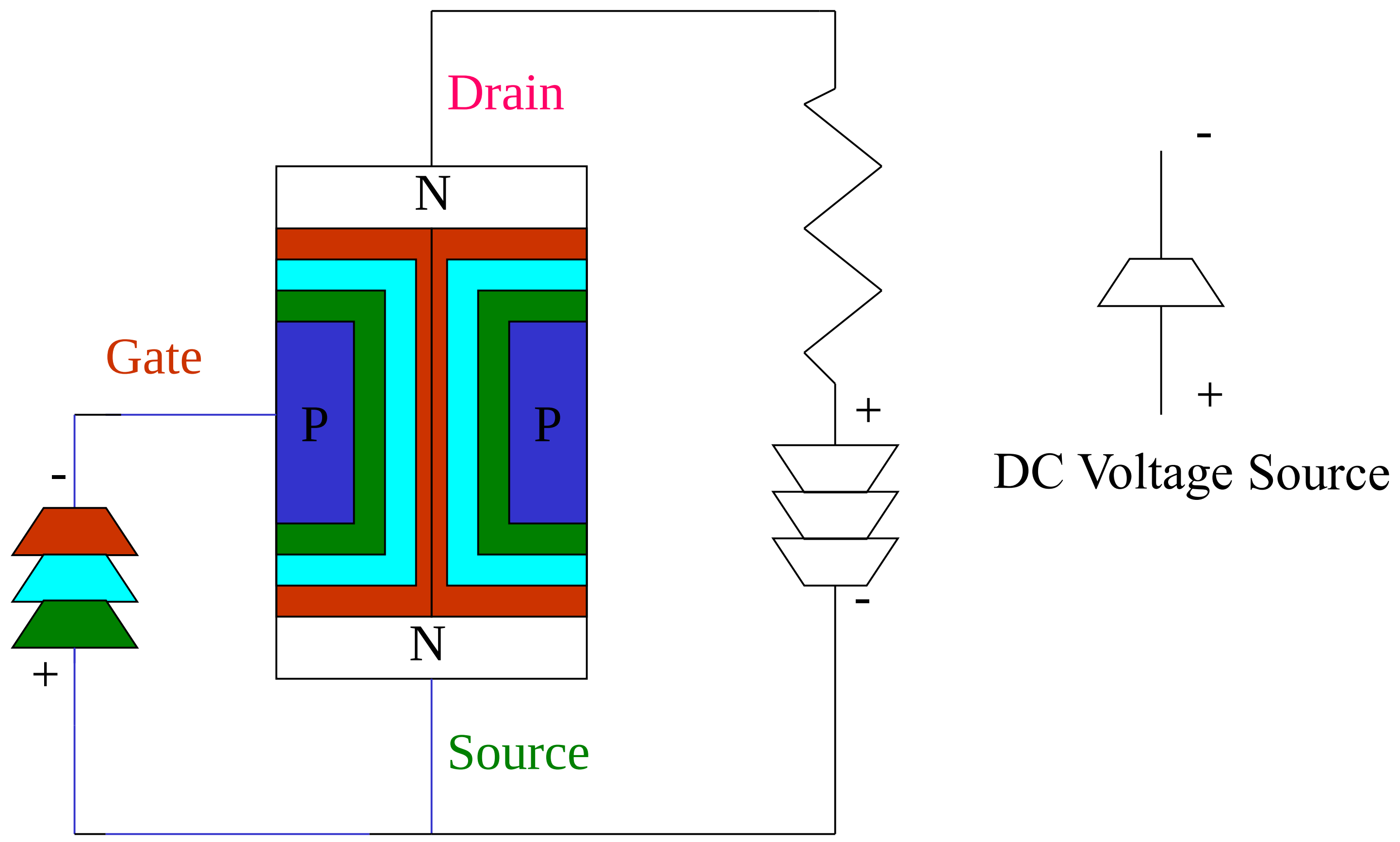


Figure: The nonconductive depletion region becomes broader with increased reverse bias. (*Note:* The two gate regions of each FET are connected to each other.)

Operation of a JFET



Output or Drain (V_D-I_D) Characteristics of n-JFET

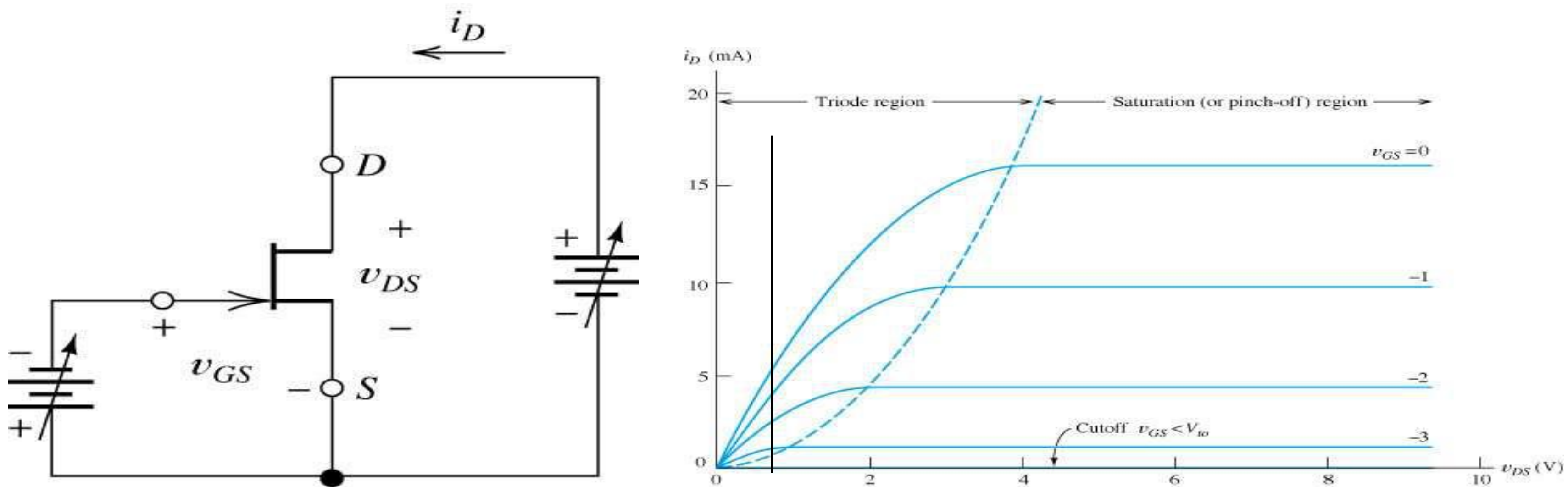


Figure: Circuit for drain characteristics of the *n*-channel JFET and its Drain characteristics.

Non-saturation (Ohmic) Region: → $V_{DS} < \left(V_{GS} - V_P\right)$

The drain current is given by $I_{DS} = \frac{2I_{DSS}}{V_P^2}\left[\left(V_{GS} - V_P\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$

Saturation (or Pinchoff) Region: → $V_{DS} \geq \left(V_{GS} - V_P\right)$

$$I_{DS} = \frac{I_{DSS}}{V_P^2}\left[\left(V_{GS} - V_P\right)^2\right] \quad \text{and} \quad I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

Where, I_{DSS} is the short circuit drain current, V_P is the pinch off voltage

Simple Operation and Break down of n-Channel JFET

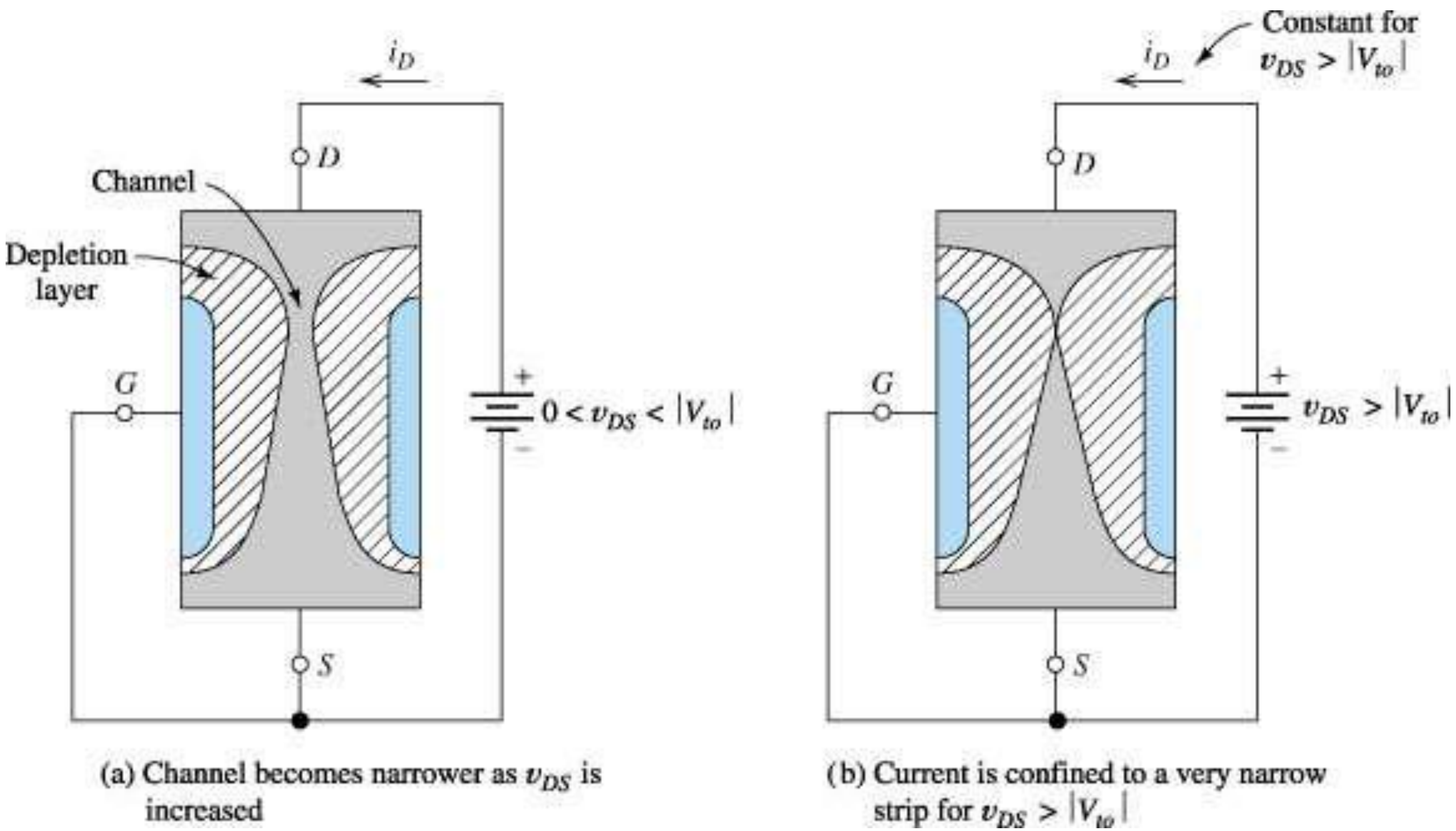


Figure: *n*-Channel FET for $v_{GS} = 0$.

N-Channel JFET Characteristics and Breakdown

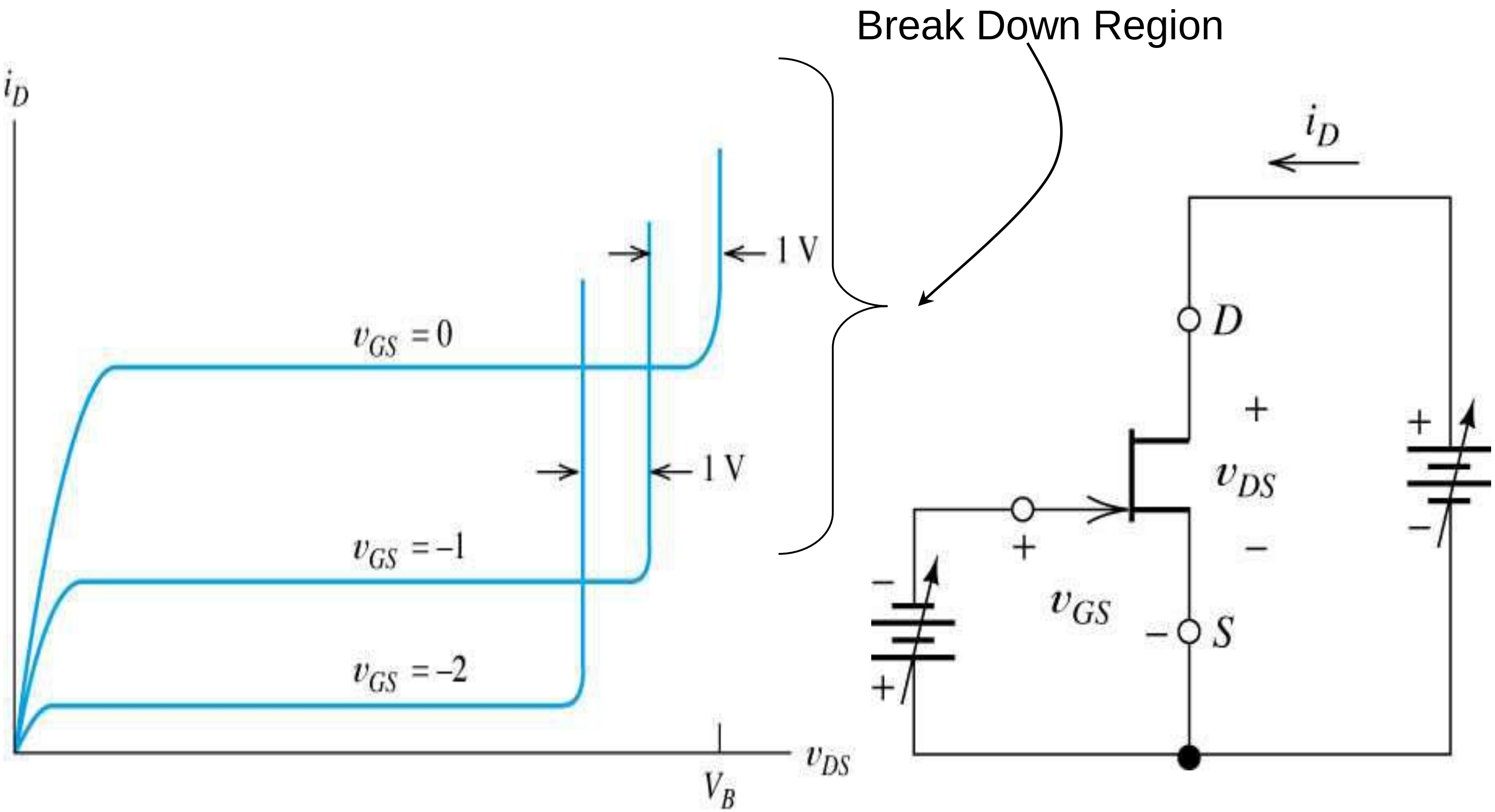
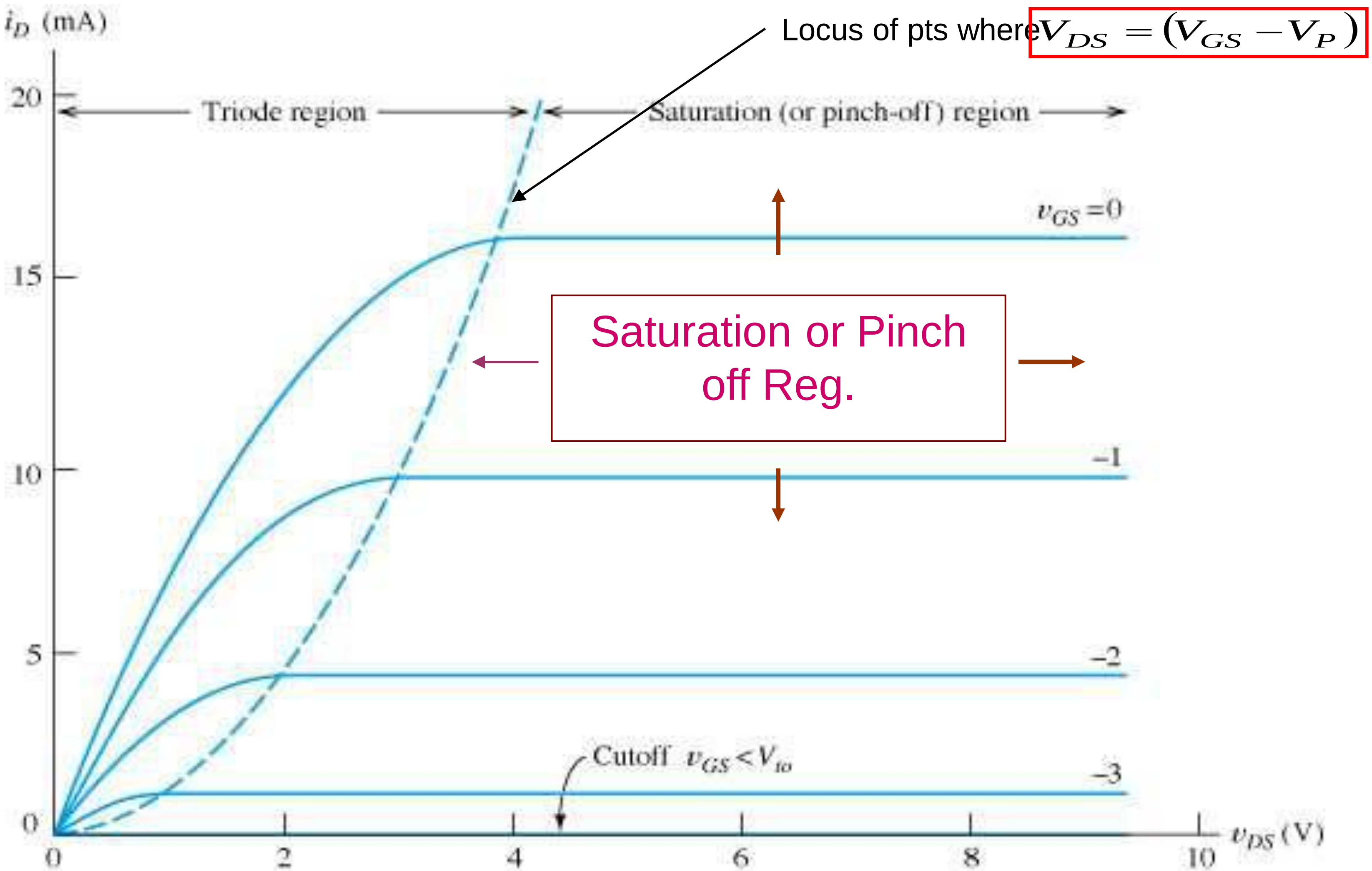
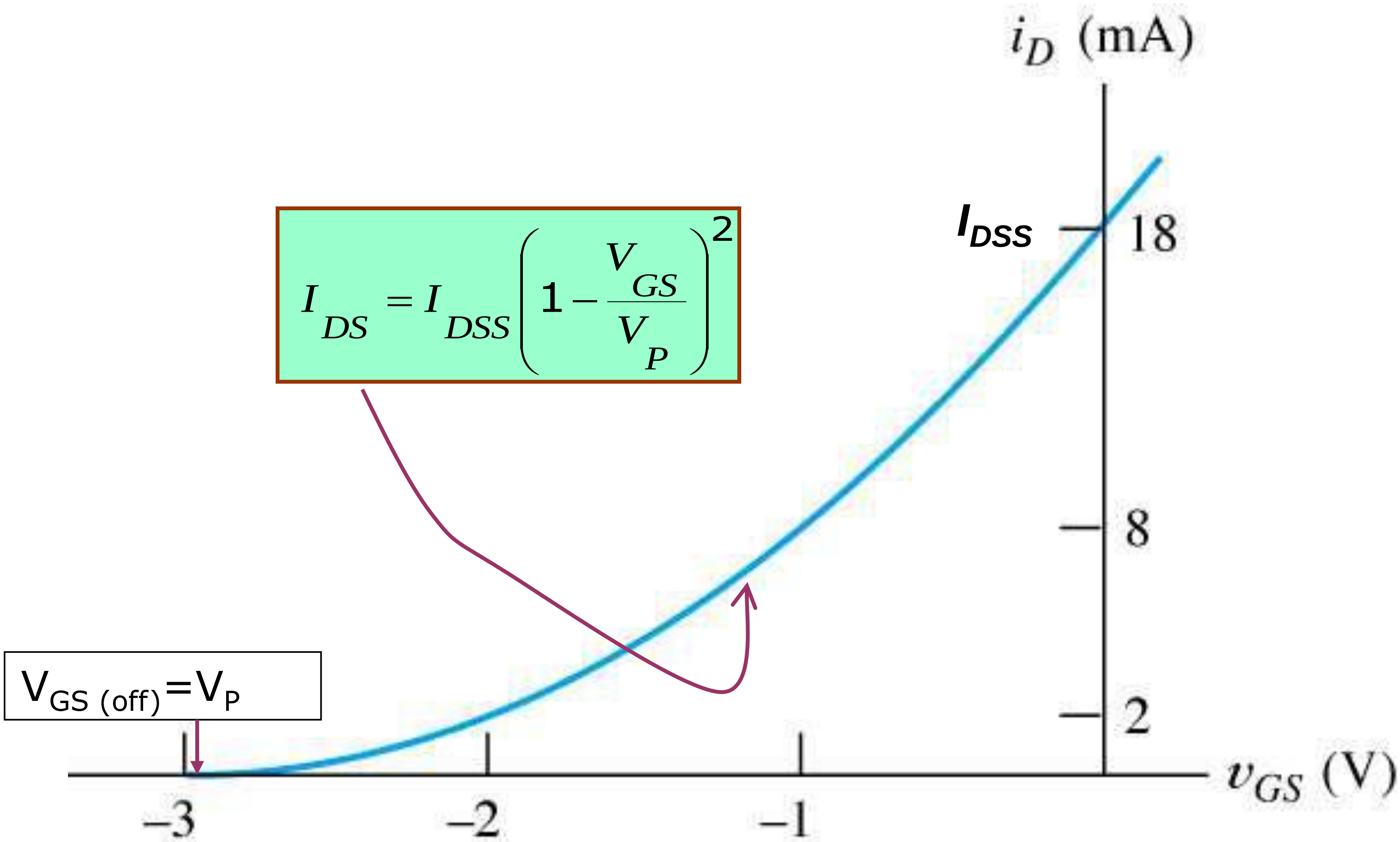


Figure: If v_{DG} exceeds the breakdown voltage V_B, drain current increases rapidly.

V_D-I_D Characteristics of EMOS FET



Transfer (Mutual) Characteristics of n-Channel JFET

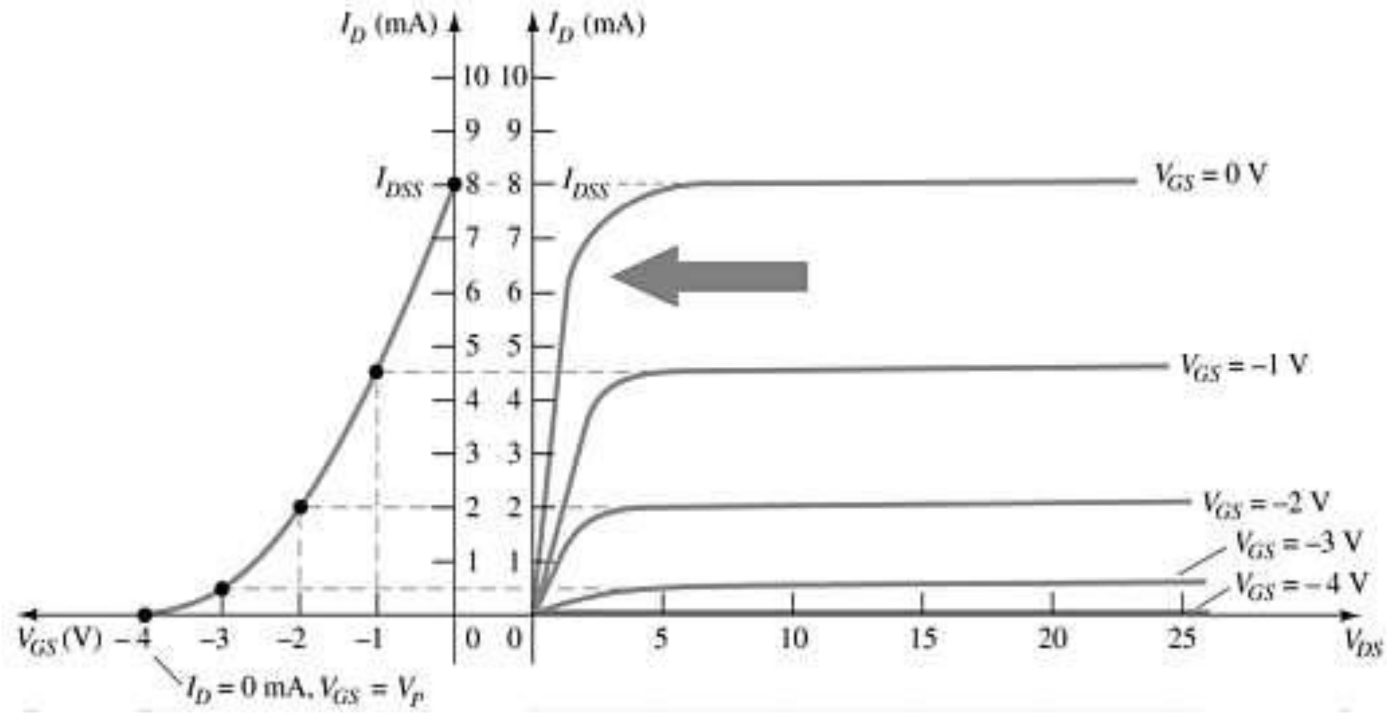


$$I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

Figure: Transfer (or Mutual) Characteristics of n-Channel JFET

JFET Transfer Curve

This graph shows the value of I_D for a given value of V_{GS}



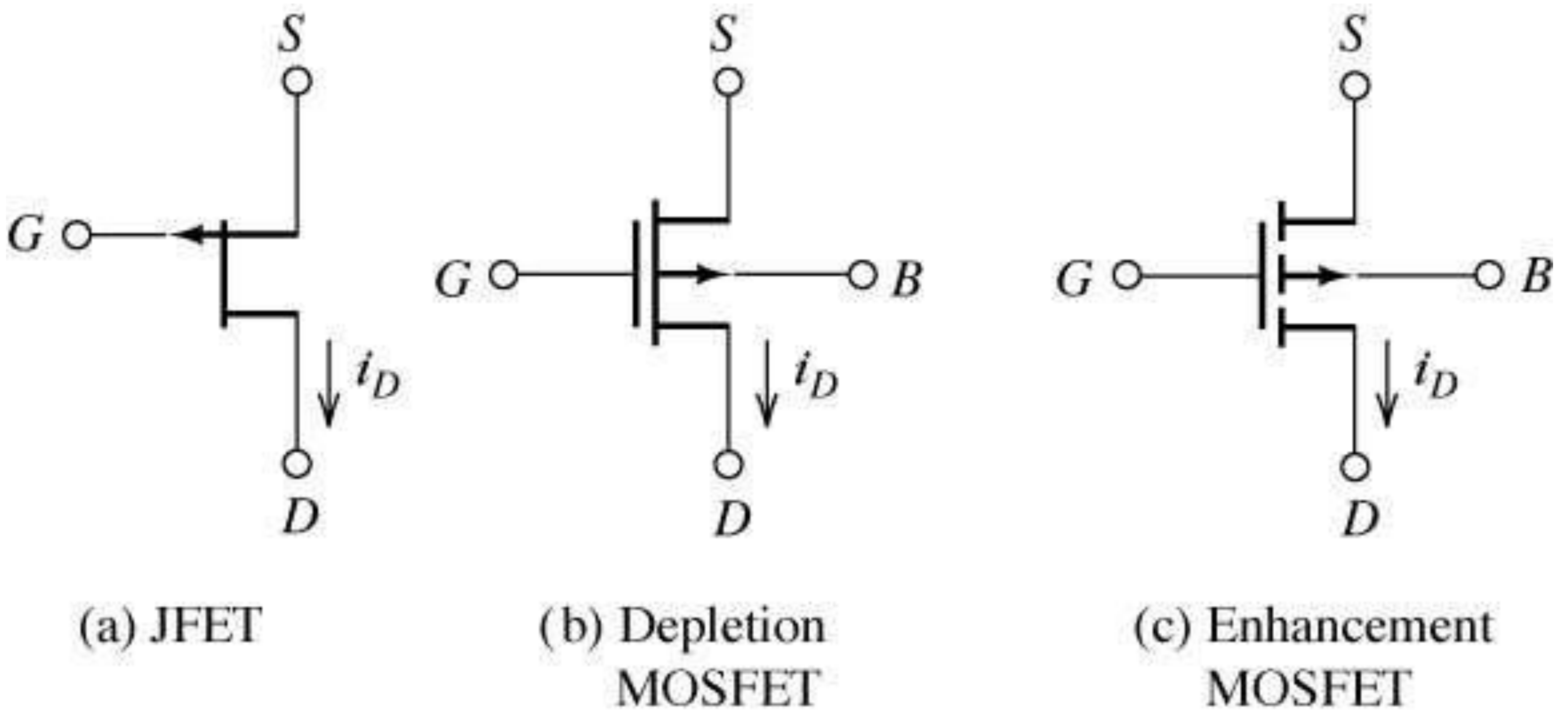


Figure *p*-Channel FET circuit symbols. These are the same as the circuit symbols for *n*-channel devices, except for the directions of the arrowheads.

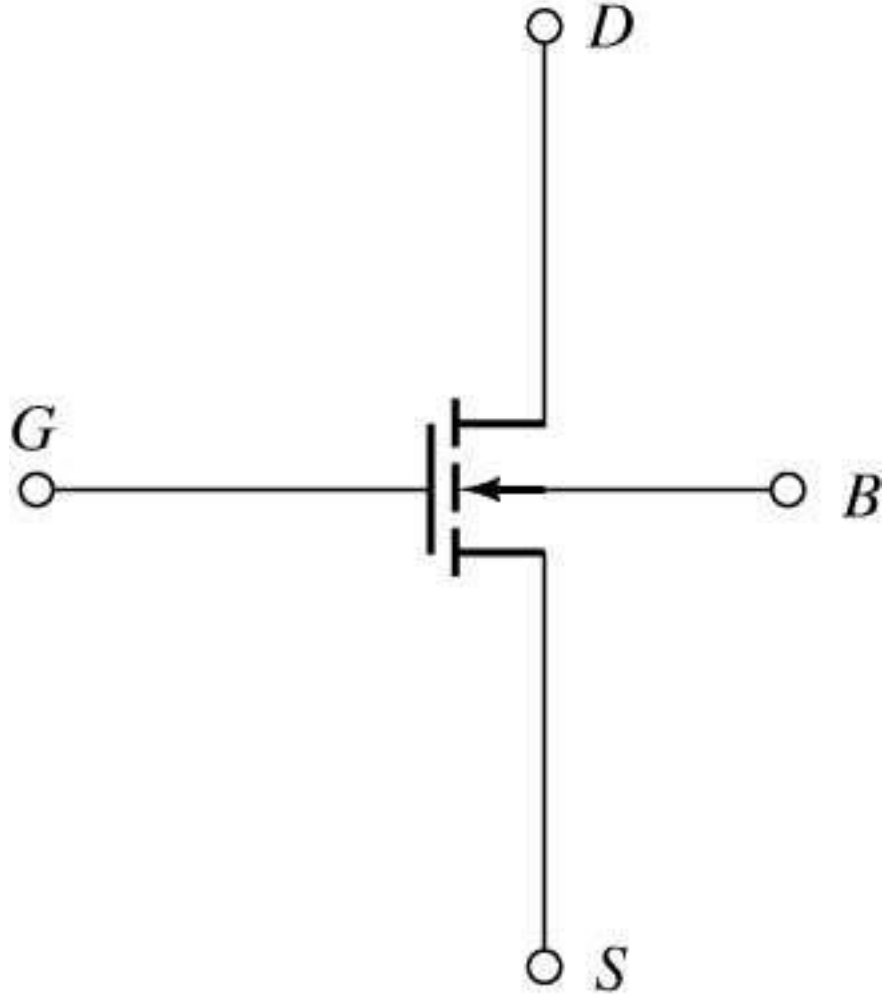


Figure: Circuit symbol for an enhancement-mode *n*-channel MOSFET.

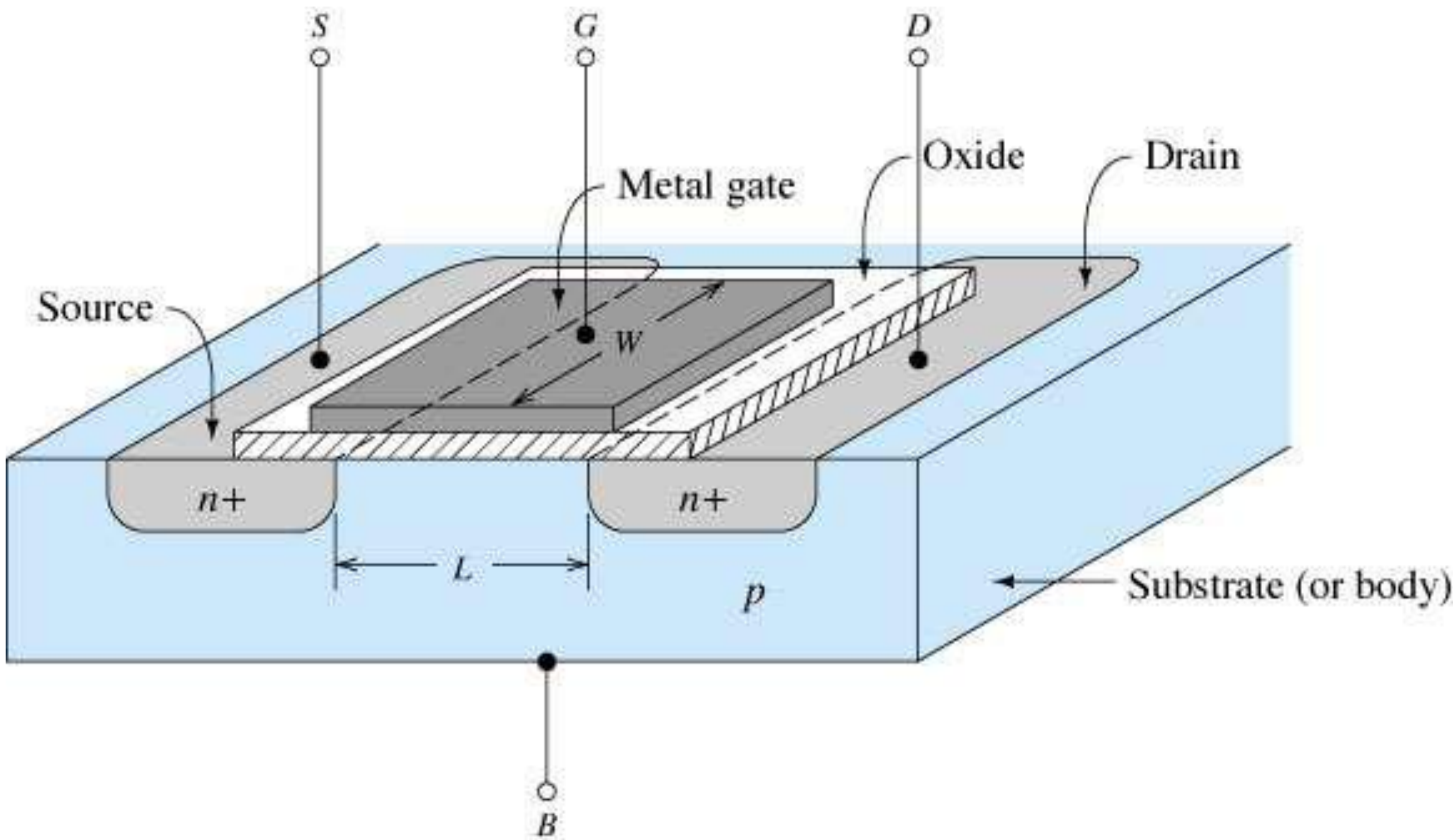


Figure: *n*-Channel Enhancement MOSFET showing channel length *L* and channel width *W*.

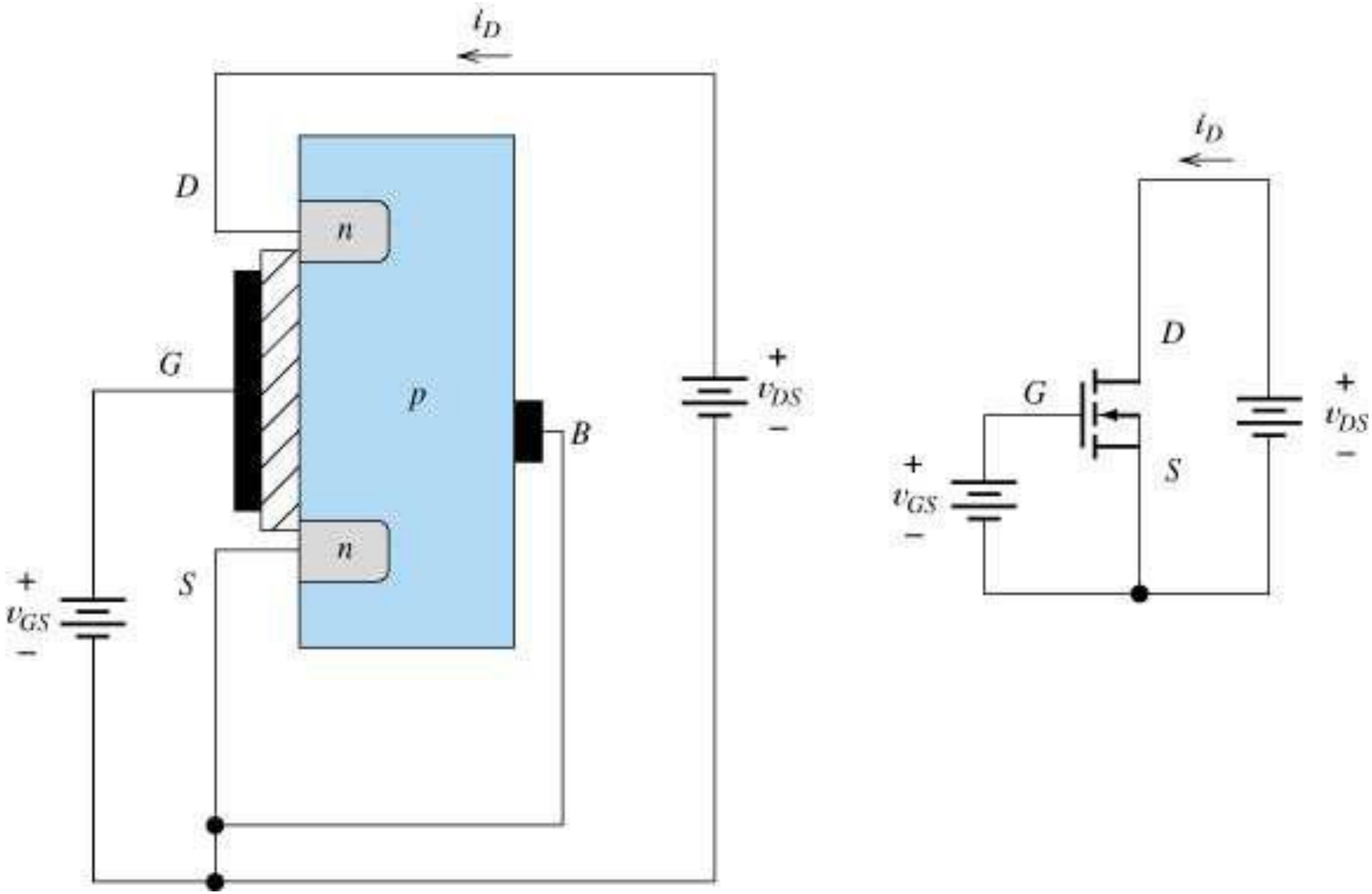


Figure: For $v_{GS} < V_{to}$ the *pn* junction between drain and body is reverse biased and i_D=0.

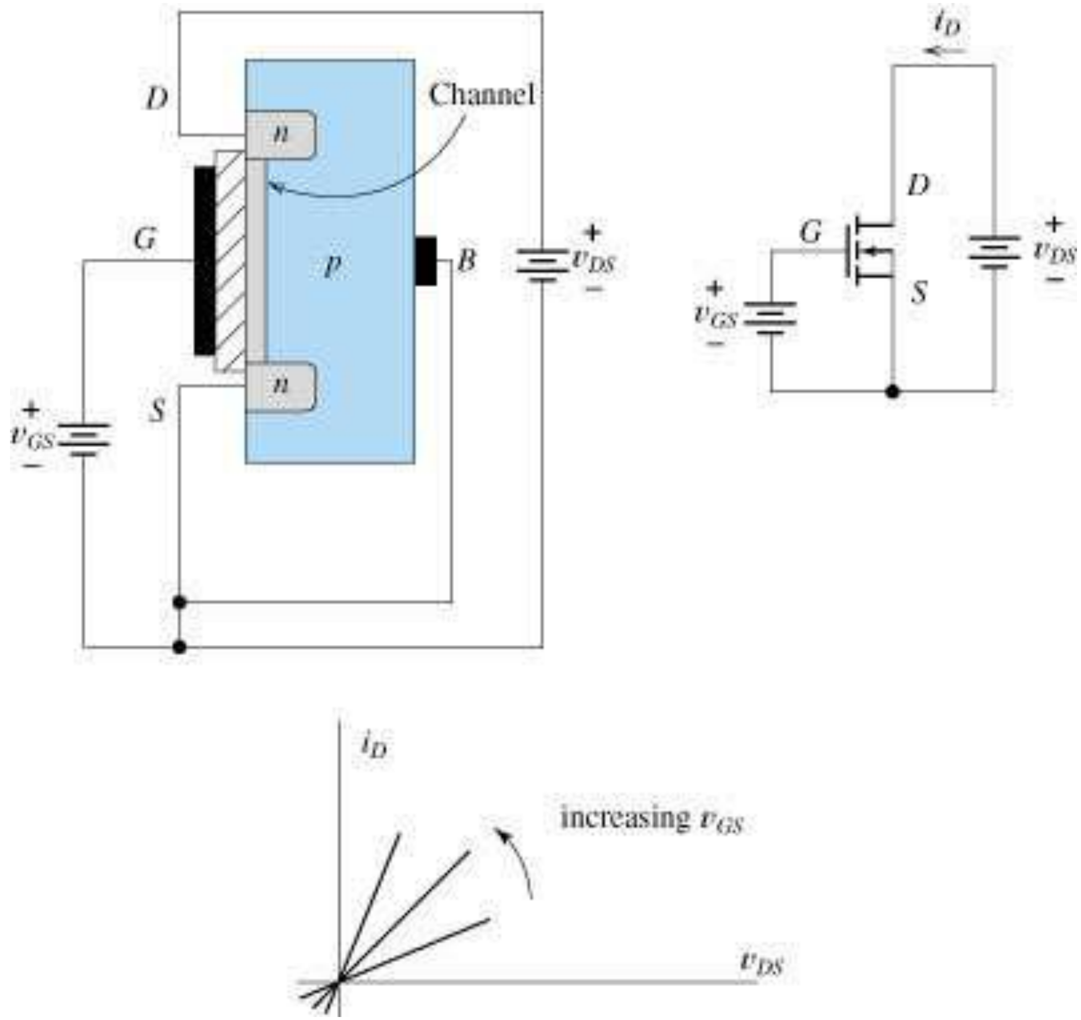


Figure: For $v_{GS} > V_{to}$ a channel of *n*-type material is induced in the region under the gate. As v_{GS} increases, the channel becomes thicker. For small values of v_{DS} ,i_D is proportional to v_{DS}. The device behaves as a resistor whose value depends on v_{GS}.

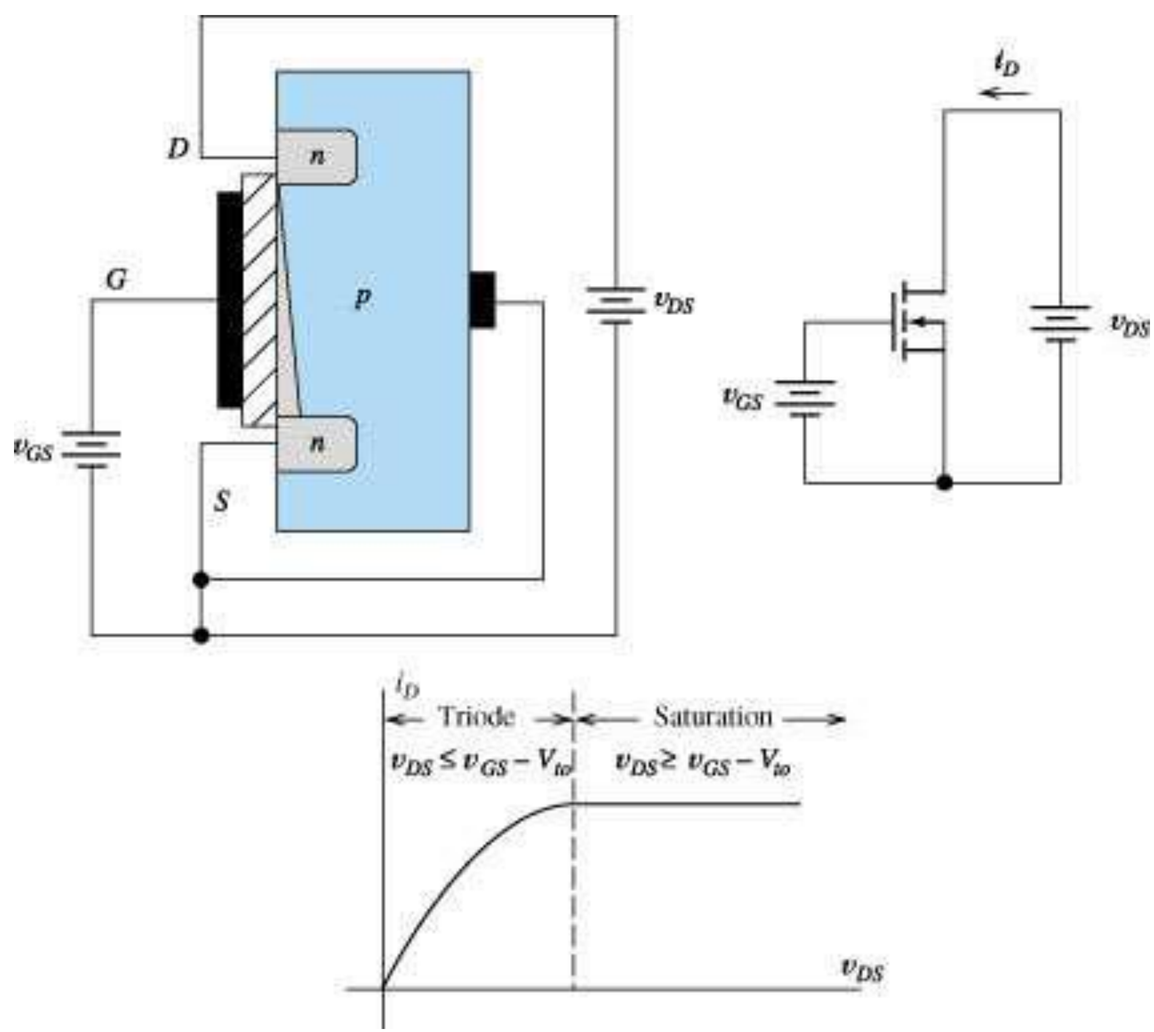
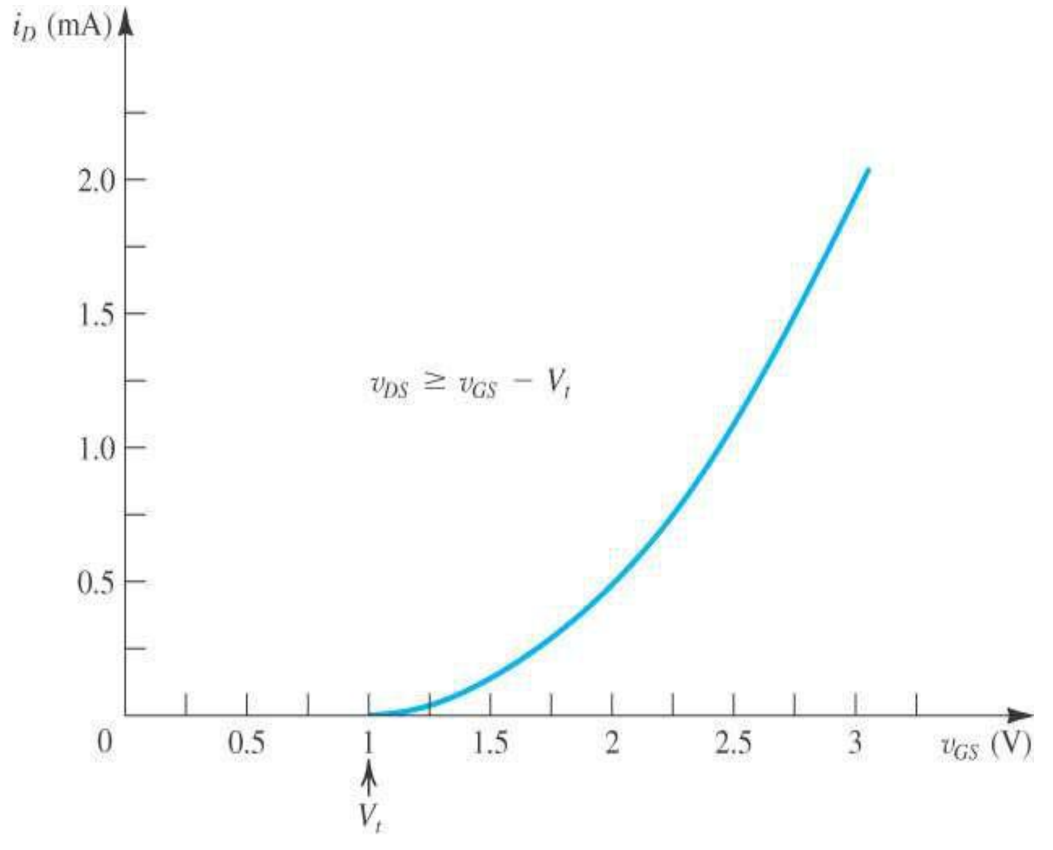


Figure: As v_{DS} increases, the channel pinches down at the drain end and i_D increases more slowly. Finally for $v_{DS} > v_{GS} - V_{to}$, i_D becomes constant.

Current-Voltage Relationship of n-EMOSFET



Locus of points where

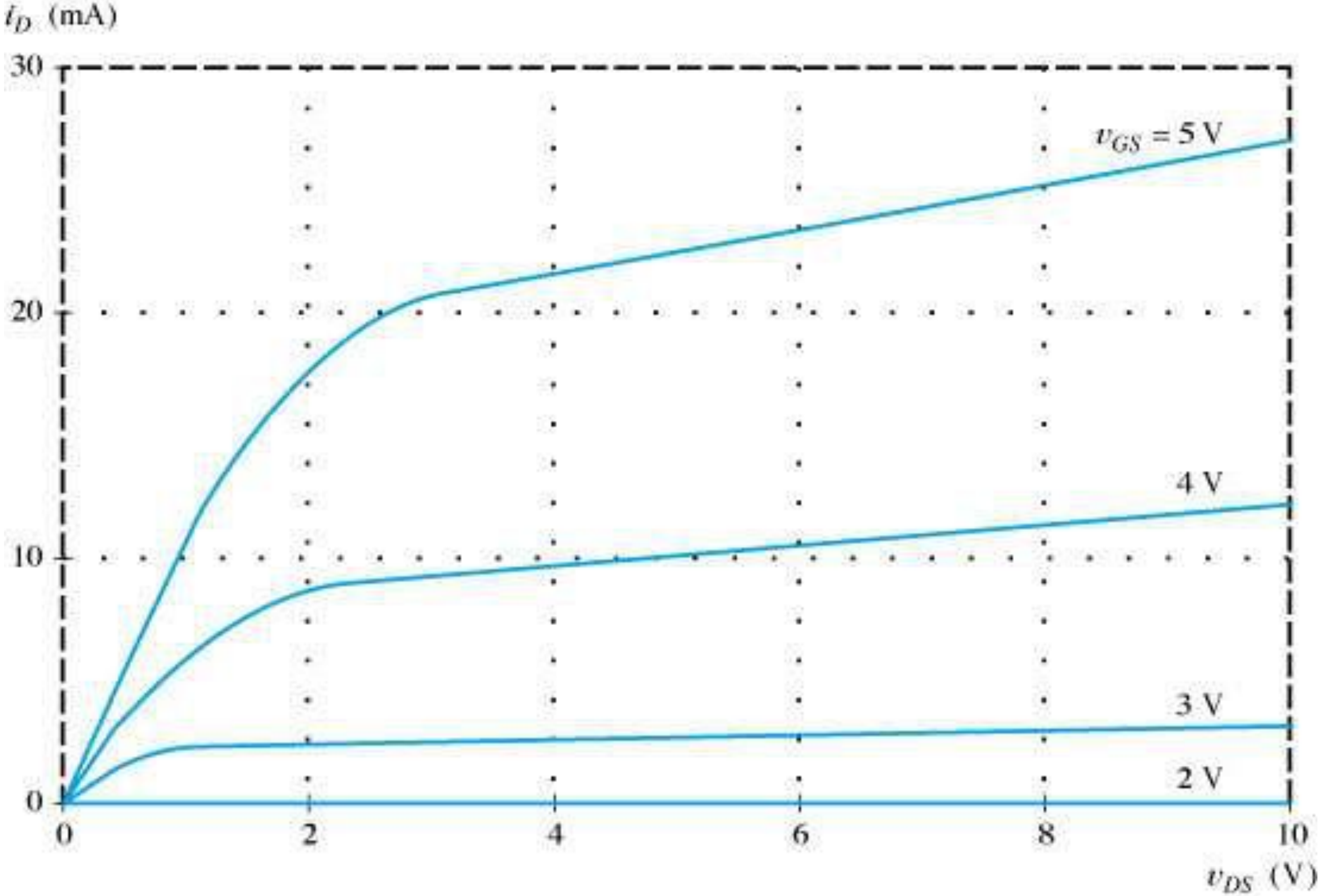


Figure: Drain characteristics

II B.Tech I-Sem (E.C.E)

(15A04301) ELECTRONIC DEVICES AND CIRCUITS

UNIT- IV

- **Transistor Biasing and Thermal Stabilization :** Need for biasing, operating point, load line analysis, BJT biasing- methods, basic stability, fixed bias, collector to base bias, self bias, Stabilization against variations in V_{BE}, Ic, and β, Stability factors, (S, S', S''), Bias compensation, Thermal runaway, Thermal stability.
- FET Biasing- methods and stabilization.

INTRODUCTION

- The BJT as a circuit element operates various circuits with many major and minor modifications.
- For the analysis of such circuits, we obtain the various conditions for proper operation of the device, and also determine the projected range of operation of the device.
- A detailed study of the device in a two-port mode simplifies the circuit analysis of the device to a large extent.
- Thus, we calculate the various parameters of the devices' performance, namely voltage gain, current gain, input impedance, and output impedance.
- The frequency response of the device is dealt with in detail, and a study of the various regions of operation in the frequency scale is also explained.
- Finally, we will discuss the various configurations of the device and take a look into the high-frequency operation of the device and its performance in those regions.

Proper Transistor Biasing

- For a transistor to function properly as an amplifier, the **emitter-base** junction must be <u>forward</u>-biased and the **collector-base** junction must be <u>reverse</u>-biased.
- The common connection for the voltage sources are at the base lead of the transistor.
- The emitter-base supply voltage is designated V_{EE} and the collector-base supply voltage is designated V_{CC}.
- For silicon, the barrier potential for both EB and CB junctions equals 0.7 V

Transistor Biasing

The basic function of transistor is amplification. The process of raising the strength of weak signal without any change in its general shape is referred as faithful amplification. For faithful amplification it is essential that:-

1. Emitter-Base junction is forward biased
2. Collector- Base junction is reversed biased
3. Proper zero signal collector current

The proper flow of zero signal collector current and the maintenance of proper collector emitter voltage during the passage of signal is called transistor biasing.

WHY BIASING?

If the transistor is not biased properly, it would work inefficiently and produce distortion in output signal.

HOW A TRANSISTOR CAN BE BIASED?

A transistor is biased either with the help of battery or associating a circuit with the transistor. The later method is more efficient and is frequently used. The circuit used for transistor biasing is called the biasing circuit.

BIAS STABILITY

❖ Through proper biasing, a desired quiescent operating point of the transistor amplifier in the active region (linear region) of the characteristics is obtained. It is desired that once selected the operating point should remain stable. The maintenance of operating point stable is called Stabilisation.

❖ The selection of a proper quiescent point generally depends on the following factors:

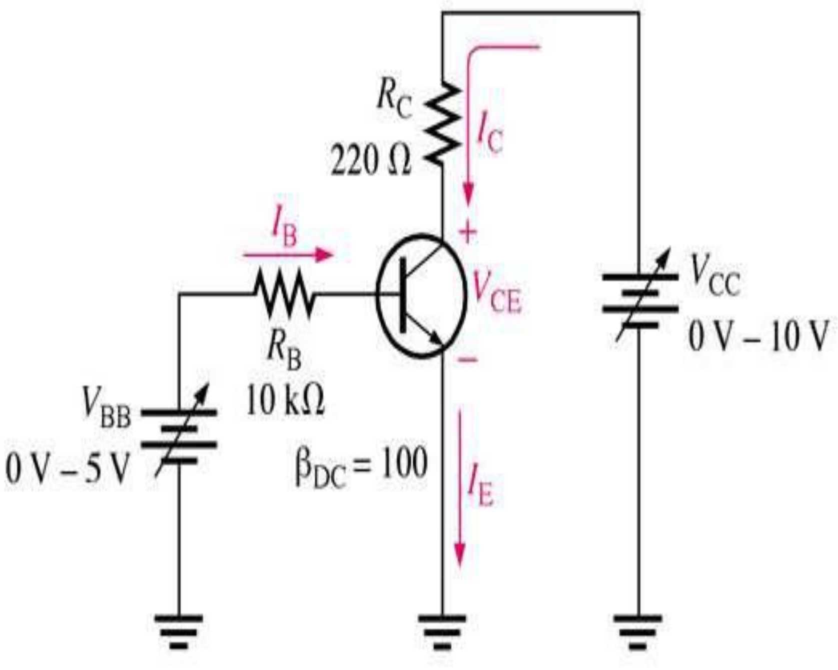
(a) The amplitude of the signal to be handled by the amplifier and distortion level in signal

(b) The load to which the amplifier is to work for a corresponding supply voltage

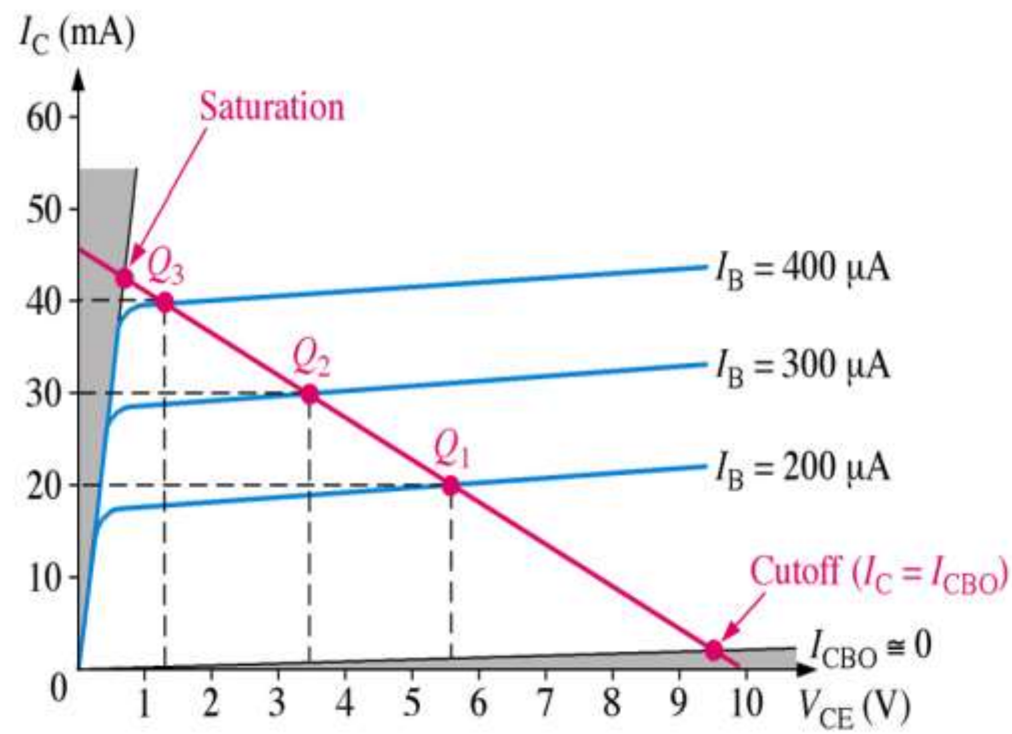
❖ The operating point of a transistor amplifier shifts mainly with changes in temperature, since the transistor parameters — β, I_{CO} *and* V_{BE} *(where the symbols carry their usual meaning)—are functions of* temperature.

The DC Operating Point

For a transistor circuit to amplify it must be properly biased with dc voltages. The dc operating point between saturation and cutoff is called the **Q-point.** The goal is to set the Q-point such that that it does not go into saturation or cutoff when an a ac signal is applied.



(a) DC biased circuit



The Thermal Stability of Operating Point (S_{Ico})

- **Stability Factor *S*:-** The stability factor *S, as the change of collector current with respect to the reverse saturation* current, keeping β *and VBE constant. This can be written as:*

The Thermal Stability Factor : S_{Ico}

$$S_{Ico} = \left. \frac{\partial I_c}{\partial I_{co}} \right|_{V_{be}, \beta}$$

This equation signifies that I_c Changes S_{Ico} times as fast as I_{co}

Differentiating the equation of Collector Current $I_C = (1+\beta)I_{co} + \beta I_b$ & rearranging the terms we can write

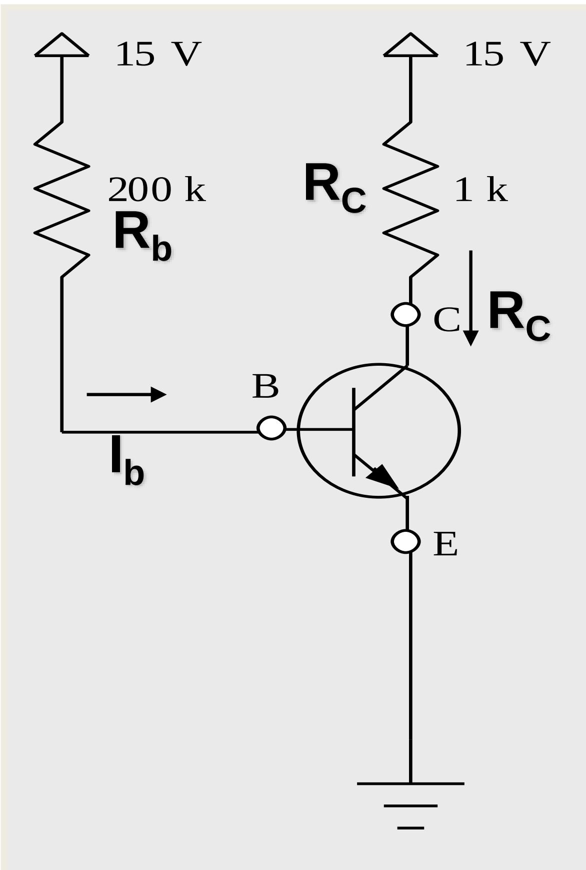
$$S_{Ico} = \frac{1+\beta}{1-\beta\,(\partial I_b/\partial I_C)}$$

It may be noted that Lower is the value of S_{Ico} better is the stability

Various Biasing Circuits

- **Fixed Bias Circuit**
- **Fixed Bias with Emitter Resistor**
- **Collector to Base Bias Circuit**
- **Potential Divider Bias Circuit**

The Fixed Bias Circuit



The Thermal Stability Factor : S_{Ico}

$$S_{Ico} = \left.\frac{\partial I_c}{\partial I_{co}}\right|_{V_{be},\ \beta}$$

General Equation of S_{Ico} Comes out to be

$$S_{Ico} = \frac{1 + \beta}{1 - \beta\,(\partial I_b/\partial I_C)}$$

Applying KVL through Base Circuit we can write, $I_b R_b + V_{be} = V_{cc}$

Diff w. r. t. I_C, we get $(\partial I_b / \partial I_c) = 0$

$S_{Ico} = (1+\beta)$ is very large

Indicating high un-stability

Merits:

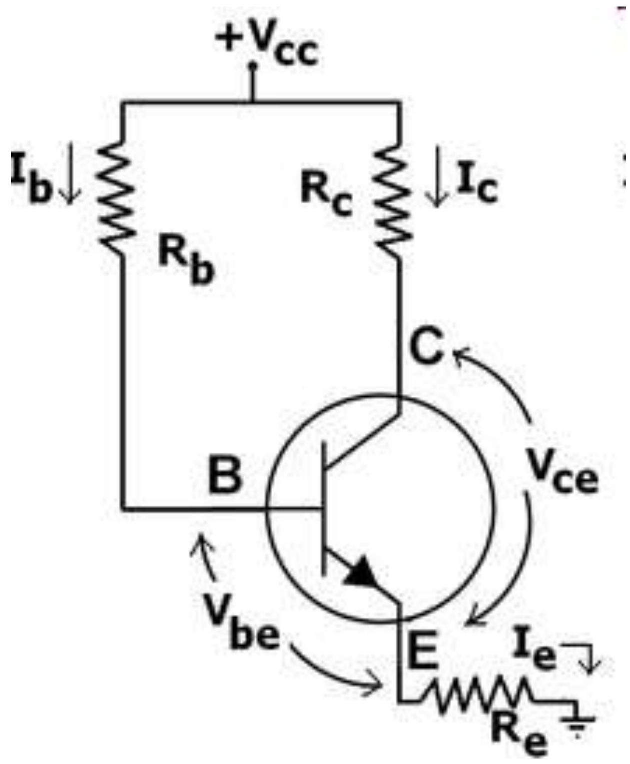
- It is simple to shift the operating point anywhere in the active region by merely changing the base resistor (R_B).
- A very small number of components are required.

Demerits:

- The collector current does not remain constant with variation in temperature or power supply voltage. Therefore the operating point is unstable.
- When the transistor is replaced with another one, considerable change in the value of β can be expected. Due to this change the operating point will shift.
- For small-signal transistors (e.g., not power transistors) with relatively high values of β (i.e., between 100 and 200), this configuration will be prone to thermal runaway. In particular, the stability factor, which is a measure of the change in collector current with changes in reverse saturation current, is approximately β+1. To ensure absolute stability of the amplifier, a stability factor of less than 25 is preferred, and so small-signal transistors have large stability factors.

Fixed bias with emitter resistor

The fixed bias circuit is modified by attaching an external resistor to the emitter. This resistor introduces negative feedback that stabilizes the Q-point.



Merits:

- The circuit has the tendency to stabilize operating point against changes in temperature and β-value.

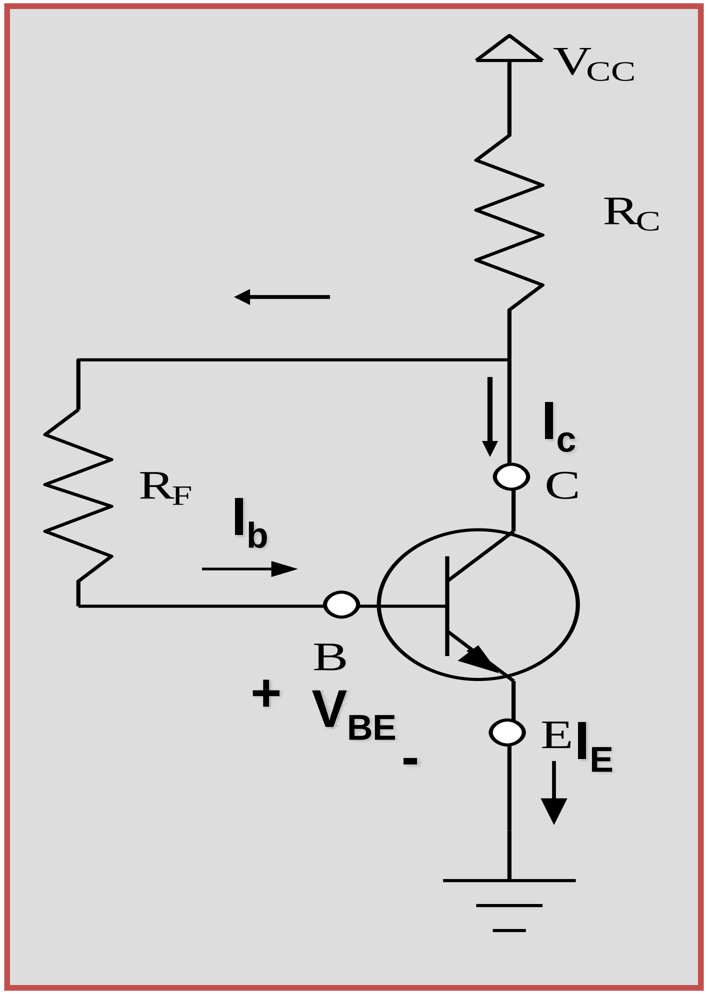
Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping R_E very large, or making R_B very low.
  - If R_E is of large value, high V_{CC} is necessary. This increases cost as well as precautions necessary while handling.
  - If R_B is low, a separate low voltage supply should be used in the base circuit. Using two supplies of different voltages is impractical.
- In addition to the above, R_E causes ac feedback which reduces the voltage gain of the amplifier.

Usage:

The feedback also increases the input impedance of the amplifier when seen from the base, which can be advantageous. Due to the above disadvantages, this type of biasing circuit is used only with careful consideration of the trade-offs involved.

The Collector to Base Bias Circuit



This configuration employs negative feedback to prevent thermal runaway and stabilize the operating point. In this form of biasing, the base resistor R_F is connected to the collector instead of connecting it to the DC source V_{CC}. So any thermal runaway will induce a voltage drop across the R_C resistor that will throttle the transistor's base current.

Applying KVL through base circuit

we can write $(I_b + I_C) R_C + I_b R_f + V_{be} = V_{cc}$

Diff. w. r. t. I_C we get

$$(\partial I_b / \partial I_c) = - R_C / (R_f + R_C)$$

Therefore,
$$S_{Ico} = \frac{(1+\beta)}{1 + [\beta R_C / (R_C + R_f)]}$$

Which is less than $(1+\beta)$, signifying better thermal stability

Merits:

- Circuit stabilizes the operating point against variations in temperature and β (i.e. replacement of transistor)

Demerits:

• As β -value is fixed (and generally unknown) for a given transistor, this relation can be satisfied either by keeping R_c fairly large or making R_f very low.

- If R_c is large, a high V_{cc} is necessary, which increases cost as well as precautions necessary while handling.
- If R_f is low, the reverse bias of the collector–base region is small, which limits the range of collector voltage swing that leaves the transistor in active mode.

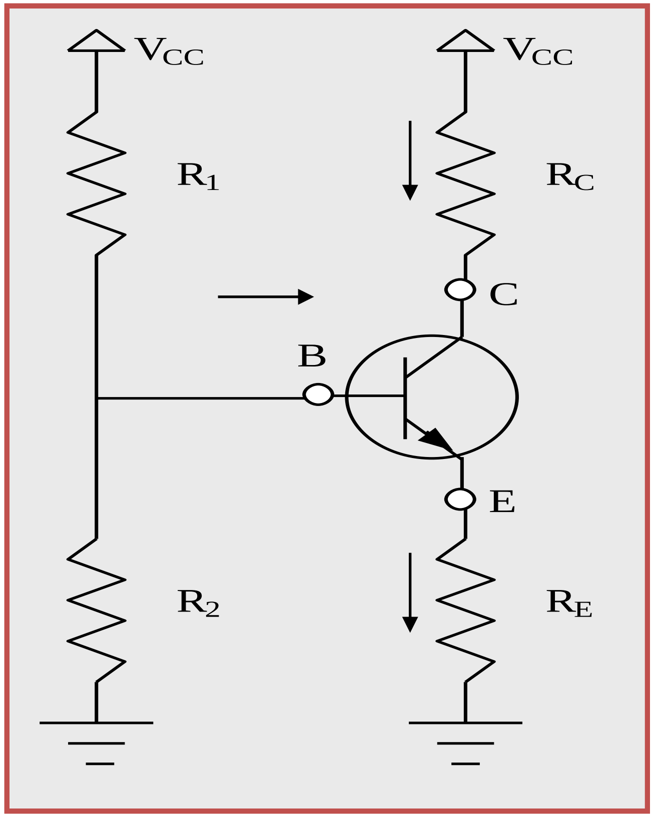
•The resistor R_f causes an AC feedback, reducing the voltage gain of the amplifier. This undesirable effect is a trade-off for greater Q-point stability.

Usage: The feedback also decreases the input impedance of the amplifier as seen from the base, which can be advantageous. Due to the gain reduction from feedback, this biasing form is used only when the trade-off for stability is warranted.

The Potential Divider Bias Circuit

This is the most commonly used arrangement for biasing as it provide good bias stability. In this arrangement the emitter resistance 'R_E' provides stabilization. The resistance 'R_E' cause a voltage drop in a direction so as to reverse bias the emitter junction. Since the emitter-base junction is to be forward biased, the base voltage is obtained from R_1-R_2 network. The net forward bias across the emitter base junction is equal to V_B- dc voltage drop across 'R_E'. The base voltage is set by Vcc and R_1 and R_2. The dc bias circuit is independent of transistor current gain. In case of amplifier, to avoid the loss of ac signal, a capacitor of large capacitance is connected across R_E. The capacitor offers a very small reactance to ac signal and so it passes through the condensor.

The Potential Divider Bias Circuit

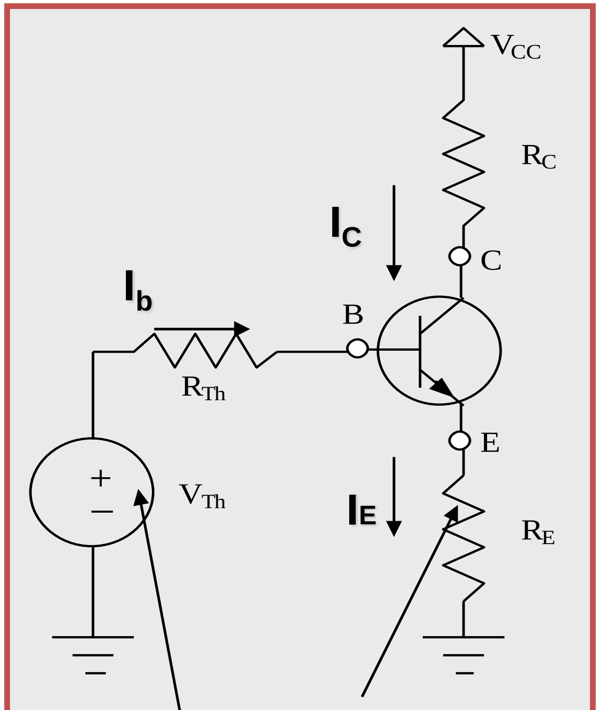


To find the stability of this circuit we have to convert this circuit into its Thevenin's Equivalent circuit

$$R_{th} = \frac{R_1 * R_2}{R_1 + R_2} \quad \& \quad V_{th} = \frac{Vcc\, R_2}{R_1 + R_2}$$

The Potential Divider Bias Circuit

Thevenin Equivalent Ckt



Self-bias Resistor

Thevenin Equivalent Voltage

Applying KVL through input base circuit

we can write $I_bR_{Th} + I_E R_E + V_{be} = V_{Th}$

Therefore, $I_bR_{Th} + (I_C + I_b) R_E + V_{BE} = V_{Th}$

Diff. w. r. t. I_C & rearranging we get

$$(\partial I_b / \partial I_c) = - R_E / (R_{Th} + R_E)$$

Therefore,

$$S_{Ico} = \frac{1+\beta}{1+\left[\beta \frac{R_E}{R_E+R_{Th}}\right]}$$

This shows that S_{Ico} is inversely proportional to R_E and It is less than $(1+\beta)$, signifying better thermal stability

Merits:

- Operating point is almost independent of β variation.
- Operating point stabilized against shift in temperature.

Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping R_E fairly large, or making R1||R2 very low.
  - If R_E is of large value, high V_{CC} is necessary. This increases cost as well

as precautions necessary while handling.

  - If R1 || R2 is low, either R1 is low, or R2 is low, or both are low. A low R1 raises V_B closer to V_C, reducing the available swing in collector voltage, and limiting how large R_C can be made without driving the transistor out of active mode. A low R2 lowers Vbe, reducing the allowed collector current. Lowering both resistor values draws more current from the power supply and lowers the input resistance of the amplifier as seen from the base.
  - AC as well as DC feedback is caused by RE, which reduces the AC voltage gain of the amplifier. A method to avoid AC feedback while retaining DC feedback is discussed below.

Usage:

The circuit's stability and merits as above make it widely used for linear circuits.

BIASING AND BIAS STABILITY

❖ Biasing refers to the establishment of suitable dc values of different currents and voltages of a transistor.

❖ Through proper biasing, a desired quiescent operating point of the transistor amplifier in the active region (linear region) of the characteristics is obtained.

❖ The selection of a proper quiescent point generally depends on the following factors:

(a) The amplitude of the signal to be handled by the amplifier and distortion level in signal

(b) The load to which the amplifier is to work for a corresponding supply voltage

❖ The operating point of a transistor amplifier shifts mainly with changes in temperature, since the transistor parameters — *β*, I_{CO} *and* V_{BE} *(where the symbols carry their usual meaning)—are functions of* temperature.

❖ **Circuit Configurations**

- **Fixed-bias circuit**
- **Fixed bias with emitter resistance**
- **Voltage-divider bias**
- **Voltage-feedback biasing**

BIASING AND BIAS STABILITY

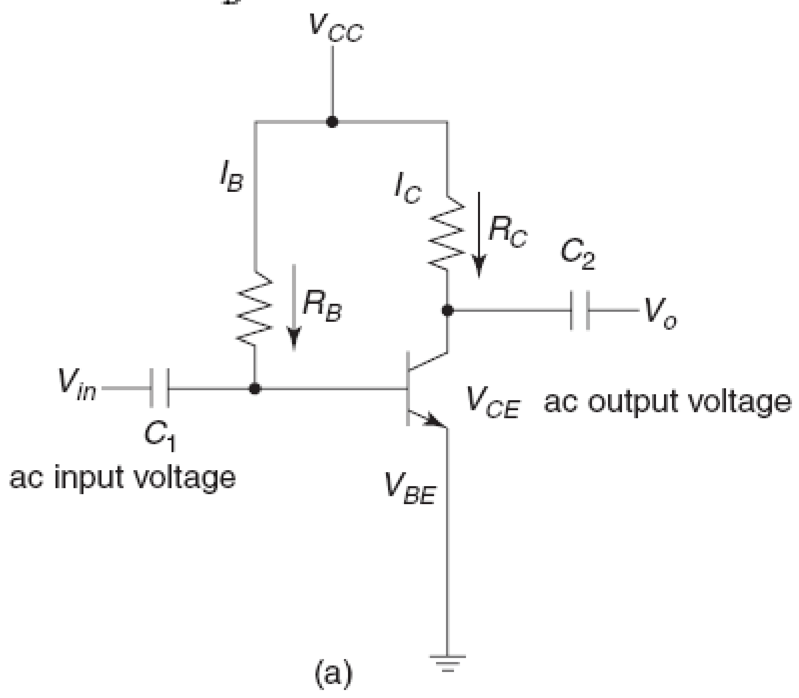
- **Fixed-bias circuit**
  - Base–emitter loop
  - Collector–emitter loop

$$V_{CC} = I_B R_B + V_{BE}$$

$$V_{CE} = V_{CC} - I_C R_C \quad \text{and} \quad I_C = \beta I_B$$

$$\text{or, } I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$\text{or, } I_C = \frac{V_{CC} - V_{CE}}{R_C}$$



(a) Representation of fixed-bias circuit (b) Equivalent circuit

BIASING AND BIAS STABILITY

- **Fixed bias with emitter resistance**
  - Base–emitter loop

$$V_{CC} = I_B R_B + V_{BE} + I_E R_E$$

and the emitter current can be written as $I_E = (\beta + 1) I_B$

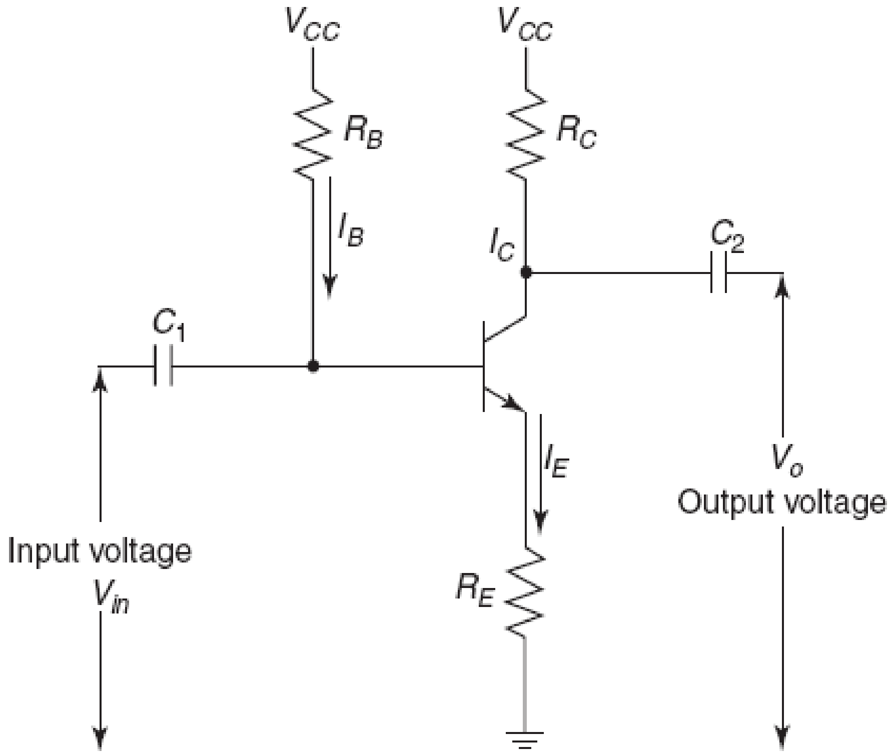
From above two equation we get:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1) R_E}$$

  - Collector–emitter loop

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

with the base current known, I_C *can be easily calculated by the relation* $I_C = \beta I_B$.



Fixed-bias circuit with emitter resistance

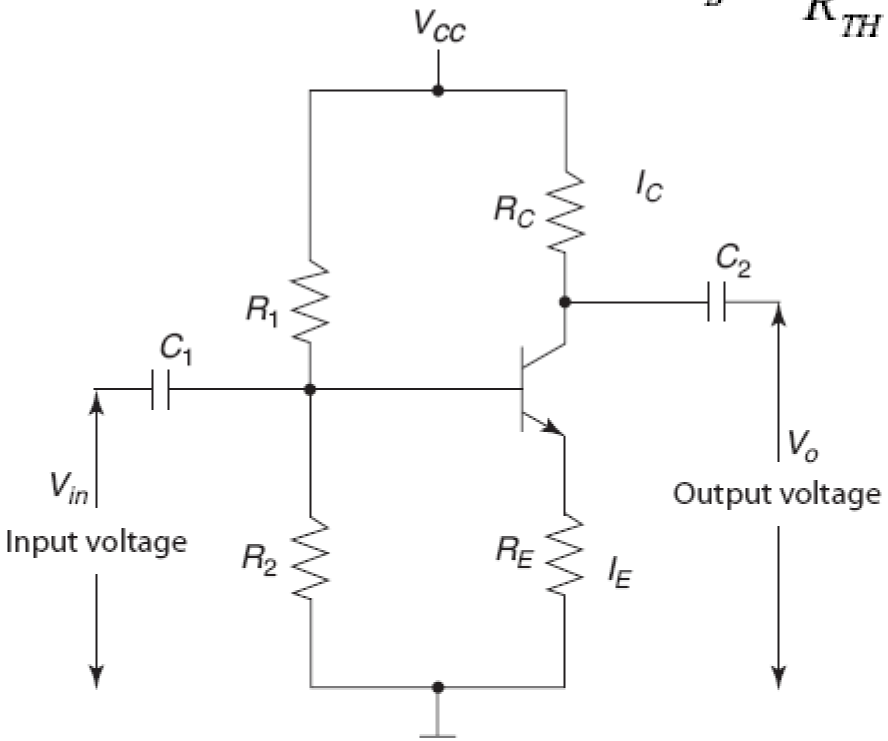
BIASING AND BIAS STABILITY

➤ **Voltage-divider bias:-** The Thevenins equivalent voltage and resistance for the input side is given by:

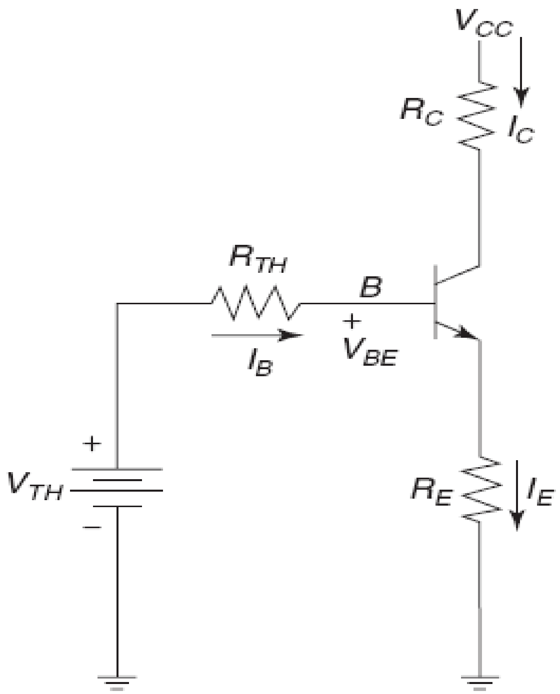
$$V_{TH} = V_{CC}\frac{R_2}{R_1 + R_2} \quad \text{and} \quad R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

The KVL equation for the input circuit is given as:

$$I_B = \frac{V_{TH} - V_{BE}}{R_{TH} + (\beta + 1)R_E}$$



Voltage-divider bias circuit



Simplified voltage-divider circuit

BIASING AND BIAS STABILITY

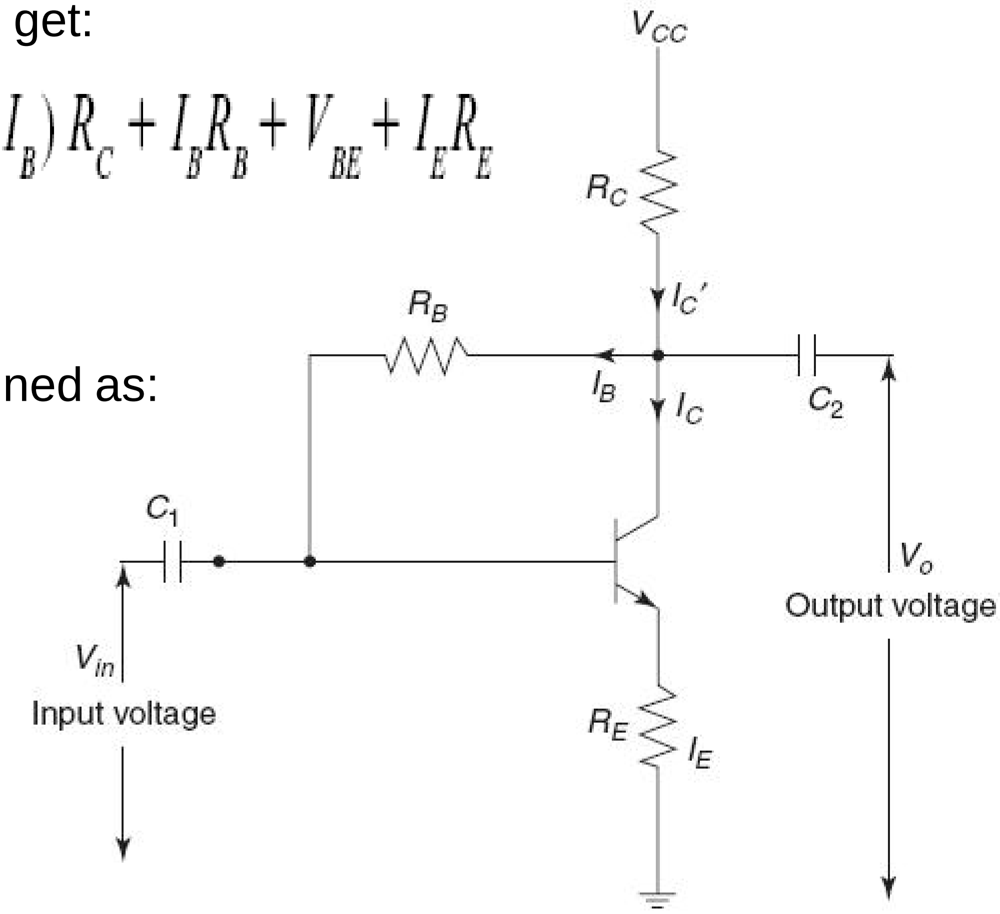
- **Voltage-feedback biasing**
  - Base–emitter loop

  Applying KVL for this part, we get:

$$V_{CC} = I_C' R_C + I_B R_B + V_{BE} + I_E R_E = (I_C + I_B) R_C + I_B R_B + V_{BE} + I_E R_E$$

Thus, the base current can be obtained as:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)}$$

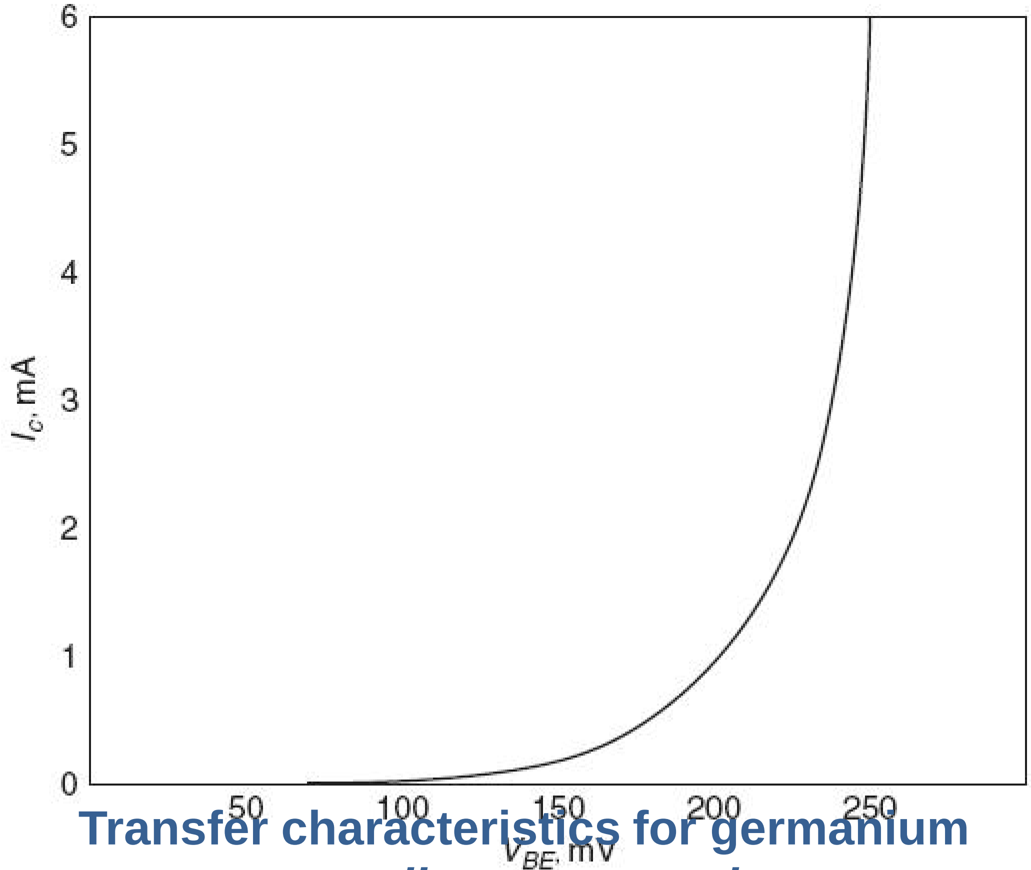


Representation of Voltage-feedback biased circuit

BIASING AND BIAS STABILITY

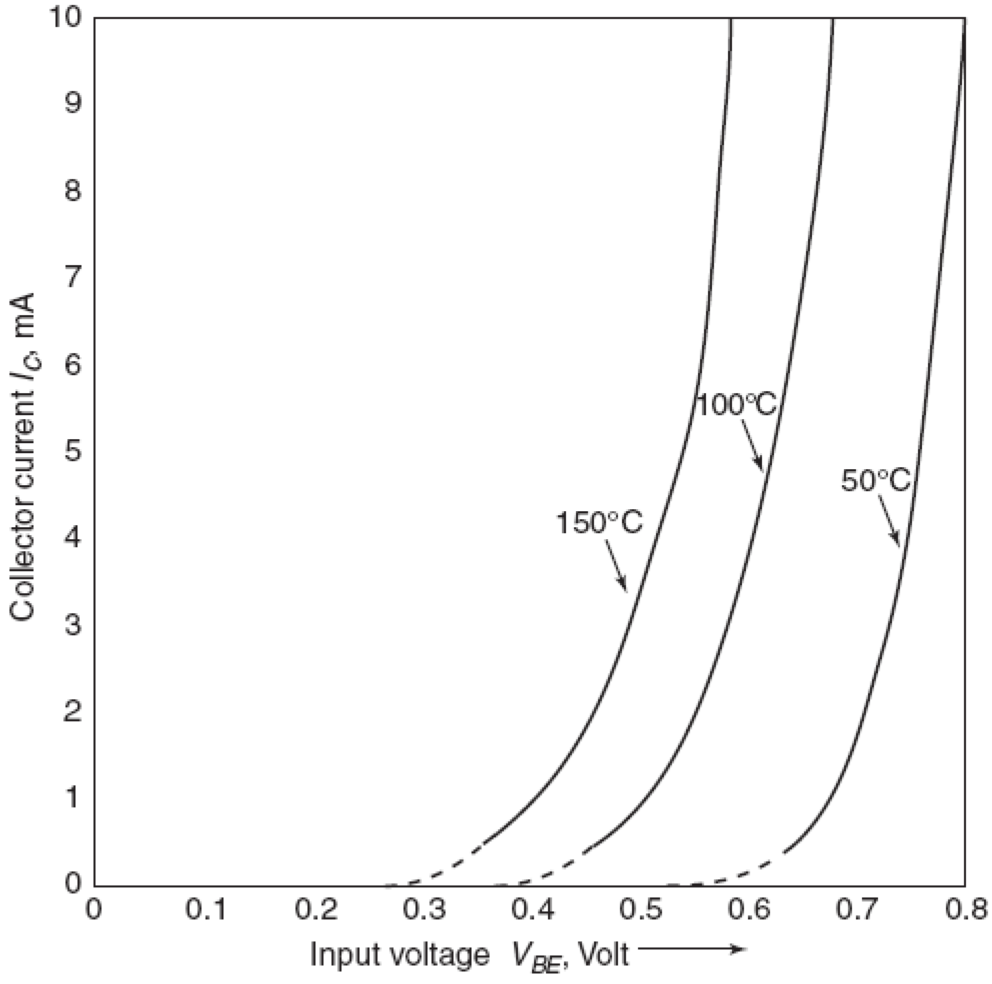
❖ **Stabilization Against Variations in *ICO, VBE , and β***

➢**Transfer characteristic:-** In this particular characteristic, the output current I_C *is a function of input voltage for* the germanium transistor. Thus, the word “transfer” is used for this characteristic.

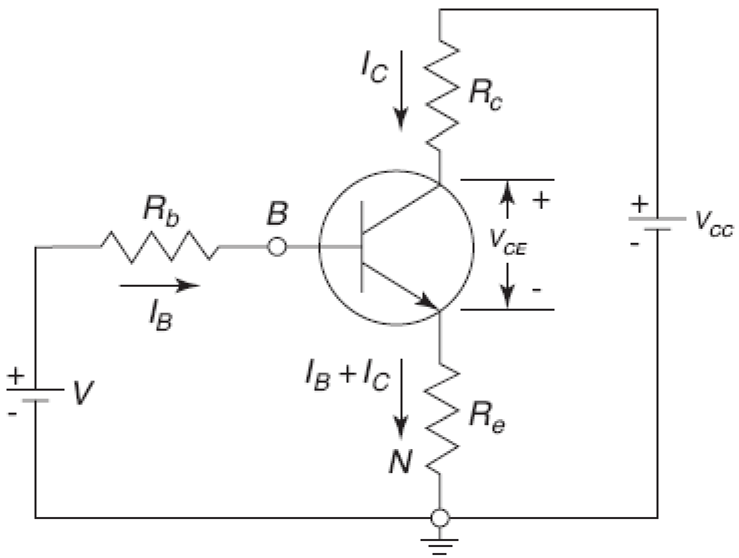


Transfer characteristics for germanium *p–n–p alloy type transistor*

BIASING AND BIAS STABILITY

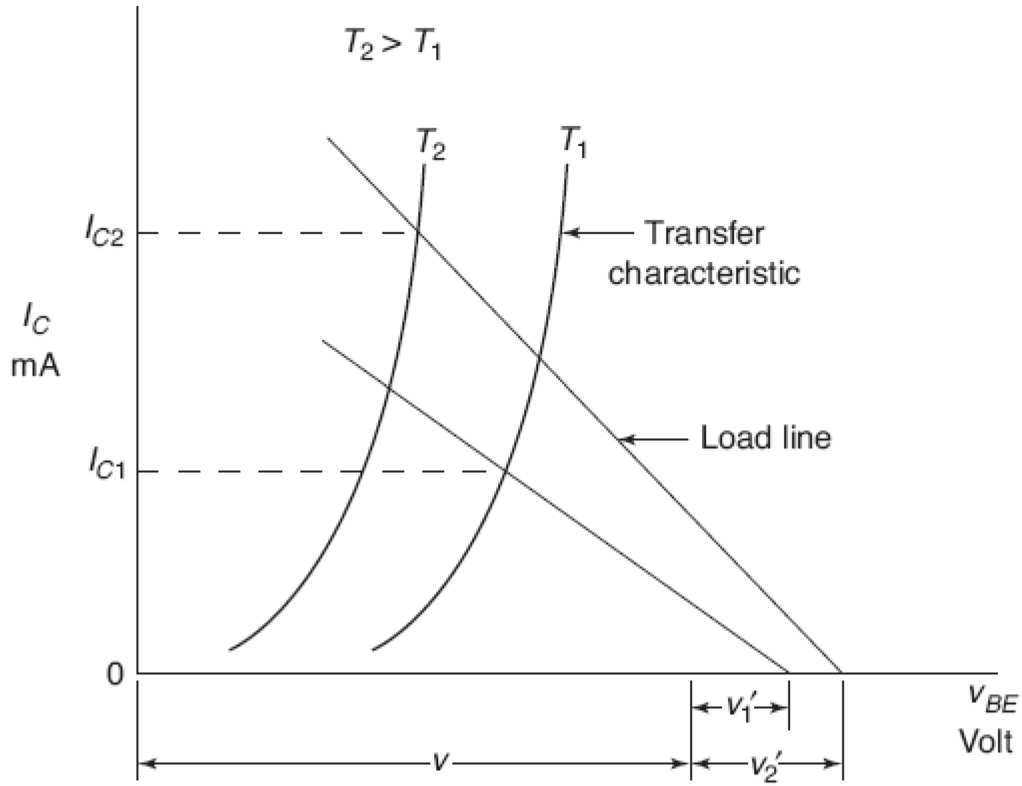


Collector current vs. base-to-emitter voltage for a silicon transistor



Self-bias circuit

BIASING AND BIAS STABILITY



Variation of the collector current with temperature because of *VBE, ICO and β*

Transistor Biasing

- For a transistor to function properly as an amplifier, an external dc supply voltage must be applied to produce the desired collector current.
- Bias is defined as a control voltage or current.
- Transistors must be biased correctly to produce the desired circuit voltages and currents.
- The most common techniques used in biasing are
  - Base bias
  - Voltage-divider bias
  - Emitter bias

Transistor Biasing

- Fig. -1 (a) shows the simplest way to bias a transistor, called **base bias**.
- V_{BB} is the base supply voltage, which is used to forward-bias the base-emitter junction.
- R_B is used to provide the desired value of base current.
- V_{CC} is the collector supply voltage, which provides the reverse-bias voltage required for the collector-base junction.
- The collector resistor, R_C, provides the desired voltage in the collector circuit

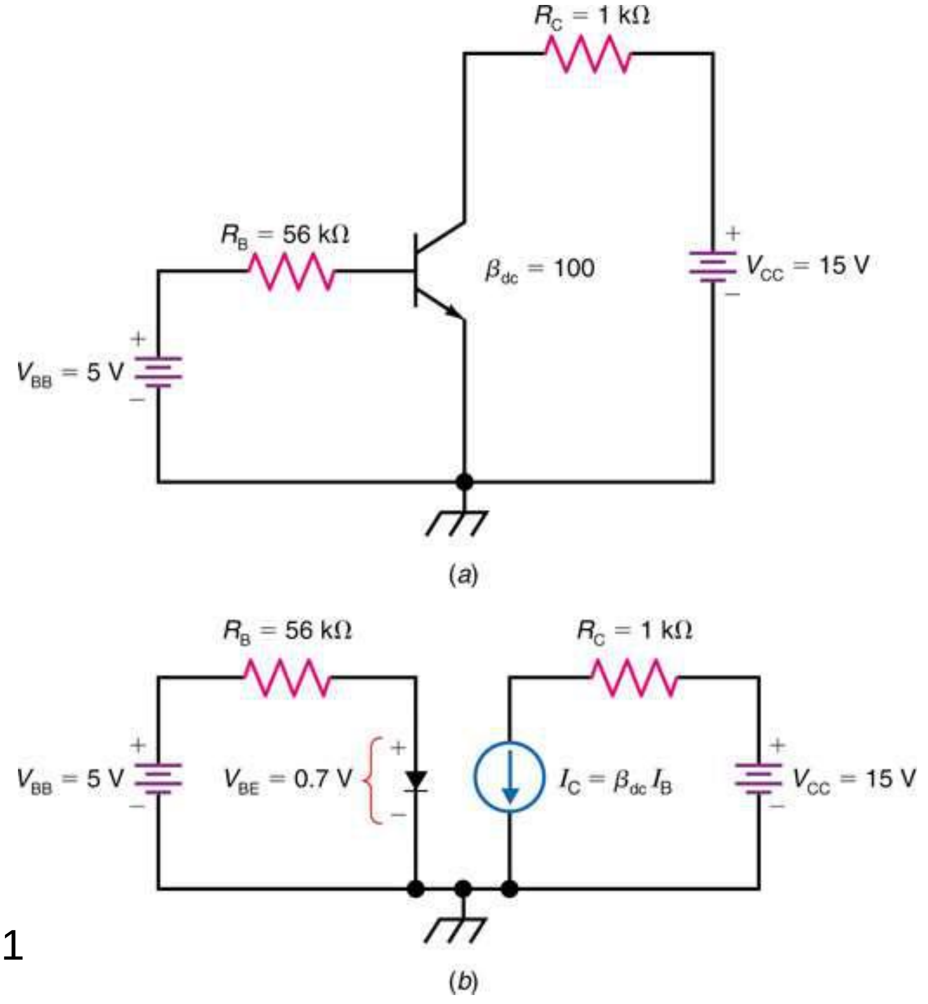


Fig. -1

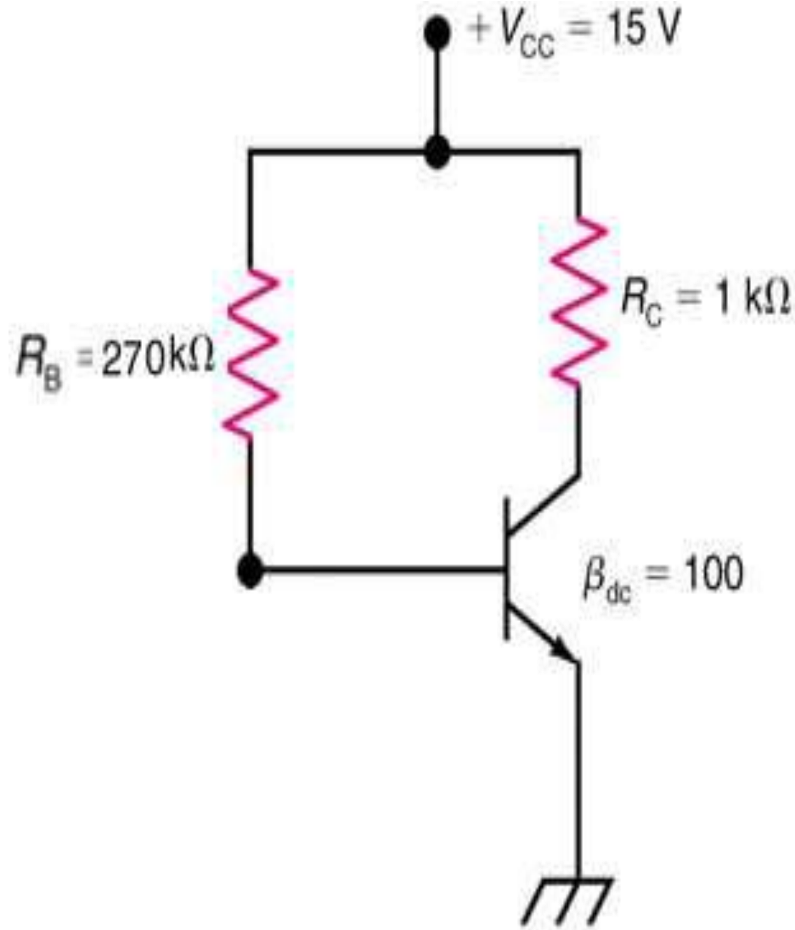
Transistor Biasing: Base Biasing

- A more practical way to provide base bias is to use one power supply.

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C \approx \beta_{dc} \times I_B$$

$$V_{CE} \approx V_{CC} - I_C R_C$$



Transistor Biasing

- The **dc load line** is a graph that allows us to determine all possible combinations of I_C and V_{CE} for a given amplifier.

- For every value of collector current, I_C, the corresponding value of V_{CE} can be found by examining the dc load line.

- A sample dc load line is shown in Fig. 1.

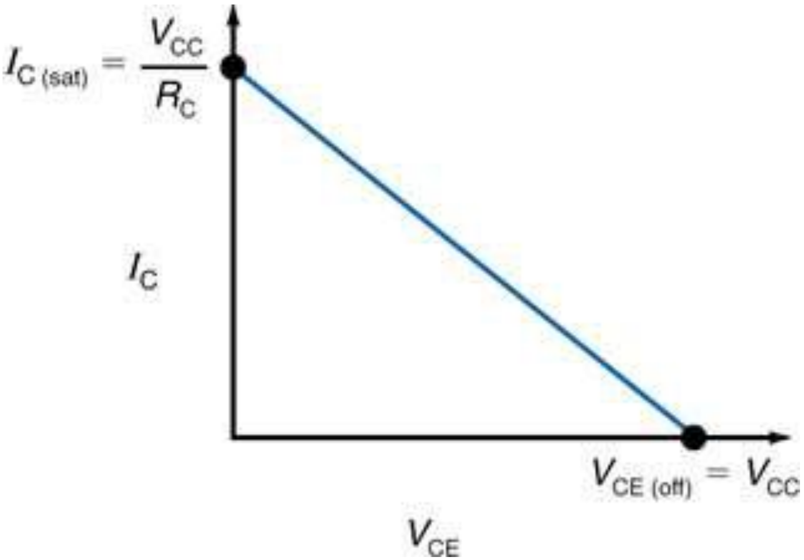


Fig. 1

Transistor Biasing

Midpoint Bias

- Without an ac signal applied to a transistor, specific values of I_C and V_{CE} exist at a specific point on a dc load line
- This specific point is called the Q point (quiescent currents and voltages with no ac input signal)
- An amplifier is biased such that the Q point is near the center of dc load line
  - $I_{CQ} = ½ I_{C(sat)}$
  - $V_{CEQ} = ½ V_{CC}$
- Base bias provides a very unstable Q point, because I_C and V_{CE} are greatly affected by any change in the transistor's beta value

Transistor Biasing

Fig. 2 illustrates a **dc load line** showing the end points I_C (sat) and $V_{CE\ (off)}$, as well as the Q point values I_{CQ} and V_{CEQ}.

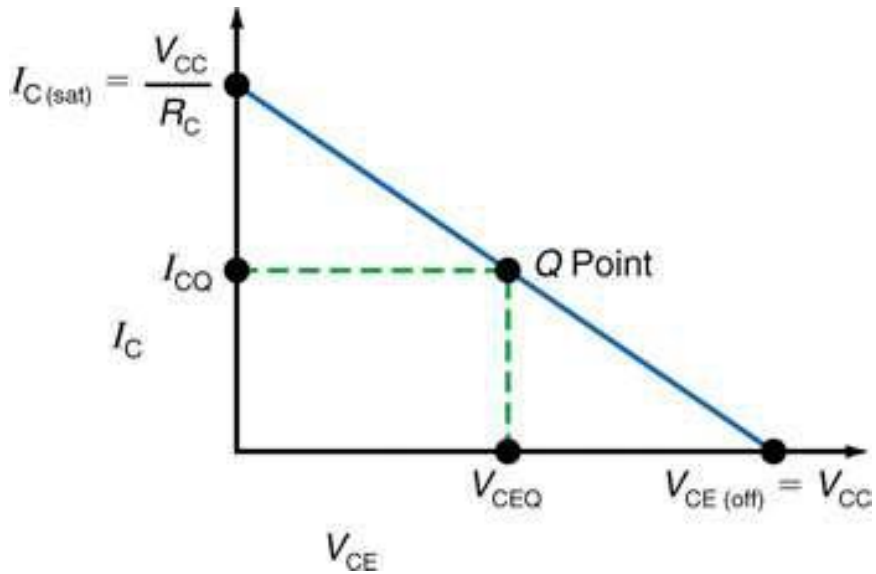
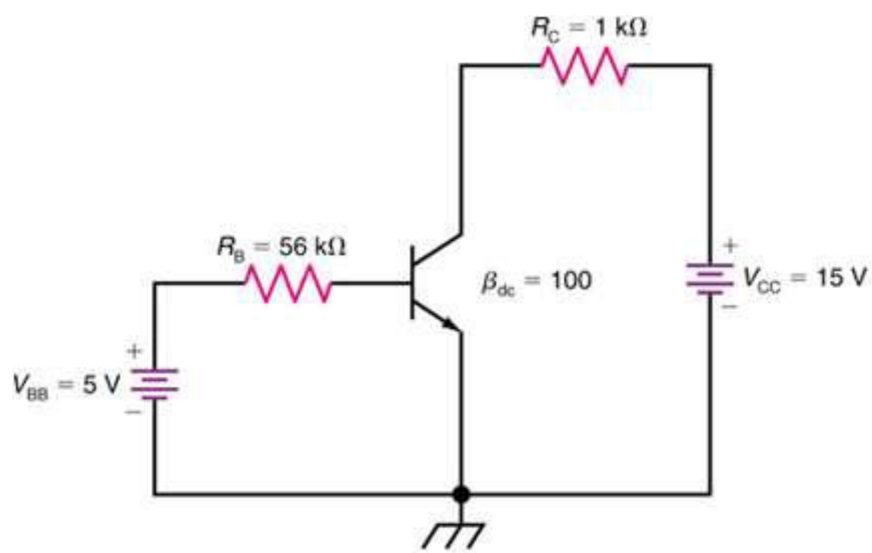


Fig. 2

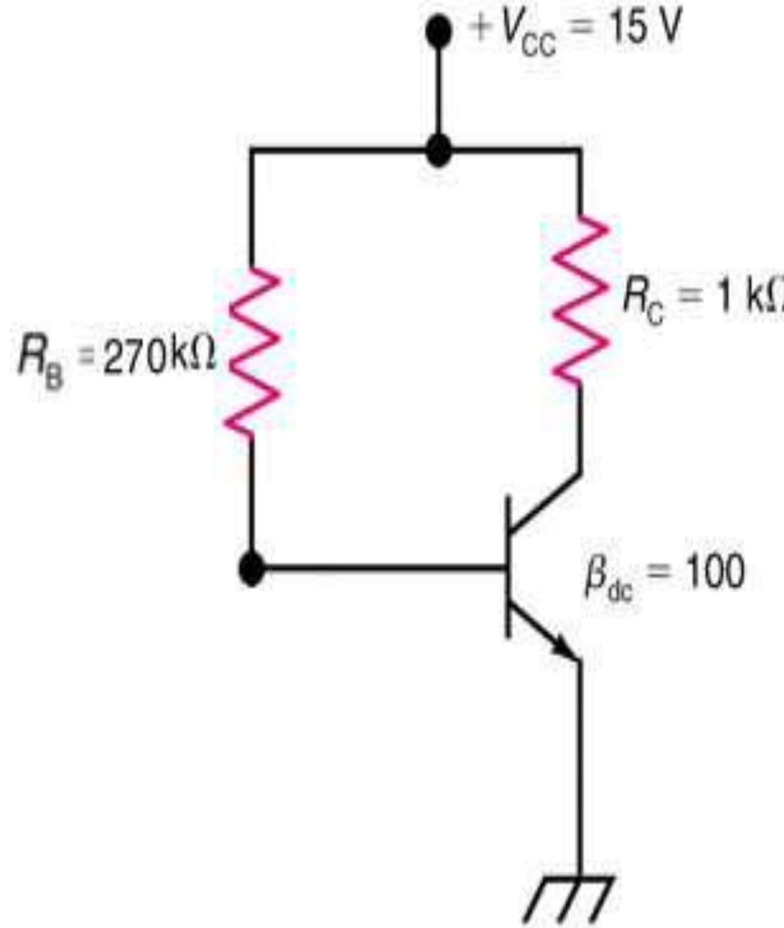
Base Bias – Example 1

- Solve for I_B, I_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



Base Bias – Example 2

- Solve for I_B, I_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



28-6: Transistor Biasing

- The most popular way to bias a transistor is with **voltage-divider bias**.
- The advantage of voltage-divider bias lies in its stability.
- An example of voltage-divider bias is shown in Fig. 28-18.

$$V_B = \frac{R_2}{R_1 + R_2} \times V_{CC}$$

$$V_E = V_B - V_{BE}$$

$$I_E \approx I_C$$

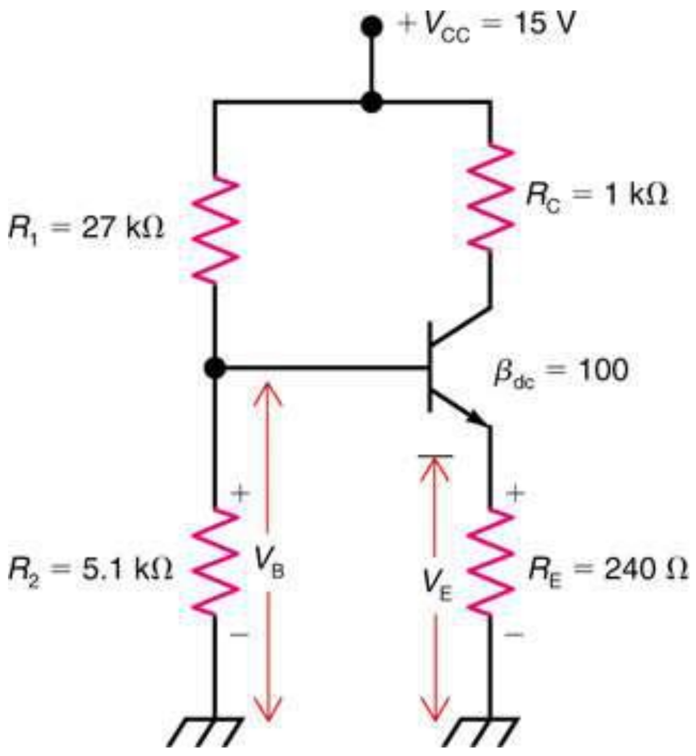
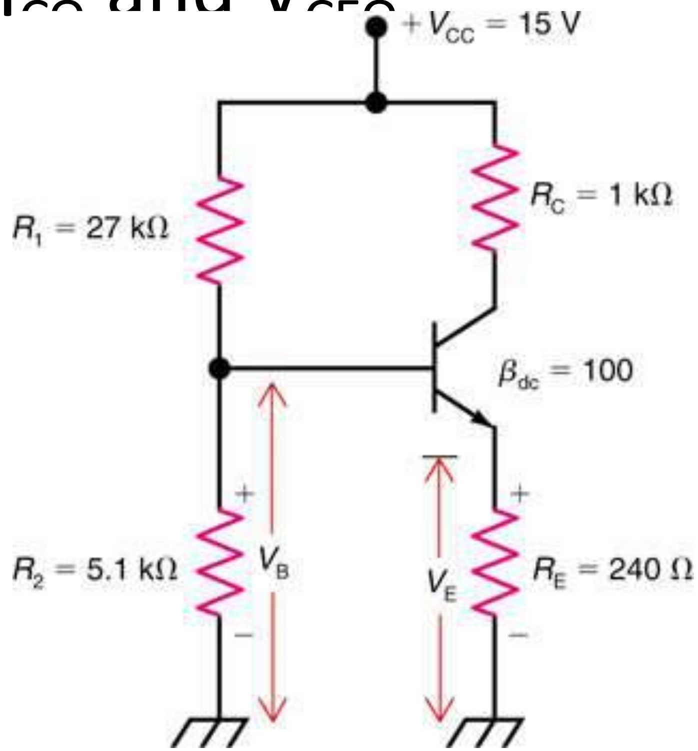


Fig. 28-18

Voltage Divider Bias – Example

- Solve for V_B, V_E, I_E, I_C, V_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



28-6: Transistor Biasing

- Fig. 28-19 shows the **dc load line** for voltage-divider biased transistor circuit in Fig. 28-18.
- End points and Q points are
  - I_C (sat) = 12.09 mA
  - V_{CE} (off) = 15 V
  - I_{CQ} = 7 mA
  - V_{CEQ} = 6.32 V

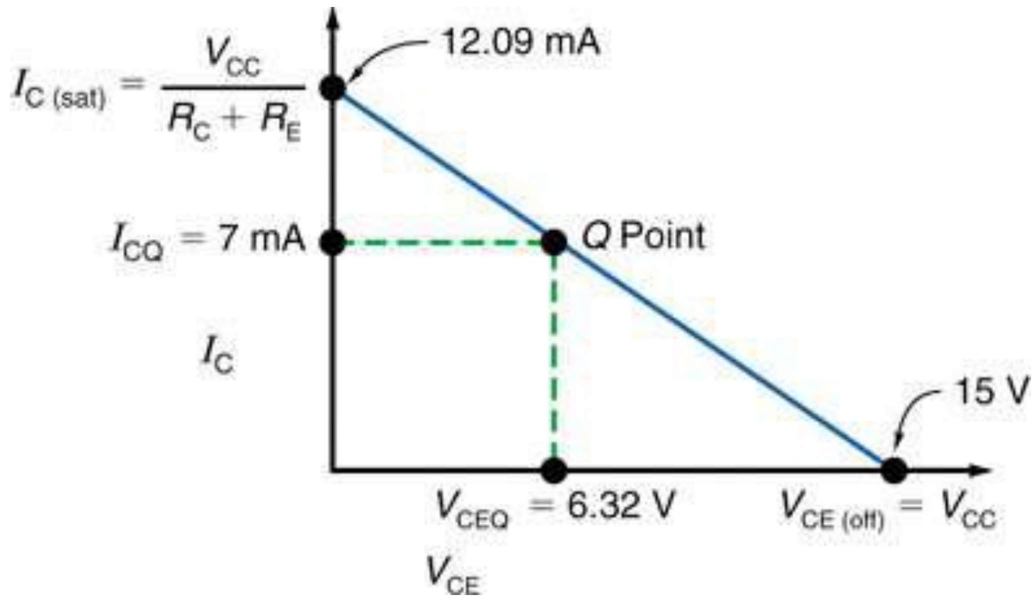


Fig. 28-19

Transistor Biasing

- Both positive and negative power supplies are available

- **Emitter bias** provides a solid Q point that fluctuates very little with temperature variation and transistor replacement.

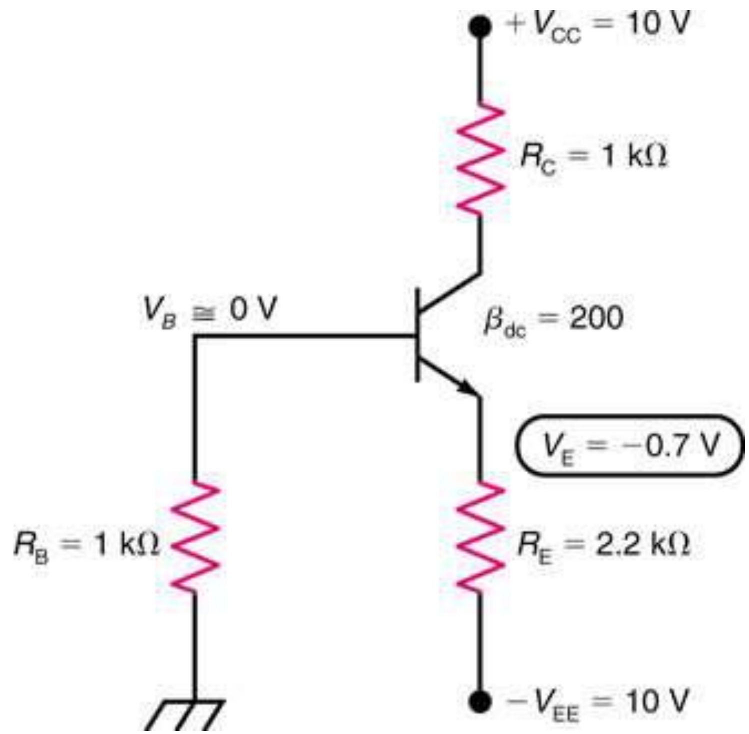
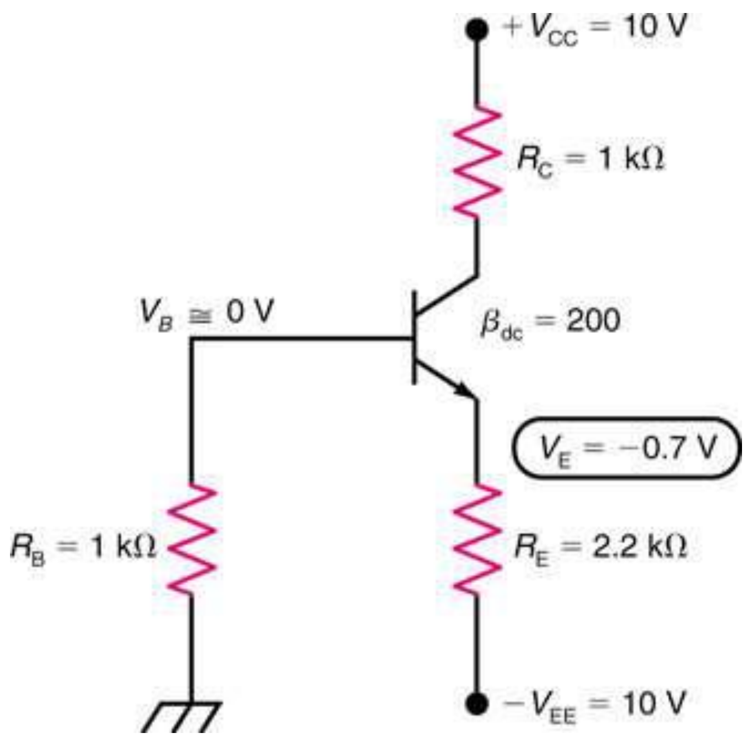


Fig.

Emitter Bias – Example

- Solve for I_E, and V_C



CALCULATION OF STABILITY FACTORS

❖ **Stability Factor *S*:-** The stability factor *S, as the change of collector current with respect to the reverse saturation* current, keeping β *and* V_{BE} *constant. This can be written as:*

$$S \equiv \frac{\partial I_C}{\partial I_{CO}} \qquad \text{Or,} \qquad S = (1+\beta)\frac{1 + R_b/R_e}{1+\beta+R_b/R_e}$$

❖ **Stability Factor *S'*:-** The variation of I_C *with* V_{BE} *is given by the stability factor S defined by the partial derivative:*

$$S' \equiv \frac{\partial I_C}{\partial V_{BE}} \approx \frac{\Delta I_C}{\Delta V_{BE}}$$

❖ **Stability Factor *S"*:-** The variation of I_C *with respect to β is represented by the stability factor, S", given as:*

$$S'' \equiv \frac{\partial I_C}{\partial \beta} \approx \frac{\Delta I_C}{\Delta \beta}$$

❖ **General Remarks on Collector Current Stability:-** The stability factors have been defined earlier keeping in mind the change in collector current with respect to changes in I_{CO} *,* V_{BE} *and β. These stability factors are repeated here for simplicity.*

$$\frac{\Delta I_C}{\Delta_{C1}} = \left(1 + \frac{R_b}{R_e}\right)\frac{M_1 \Delta I_{CO}}{I_{C1}} - \frac{M_1 \Delta V_{BE}}{I_{C1} R_e} + \left(1 + \frac{R_b}{R_e}\right)\frac{M_2 \Delta\beta}{\beta_1 \beta_2}$$

Thermal Runaway

The maximum average power $P_{D(max)}$ which a transistor can dissipate depends upon the transistor construction and may lie in the range from a few milliwatts to 200 W. As mentioned earlier, the power dissipated within a transistor is predominantly the power dissipated at its collector base junction. Thus maximum power is limited by the temperature that the collector-base junction can withstand. For silicon transistor this temperature is in the range 150 to 225 °C, and for germanium it is between 60 to 100 °C. The collector-base junction temperature may rise because of two reasons :

- Due to rise in ambient temperature
- Due to self heating.

The self heating can be explained as follows :

The increase in the collector current increases the power dissipated at the collector junction. This, in turn further increases the temperature of the junction and hence increase in the collector current. The process is cumulative and it is referred to as **self heating**. The excess heat produced at the collector base junction may even burn and destroy the transistor. This situation is called '**Thermal runaway**' of the transistor.

Thermal Resistance

The steady state temperature rise at the collector junction is proportional to the power dissipated at the junction. It is given as

$$\partial T = T_j - T_A = \theta P_D \quad \text{... (1)}$$

The Condition for Thermal Stability

As we know, the thermal runaway may even burn and destroy the transistor, it is necessary to avoid thermal runaway. The required condition to avoid thermal runaway is that the rate at which heat is released at the collector junction must not exceed the rate at which the heat can be dissipated. It is given by,

$$\frac{\partial P_C}{\partial T_j} < \frac{\partial P_D}{\partial T_j} \qquad \text{... (3)}$$

If we differentiate equation (1)

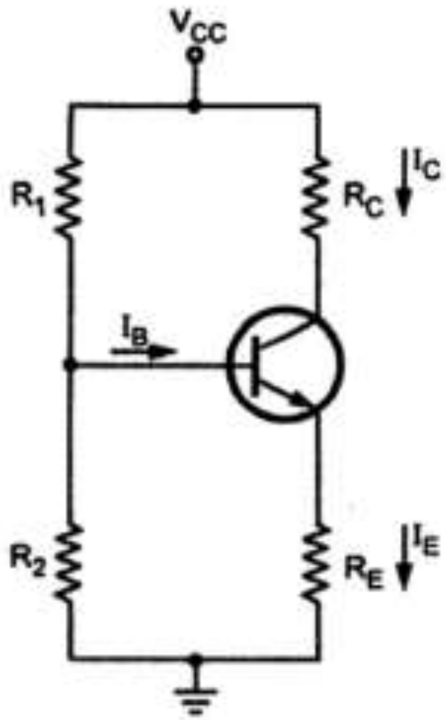
$T_j - T_A = \theta P_D$ with respect to T_j we get,

$$1 = \theta \frac{\partial P_D}{\partial T_j}$$

$$\therefore \quad \frac{\partial P_D}{\partial T_j} = \frac{1}{\theta} \qquad \text{... (4)}$$

Now substituting equation (4) in equation (3) we get

$$\frac{\partial P_C}{\partial T_j} < \frac{1}{\theta} \qquad \text{... (5)}$$



This condition must be satisfied to prevent thermal runaway. By proper design of biasing circuit it is possible to ensure that the transistor cannot runaway below a specified ambient temperature or even under any condition.

Let us consider voltage divider bias circuit for the analysis.

From the Fig. 1.73 we can say that,

P_C = Heat generated at the collector junction

= D.C. Power input to the circuit – The power lost as I^2R in R_C and R_E

$$P_C = V_{CC} \times I_C - I_C^2 R_C - I_E^2 R_E \quad \text{... (6)}$$

If we consider $I_C \cong I_E$ we get

$$P_C = V_{CC} \times I_C - I_C^2 (R_C + R_E) \quad \text{... (7)}$$

Differentiating equation (7) with respect to I_C we get

$$P_C = V_{CC} \times I_C - I_C^2 (R_C + R_E) \qquad \dots (7)$$

Differentiating equation (7) with respect to I_C we get

$$\frac{\partial P_C}{\partial I_C} = V_{CC} - 2 I_C (R_C + R_E) \qquad \dots (8)$$

Referring and rewriting condition equation (5) to avoid thermal runaway we get,

$$\frac{\partial P_C}{\partial I_C} \cdot \frac{\partial I_C}{\partial T_j} < \frac{1}{\theta} \qquad \dots (9)$$

In the above equation $\frac{\partial I_D}{\partial T_j}$ can be written as,

$$\frac{\partial I_D}{\partial T_j} = S\frac{\partial I_{CO}}{\partial T_j} + S'\frac{\partial V_{BE}}{\partial T_j} + S''\frac{\partial \beta}{\partial T_j} \qquad \dots (10)$$

Since junction temperature affects collector current by affecting I_{CO}, V_{BE} and β. But as ve are doing analysis for thermal runaway the affect of I_{CO} dominates. Thus we can write

$$\frac{\partial I_C}{\partial T_j} = \frac{\partial I_{CO}}{\partial T_j} \qquad \dots (11)$$

As the reverse saturation current for both silicon and germanium increases about 7 percent per °C, we can write

$$\frac{\partial I_{CO}}{\partial T_j} = 0.07\, I_{CO} \qquad \text{... (12)}$$

Now substituting value of $\frac{\partial I_C}{\partial T_j}$ and $\frac{\partial P_C}{\partial I_C}$ in equation (11) we get,

$$\frac{\partial I_C}{\partial T_j} = S \times 0.07\, I_{CO} \qquad \text{... (13)}$$

Now substituting value of $\frac{\partial I_C}{\partial T_j}$ and $\frac{\partial P_C}{\partial I_C}$ from equations (13) and (8) into equation (9) we get,

$$[V_{CC} - 2\, I_C\, (R_C + R_E)]\, (S)\, (\, 0.07\, I_{CO}) < \frac{1}{\theta} \qquad \text{... (14)}$$

As S, I_{CO} and θ are positive, we see that the inequality in equation (14) is always satisfied provided that the quantity in the square bracket is negative.

$$\therefore \quad V_{CC} < 2 I_C (R_C + R_E)$$

$$\therefore \quad \frac{V_{CC}}{2} < I_C (R_C + R_E) \qquad \text{... (15)}$$

Applying KVL to the collector circuit of Fig. 1.73 we get,

$$V_{CE} = V_{CC} - I_C (R_E + R_C) \quad \because \quad I_C \cong I_E$$

$$\therefore \quad I_C (R_E + R_C) = V_{CC} - V_{CE}$$

Substituting value of $I_C (R_E + R_C)$ in equation (15) we get,

$$\frac{V_{CC}}{2} < V_{CC} - V_{CE}$$

$$\therefore \quad V_{CE} < V_{CC} - \frac{V_{CC}}{2}$$

$$\therefore \quad V_{CE} < \frac{V_{CC}}{2}$$

Thus if $V_{CE} < \frac{V_{CC}}{2}$, the stability is ensured. But in transformer coupled circuit, R_C and R_E are quite small and $V_{CE} \cong V_{CC}$. Hence it is necessary to design transformer coupled circuits with stability factor as close to 1 as possible to avoid thermal runaway.

. **Diode Compensation Techniques**

Compensation for V_{BE} :

a) Diode in Emitter Circuit

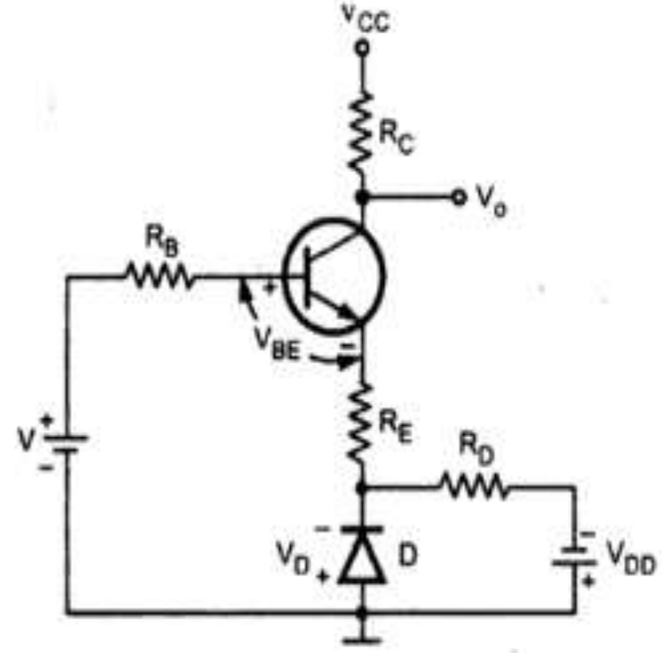


Fig. Stabilization by means of voltage divider bias and diode compensation technique

Fig. shows the voltage divider bias with bias compensation technique.

Here, separate supply V_{DD} is used to keep diode in forward biased condition. If the diode used in the circuit is of same material and type as the transistor, the voltage across the diode will have the same temperature coefficient ($-2.5\,mV/°C$) as the base to emitter voltage V_{BE}. So when V_{BE} changes by ∂V_{BE} with change in temperature, V_D changes by ∂V_D and

$\partial V_D' \approx \partial V_{BE}$, the changes tend to cancel each other.

We know,

$$V_{BE} = V_T \frac{[R_B + (1+\beta)R_E]}{\beta} I_C + \left[\frac{(R_E + R_B)(1+\beta)}{\beta}\right] I_{CO}$$

$$\therefore \quad \frac{[R_B + (1+\beta)R_E]}{\beta} I_C = V_T - V_{BE} + \left[\frac{(R_E + R_B)(1+\beta)}{\beta}\right] I_{CO}$$

$$\therefore \quad I_C = \frac{\beta[V_T - V_{BE}] + (R_E + R_B)(1+\beta) I_{CO}}{R_B + (1+\beta) R_E} \quad \text{... (1)}$$

If we write KVL to the base circuit of the Fig. 1.36, then equation 1 becomes

$$I_C = \frac{\beta[V - (V_{BE} - V_D)] + (R_E + R_B)(1+\beta) I_{CO}}{R_B + (1+\beta) R_E} \quad \text{... (2)}$$

Since V_D tracks V_{BE} with respect to temperature, it is clear from equation (2) that I_C will be insensitive to variations in V_{BE}.

Compensation for I_{co}

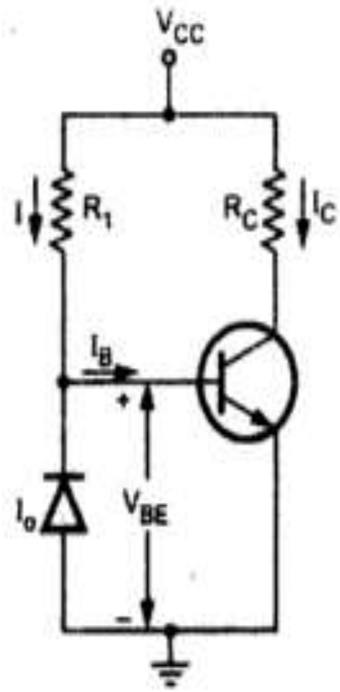


Fig. Diode compensation for a germanium transistor

In case of germanium transistors, changes in I_{CO} with temperature are comparatively larger than silicon transistor. Thus, in germanium transistor changes in I_{CO} with temperature play the more important role in collector current stability than the changes in the V_{BE}. The Fig. shows diode compensation technique commonly used for stabilizing germanium transistors. It offers stabilization against variation in I_{CO}. In this circuit diode is kept in reverse biased condition. In reverse biased condition the current flowing through diode is only the leakage current. If the diode and the transistor are of the same type and material, the leakage current I_O of the diode will increase with temperature at the same rate as the collector leakage current I_{CO}.

Thermistor Compensation

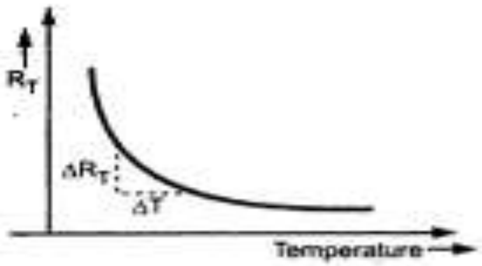


Fig. Temperature Vs R_T resistance of thermistor

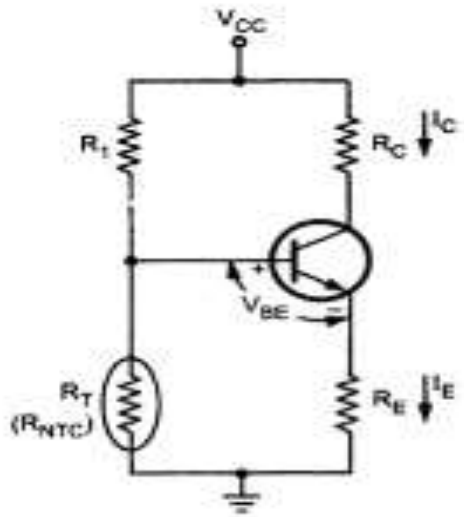


Fig. (a) Thermistor compensation technique

This method of transistor compensation uses temperature sensitive resistive elements, thermistors rather than diodes or transistors. It has a negative temperature coefficient, its resistance decreases exponentially with increasing temperature as shown in the Fig. 1.36.

$$\text{Slope of this curve} = \frac{\partial R_T}{\partial T}$$

$\frac{\partial R_T}{\partial T}$ is the temperature coefficient for thermistor, and the slope is negative. So we can say that thermistor has negative temperature coefficient of resistance (NTC). Fig. (a) shows thermistor compensation technique. As shown in Fig. 1.37 (a), R_2 is replaced by thermistor R_T in self bias circuit. With increase in temperature, R_T decreases. Hence voltage drop across it also decreases. This voltage drop is nothing but the voltage at the base with respect to ground. Hence, V_{BE} decreases which reduces I_B. This behaviour will tend to offset the increase in collector current with temperature.

We know, $I_C = \beta I_B + (1+\beta) I_{CBO}$

In this equation, there is increase in I_{CBO} and decrease in I_B which keeps I_C almost constant.

Sensistor Compensation Technique

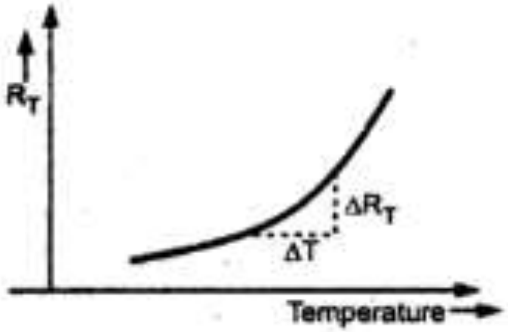
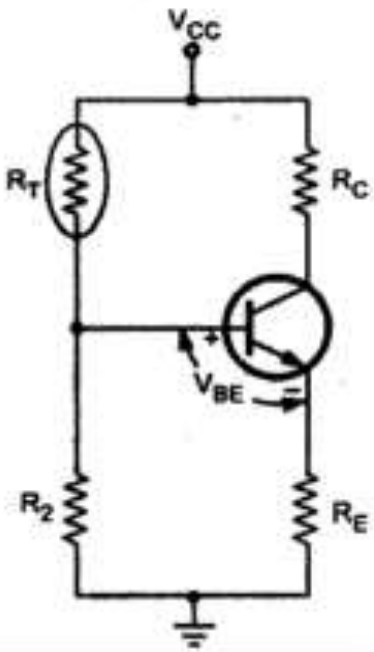


Fig. 1 Temperature Vs resistance of sensistor, R_T



This method of transistor compensation uses temperature sensitive resistive element, sensistors rather than diodes or transistors. It has a positive temperature coefficient, its resistance increases exponentially with increasing temperature as shown in the Fig. 1 .

$$\text{Slope of this curve} = \frac{\partial R_T}{\partial T}$$

$\frac{\partial R_T}{\partial T}$ is the temperature coefficient for thermistor, and the slope is positive.

So we can say that sensistor has positive temperature coefficient of resistance (PTC).

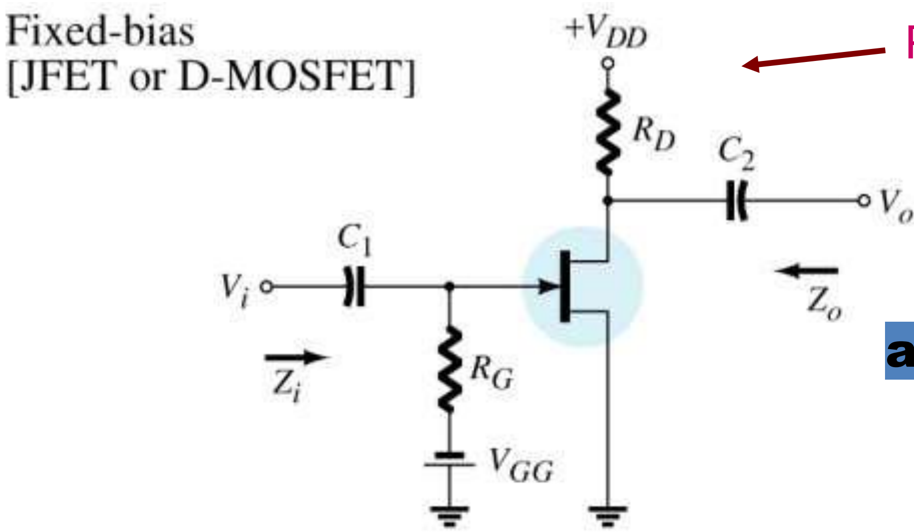
Fig. shows sensistor compensation technique.

As shown in Fig. 1.39, R_1 is replaced by sensistor R_T in self bias circuit. Now, R_T and R_2 are the two resistors of the potential divider.

Biasing Circuits used for JFET

- Fixed bias circuit
- Self bias circuit
- Potential Divider bias circuit

JFET (n-channel) Biasing Circuits



For Fixed Bias Circuit

Applying KVL to gate circuit we get

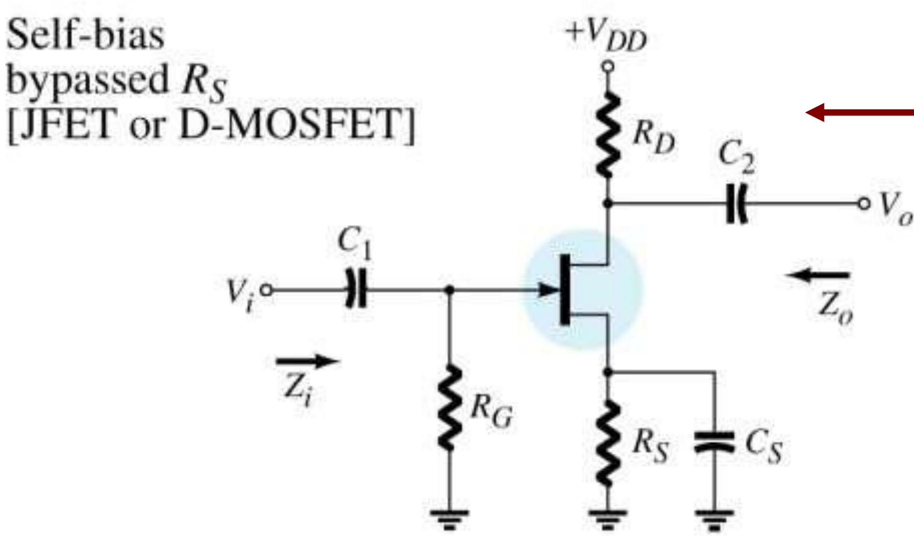
$$V_{GG} = I_G R_G + V_{GS} = V_{GS} = Fixed, \because I_G = 0$$

and

$$I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

and $V_{DS} = V_{DD} - I_{DS} R_D$

Where, $V_p = V_{GS\text{-}off}$ & I_{DSS} is Short ckt. I_{DS}



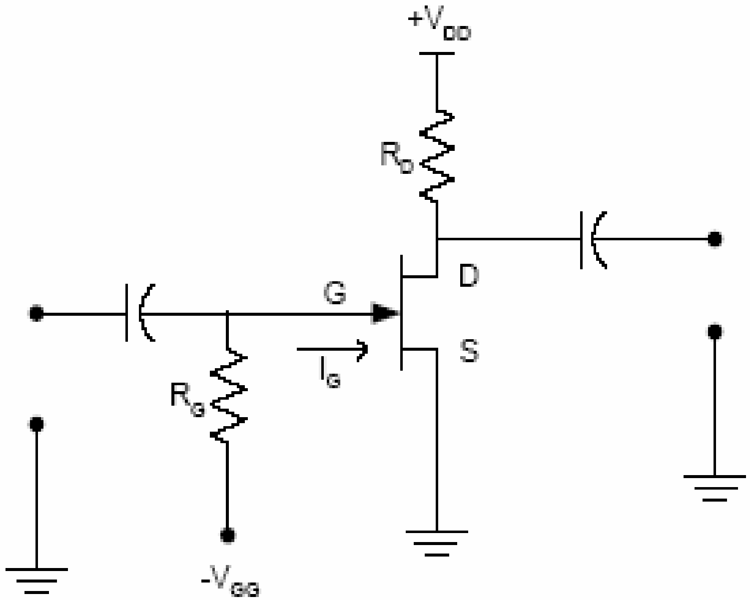
For Self Bias Circuit

$$V_{GS} + I_{DS} R_S = 0$$

$$\therefore I_{DS} = -\frac{V_{GS}}{R_S}$$

JFET Biasing Circuits Count…

Gate Bias: or Fixed Bias Ckt.



Since $I_G = 0$,

$V_{GS} = V_{GG}$

$V_{DS} = V_{DD} - I_D R_D$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

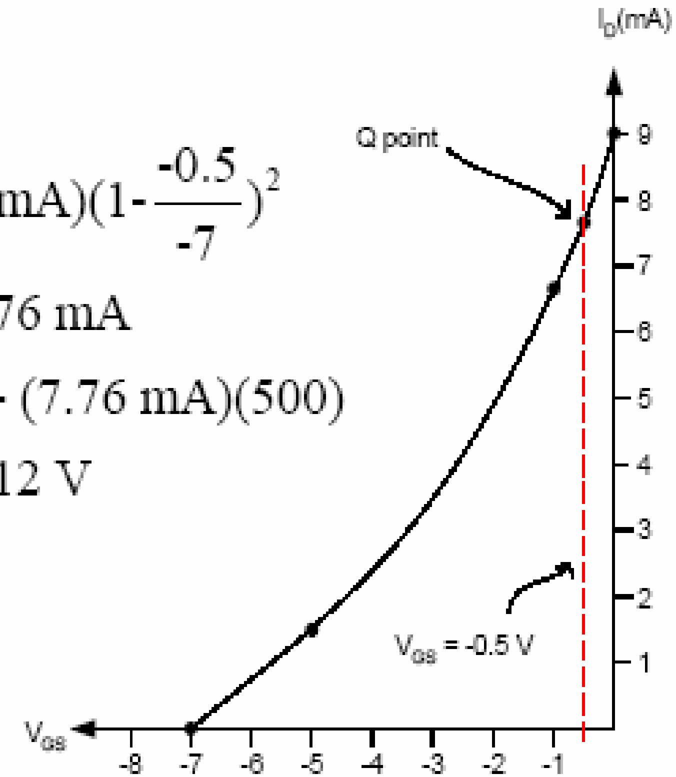
- Example: Determine the Q-point values for the gate biasing circuit if $V_{GG} = -0.5$ V, $V_{GS(off)} = -7$ V, $I_{DSS} = 9$ mA, $V_{DD} = 5$ V and $R_D = 500\Omega$.

$$I_D = (9\text{mA})\left(1 - \frac{-0.5}{-7}\right)^2$$

$$= 7.76 \text{ mA}$$

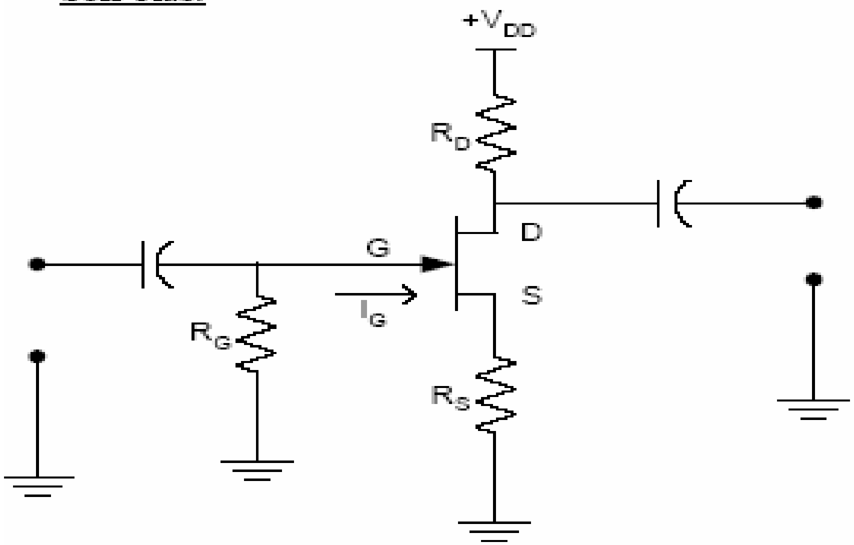
$$V_{DS} = 5 - (7.76 \text{ mA})(500)$$

$$= 1.12 \text{ V}$$



JFET Self (or Source) Bias Circuit

Self bias:



Since $I_G = 0$, $V_G = 0$

$V_S = I_D R_S$

$V_{GS} = -I_D R_S$

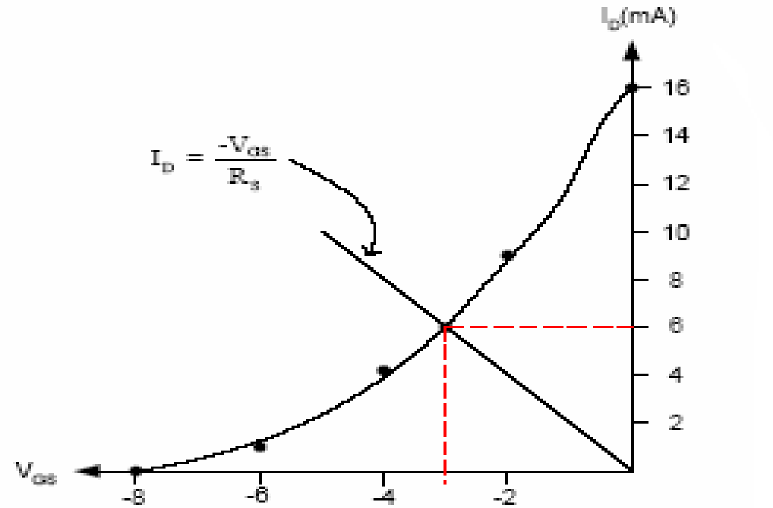
$$I_D = \frac{-V_{GS}}{R_S}$$

$V_{DS} = V_{DD} - I_D(R_D + R_S)$

$$\text{and } I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$\therefore I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = -\frac{V_{GS}}{R_S}$$

- Example: Determine the Q-point values for the self biasing circuit if $V_{GS(off)} = -8$ V , $I_{DSS} = 16$ mA , $V_{DD} = 10$ V , $R_D = 500\ \Omega$, $R_G = 1\ M\Omega$ and $R_S = 500\ \Omega$.



$I_D = 6$ mA

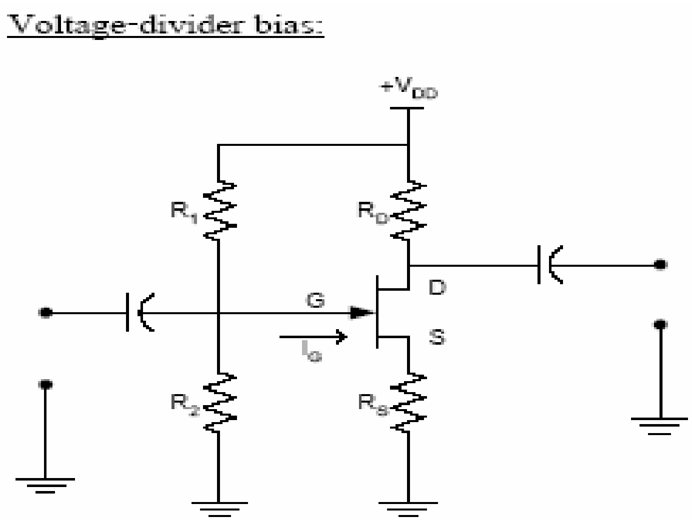
$V_{DS} = 10 - (6\text{mA})(500+500)$

$= 4$ V

$$I_{DSS}\left[1 - 2\frac{V_{GS}}{V_P} + \left(\frac{V_{GS}}{V_P}\right)^2\right] + \frac{V_{GS}}{R_S} = 0$$

This quadratic equation can be solved for V_{GS} & I_{DS}

The Potential (Voltage) Divider Bias



The method used to plot the dc bias line for the voltage-divider bias is as follows:

1. Plot the transconductance curve for the specific JFET.
2. Calculate V_G.
3. Plot V_G on the positive x-axis.
4. Solve for I_D using

$$I_D = \frac{V_G}{R_S}$$

5. Plot I_D found in (4) on the y-axis.
6. Extend the line to intersect the transconductance curve to obtain the Q-point values.

Since $I_G = 0$,

$$V_G = \frac{R_2}{R_1 + R_2} V_{DD}$$

$$I_D = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S}$$

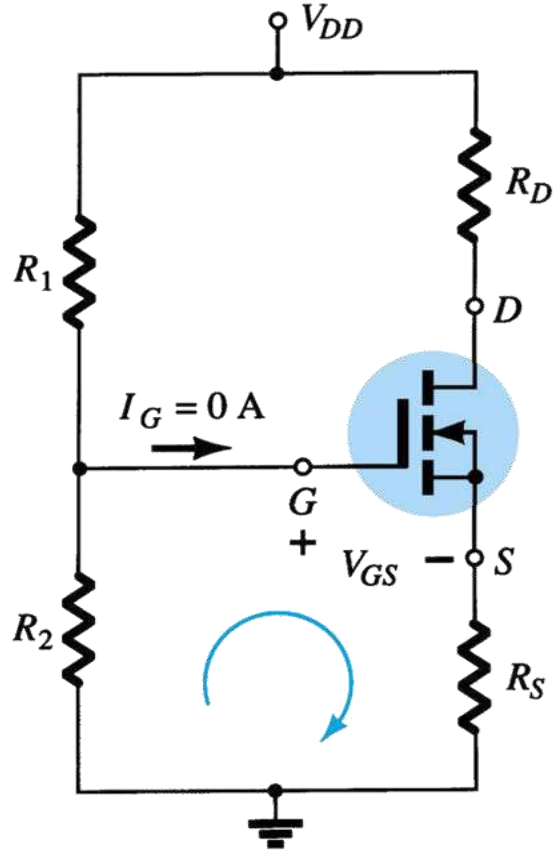
$$\therefore I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 - \frac{V_G - V_{GS}}{R_S} = 0$$

Solving this quadratic equation gives V_{GS} *and* I_{DS}

DC analysis step for Feedback Biasing Enhancement type MOSFET

- Find k using the datasheet or specification given;
  ex: $V_{GS(ON)}$,$V_{GS(TH)}$
- Plot transfer characteristics using the formula
  $I_D=k(V_{GS} – V_T)^2$. Three point already defined that is $I_{D(ON)}$, $V_{GS(ON)}$ and $V_{GS(TH)}$
- Plot a point that is slightly greater than V_{GS}
- Plot the linear characteristics (network bias line)
- The intersection defines the Q-point

Voltage-Divider Biasing



Again plot the line and the transfer curve to find the Q-point.
Using the following equations:

$$V_G = \frac{R_2 V_{DD}}{R_1 + R_2}$$

Input loop : $V_{GS} = V_G - I_D R_S$

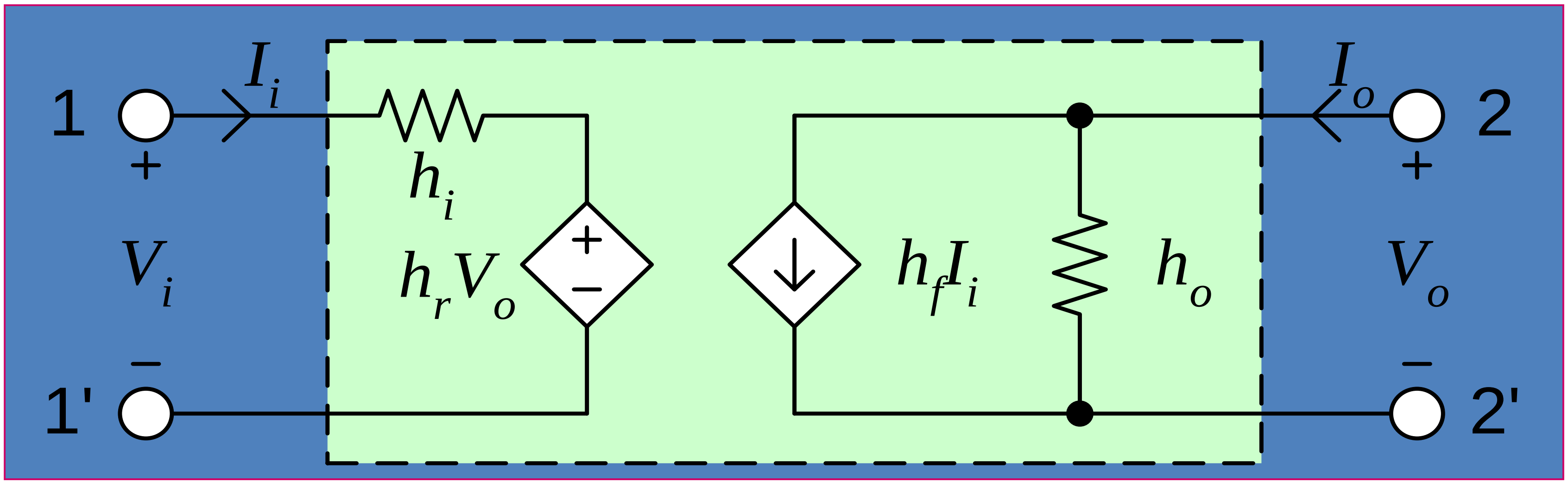
Output loop : $V_{DS} = V_{DD} - I_D (R_S + R_D)$

UNIT- V

Small Signal Low Frequency Transistor Amplifier Models:

- **BJT:** Two port network, Transistor hybrid model, determination of h- parameters, conversion of h-parameters, generalized analysis of transistor amplifier model using h-parameters, Analysis of CB, CE and CC amplifiers using exact and approximate analysis, Comparison of transistor amplifiers.
- **FET:** Generalized analysis of small signal model, Analysis of CG, CS and CD amplifiers, comparison of FET amplifiers.

Hybrid Parameter Model



$$V_i = h_{11} I_i + h_{12} V_o = h_i I_i + h_r V_o$$

$$I_o = h_{21} I_i + h_{22} V_o = h_f I_i + h_o V_o$$

h-Parameters

$$h_{11} = \frac{V_i}{I_i}\bigg|_{V_o = 0} \qquad h_{12} = \frac{V_i}{V_o}\bigg|_{I_i = 0}$$

$$h_{21} = \frac{I_o}{I_i}\bigg|_{V_o = 0} \qquad h_{22} = \frac{I_o}{V_o}\bigg|_{I_i = 0}$$

$h_{11} = h_i$ = Input Resistance

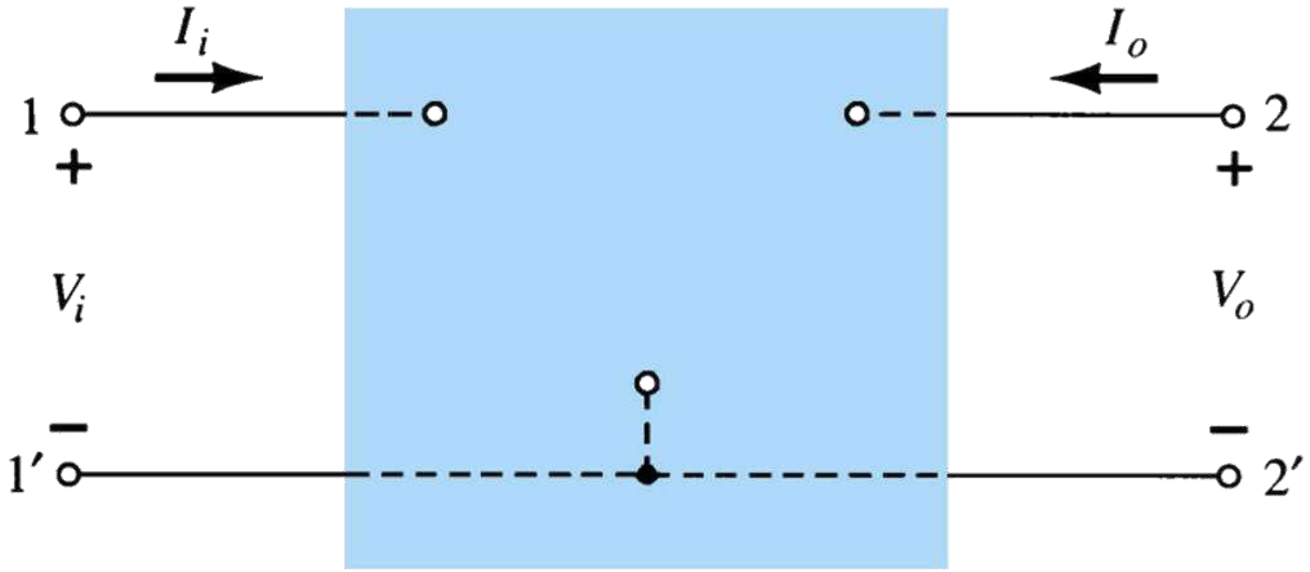
$h_{12} = h_r$ = Reverse Transfer Voltage Ratio

$h_{21} = h_f$ = Forward Transfer Current Ratio

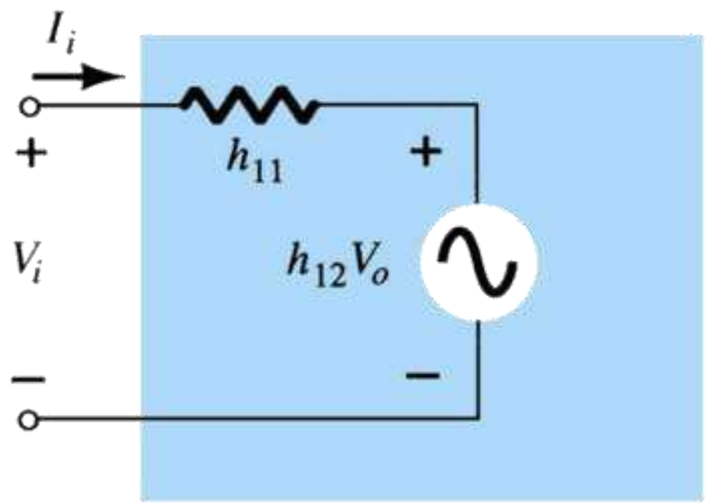
$h_{22} = h_o$ = Output Admittance

Hybrid Equivalent Model

The hybrid parameters: hie, hre, hfe, hoe are developed and used to model the transistor. These parameters can be found in a specification sheet for a transistor.



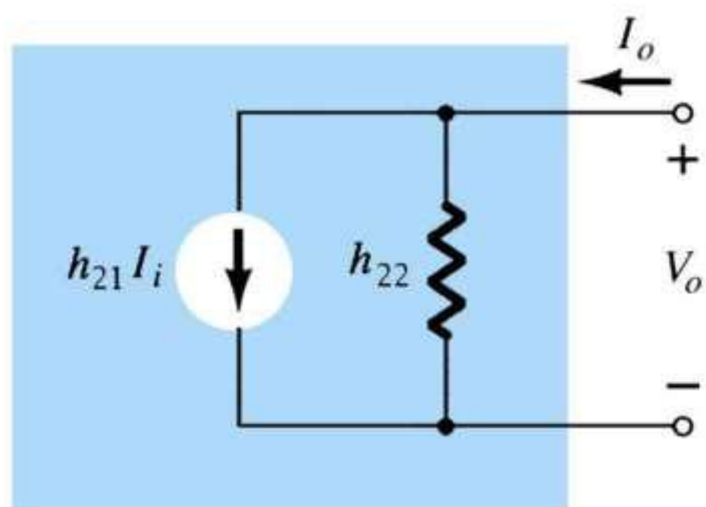
Determination of parameter



$$V_i = h_{11}I_i + h_{12}V_o$$

$$h_{11} = \left.\frac{V_i}{I_i}\right|_{V_o=0V}$$

$$h_{12} = \left.\frac{V_i}{V_o}\right|_{V_o=0V}$$



$$I_o = h_{21}I_i + h_{22}V_o$$

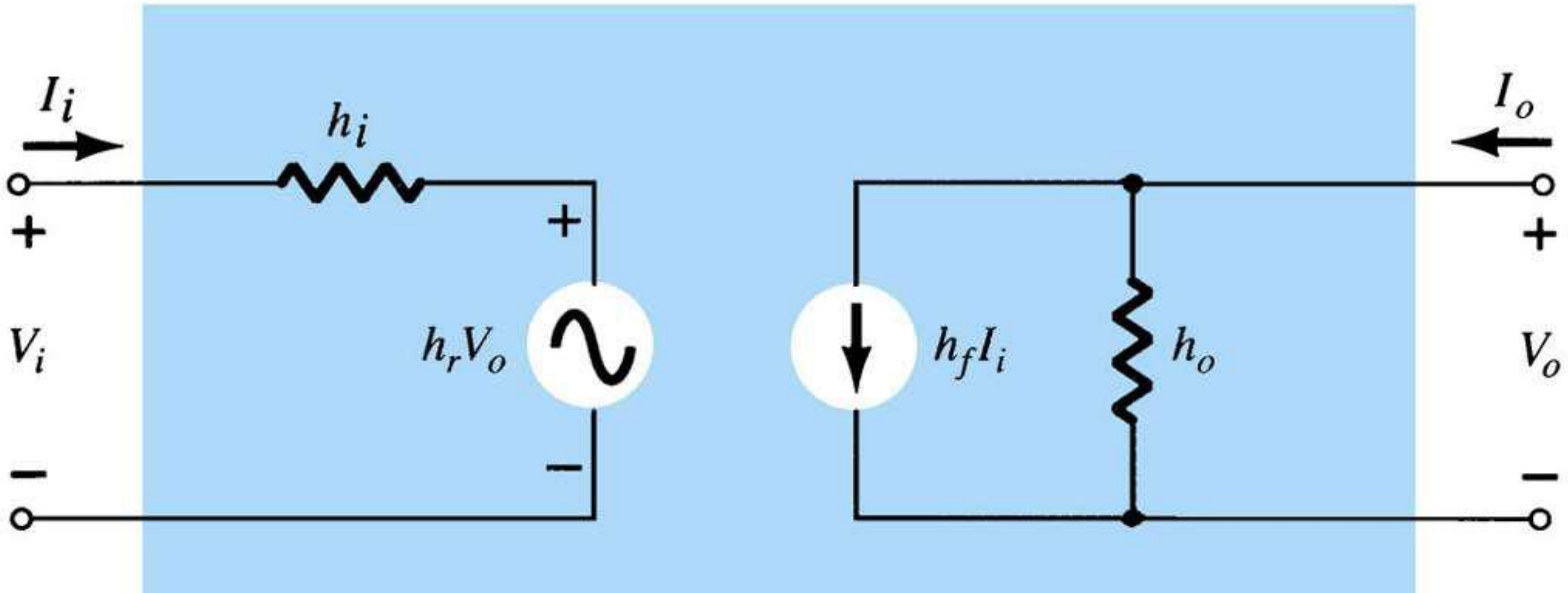
Solving $V_o = 0V$,

$$h_{21} = \left.\frac{I_i}{I_o}\right|_{V_o=0V}$$

$$h_{22} = \left.\frac{I_o}{V_o}\right|_{I_o=0A}$$

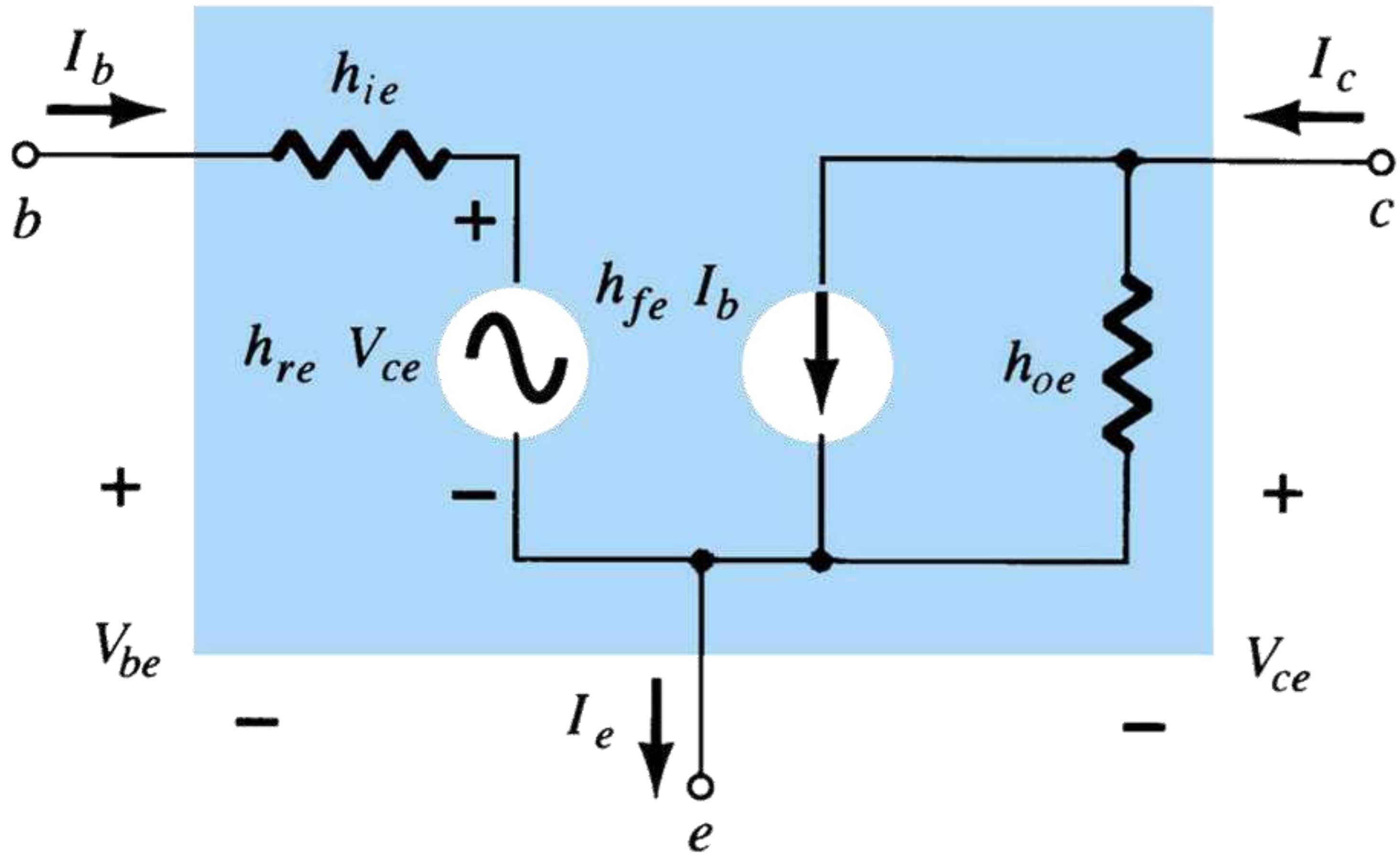
H_{22} is a conductance!

General h-Parameters for any Transistor Configuration



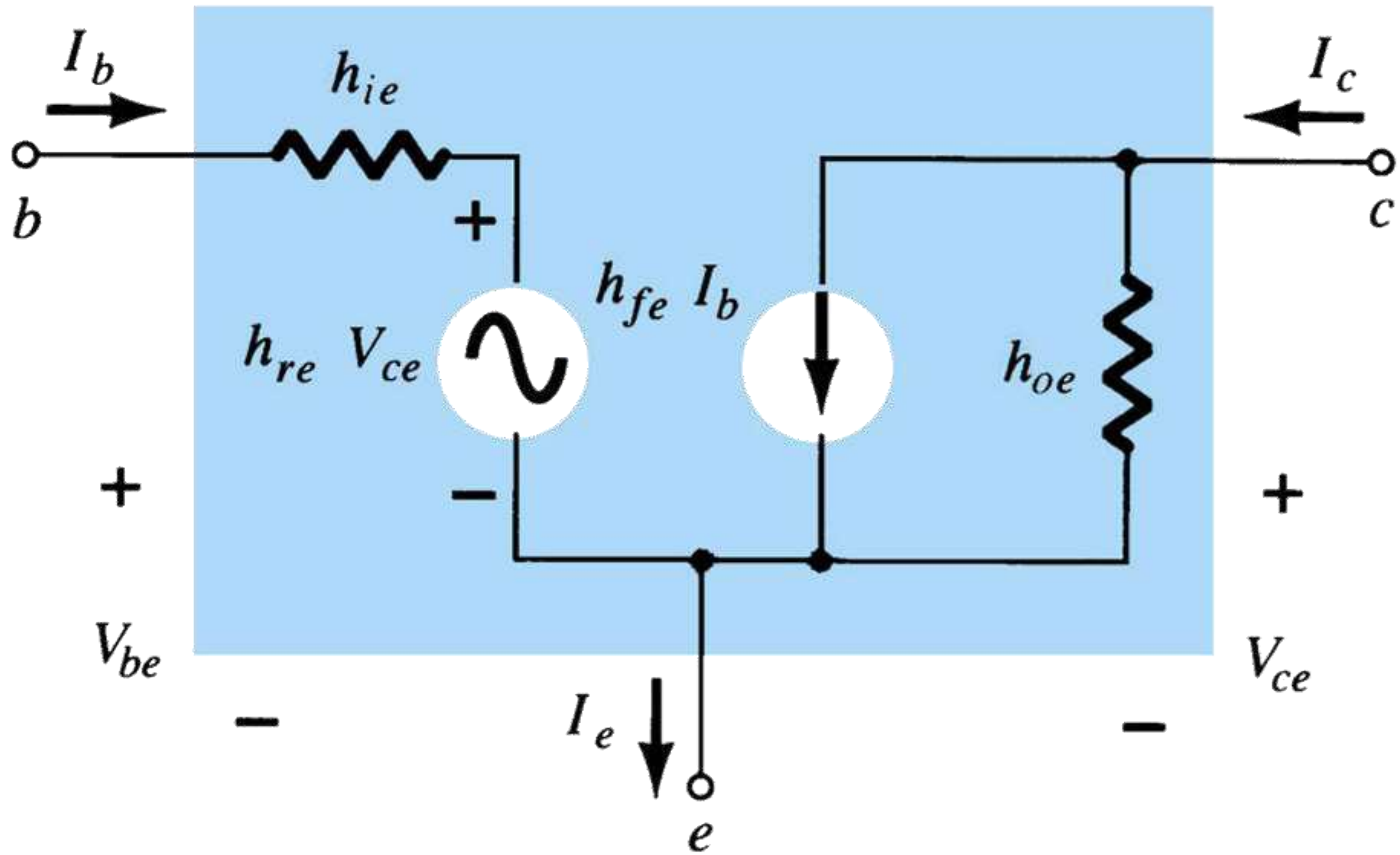
hi = input resistance
hr = reverse transfer voltage ratio (Vi/Vo)
hf = forward transfer current ratio (Io/Ii)
ho = output conductance

Common emitter hybrid equivalent circuit



(b)

Common base hybrid equivalent circuit

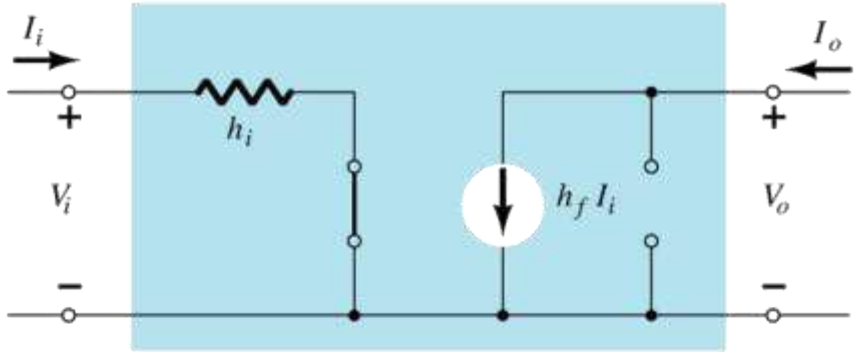


(b)

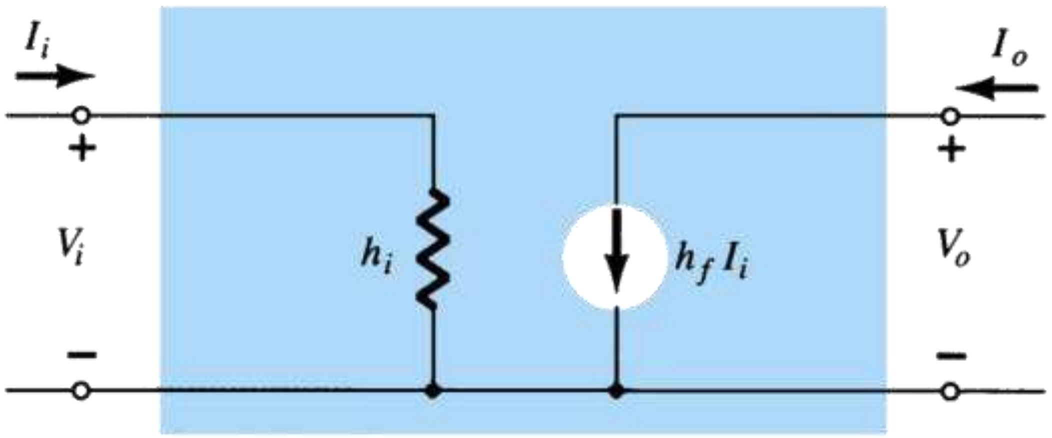
Simplified General h-Parameter Model

The model can be simplified based on these approximations:

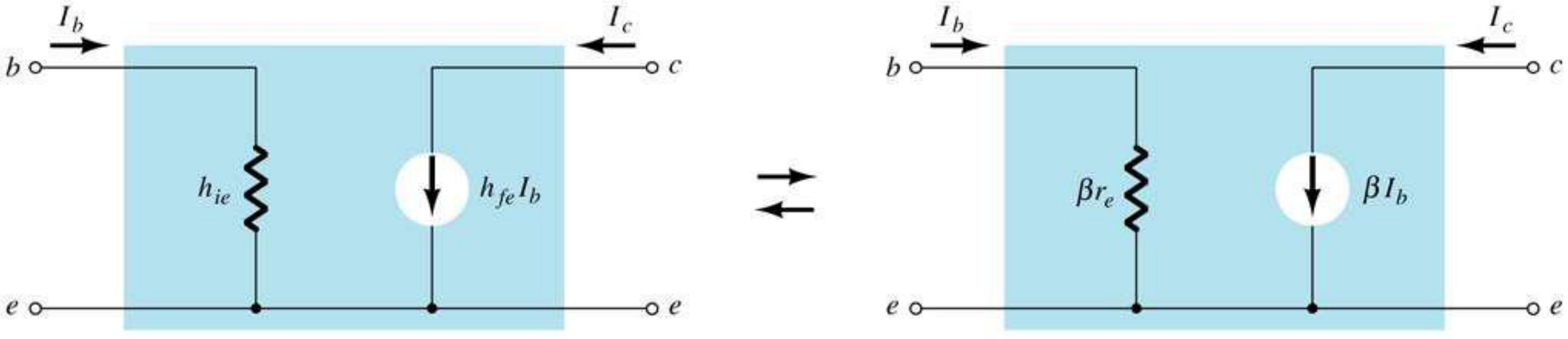
hr ≅ 0 therefore hrVo = 0 and ho ≅ ∞ (high resistance on the output)



Simplified



Common-Emitter re vs. h-Parameter Model



(a)

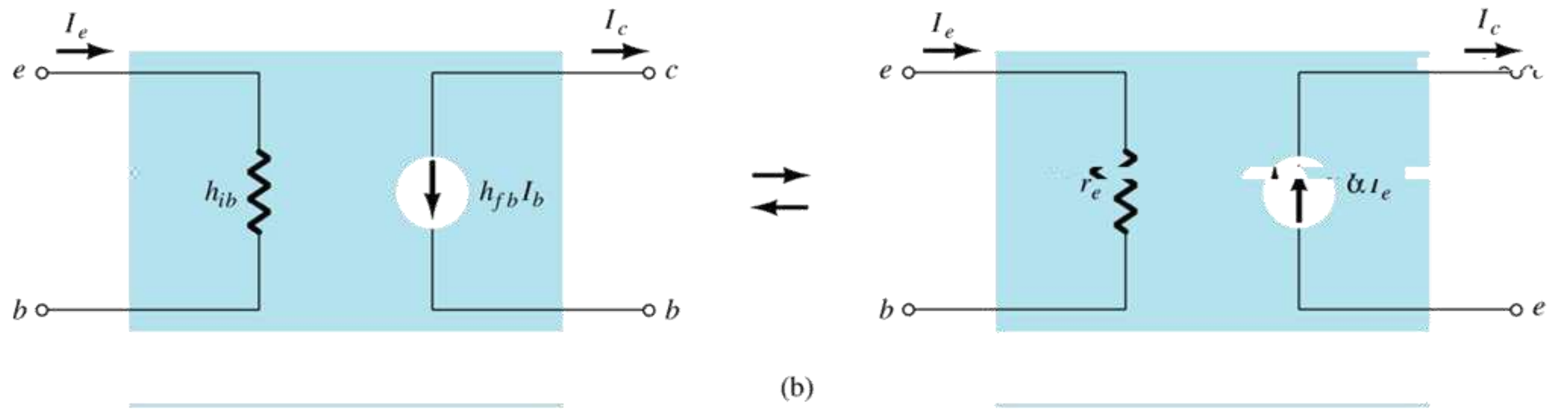
hie = βre
hfe = β
hoe = 1/ro

Common-Emitter h-Parameters

$$h_{ie} = \mathrm{B} r_e$$ [Formula 7.28]

$$h_{fe} = \mathrm{B}_{ac}$$ [Formula 7.29]

Common-Base re vs. h-Parameter Model



hib = re
hfb = -α

Common-Base h-Parameters

$$h_{ib} = r_e$$ [Formula 7.30]

$$h_{fb} = -\alpha \cong -1$$ [Formula 7.31]

SMALL-SIGNAL LOW-FREQUENCY OPERATION OF TRANSISTORS

Hybrid Parameters and Two-Port Network

For the hybrid equivalent model to be described, the parameters are defined at an operating point that may or may not give an actual picture of the operating condition of the amplifier. The quantities h_{ie} , h_{re} , h_{fe} *and* h_{oe} *are called the hybrid parameters and are the components of a small-signal equivalent circuit.* The description of the hybrid equivalent model begins with the general two-port system.

$$V_i = h_{11} I_i + h_{12} V_o$$

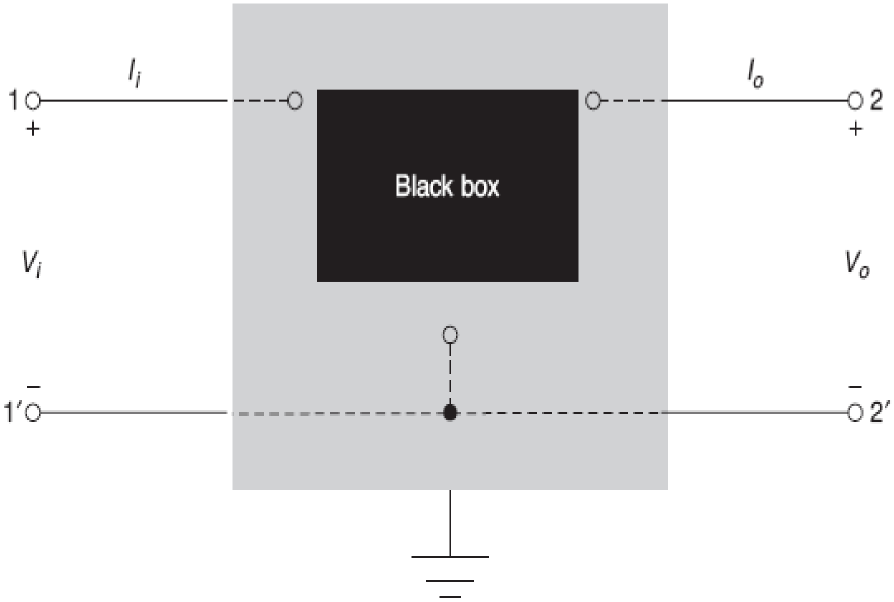
$$I_o = h_{21} I_i + h_{22} V_o$$

(i) $h_{11} \rightarrow$ input impedance $\rightarrow h_i$

(ii) $h_{12} \rightarrow$ reverse transfer voltage ratio $\rightarrow h_r$

(iii) $h_{21} \rightarrow$ forward transfer current gain $\rightarrow h_f$

(iv) $h_{22} \rightarrow$ output admittance $\rightarrow h_o$



Two-port system representation (Black model realisation)

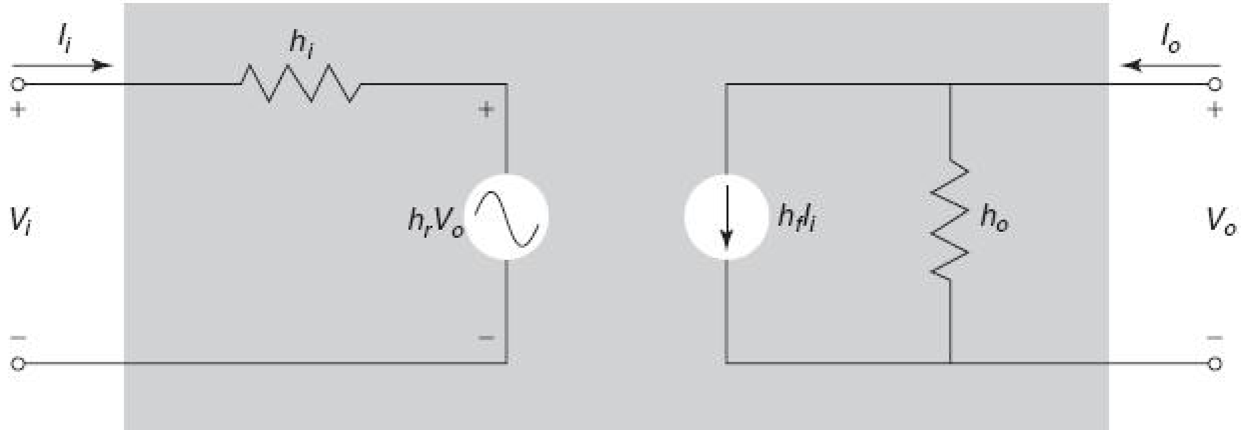
EQUIVALENT CIRCUITS THROUGH HYBRID PARAMETERS AS A TWO-PORT NETWORK

For the transistor, even though it has three basic configurations, they are all four-terminal configurations, and thus, the resulting equivalent circuit will have the same format. The *h-parameter will* however change with each configuration. To distinguish which parameter has been used or which is available, a second subscript has been added to the *h-parameter notation.*

(i) For the common-base configuration: the lower case letter b

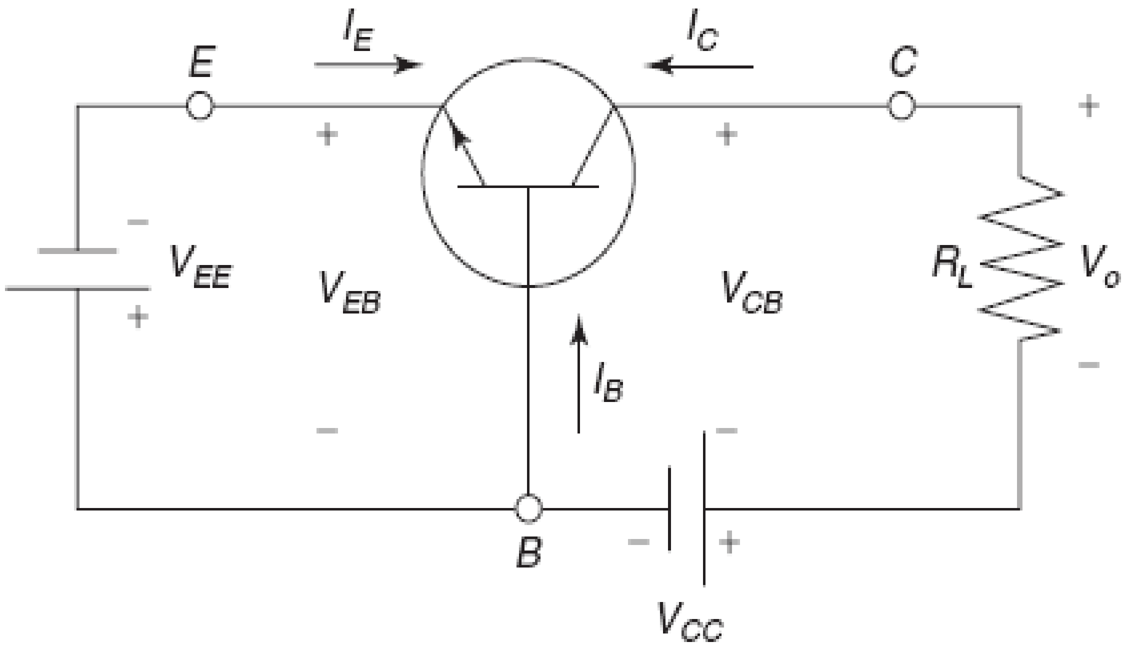
(ii) For the common-emitter configuration: the lower case letter e

(iii) For the common-collector configuration: the lower case letter c



Complete hybrid equivalent model

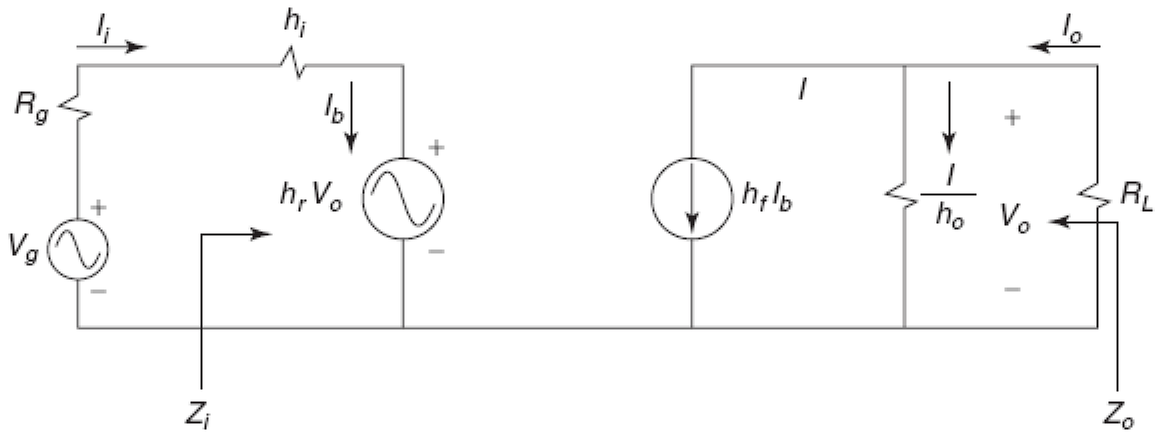
TRANSISTOR AS AMPLIFIER



An *n–p–n transistor in the common-base bias mode*

EXPRESSIONS OF CURRENT GAIN, INPUT RESISTANCE, VOLTAGE GAIN AND OUTPUT RESISTANCE

The *h-parameter equivalent circuit of a transistor amplifier having a voltage source* V_g *,* with its input resistance R_g *connected to the input terminals and a load resistance* R_L *connected to the output* terminals.



h-Parameter equivalent circuit of a transistor

EXPRESSIONS OF CURRENT GAIN, INPUT RESISTANCE, VOLTAGE GAIN AND OUTPUT RESISTANCE

Current Gain (A_I)

$$A_I = \frac{I_L}{I_1} = -\frac{I_2}{I_1} \quad \text{or,} \quad A_I = \frac{-h_f}{(1 + h_o R_L)}$$

Input Resistance (R_I)

$$R_I = \frac{V_1}{I_1} \quad \text{or,} \quad R_I = h_i - \frac{h_f h_r R_L}{1 + h_o R_L}$$

EXPRESSIONS OF CURRENT GAIN, INPUT RESISTANCE, VOLTAGE GAIN AND OUTPUT RESISTANCE

Voltage Gain:- Voltage gain or voltage amplification is defined as the ratio of the output voltage *V2 to the input voltage V1.*

$$A_V = \frac{V_2}{V_1} \quad \text{or,} \quad A_V = -\frac{h_f R_L}{h_i + \Delta h R_L}$$

Where,

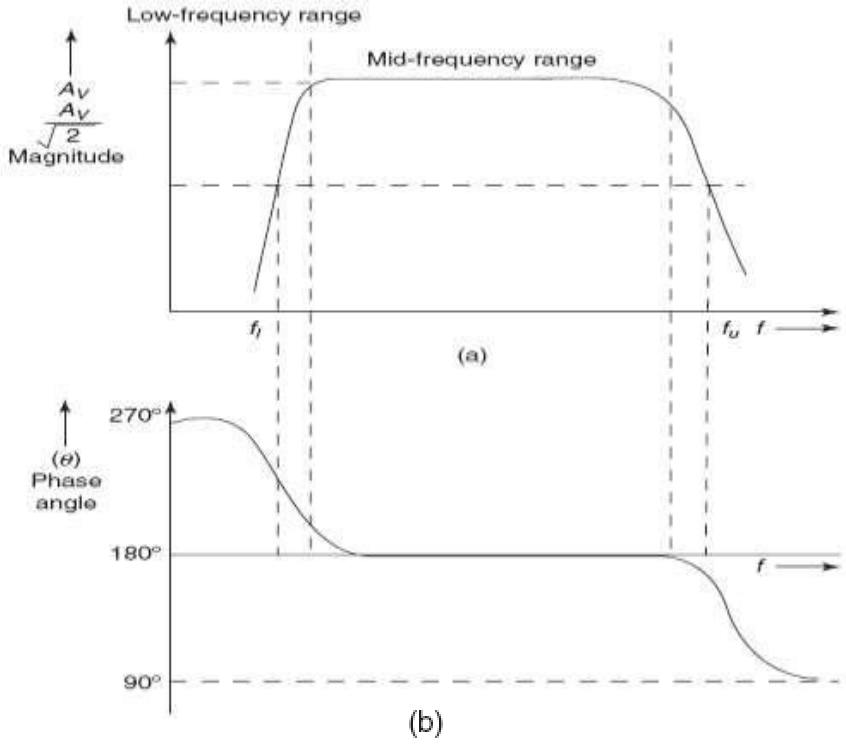
$$\Delta h = h_i h_o - h_f h_r$$

Output Resistance (R_O)

$$R_o = \frac{V_2}{I_2} \quad \text{or,} \quad R_o = \frac{V_2}{I_2} = \frac{R_g + h_i}{R_g h_o + h_i h_o - h_f h_r}$$

FREQUENCY RESPONSE FOR CE AMPLIFIER WITH AND WITHOUT SOURCE IMPEDANCE

At different frequencies of the input signal, the performance of the device is different. The analysis till now has been limited to the mid-frequency spectrum. Frequency response of an amplifier refers to the variation of the magnitude and phase of the amplifier with frequency.



a) Gain vs. frequency for a CE amplifier (b) Phase angle vs. frequency for a CE amplifier

EMITTER FOLLOWER

The emitter follower transistor is a design which is basically a CC amplifier.

Current gain:

$$A_i = -\frac{I_e}{I_b} = 1 + \frac{h_{fe}}{1 + h_{oe}R_L}$$

Input resistance:

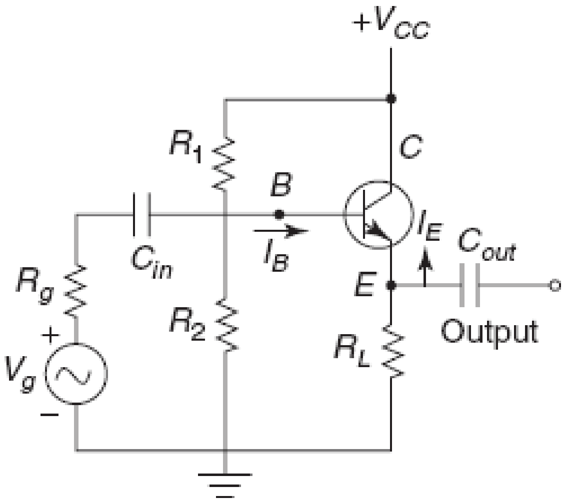
$$R_i = \frac{V_i}{I_b} = h_{ie} + A_i R_L$$

Voltage gain:

$$A_V = \frac{V_L}{V_i} = \frac{A_i R_l}{R_i}$$

Output resistance

$$R_o = \frac{R_G + h_{ie}}{1 + R_G h_{oe} + h_{ie} h_{oe} + h_{fe}}$$



An emitter follower configuration with biasing

The emitter follower is used for impedance matching.

Table Characteristics of the three BJT amplifier configurations

Configuration	Voltage gain	Current gain	Input resistance	Output resistance
Common emitter	$A_v > 1$	$A_i > 1$	Moderate	Moderate to high
Emitter follower	$A_v \cong 1$	$A_i > 1$	High	Low
Common base	$A_v > 1$	$A_i \cong 1$	Low	Moderate to high

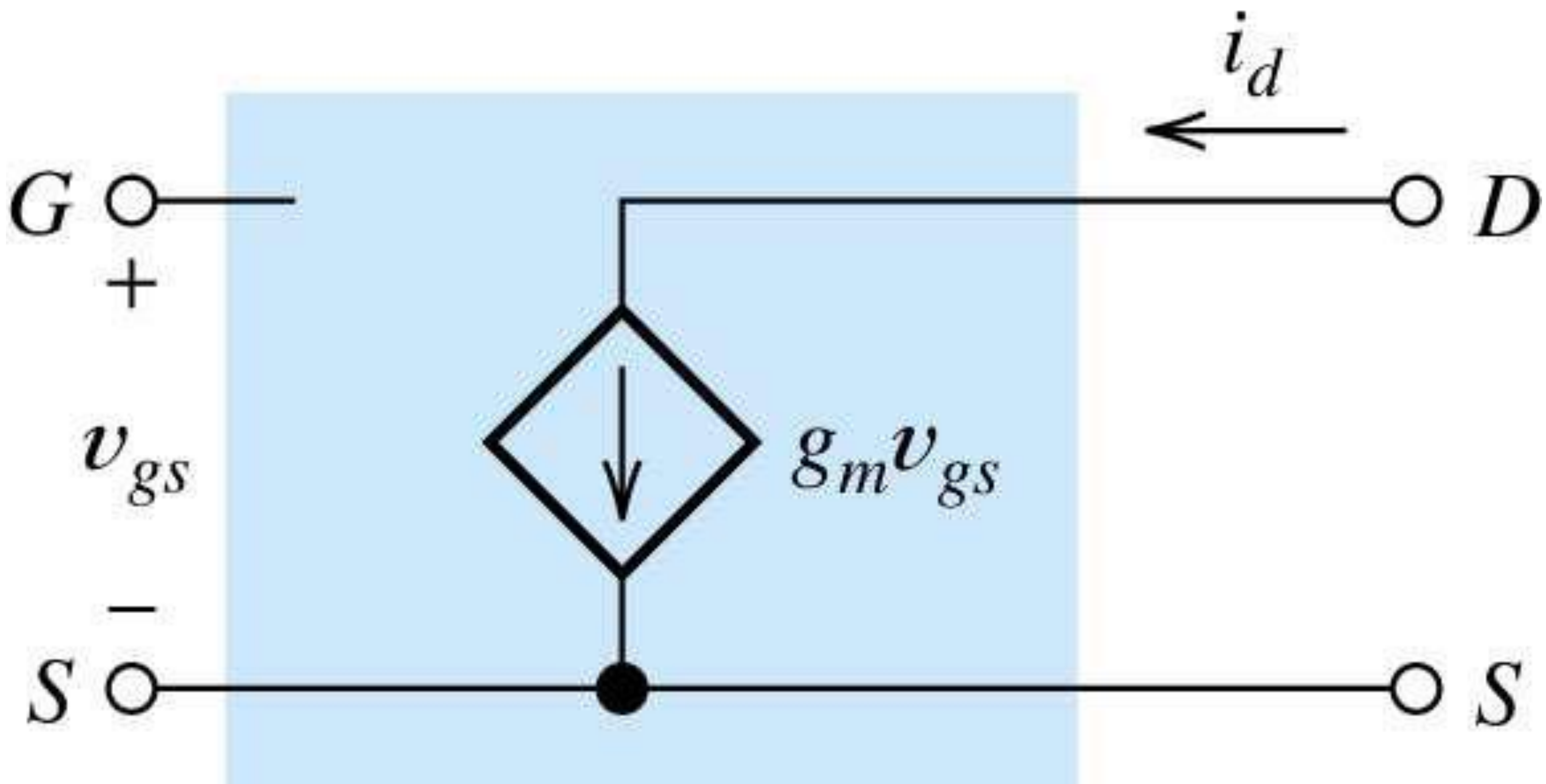


Figure Small-signal equivalent circuit for FETs.

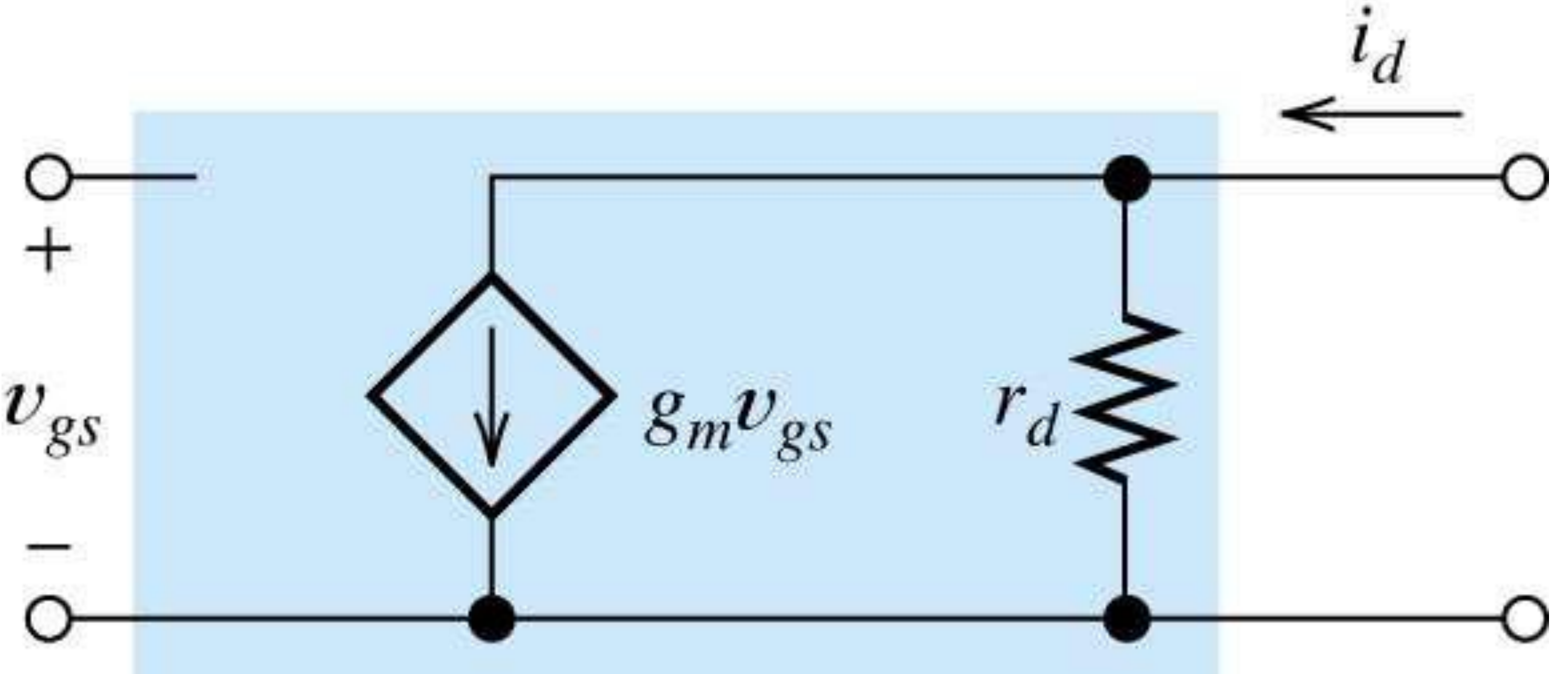


Figure FET small-signal equivalent circuit that accounts for the dependence of i_D on v_{DS}.

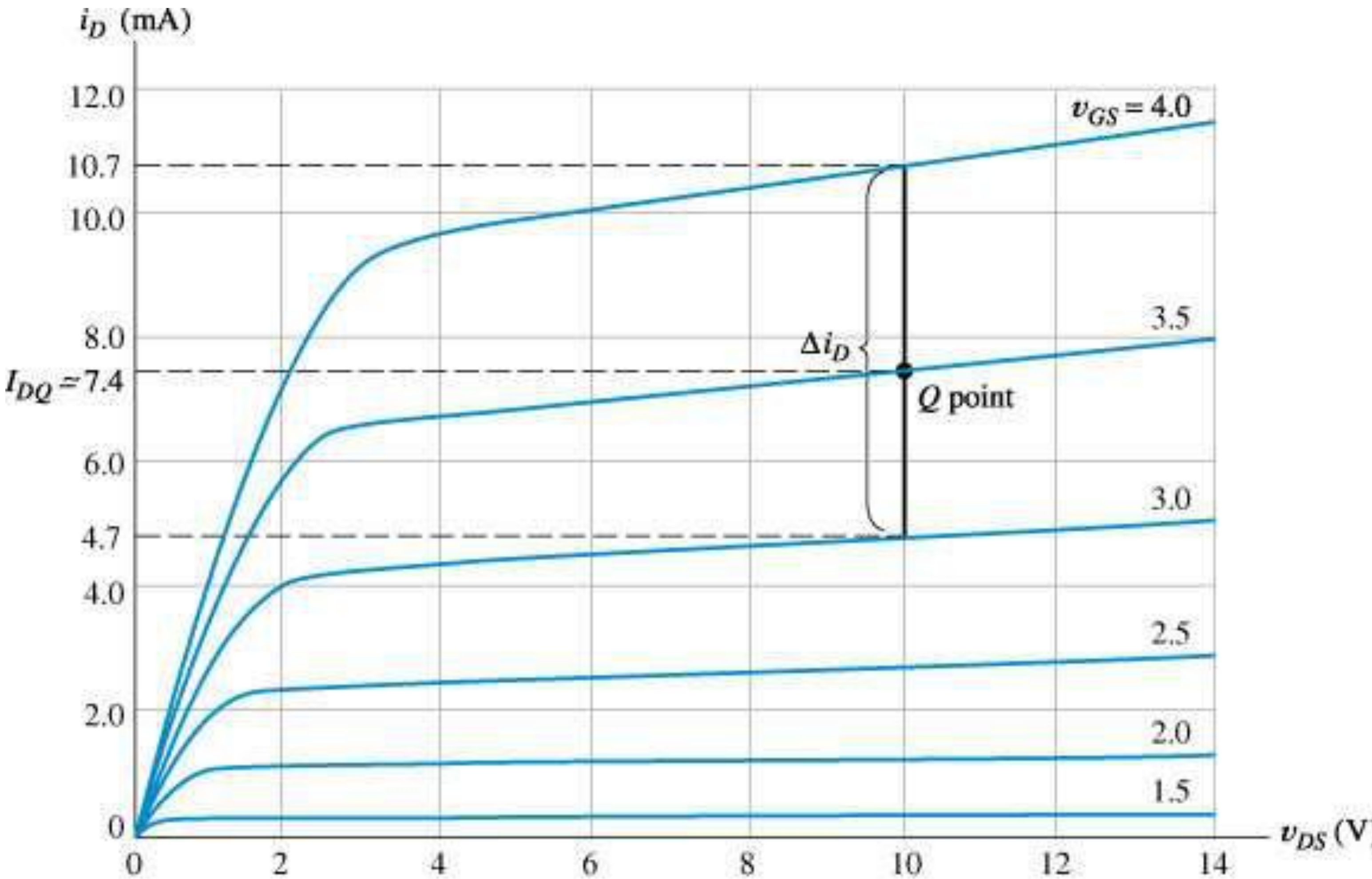


Figure Determination of g_m and r_d. See Example 5.5.

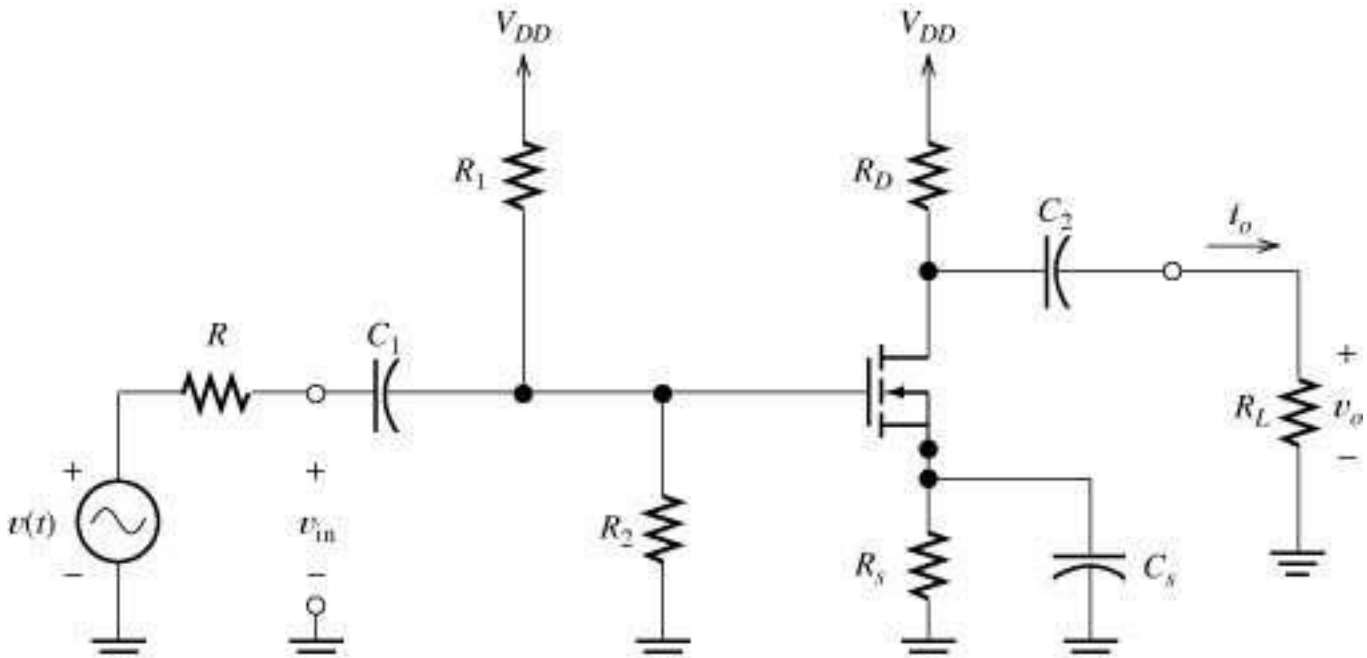
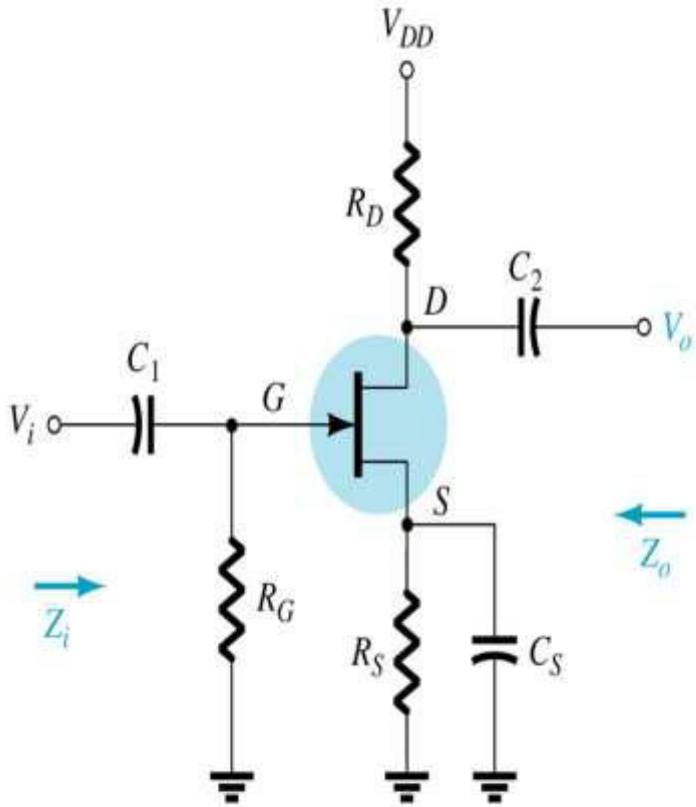
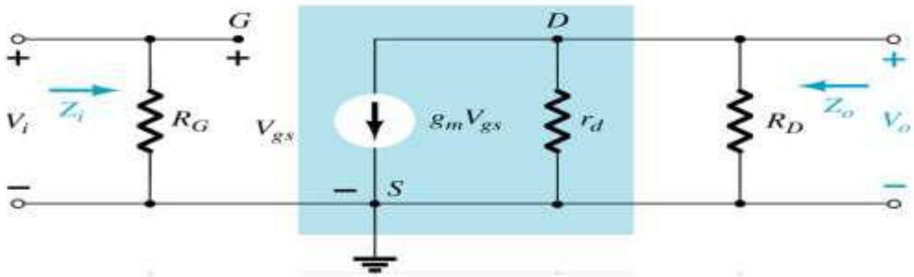


Figure Common-source amplifier.

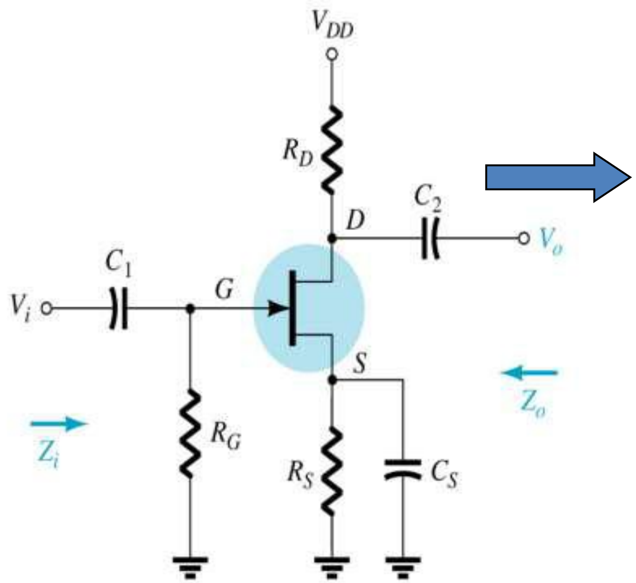


For drawing an a c equivalent circuit of Amp.

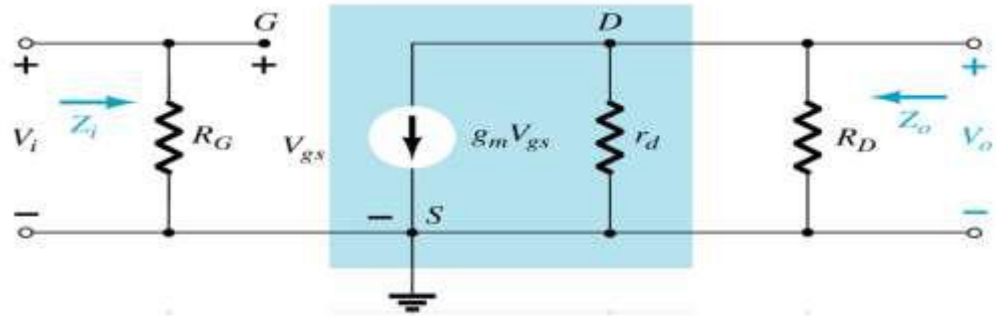
- Assume all Capacitors C1, C2, Cs as short circuit elements for ac signal
- Short circuit the d c supply
- Replace the FET by its small signal model



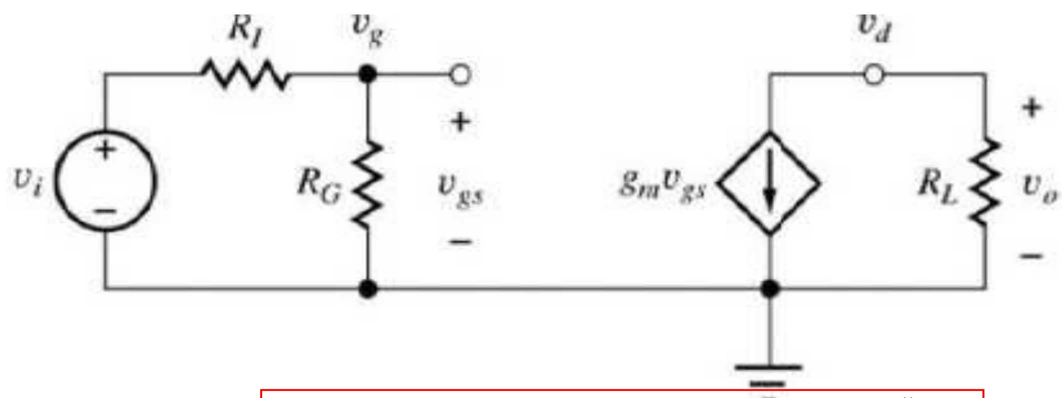
Analysis of CS Amplifier



A C Equivalent Circuit



Simplified A C Equivalent Circuit



Voltage gain, $A_v = \dfrac{v_o}{v_{gs}}$

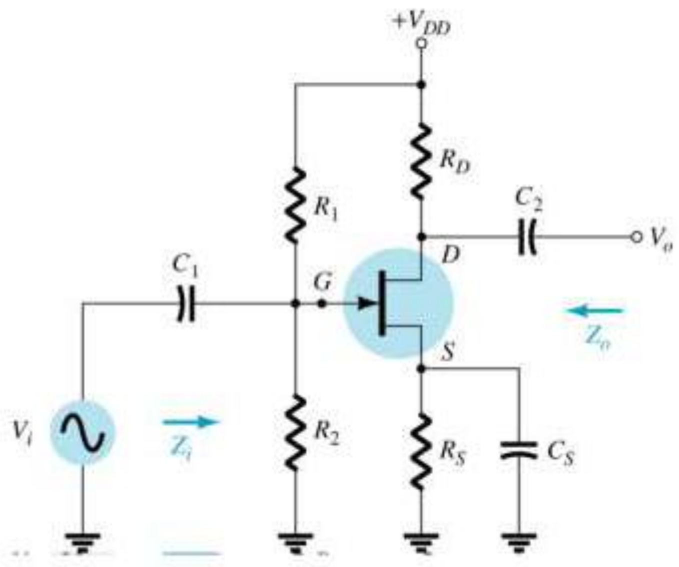
$$\therefore v_o = i_o R_L = -g_m v_{gs} R_L$$

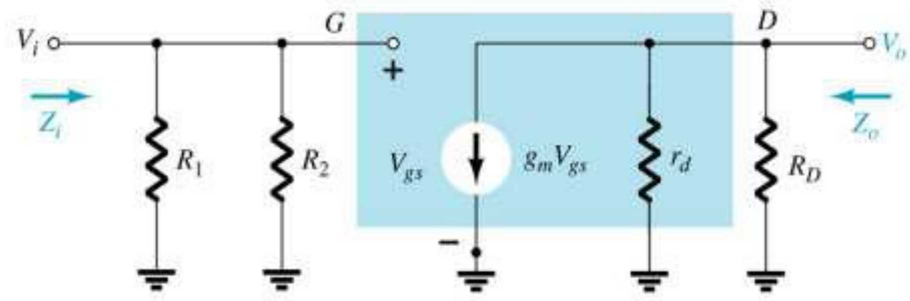
$$\therefore A_v = \frac{v_o}{v_{gs}} = -g_m R_L,\ R_L = R_D \| r_d$$

Input imp., $Z_{in} = R_G = R_1 \| R_2$

Out put imp., $Z_o = r_d \| R_D = \dfrac{r_d R_D}{r_d + R_D}$

Analysis of CS Amplifier with Potential Divider Bias





This is a CS amplifier configuration therefore the input is on the gate and the output is on the drain.

$$Z_i = R_1 \| R_2$$

$$A_v = -g_m(r_d \| R_D)$$

$$Z_o = r_d \| R_D$$

$$Z_o \cong R_D \Big/ r_d \geq 10R_D$$

$$A_v \cong -g_m R_D, \quad \because r_d \geq 10R_D$$

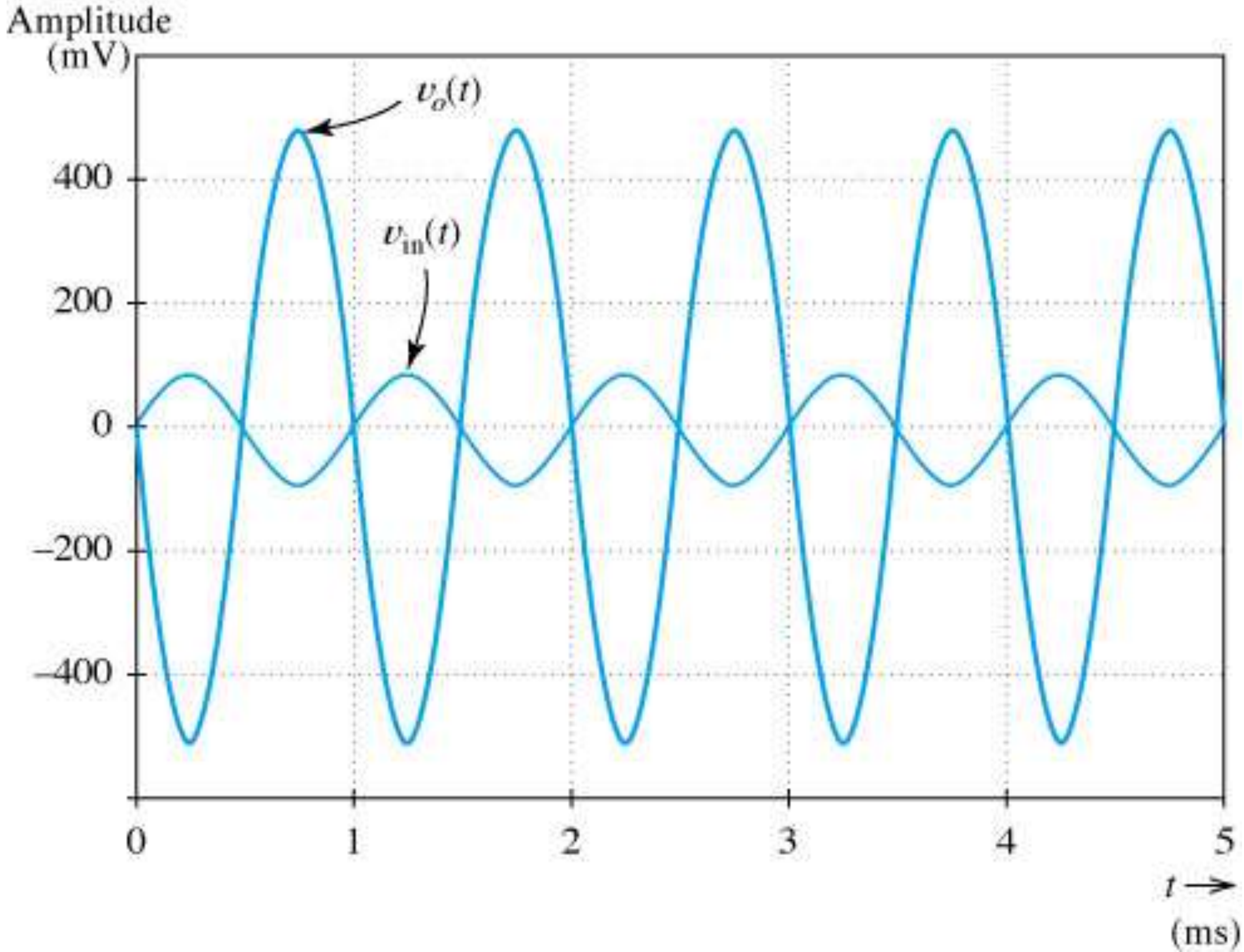


Figure $v_o(t)$ and $v_{in}(t)$ versus time for the common-source amplifier of Figure 5.28.

An Amplifier Circuit using MOSFET(CS Amp.)

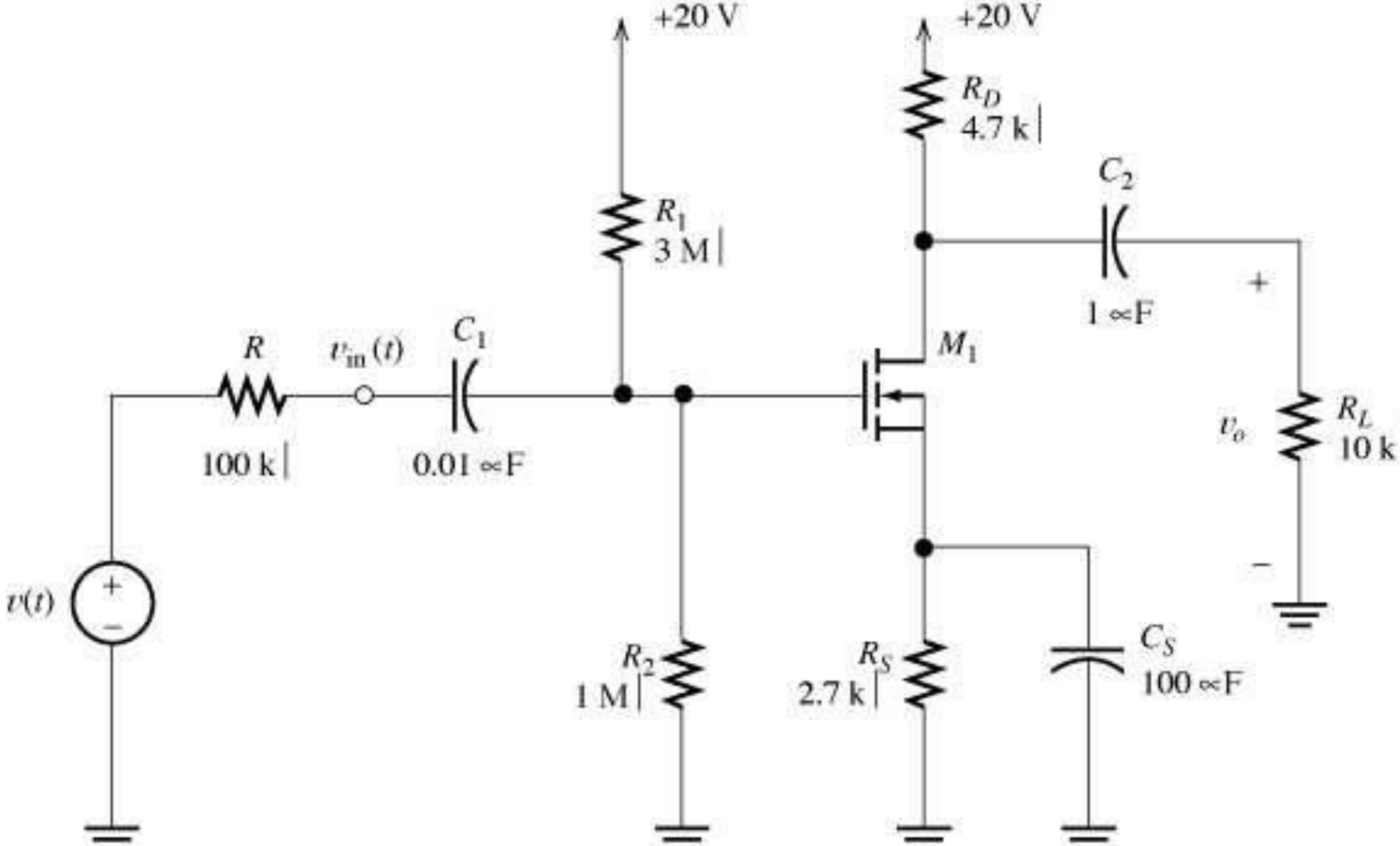


Figure Common-source amplifier.

A small signal equivalent circuit of CS Amp.

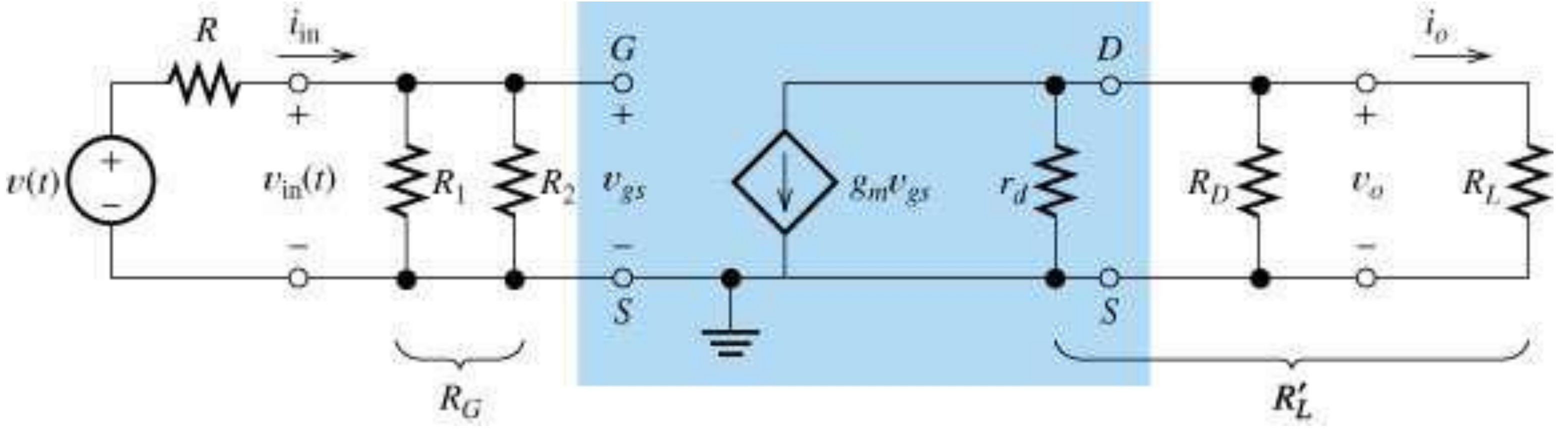


Figure Small-signal equivalent circuit for the common-source amplifier.

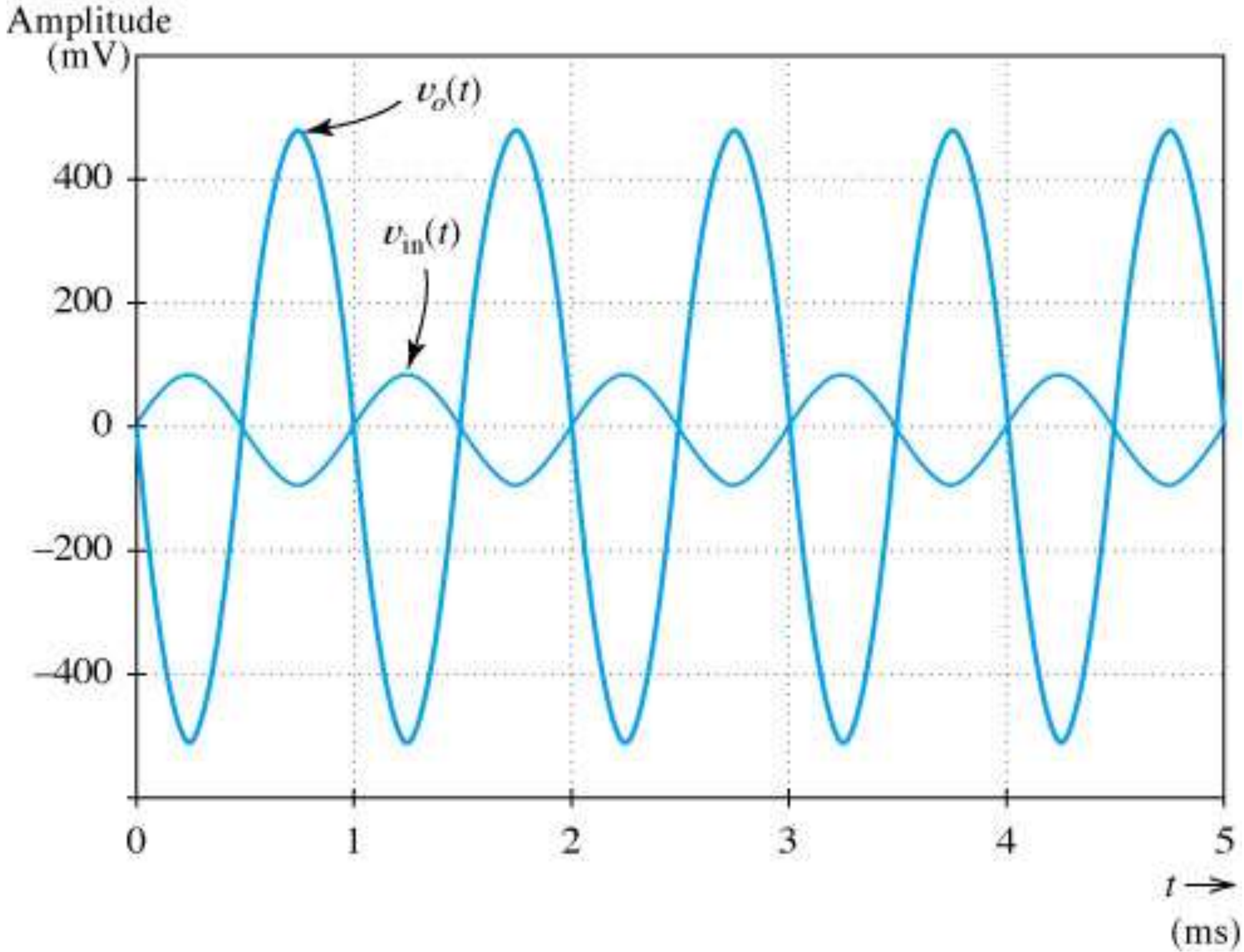


Figure $v_o(t)$ and $v_{in}(t)$ versus time for the common-source amplifier of Figure 5.28.

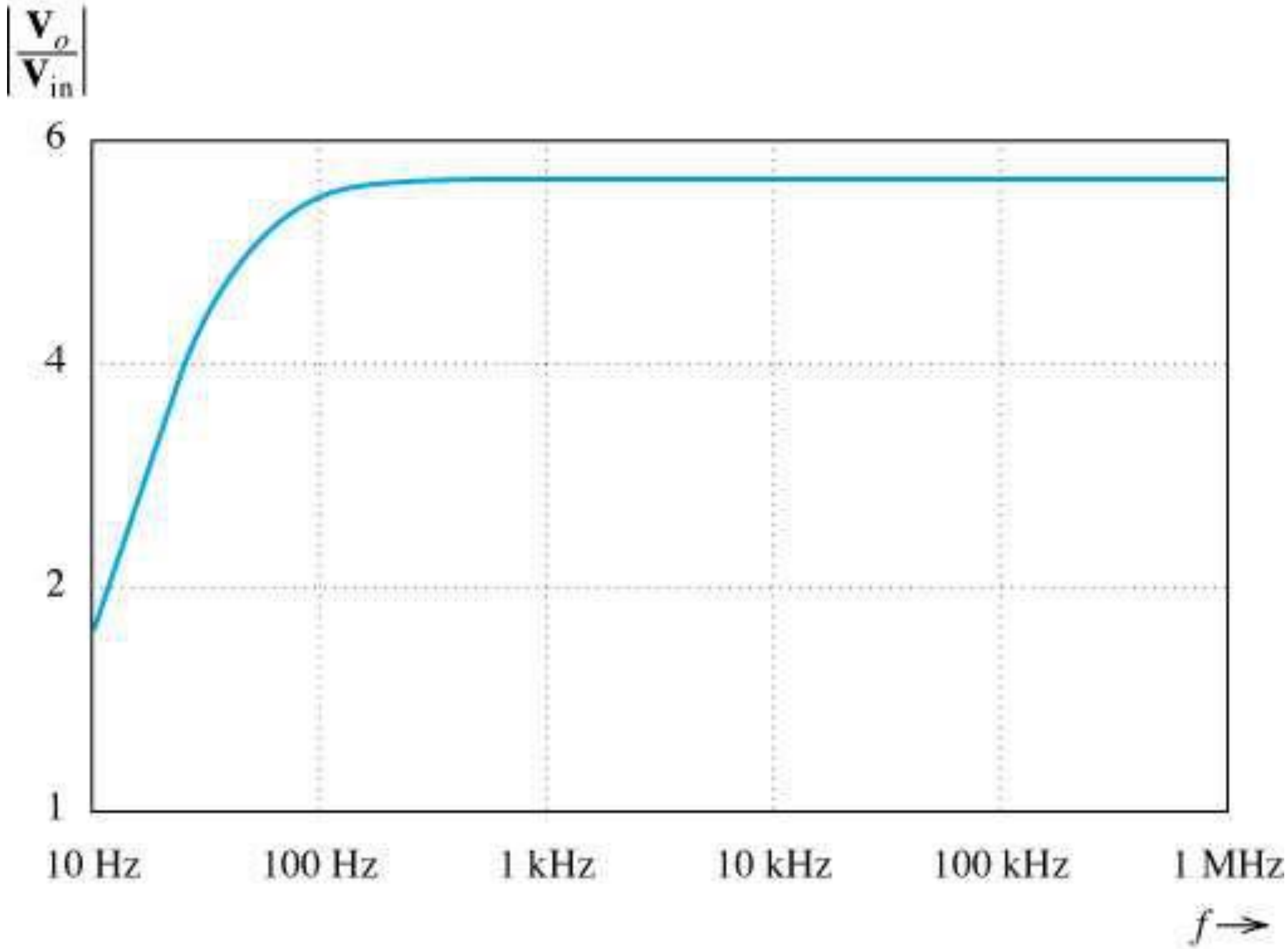


Figure Gain magnitude versus frequency for the common-source amplifier of Figure 5.28.

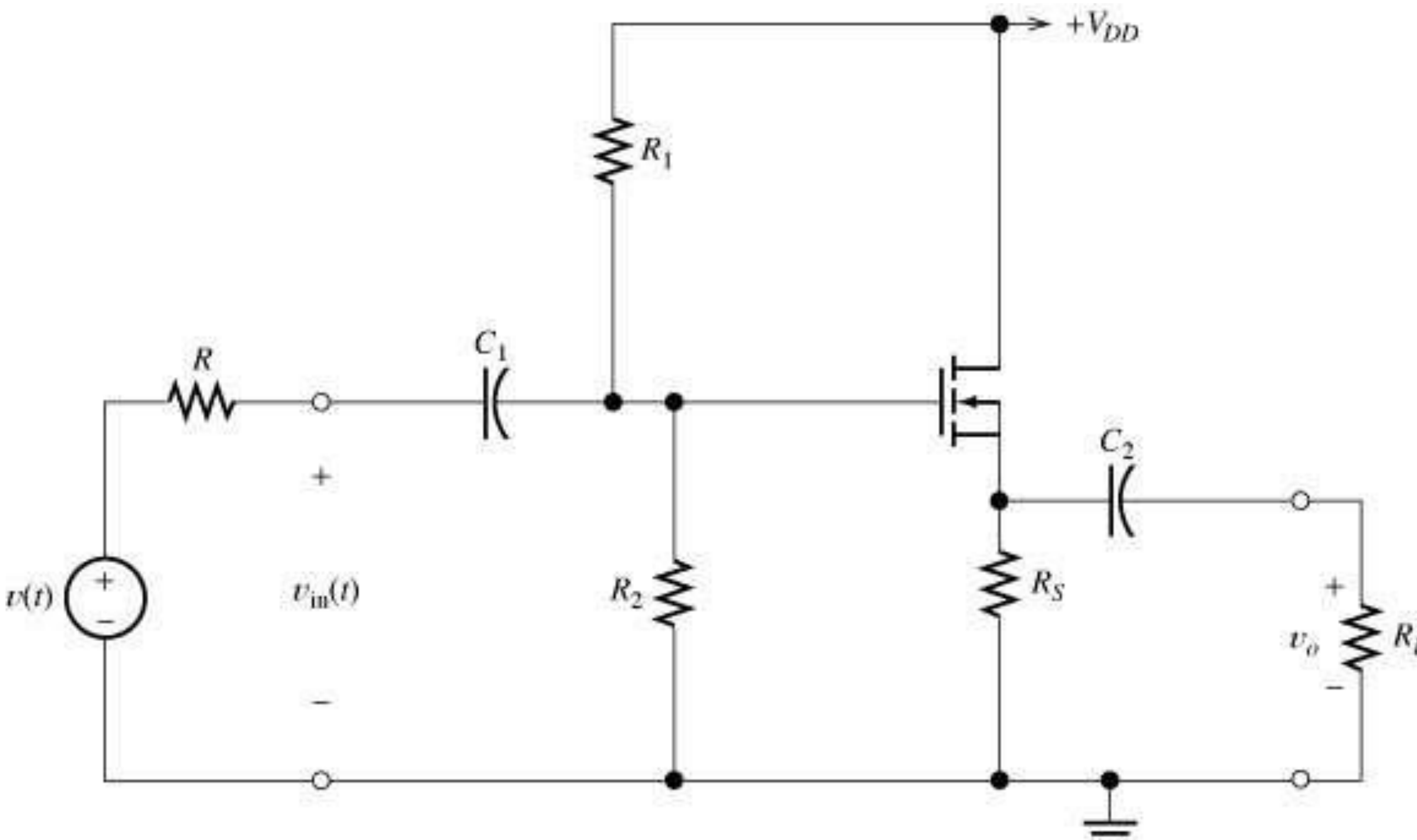


Figure Source follower.

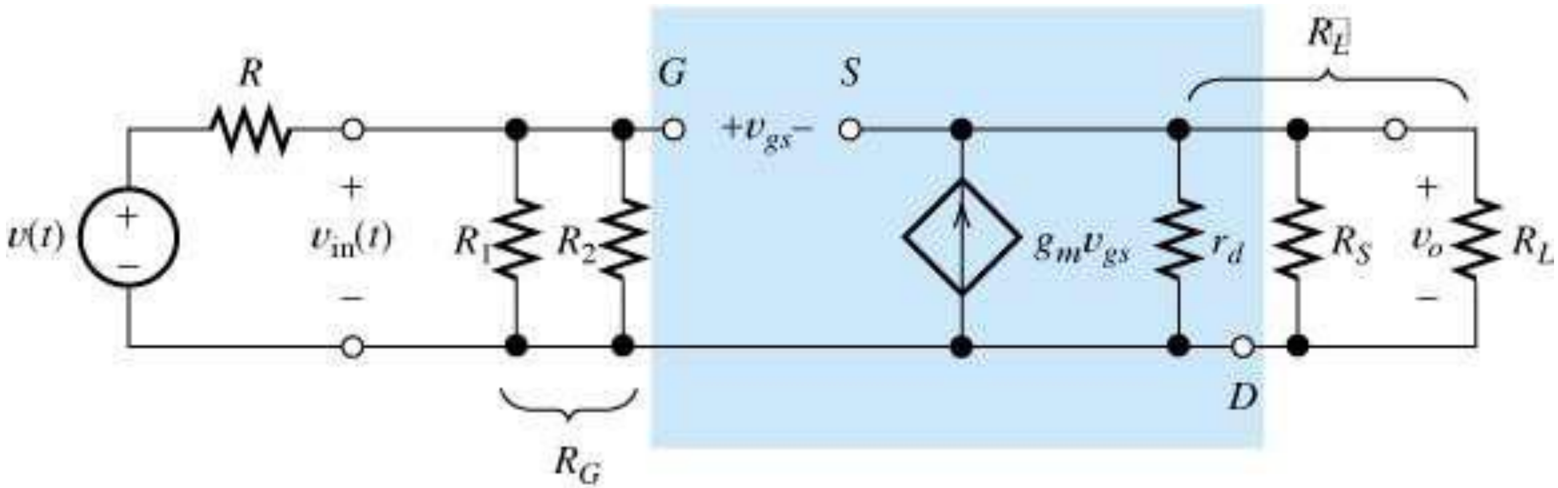


Figure Small-signal ac equivalent circuit for the source follower.

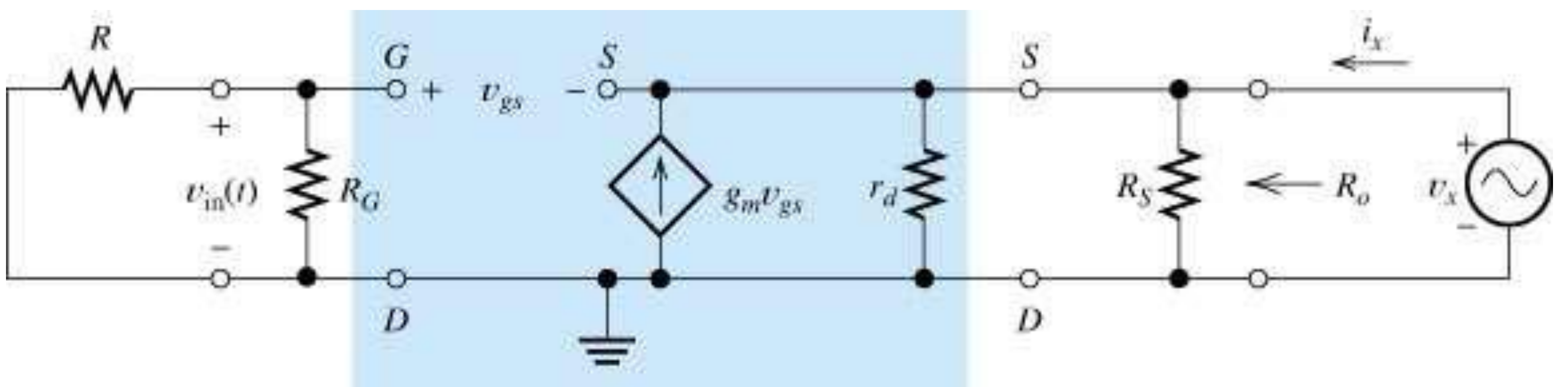


Figure Equivalent circuit used to find the output resistance of the source follower.

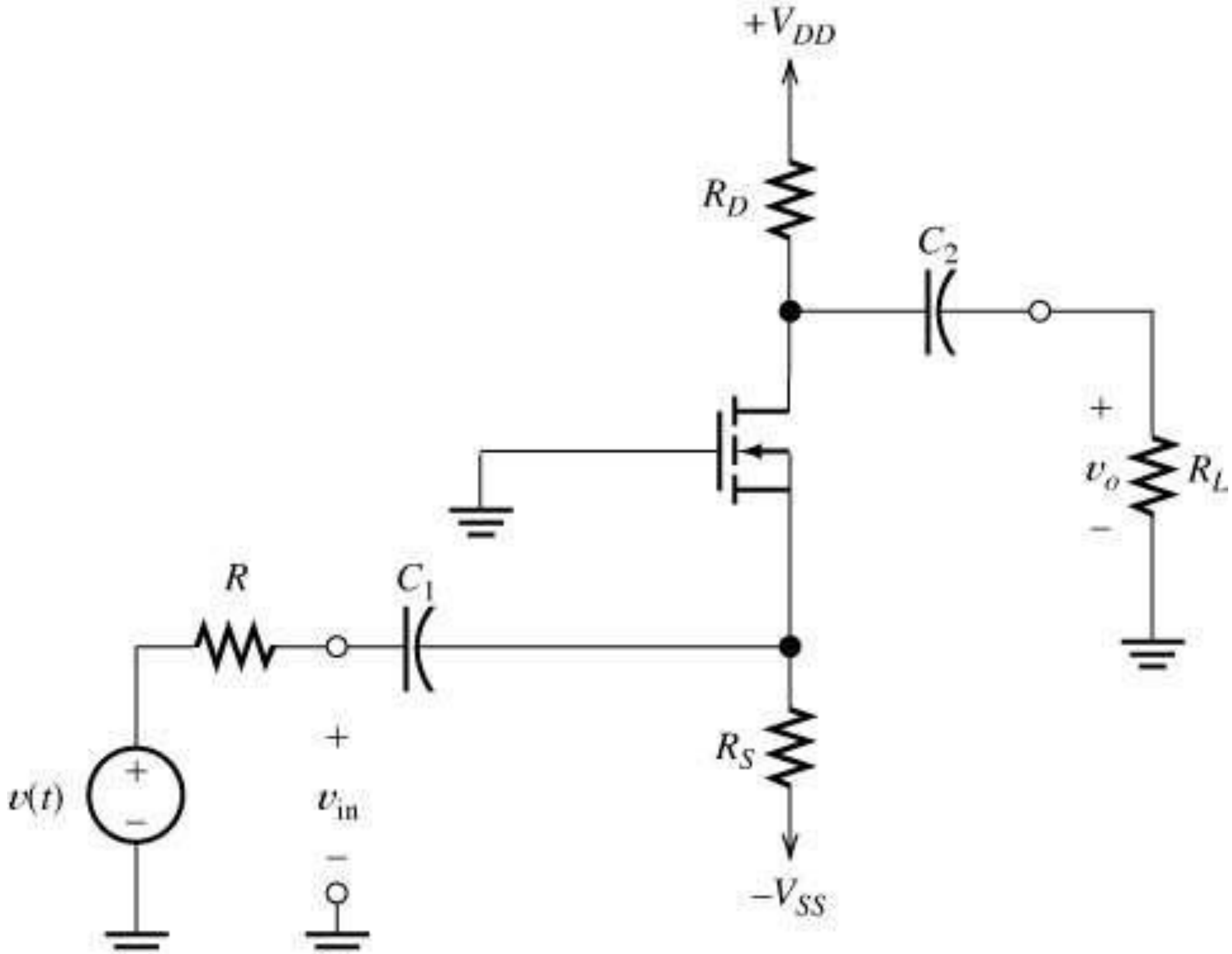
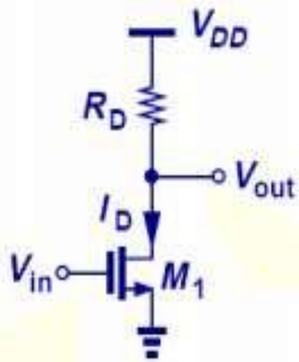


Figure Common-gate amplifier.

Summary of CS, CG, and CD Amplifiers

<table>
<tr><th>CS</th><th>CS Deg</th><th>CG</th><th>CD</th></tr>
<tr>
<td>
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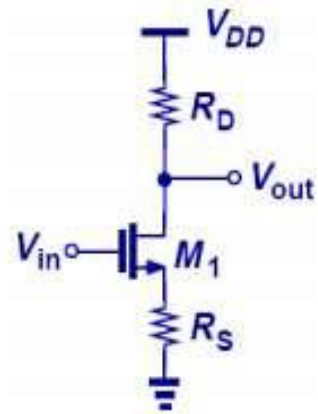
<td>
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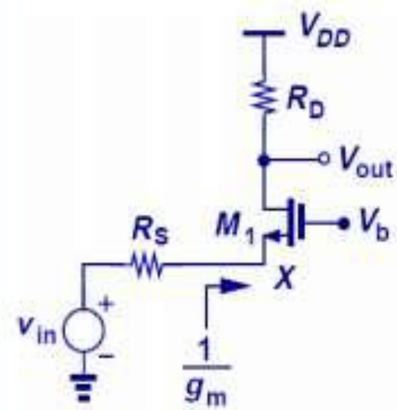
<td>
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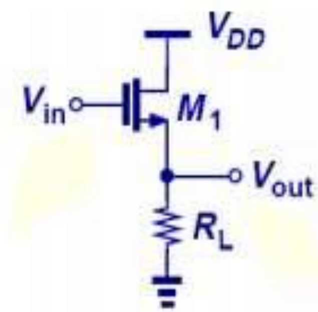
<td>
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</tr>
<tr>
<td>$A_v = -g_m (R_D \parallel r_O)$

$R_{in} = \infty$
$R_{out} = R_D \parallel r_O$</td>
<td>$A_v = -\dfrac{R_D}{\dfrac{1}{g_m} + R_S}$
$R_{in} = \infty$
$R_{out} = [(1 + g_m r_O) R_S + r_O] \square R_D$</td>
<td>$A_v = \dfrac{R_D}{\dfrac{1}{g_m} + R_S}$
$R_{in} = \dfrac{1}{g_m}$
$R_{out} = [(1 + g_m r_O) R_S + r_O] \square R_D$</td>
<td>$A_v = \dfrac{r_O \parallel R_L}{\dfrac{1}{g_m} + r_O \parallel R_L}$
$R_{in} = \infty$
$R_{out} = \dfrac{1}{g_m} \parallel r_O \parallel R_L$</td>
</tr>
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