Electronic Devices and Applications

* **Classification of semiconductors** : (i) intrinsic
(ii) extrinsic → p type, n type

Intrinsic semiconductor : pure semi-conducting tetravalent crystals, electron-hole pairs are created even at room temperature.

Extrinsic semiconductor : they are tetravalent crystals doped with impurity atoms from Group III or V. They are further classified as n-type and p-type semiconductors.

* **Doping** : The process of deliberate addition of a desirable impurity to a pure semiconductor so as to increase its conductivity is called doping.

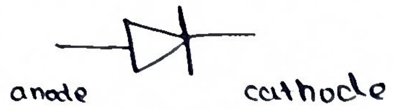
* **n-type semiconductors** : Extrinsic semiconductors obtained by doping pentavalent impurities (Group V atoms) to Ge or Si.
The impurity atoms added provide free electrons and are called donors.
The electrons are majority charge carriers while the holes are the minority charge carriers
Electron density >> hole density

* **p-type semiconductors** : Extrinsic semiconductors obtained by doping trivalent atoms (Group III) to Ge or Si.
The impurity atoms added create vacancies of electrons and are called acceptors.
majority charge carriers : holes
minority charge carriers : electrons
hole density >> electron density

* **Holes**: The absence of an electron in a covalently bonded crystal is called a hole.

* **p-n Junction**: It is a single crystal of Ge or Si doped in such a manner that one half of it acts like a p-type semiconductor and another half of it acts as an n-type semiconductor.

Symbol :



Depletion region and potential barrier.

Two important processes are involved in the formation of a p-n junction: diffusion and drift.

Diffusion : In an n-type semiconductor, concentration of e^-s > con. of holes

In a p-type semiconductor, conc. of holes > conc. of electrons

• During the formation of a p-n junction diode, due to a concentration gradient, electrons diffuse from the n-side → p-side and holes from p side to n-side.

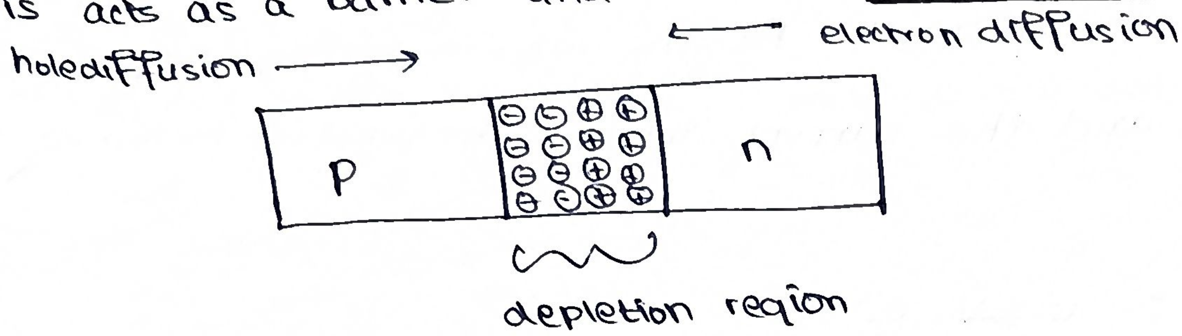
• The diffusion of majority charge carriers across the junction due to a concentration gradient leads to $\boxed{\text{DIFFUSION CURRENT.}}$

• When an electron diffuses from n→p, it leaves behind an ionized donor (a +ve charge) on the n-side. IIIly, when a hole diffuses from p→n, it leaves behind an ionized acceptor (a -ve charge) on the p side.

• These ~~a~~ ~~&~~ ionized donors and acceptors are immobile, as they are bonded to the surrounding atoms. Thus, there is an accumulation of +ve charge on the n-side, and -ve charge on the p-side. This sets up a potential difference across the junction.

* The small region in the vicinity of the junction which is depleted of free charges carriers and has only immobile ~~atom~~ ions is called the $\boxed{\text{depletion region}}$.

The accumulation of +ve charge on the n-side and -ve charge on the p-side sets up a potential difference across the junction. This acts as a barrier and is called $\boxed{\text{barrier potential.}}$



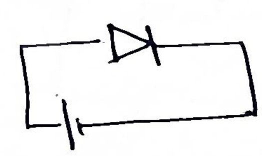
The barrier potential sets up an electric field from the n-side to the p-side. (positive charge space to negative charge space). Due to this electric field, an electron on the p-side of the junction moves towards the n-side and a hole on the n-side moves to the p-side. The motion of charge carriers due to this electric field sets up a $\boxed{\text{drift current,}}$ which is in the opposite direction of diffusion current.

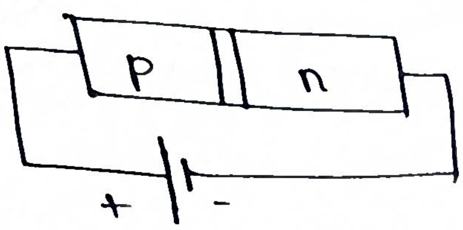
* p-n Junction under Forward Bias

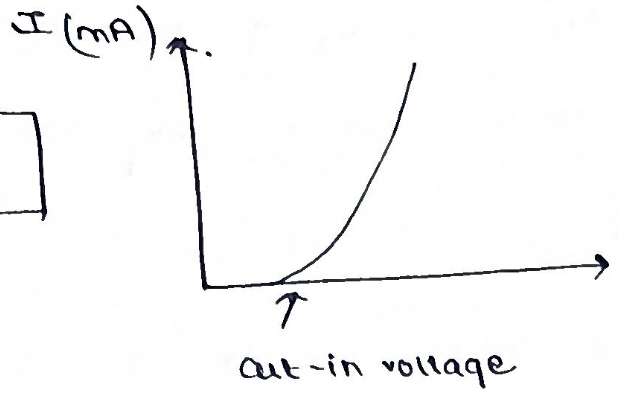
- When an external voltage V is applied across a semiconductor diode such that the p-side is connected to the +ve terminal, and the n-side is connected to the -ve terminal, it is said to be forward biased,

- The applied voltage mainly drops across the depletion region, ~~and the direction of applied voltage is opposite to the barrier potential~~.

- Thus, the potential barrier reduces,
  junction resistance decreases
  the diode conducts.







Characteristic eqn:

$$i = I_s\left(e^{\frac{V}{nV_T}} - 1\right)$$

- There is an exponential relationship
- I_s = saturation current
- n = 1 or 2
- V_T = thermal voltage

- Under forward bias, there exists a cut-in voltage / threshold voltage below which the current is very small. At the cut-in voltage, the potential barrier is overcome, and the current through the junction increases rapidly.

Cut-in voltage for silicon : ~~0.3V~~ 0.7V

for germanium : 0.3V

* p-n junction under reverse bias

- When an external voltage (V) is applied across the diode, such that the n-side is connected to the +ve terminal and the p-side is connected to the -ve terminal, the diode is said to be reverse biased.

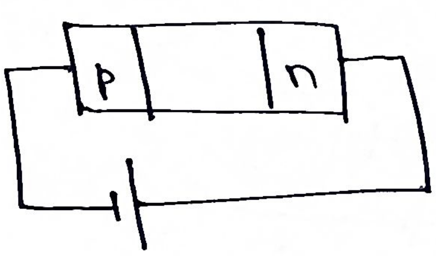
- The applied voltage mostly drops across the depletion region. The direction of applied voltage is the same as the direction of the barrier potential

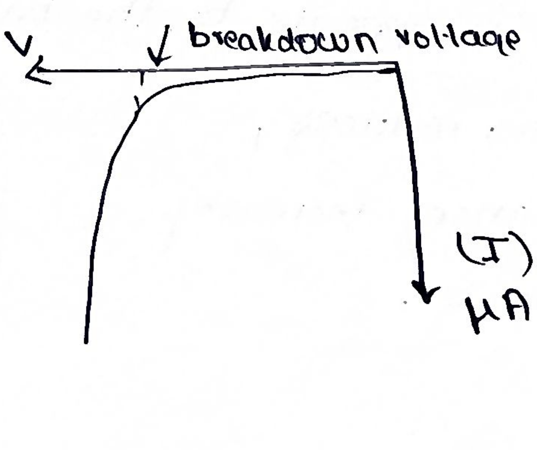
IV characteristic eqn

$i_s = -I_s$

(independent of voltage)

- Thus, the potential barrier increases, the junction resistance increases and the diode does not conduct.

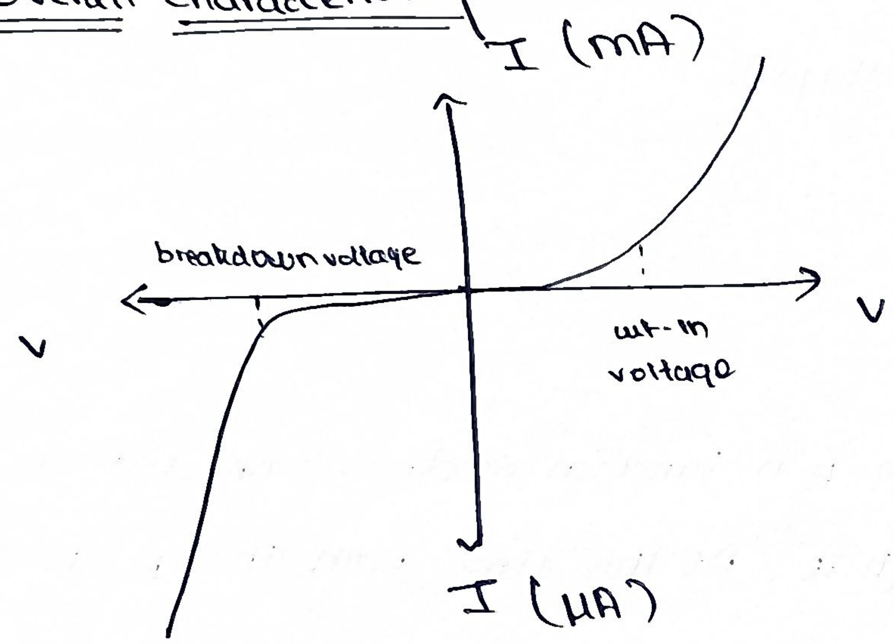




• The current under reverse bias is essentially voltage independent upto a critical reverse bias voltage, known as the breakdown voltage (V_{br}). At V_{br}, diode reverse current increases sharply. Even a slight change in the bias voltage causes large changes in the current

• If the reverse current is not limited by an external circuit below the rated value, the p-n junction will get destroyed.

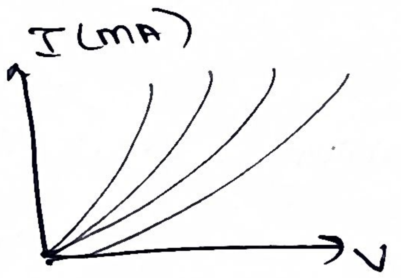
Overall characteristics



* p-n junction diode as an LED

• A light emitting diode is a forward-biased p-n junction diode, which emits spontaneous light emission.

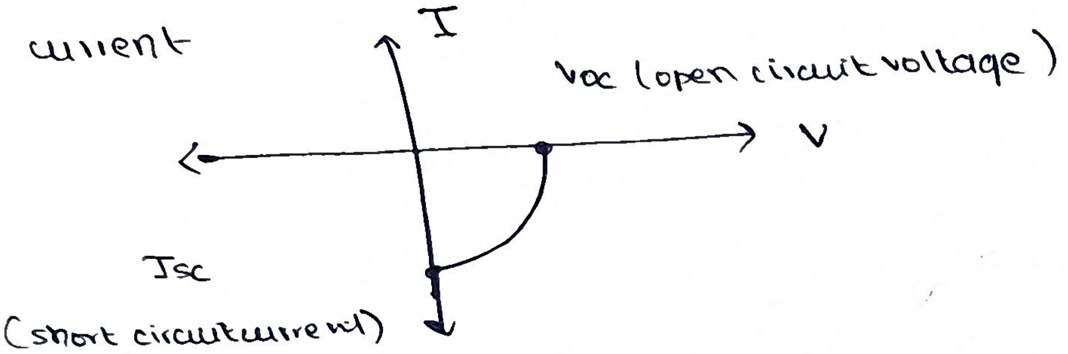
• When a forward bias is applied, the electrons and holes at the junction recombine, and energy released is emitted in the form of light.



* p-n junction diode as a solar cell

- A solar cell is a p-n junction diode which converts light energy into electrical energy. A solar cell has a large p-n junction with no external biasing.

- When photons of energy greater than the band gap are incident on the junction, electron-hole pairs are created which move in opposite directions due to the junction field. These are collected at the 2 sides of the junction, producing a photo-voltage, which gives rise to photo current



*** Junction Capacitance**: When a p-n junction diode is connected in reverse bias, no current flows through it. At this time, both the p and the n regions act as electrodes, and the depletion region in between them acts as a dielectric medium. Thus, electric charge may be stored. The junction capacitance is given by:

$$C_j = \frac{A\epsilon}{w}$$, where w is the width of the depletion region.

- The junction capacitance gets charged and discharged every time the diode is turned on and off.

- Transistors have p-n junctions. The junction capacitance limits the high frequency performance of the transistors.

  $Z_C = 1/j\omega C$ becomes a short circuit at high frequencies.

- This is a fundamental principle that limits the performance of all electronic devices.

* Drift and drift current density of electrons & holes

Drift velocity:

$v_{drift} = \mu_p E$

$v_{drift} = -\mu_n E$

μ_p → hole mobility, μ_n → electron mobility:

Current density ($J = \rho v$)

ρ → charge density, v → velocity

$$J_{n\text{-drift}} = (-qn)(-\mu_n E) = qn\mu_n E$$

$$J_{p\text{-drift}} = qp\mu_p E$$

Total drift current density: $= J_{n\text{-drift}} + J_{p\text{drift}}$

$$= qE(n\mu_n + p\mu_p)$$

Resistivity: $\rho = \dfrac{1}{q(n\mu_n + p\mu_p)}$ (for an intrinsic semiconductor, the resistivity would be $\dfrac{1}{qn(\mu_n + \mu_p)}$)

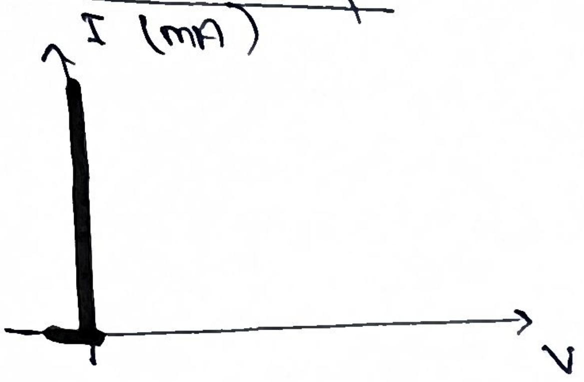
* Diode Equivalent Models:

An equivalent circuit is a combination of elements that best represents the actual terminal characteristics of the device. It means that the diode in the circuit can be replaced by some other elements in such a way that the behaviour of the circuit is not severely affected. Some models are:

① Ideal Diode Model

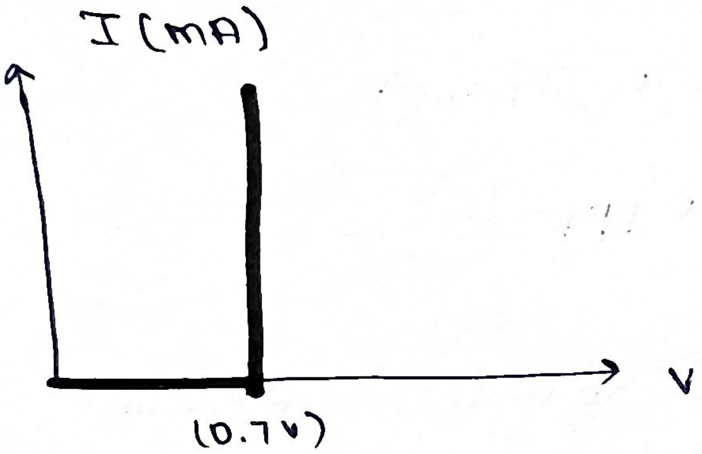
An ideal diode does not allow any current to flow in the reverse biased condition. It can be modelled into an open / closed switch based on the bias voltage.

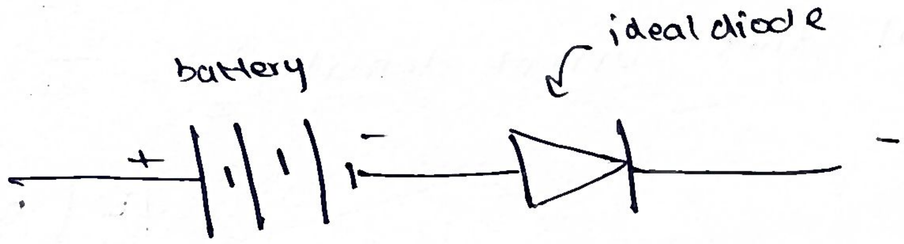
characteristics



(2) Simplified diode equivalent model : In this model, it is assumed that the diode will not conduct until the cut-in voltage is reached and after that it acts like an ideal closed switch that conducts only in one direction.

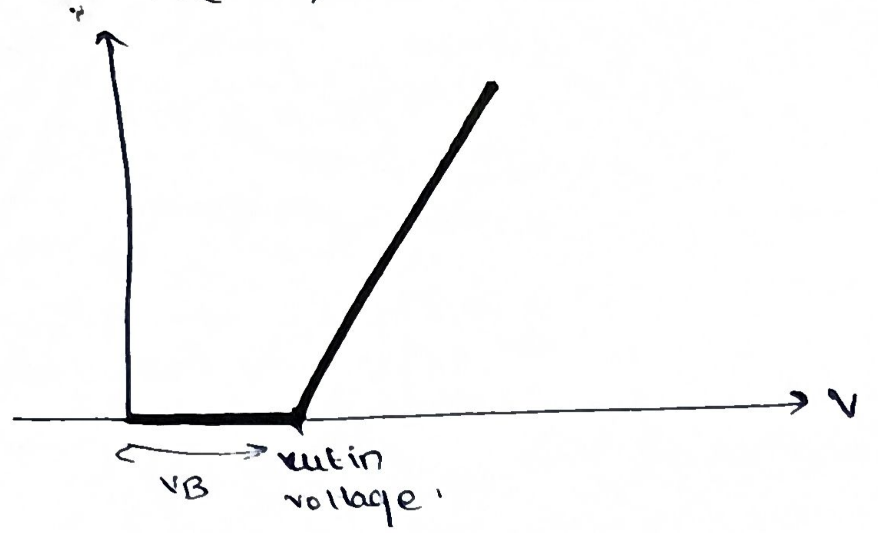
This set up consists of a battery and a diode. The battery opposes the flow of current in the forward direction until 0.7V (the cut-in voltage)
Once V > 0.7, the current flows in the forward direction

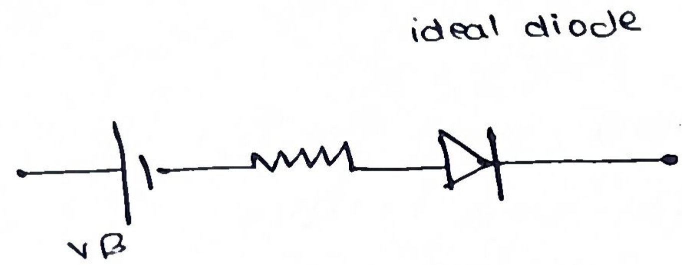




(3) Piece-wise linear model : In this model, the diode is represented by straight line segments.

The model assumes that the diode does not conduct until the cut-in voltage. ~~Once the ap~~ A battery opposes current flow until the cutin voltage. After that, the diode is represented by its dynamic resistance. The diode in the equivalent circuit is an ideal diode which conducts only in the forward direction.





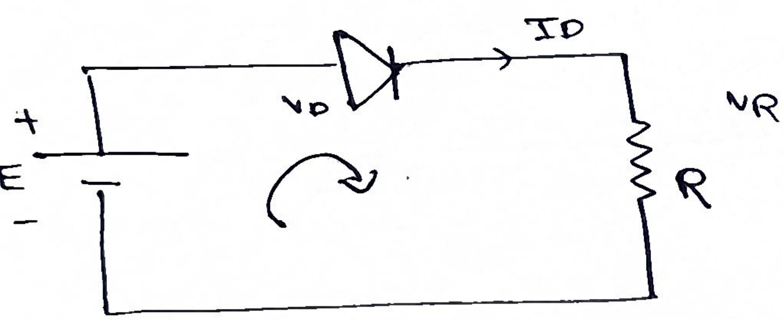
Slope = 1/R

* **Load line analysis**

Load line analysis determines the point of operation on applying a given load.

A line is drawn on a graph, representing the applied load. The intersection of the load line with the characteristics of the dives determines the point of operation.

Consider the following circuit:



Applying Kirchhoff's voltage law:

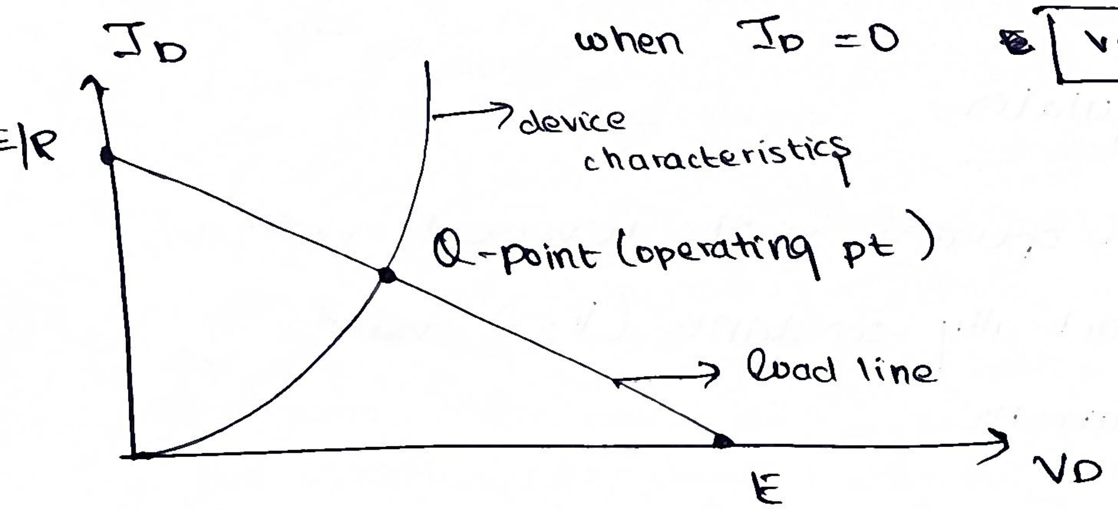
$$V_D + I_D R - E = 0$$

$$E = V_D + I_D R$$

when $V_D = 0$ $\quad E = I_D R$

$$\boxed{I_D = E/R}$$

when $I_D = 0$ $\quad \boxed{V_D = E}$



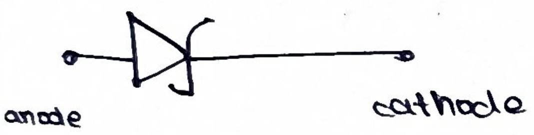
Applications of diode circuits

- rectifier circuits
  - half-wave rectifier
  - full-wave rectifier
- voltage regulator
- limiter

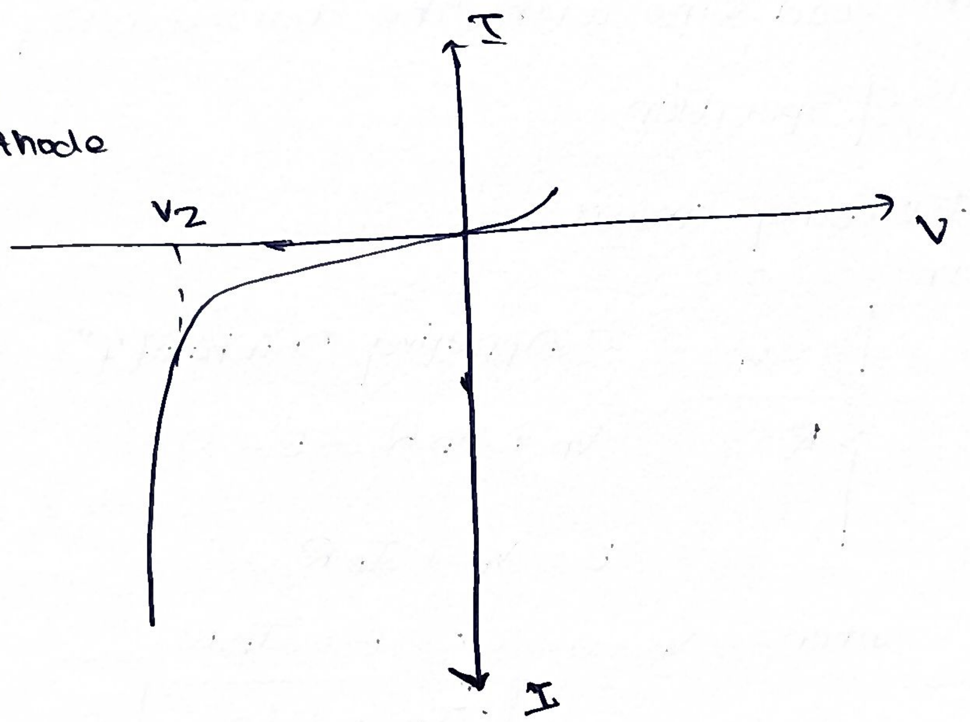
* Zener Diode

A junction diode that is specially designed to operate only in the reverse breakdown region continuously, without getting damaged is called a Zener diode.

symbol



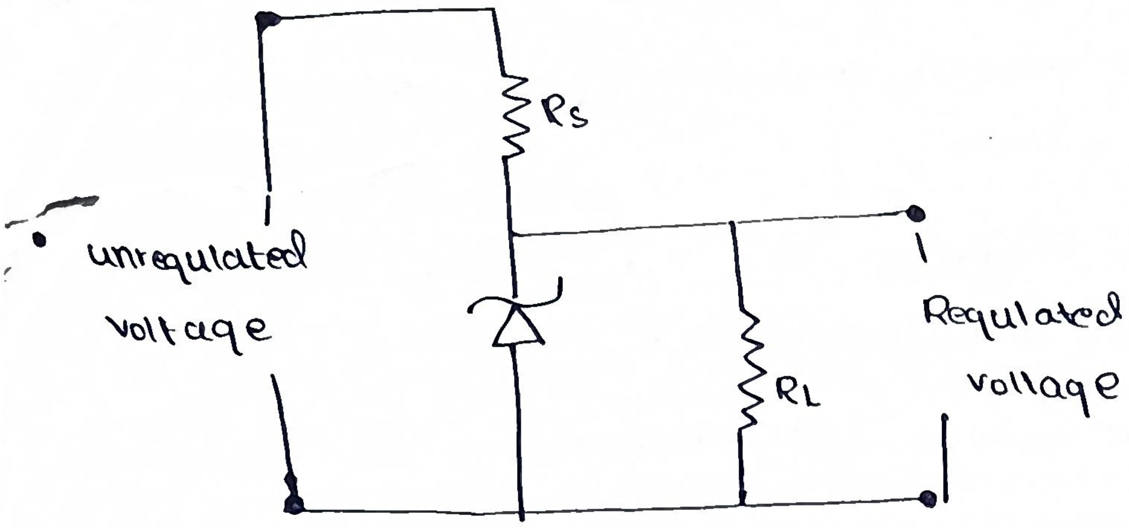
characteristics



* Zener diode as a voltage regulator

Principle: When a Zener diode is operated in the reverse breakdown region, the voltage remains practically constant (V_Z) even for large changes in the reverse current.

Working :



- A zener diode is connected in reverse bias to a source of fluctuating dc, and it passes through the resistor Rs
- Voltage gets divided across Rs and the Zener diode.
- The output is obtained across the load resistance R_L, connected in parallel to the Zener diode.
- If the input voltage increases, the current through Rs and the Zener diode also increases.
- This increases the voltage drop across Rs without any change in the voltage across the Zener diode.
- This is because in the breakdown region, Zener voltage remains a constant, even if the value of current through it changes.
- A decrease in voltage also would be reflected only across Rs and not across the Zener diode.
- Thus, the Zener diode acts as a voltage regulator.

* PN Junction Breakdown

The electrical breakdown of any ~~matter~~ semiconductor can happen due to 2 phenomena:

(i) Zener breakdown
(ii) Avalanche breakdown

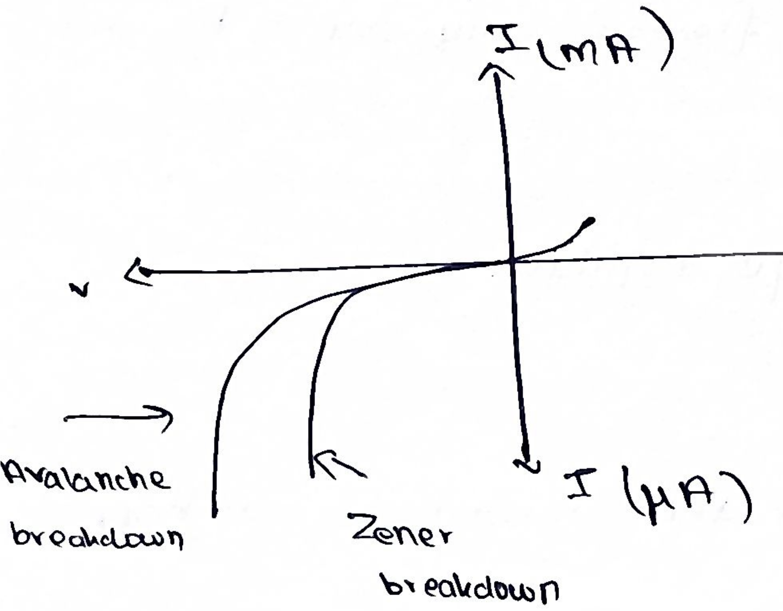
Zener breakdown

- occurs in heavily doped p-n junction diodes
- Due to the high dopant density, the width of the junction layer is small ⟹ Electric field is high.
- When a large reverse bias is applied, the K.E of the electrons increases, and they move at a high velocity.
- The high velocity electrons collide w/ other atoms and give rise to free electrons.
- This leads to a large value of reverse saturation current

Avalanche breakdown

- occurs in diodes having low levels of doping
- This means the junction is wide.
- When there is a high reverse voltage, the minority charge carriers get excited.
- Their KE becomes high enough that they exert force on the electrons at the junction and break the covalent bonds.
- These free electrons move w/ high velocity across the junction and collide with the other atoms, creating more free electrons.

This cause a rapid increase in reverse current



* Differences between Zener breakdown & avalanche breakdown

Zener breakdown	Avalanche breakdown
• Zener breakdown occurs because of the high electric field.	• Avalanche breakdown occurs because of the collisions of free electrons with atoms
• Occurs in heavily doped p-n junction diodes	• Occurs in minimally doped p-n junction diodes
• Occurs in a thin depletion region caused by high doping	• Occurs in a thick depletion region due to low doping
• After the voltage reaches the Zener breakdown voltage, the diode can be brought back to its original state.	• The diode cannot be brought back to its original state after an avalanche breakdown.
• Zener breakdown occurs with the production of electron pairs.	• Avalanche breakdown produces electron & hole pairs
• Temperature coeff of Zener breakdown is -ve.	• Temp. coeff of avalanche breakdown is +ve
• Observed in Zener diodes having a Zener breakdown voltage of 5-8V.	• Occurs in Zener diodes having a breakdown voltage of $V_Z > 8V$
• VI characteristics are very sharp.	sharp, but not as sharp as Zener breakdown.

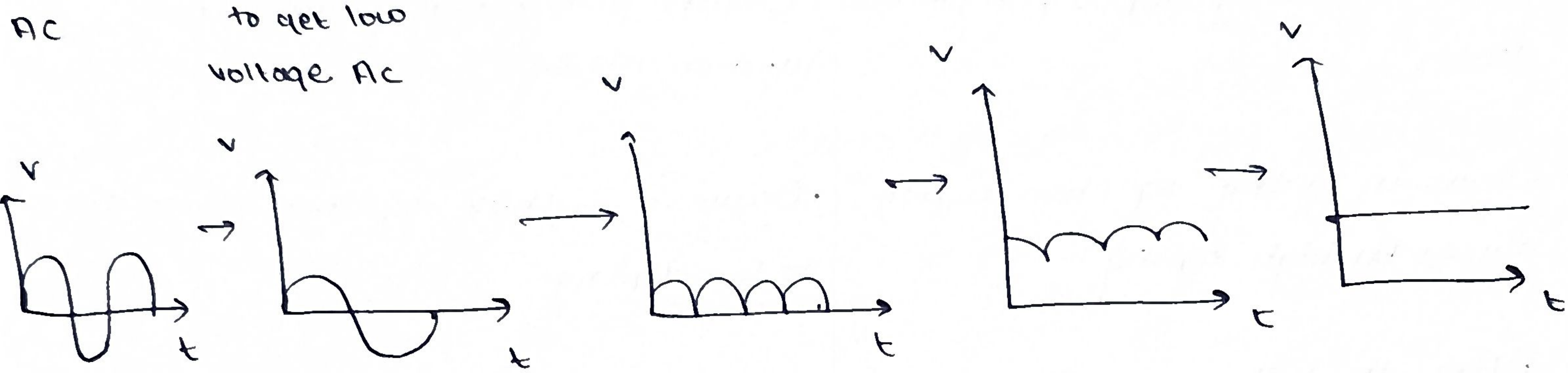
Rectifiers

Rectification: Conversion of AC to DC

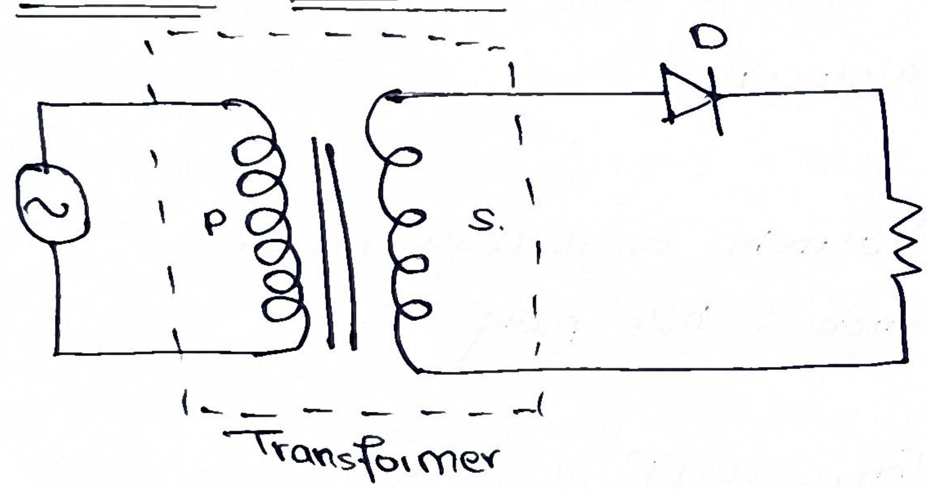
*Why are diodes used as rectifiers?

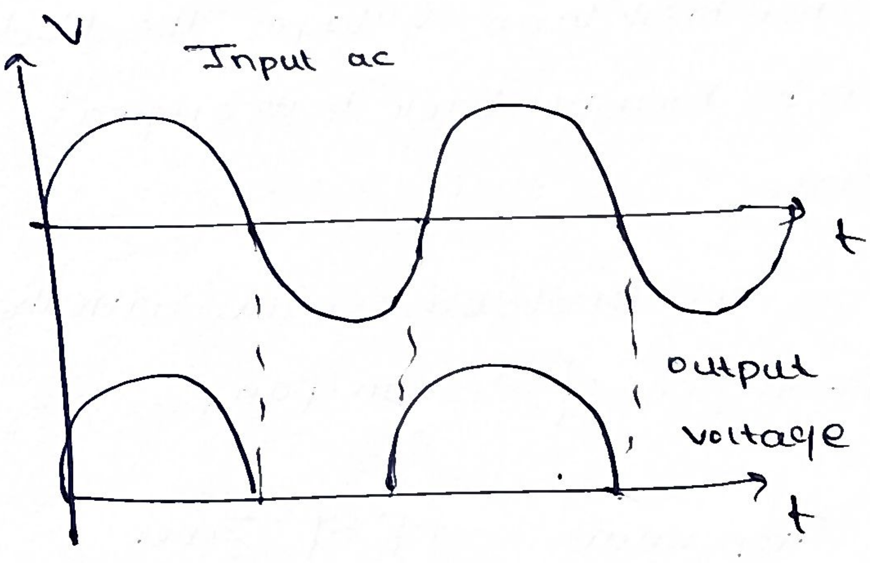
→ Diodes conduct only when they are forward biased. This helps make input current unidirectional.

Input AC → Transformer (use to get low voltage AC) → Rectifier → Filter → Regulator.



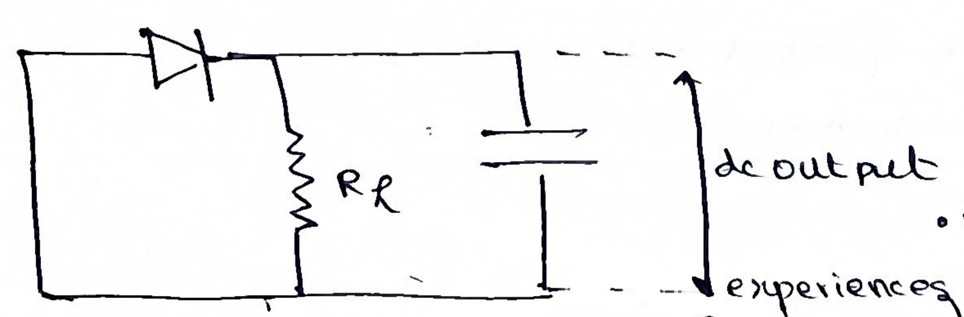
Halfwave rectifier





When the +ve half of the AC input is given to the diode, it gets forward biased and conducts. There is an output across the load resistance. When the -ve half of the AC is given, the diode becomes reverse biased and does not conduct.

Half-wave rectifier with filter



- pulsating DC has both AC & DC components.
- capacitor blocks DC, only the AC component is allowed through
- DC experiences a high resistance, AC experiences a low resistance.
- AC components flow through capacitor.
- DC finds alternate path, flows through RL

* Average output voltage of a half-wave rectifier.

Let V_{dc} be the average voltage of a half-wave rectifier.

$$V_o(t) = \begin{cases} V_m \sin\omega t, & 0 \le t \le T/2 \\ 0, & T/2 \le t \le T \end{cases}$$

$$V_{dc} = \frac{1}{T}\int_0^T V_o(t)\,dt$$

$$V_{dc} = \frac{1}{T}\int_0^{T/2} V_m \sin\omega t\,dt + \frac{1}{T}\int_{T/2}^{T} 0\,dt$$

$$V_{dc} = \frac{1}{T} V_m \cdot \left(\frac{-1}{\omega}\right) (\cos\omega t)_0^{T/2}$$

$$V_{dc} = \frac{-V_m}{\omega T}\left\{\cos\frac{\omega T}{2} - \cos 0\right\}$$

$$V_{dc} = \frac{V_m}{\omega T}\left\{1 - \cos\frac{\omega T}{2}\right\}$$

$$= \frac{V_m}{\omega T}\left\{1 - \cos\frac{T}{2}\cdot\frac{2\pi}{T}\right\}$$

$$= \frac{V_m(2)}{\omega T} = \frac{2V_m}{\omega\cdot\left(\frac{2\pi}{\omega}\right)} = \frac{V_m}{\pi}$$

$$\boxed{V_{dc} = \frac{V_m}{\pi}}$$

* RMS value of the output voltage of a half wave rectifier

Let the RMS value of the output voltage be V_{rms}.

$$V_{rms}^2 = \frac{1}{T}\int_0^T V_o^2(t)\,dt$$

$$= \frac{1}{T}\int_0^T V_m^2 \sin^2\omega t\,dt$$

$$= \frac{V_m^2}{T}\int_0^{T/2} \sin^2\omega t\,dt$$

$$= \frac{V_m^2}{2T}\int_0^{T/2} 1-\cos 2\omega t$$

$$= \frac{V_m^2}{2T}\left(t - \frac{\sin 2\omega t}{2\omega}\right)_0^{T/2}$$

$$= \frac{V_m^2}{2T}\left(\frac{T}{2} - \frac{\sin 2\omega\frac{T}{2}}{2\omega}\right)$$

$$= \frac{V_m^2}{2T}\left(\frac{T}{2} - \frac{\sin \omega\cdot\frac{2\pi}{\omega}}{2\omega}\right)$$

$$= \frac{V_m^2}{4}$$

$$V_{rms}^2 = \frac{V_m^2}{4}$$

$$\boxed{V_{rms} = \frac{V_m}{2}}$$

* Ripple factor of a half-wave rectifier

Ripple is the unwanted AC component remaining when converting the AC voltage wave-form into a DC wave form.

$$\gamma = \frac{V_{rms}\ (ripple)}{V_{dc}}$$

To calculate V_{rms} (ripple), the AC component present in the output is written as

$$V_o(t) = V_{ac} + V_{dc}$$

$$V_{rms}^2(ripple) = \frac{1}{T}\int_0^T V_{ac}^2\, dt$$

$$= \frac{1}{T}\int_0^T (V_o - V_{dc})^2\, dt$$

$$= \frac{1}{T}\int_0^T V_o^2 + V_{dc}^2 - 2V_oV_{dc}\ dt$$

$$= \frac{1}{T}\Big[V_o^2 t + V_{dc}^2 t - 2V_oV_{dc}t \Big]_0^T$$

$$= \frac{1}{T}\left\{ V_o^2 T + V_{dc}^2 T - 2V_oV_{dc}T \right\}$$

$$= V_o^2 + V_{dc}^2 - 2V_oV_{dc}$$

$$= V_{rms}^2 + V_{dc}^2 - 2V_{dc}^2$$

$$= V_{rms}^2 - V_{dc}^2$$

$$\frac{V_{rms}\ (ripple)}{V_{dc}} = \gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

$$\gamma = \sqrt{\left(\frac{V_m}{2} \times \frac{\pi}{V_m}\right)^2 - 1} = \sqrt{\frac{\pi}{4} - 1} = 1.21$$

* Efficiency of a half wave rectifier

$$\eta = \frac{\text{DC power input}}{\text{AC power output}} = 40.6\%$$

* Form Factor of a half wave rectifier

→ Ratio between rms load voltage and average load voltage

$$\text{Form Factor} = \frac{V_{rms}}{V_{dc}} = \frac{V_m/2}{V_m/\pi} = \frac{\pi}{2} = 1.57$$

* Peak inverse voltage of a half wave rectifier

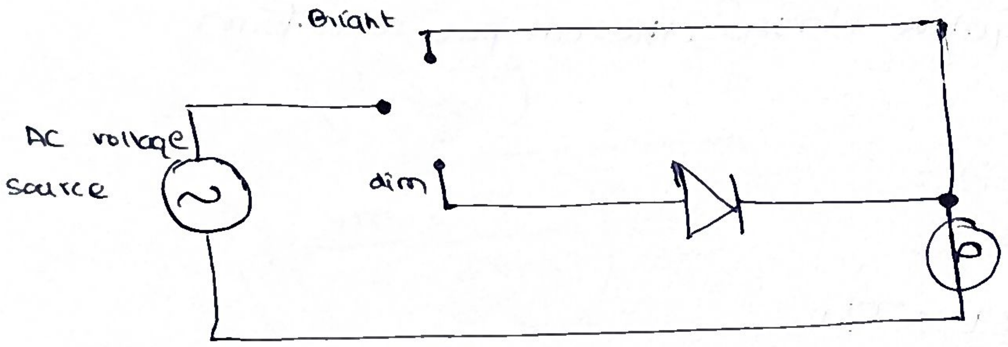
Peak inverse = maximum voltage that a diode can withstand during reverse bias conditions.

In a half wave rectifier : $PIV = V_m$

* Peak factor = $V_m / V_{rms} = 2$

* Applications of half wave rectifier

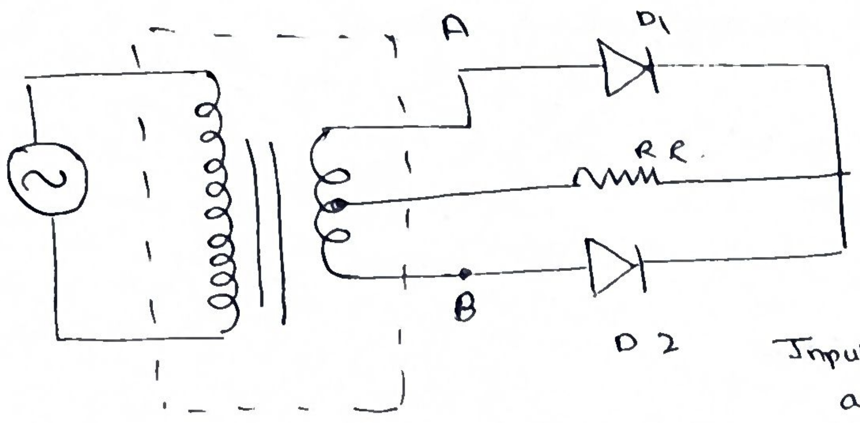
- detection of amplitude modulated radio signals
- supplies polarized voltage
- used in signal demodulation
- reduce power to a resistive load, as a 2 position lamp dimmer



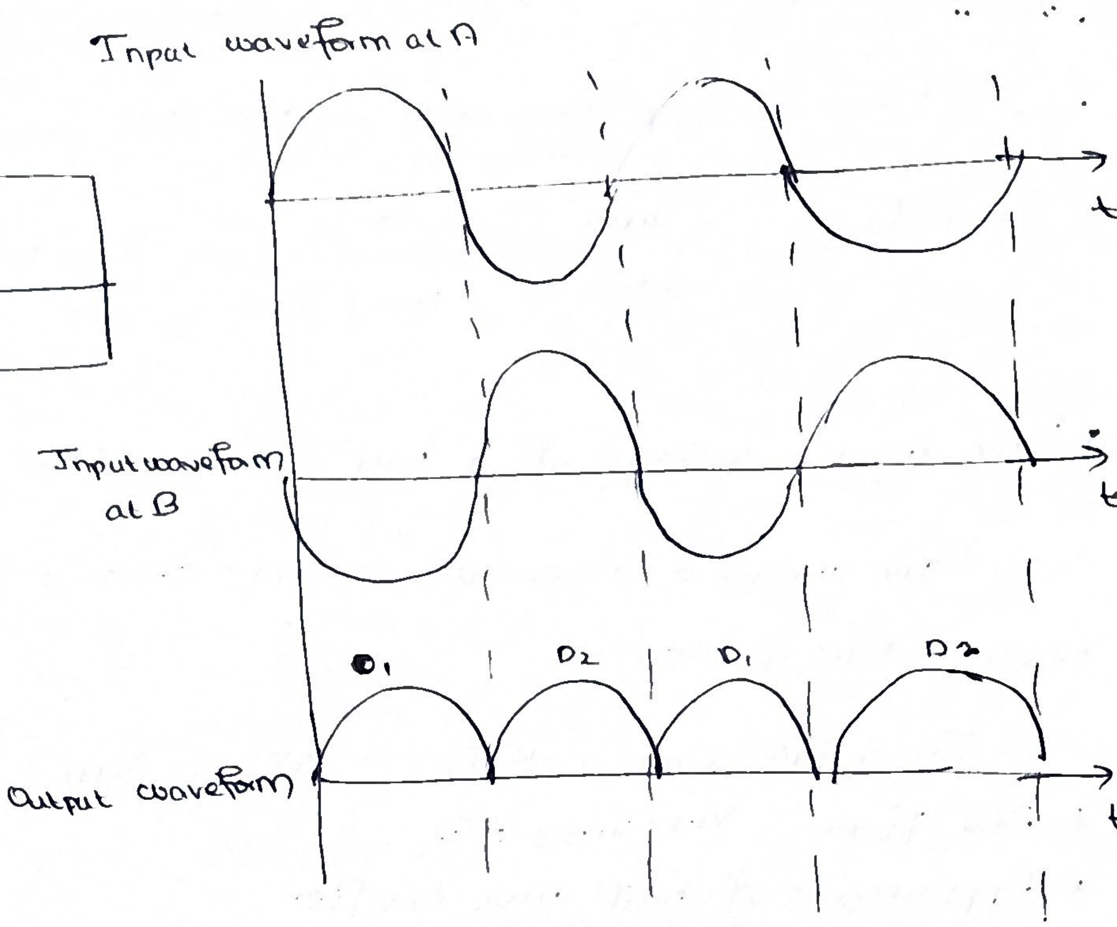
* Advantages : simpler setup
  cheaper

* Disadvantages : • high power loss as only 1 half of the sine wave is utilized
  - low output voltage
  - not a pure dc which is obtained, has a lot of ripple

* Full-wave rectifier



center tapped transforma.



• A full wave rectifier consists of a center-tapped transformer that maintains a phase difference of ~~A and B~~ 180° between D_1 and D_2. When D_1 is forward biased, D_2 is reverse biased and vice versa.

• When D_1 is forward biased, there is an output across the load resistance because of it, while when it is negative biased, the output waveform would come from D_2

The output voltage is represented as:

$$V_o(t) = \begin{cases} V_m \sin\omega t & , 0 \le t \le T/2 \\ V_m \sin(\omega t - \pi) & , T/2 \le t \le T \end{cases}$$

* Average output voltage

$$V_{dc} = \frac{1}{T}\int_0^T V_o(t)\,dt$$

$$= \frac{1}{T/2}\int_0^{T/2} V_m \sin(\omega t)\,dt$$

$$= \frac{2V_m}{\pi}$$

RMS value of the output voltage

$$V^2_{rms} = \frac{1}{T}\int_0^T V_o^2(t)\,dt$$

$$= \frac{1}{T/2}\int_0^{T/2} V_m^2 \sin^2\omega t \; dt$$

$$= \frac{2V_m^2}{2T}\int (1-\cos 2\omega t)\Big|_0^{T/2}$$

$$= \frac{V_m^2}{T}\left(\frac{T}{2} - \frac{\sin 2\omega T/2}{2}\right)_0$$

$$= \frac{V_m^2}{T}\left(\frac{T}{2} - 0\right)$$

$$= \frac{V_m^2}{2}$$

$$\boxed{V_{rms} = \frac{V_m}{\sqrt{2}}}$$

Ripple factor

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

$$= \sqrt{\left(\frac{V_m}{\sqrt{2}} \times \frac{\pi}{2V_m}\right)^2 - 1} = 0.48$$

* Efficiency: ~~~~81.6~~~~ 81.2%.

* Form Factor $= \frac{V_{rms}}{V_{dc}} = \frac{V_m}{\sqrt{2}} \times \frac{\pi}{2V_m} = \frac{\pi}{2\sqrt{2}} = 1.11$

* Peak inverse voltage $= 2V_m$

* peak factor $= \frac{V_m}{V_{rms}} = \sqrt{2}$

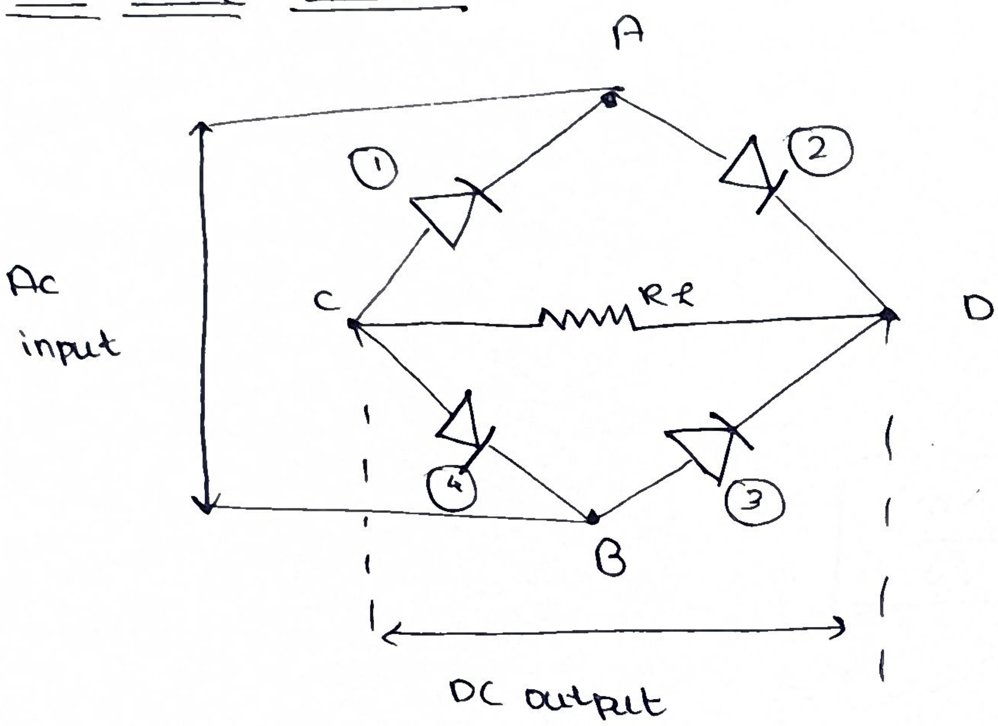
Advantages: greater efficiency

low power loss

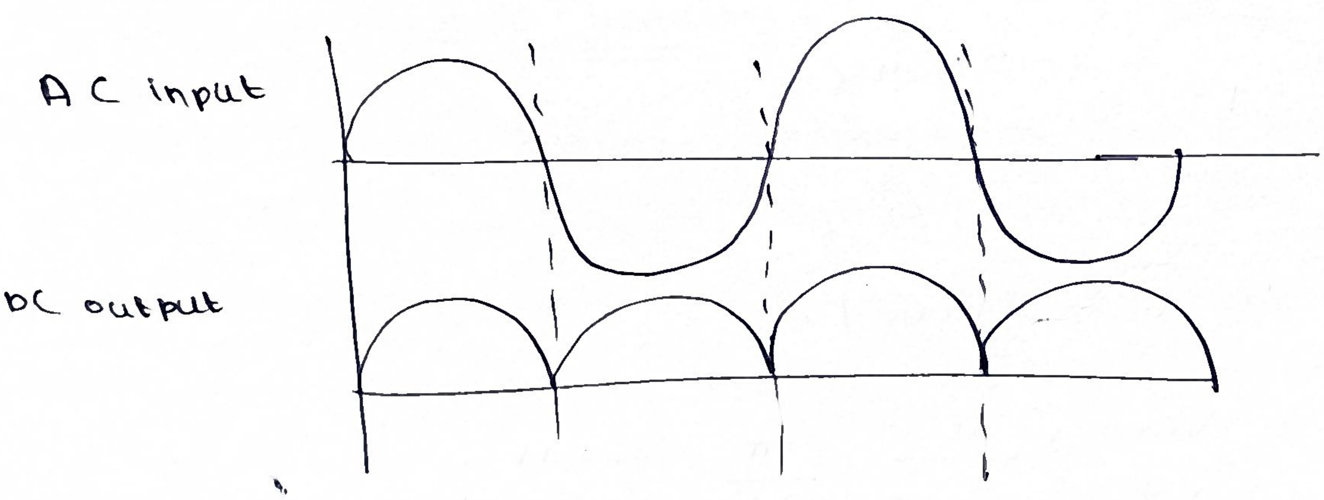
lower ripples

Disadvantages : expensive

Full Bridge Rectifier



· In one half cycle, ① & ③ conduct. In another half cycle ② & ④ conduct

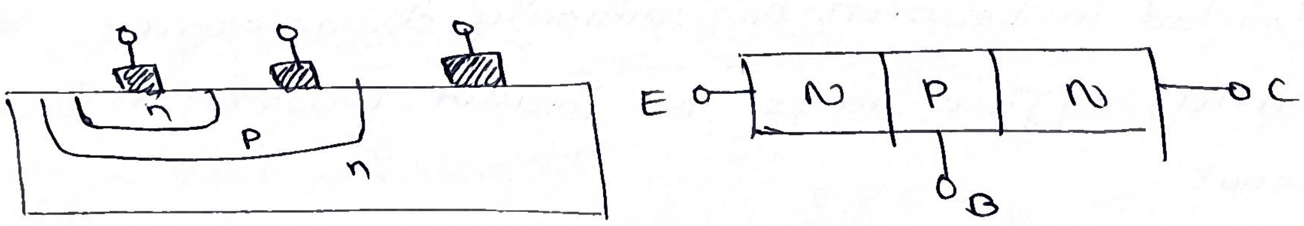


Comparison of parameters

Parameter	Half-wave rectifier	Center tapped Full wave rectifier	Bridge full wave rectifier
No. of diodes	1	2	4
Peak Inverse Voltage	Vm	2Vm	Vm
Efficiency	40.6%	81.2%	81.2%
DC voltage	Vm/π	2Vm/π	2Vm/π
VRMS	Vm/2	Vm/√2	Vm/√2
Ripple factor	1.21	0.48	0.48
output frequency	fin	2fin	2fin

Bipolar Junction Transistor

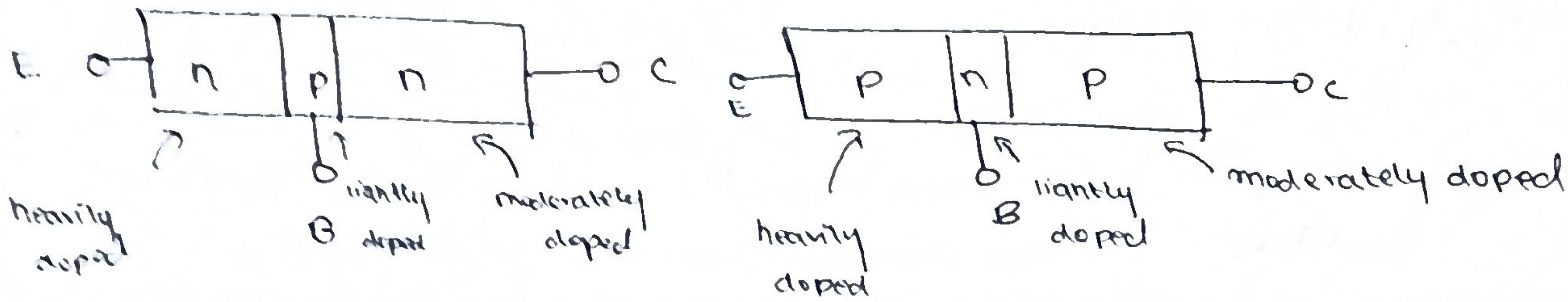
• A BJT is a 3 terminal semiconductor device that consists of 2 p-n junctions which are able to magnify a signal. The 3 terminals of a BJT are the base, the collector and the emitter. The term bipolar represents the fact that both carrier types play important roles in the operation.



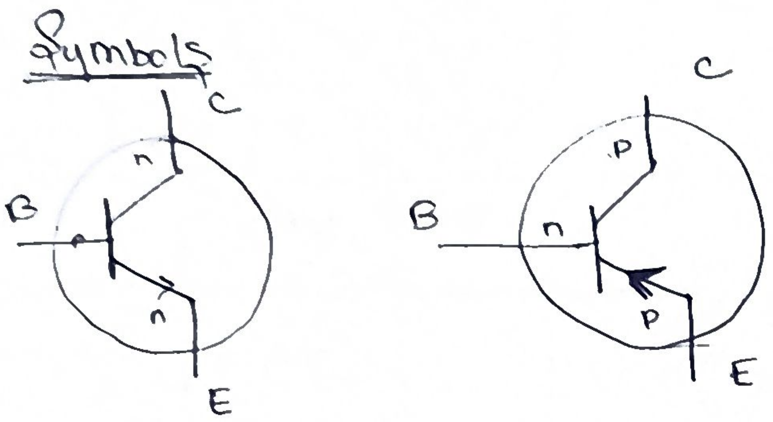
Types of BJTs

(i) npn transistor - a thin layer of p-type material sandwiched between 2 n type materials

(ii) pnp - a thin layer of n type material sandwiched between 2 ptype materials

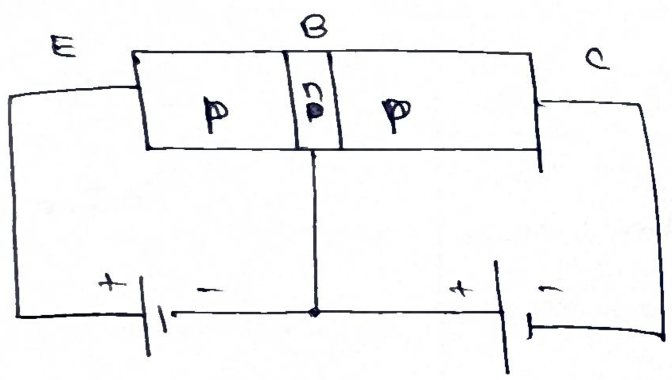


Symbols



npn

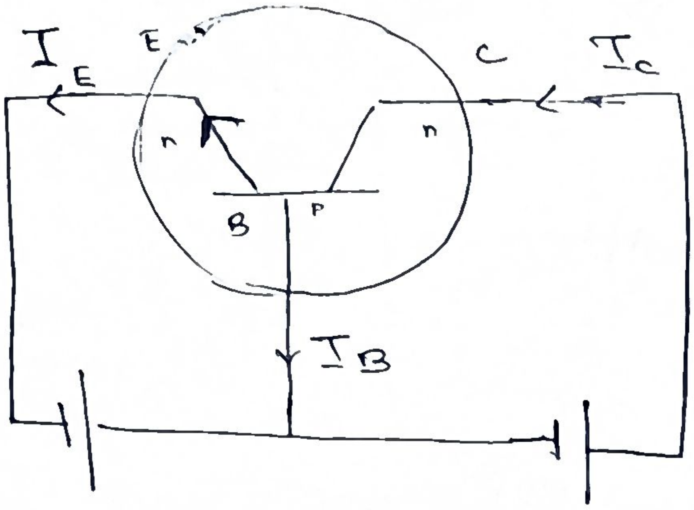
Working of a BJT



- One p-n junction of the transistor is forward biased, the other is reverse biased.
- The p-side of the emitter has majority charge carriers, while that of the collector side also has electrons, but not as many, as it's moderately doped.
- The n-part sandwiched in between has minority charge carriers, i.e. holes
- Majority charge carriers diffuse across the forward biased p-n junction into the n-type material.
- The electron-hole recombination is very small in the base region, since the base is lightly doped. Most of the electrons cross to the collector region.
- The base current is usually of the order of microamperes.
- A greater no. of majority carriers would diffuse into the reverse-biased jn. of the p-type material connected to the collector terminal, & constitute collector current.

Current Gains

Consider the following npn transistor with a common base.



$$I_E = I_c + I_B$$

The base current is very small.

$\Rightarrow I_E \propto I_c$

$$\boxed{I_c = \alpha I_E}$$

α is the fraction of electrons that diffuse across the narrow base region. ~~(current gain~~)

$1-\alpha$ is the fraction of electrons that recombine with hole in the base region to form the base current.

The current gain is expressed in terms of the β of the transistor. β is temperature & voltage dependent.

$$I_c = \alpha I_E$$

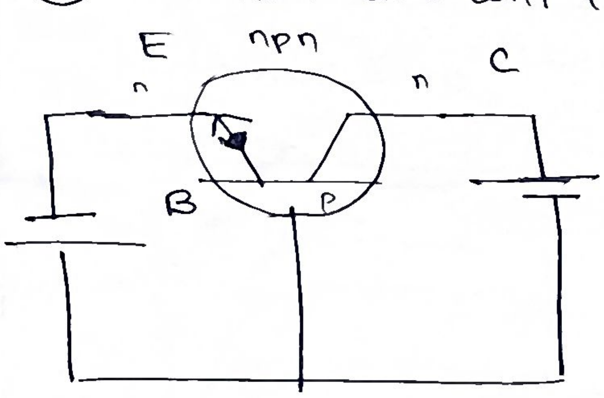
$$I_B = (1-\alpha) I_E$$

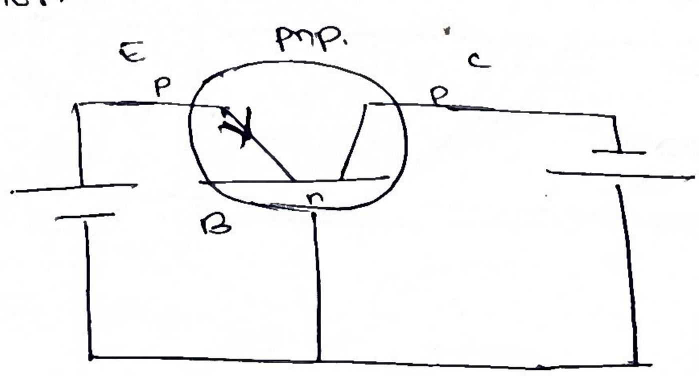
$$\beta = \frac{I_c}{I_B} = \frac{\alpha}{1-\alpha}$$

Transistor configurations & biasing

Emitter = forward biased
collector = reverse biased

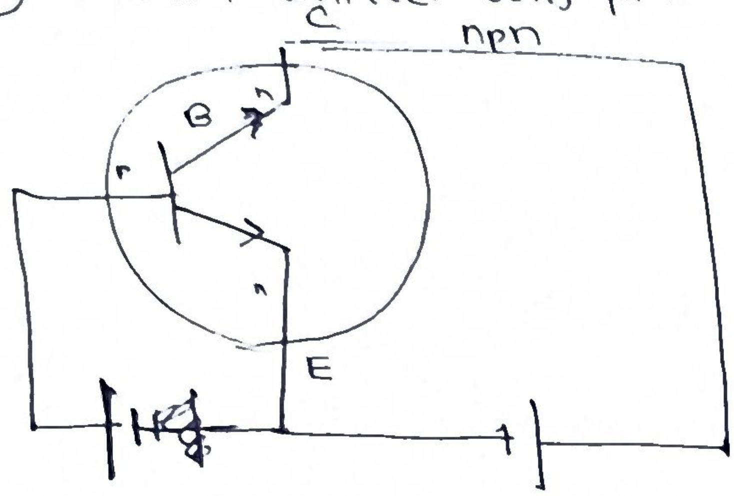
1. common base configuration



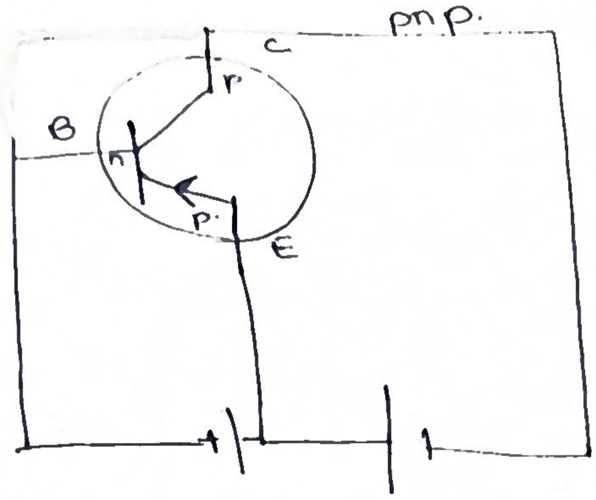


② Common emitter configuration

npn

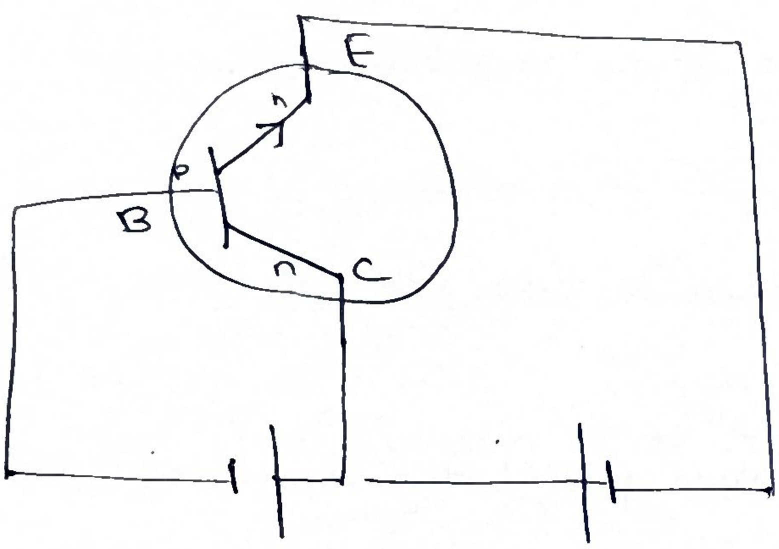


pnp.

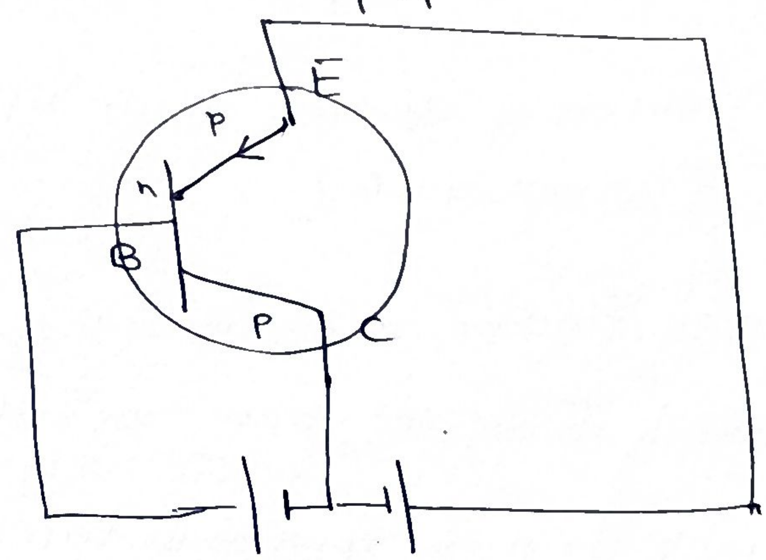


③ Common collector configuration

npn

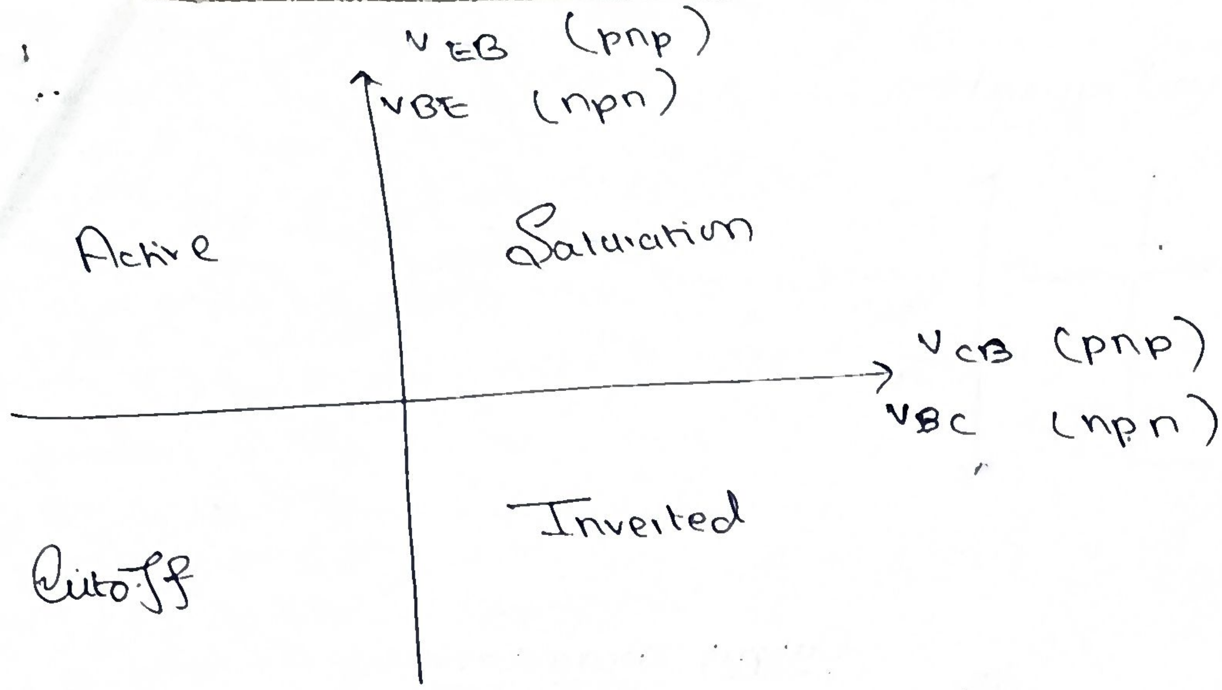


pnp



Modes of operation

Modes	Biasing polarity E-B Jn	C-B Jn	Applications
Active	Forward	Reverse	Amplifier.
Saturation	Forward	Forward	as a switch
Reverse active	Reverse	Forward	Performance degradation
Cutoff	Reverse	Reverse	as a switch



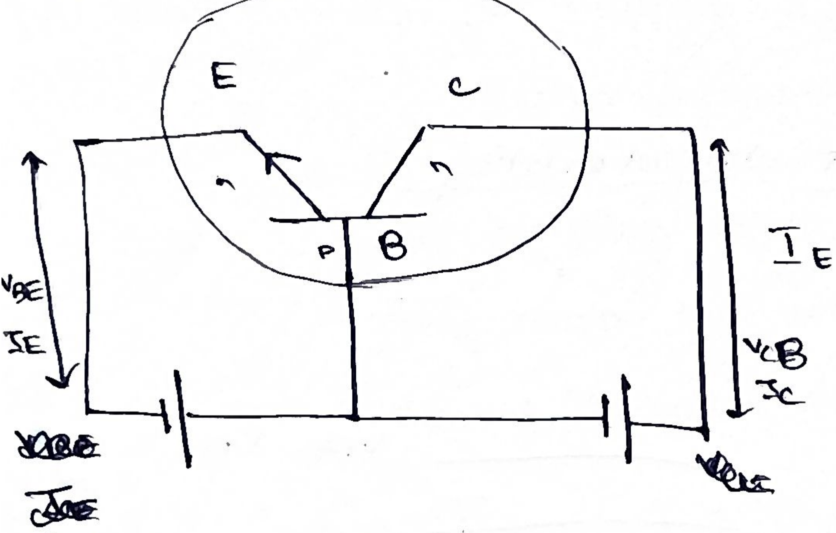
Active : most widely encountered operation : as amplifiers
has large signal gain, small signal distortion

Saturation : equivalent to an on state when the BJT is used as a switch
high current flow, low voltage ("zero" logic level)

Cutoff : equivalent to an off state when the BJT is used as a switch
low current flow, high voltage ("one" logic level)

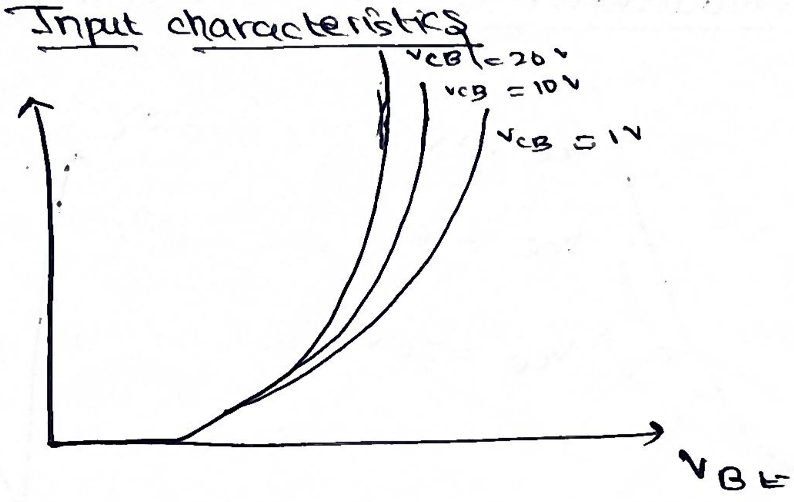
Characteristics

(i) Common ~~emitter~~ base configuration

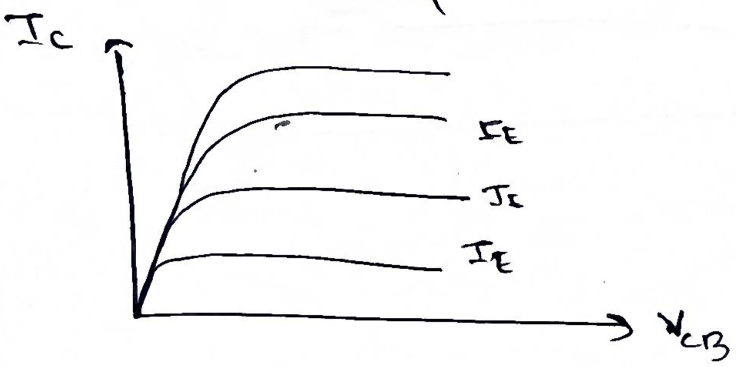


EB junction is forward biased. It is practically independent of V_{CB}

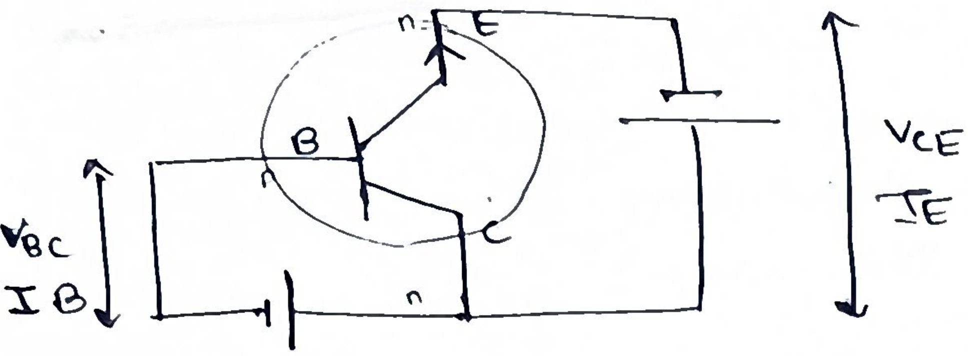
Input characteristics



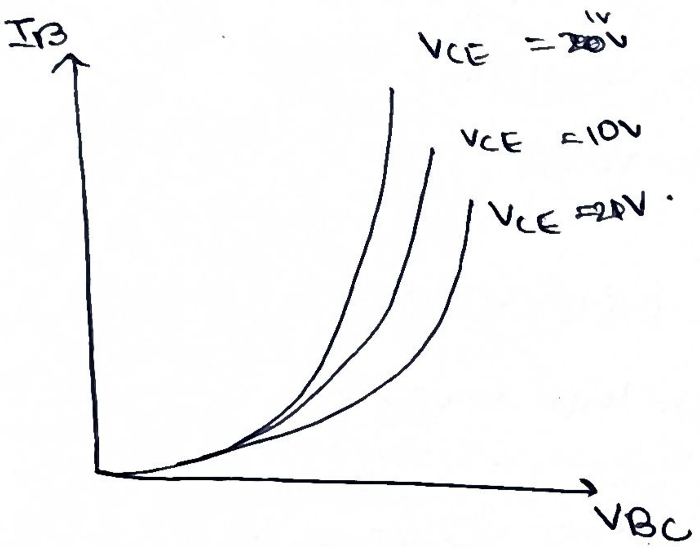
Output characteristics



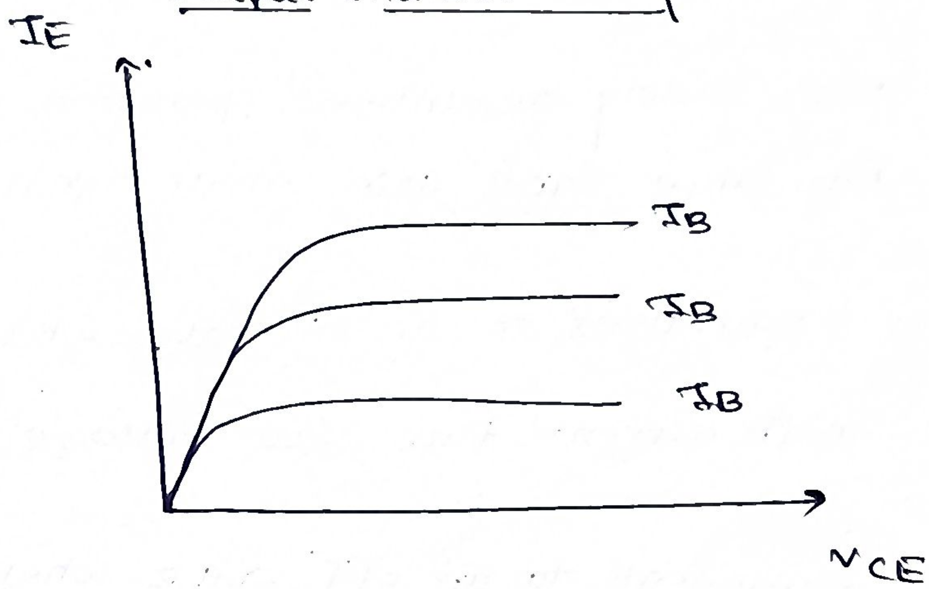
(2) Common Collector configuration.



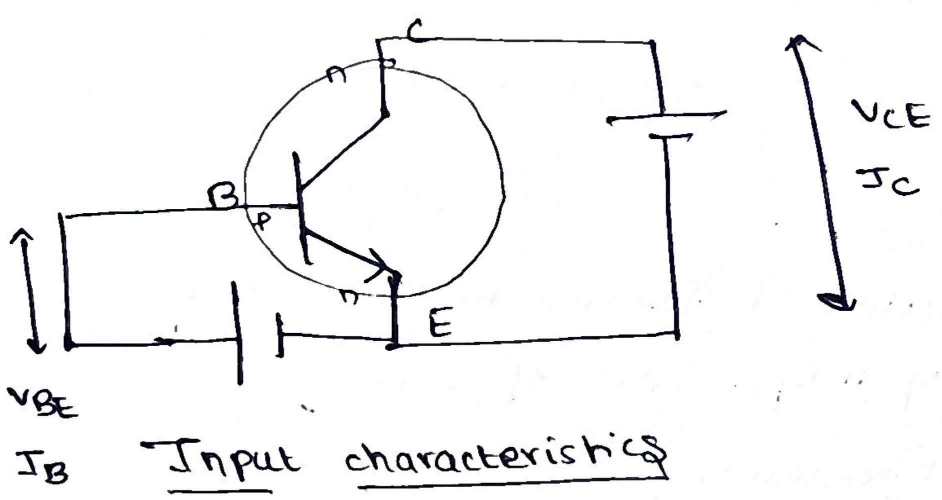
Input characteristics



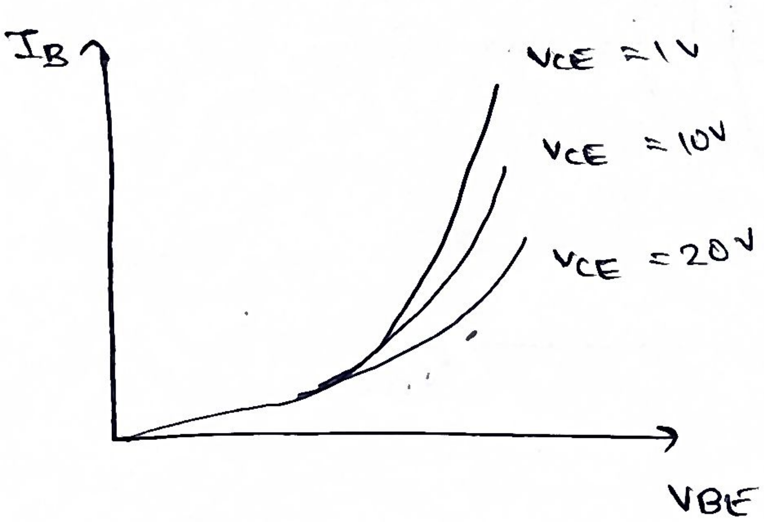
Output characteristics



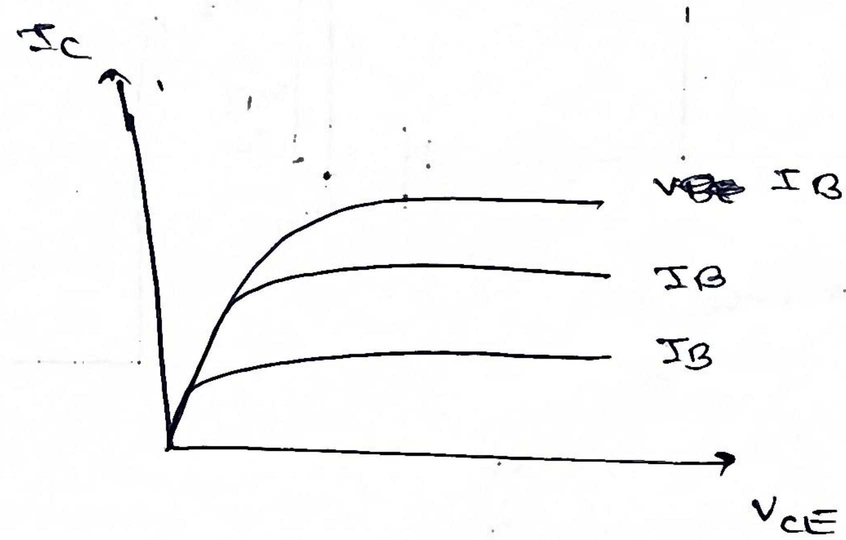
(3) Common Emitter configuration



Input characteristics



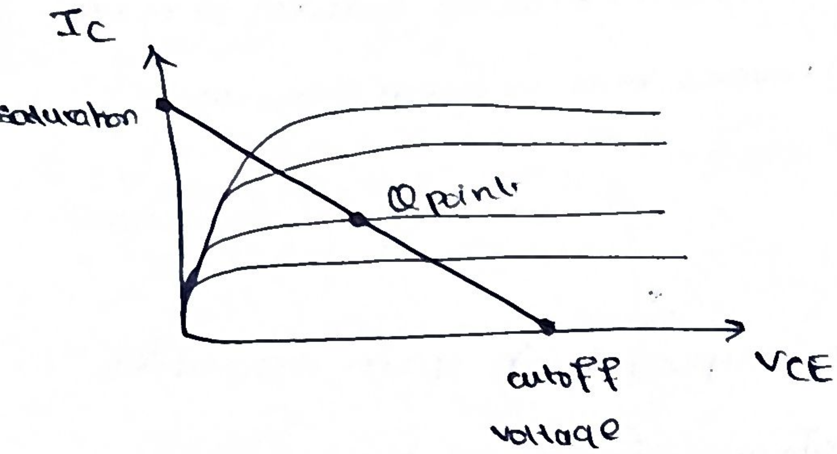
Output characteristics



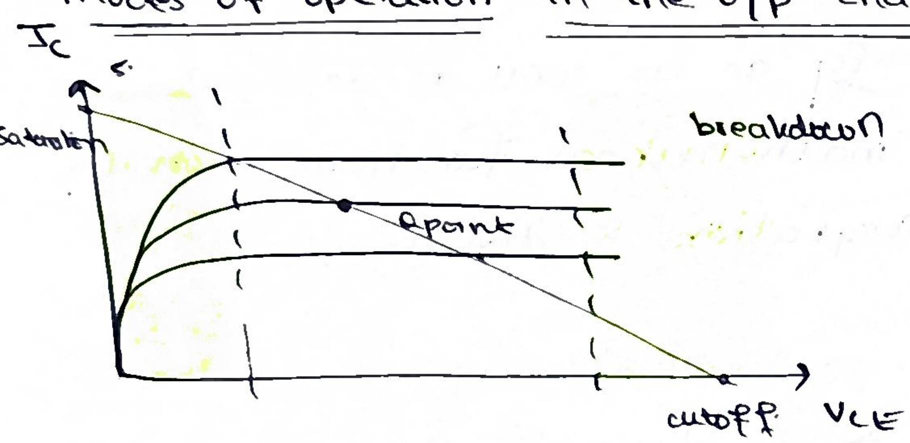
• DC Load line analysis

• The base current is established

• The point at which the base current curve intersects the dc load line is called the Q-point for the circuit.



Modes of operation in the o/p characteristics



Break down in Transistors

(i) Avalanche breakdown

(ii) Punch through : • happens due to the increased width of the CB junction with increased CB junction voltage.

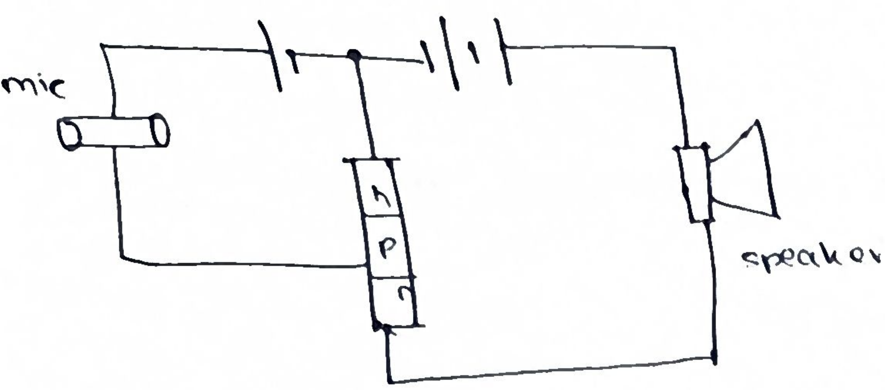
• The depletion region spreads into the base

• may reach the emitter - base junction

• current increases drastically

Early effect : The early effect is the variation in the width of the base of the BJT, due to a variation in the applied base to collector voltage.

Transistor as an amplifier



Transistor as a switch

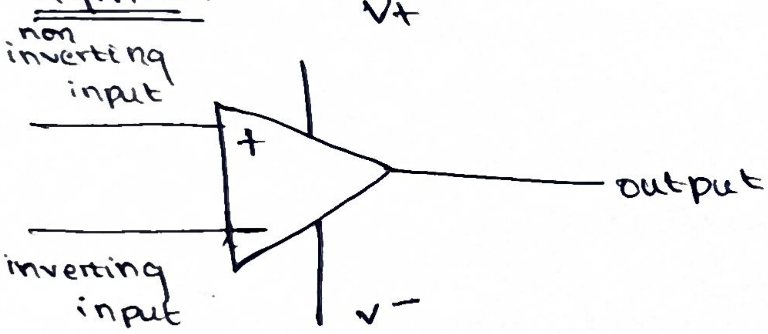
- operated alternatively in the cutoff and saturation region
- when the base - emitter jn in
  (i) forward bias ⟹ saturated region
  (ii) reverse bias ⟹ cutoff region.

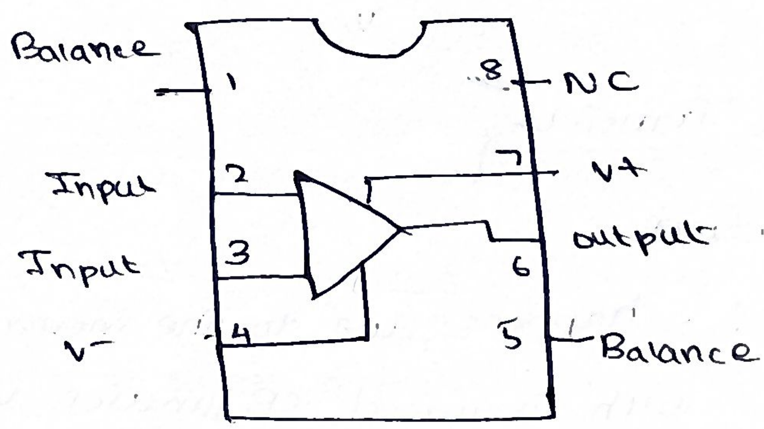
Operational Amplifiers - Op-Amps

An operational amplifier is a direct coupled high gain amplifier consisting of one or more differential amplifiers, followed by a level translator and an output stage.

The device can be used to amplify ac as well as dc input signals and is designed for computing mathematical functions such as addition, subtraction, multiplication, integration & division.

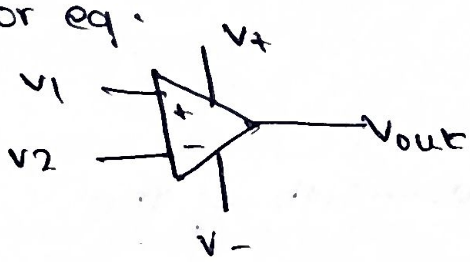
Symbol





Working: The op-amp is a differential amplifier, i.e it amplifies the difference between the 2 input signals

for eg.

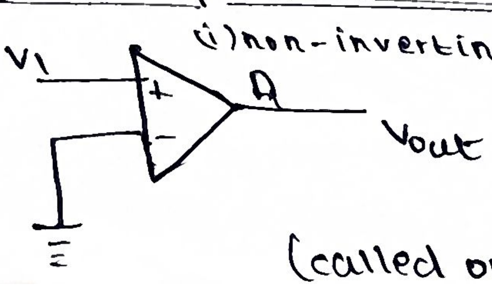


Let the gain of the op-amp be A

then o/p = $A(V_1 - V_2)$

Inverting & non-inverting input

(i) non-inverting input



$V_{out} = AV_1$

A = open loop gain of the op amp

(called open loop gain as there is no feedback between i/p & o/p

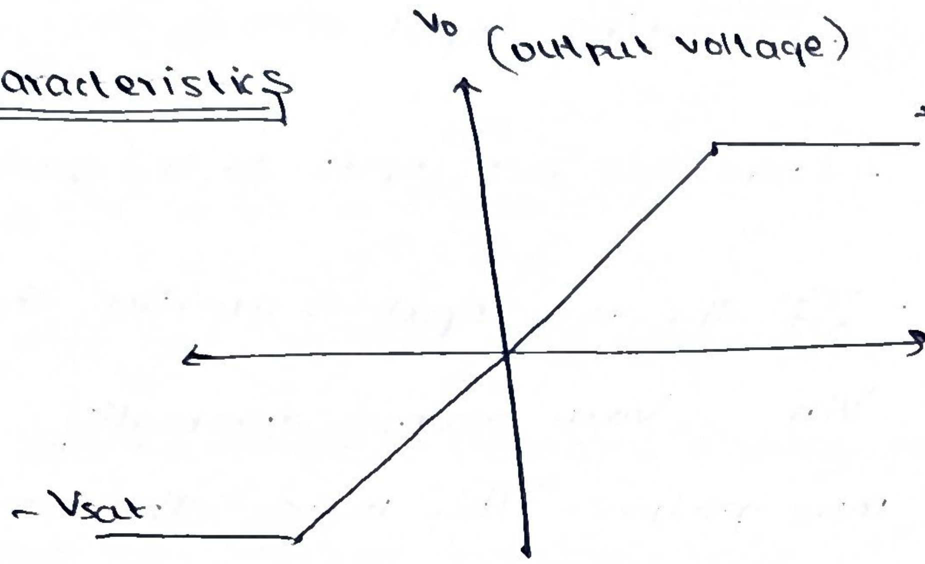
:. The amplified o/p has the same phase as the input

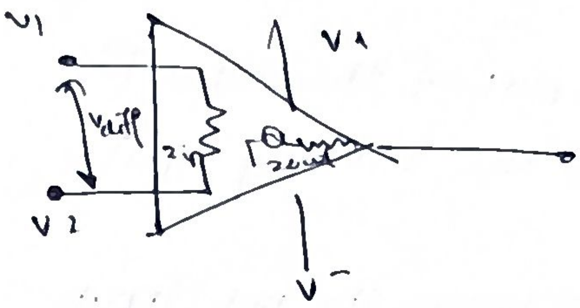
(ii) Inverting input.

$V_{out} = -AV_2$

The amplified o/p has a 180° phase difference compared to the input.

Characteristics





slope = gain of the amplifier (of the order $10^5 - 10^6$)

Ideal Op-Amp: An ideal op-amp is one fabricated in such a manner that it functions with 100% efficiency.

Features: (i) input resistance – $R_i = \infty$ → no matter the input supplied, amplification is possible

(ii) R_o = output resistance = 0 → after amplification, the entirety of the amplified o/p must drop across the load resistance.

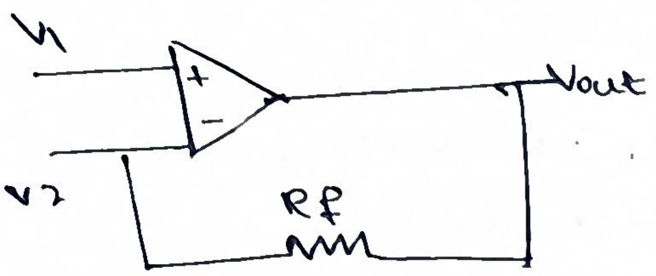
(iii) Bandwidth = ∞ → should be able to handle all possible frequencies

(iv) gain = A = ∞ → should be able to amplify signals infinitely

(v) when the 2 input voltages, V_1, V_2 are 0, the o/p voltage Vout must also be zero. (called as zero offset)

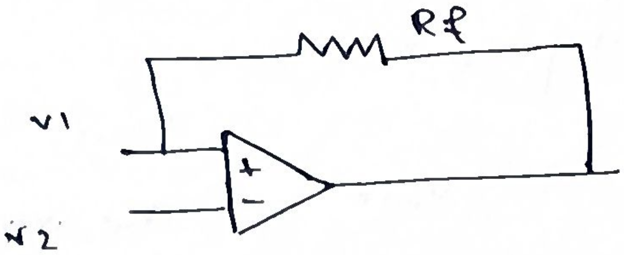
* ~~Feedb~~ Feedback: A condition in which some part of the output is fed back to the input is called feedback. The open loop DC gain of an op-amp is very high, thus some of this gain can be lost by connecting a suitable resistor from the o/p terminal to the inverting input terminal

Negative Feedback



- some part of the output fed back to the inverting input
- It decreases the net input to the op-amp; this increases stability
- $V_o < V_{in}$ ⇒ it shoots to +ve
- $V_o > V_{in}$ ⇒ it shoots -ve

Positive Feedback

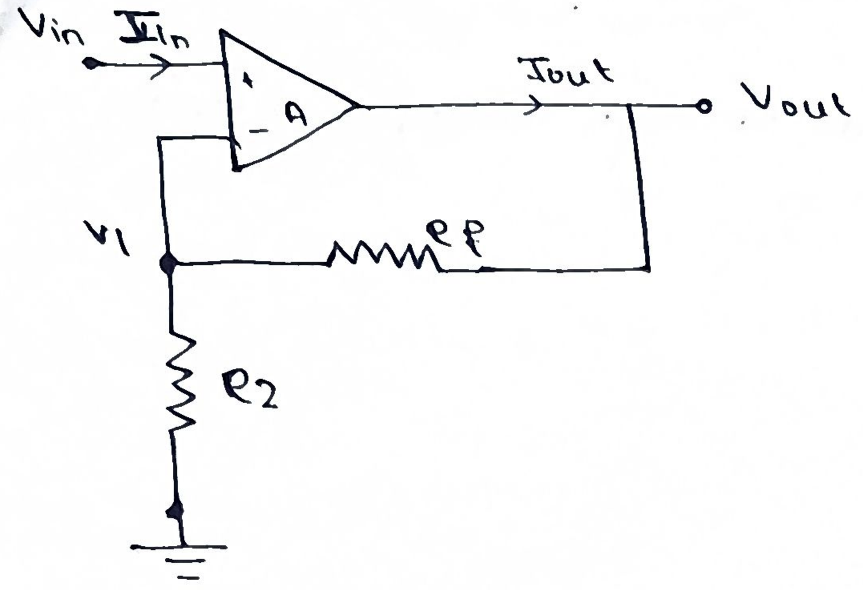


- some part of the output fed back to the non-inverting input.
- increases net input to the op-amp
- If the +ve input is greater than Vin, Vout becomes drastically more positive. This makes the +ve terminal more positive than Vin
- ⇒ positive feedback is not good.
- used in oscillators

Non-Inverting Op-Amp Configuration

- In this configuration, the input voltage signal (V_{in}) is applied to the non-inverting input terminal.
- This means that the output gain is positive and in phase with the input signal.
- Feedback control is done by applying a small part of the output voltage back to the inverting terminal via a $R_2 - R_f$ voltage divider network providing a negative feedback.
- This configuration leads to a circuit with good stability, high input impedance, and low o/p impedance.

Circuit diagram



- Vin and V_1 have the same potential.
- Rf and R_2 form a potential divider network
- Using the voltage division Rule

$$V_1 = V_{out} \times \frac{R_2}{R_2 + R_f}$$

$$V_1 = V_{in} \Rightarrow V_{in} = V_{out} \times \frac{R_2}{R_2 + R_f}$$

$$V_{out} = A\, V_{in}$$

$$\frac{V_{in}}{V_{out}} = \frac{1}{A} \Rightarrow \frac{1}{A} = \frac{R_2}{R_2 + R_f}$$

$$A = \frac{R_2 + R_f}{R_2}$$

$$\boxed{A = 1 + \frac{R_f}{R_2}}$$

Inverting Op-Amp Configuration

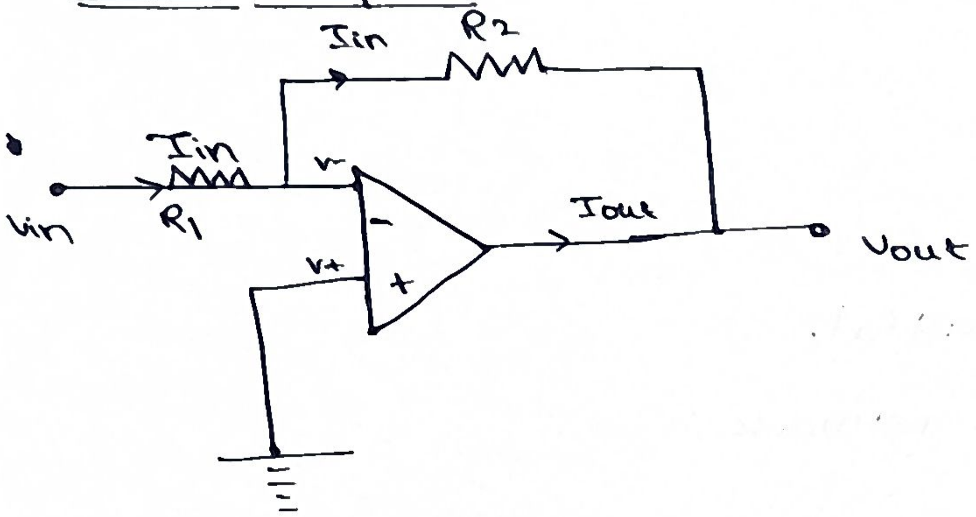
- In this configuration, the input voltage signal is connected to the inverting input terminal.
- ~~Feedback~~ The real input is separated from the inverting input using an input resistor R_1.

The feedback is done by applying a small part of the output voltage to the inverting terminal via a resistor R_2

Note that : (i) No current flows in through the input terminals

(ii) $V_1 = V_2 = 0$ / $V_+ = V_- = 0$

Circuit Diagram



$V_{in} = V_{out} = 0$

$\cancel{I_{in} = \frac{V_{in} - V_+}{R_1} = \frac{V_i}{R}}$

$$I_{in} = \frac{V_{in} - V_-}{R_1} = \frac{V_{in}}{R_1}$$

$\cancel{I_{in} = \frac{V_i - V_{out}}{R_2} = V_0}$

$$I_n = \frac{V_- - V_{out}}{R_2} = \frac{-V_{out}}{R_2}$$

$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2}$$

$V_{out} = A\, V_{in}$

$$\boxed{A = \frac{V_{out}}{V_{in}} = \frac{-R_2}{R_1}}$$

MOSFET : Metal Oxide Semiconductor Field Effect Transistor

- MOSFET is the common term used for the Insulated Gate Field Effect Transistor (IGFET).

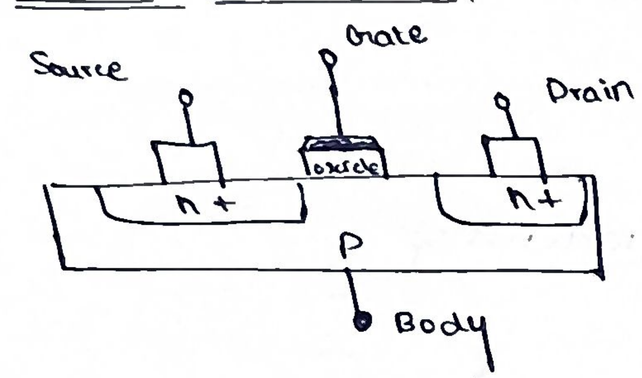
Principle: By applying a transverse electric field across an insulator deposited on a semiconducting material, the thickness and resistance of a conducting channel of a semiconductor material can be controlled.

Types of MOSFET

Depletion MOSFET: the controlling electric field reduces the no. of majority charge carriers available for conduction

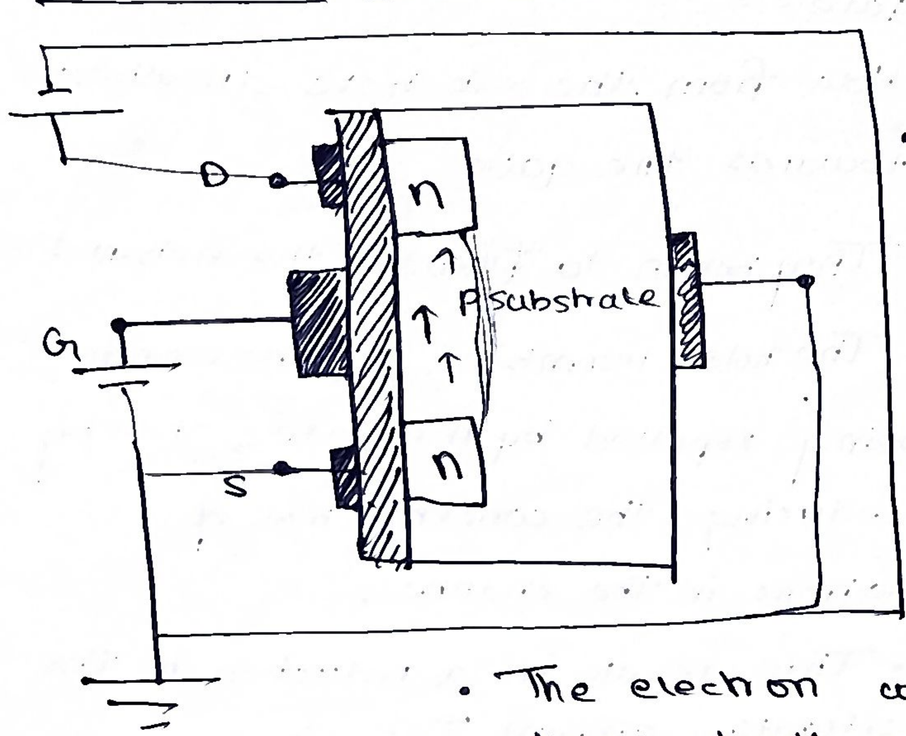
Enhancement MOSFET: the applied electric field causes an increase in the majority carrier density in the conducting regions.

General Construction



- The p type semiconductor forms the base of the MOSFET.
- The 2 bases are heavily doped with an n-type impurity
- The source & drain terminals originate from these heavily doped terminals.
- The substrate is coated with a layer of silicon dioxide for insulation.
- An insulated plate is kept on top of the SiO_2, it acts as a capacitor.

Enhancement MOSFET



- A positive potential V_{GS} is applied at the gate.
- This pushes / repels the +ve'ly charged holes towards the p-substrate.
- More electrons accumulate in the region just below the SiO_2 layer. (called the inversion layer)
- When V_{GS} increases, the conc. of electrons increases, and it sets up a channel.
- The electron concentration increases until $V_{GS} = V_{TH}$, called the threshold voltage.
- A +ve voltage V_{DS} is applied onto the drain.

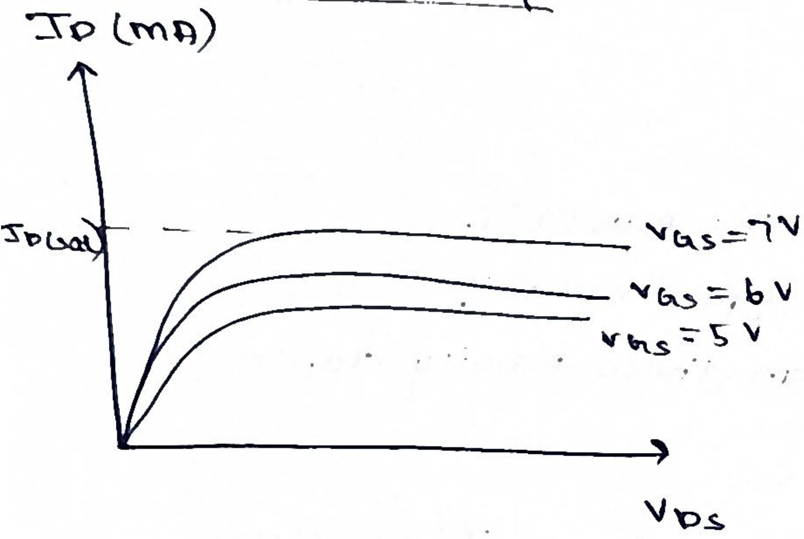
- The depletion region widens because of reverse biasing.

- When V_{DS} is made greater than V_{GS}, electrons are strongly attracted towards the drain.

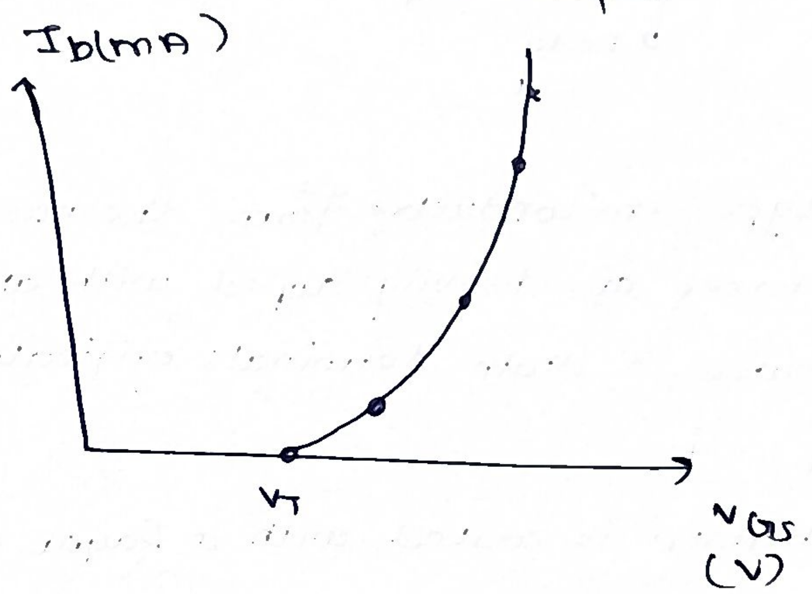
- This sets up the drain current from D to S.

- When V_{ds} is continually increased, the channel begins to narrow near the drain region. It tapers down to being almost point-like. After this, even on increasing V_d, I_D remains the same. A level of saturation is attained.

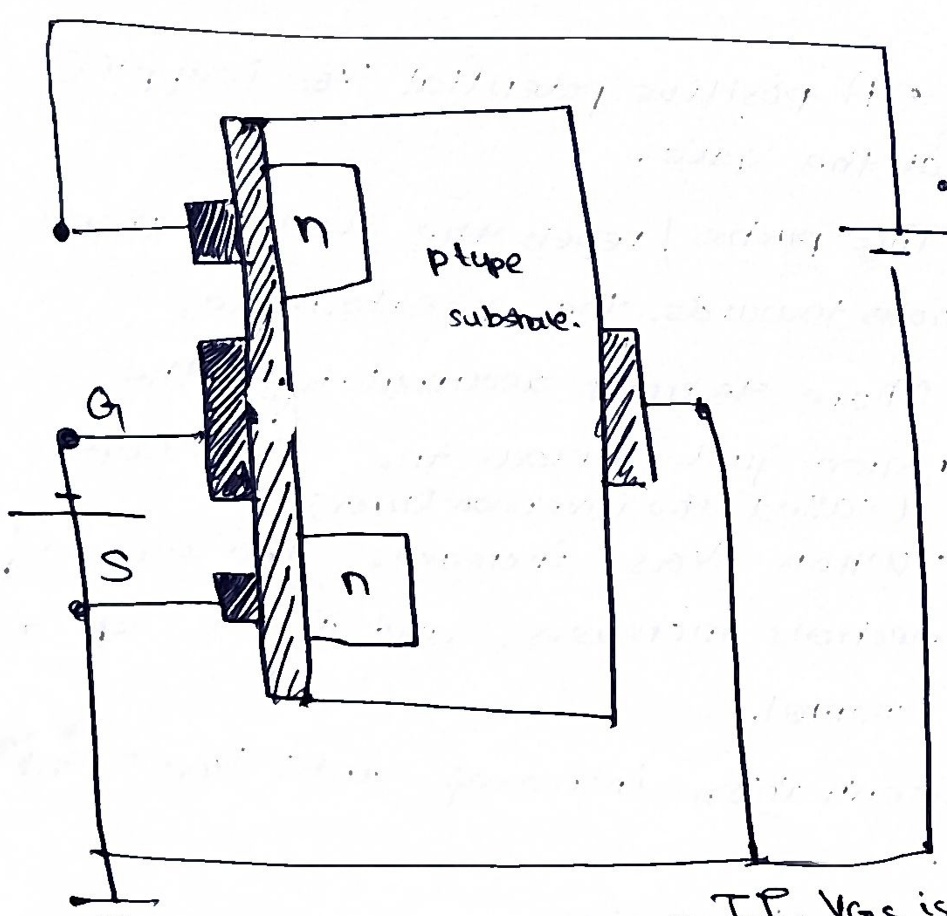
Drain Characteristics



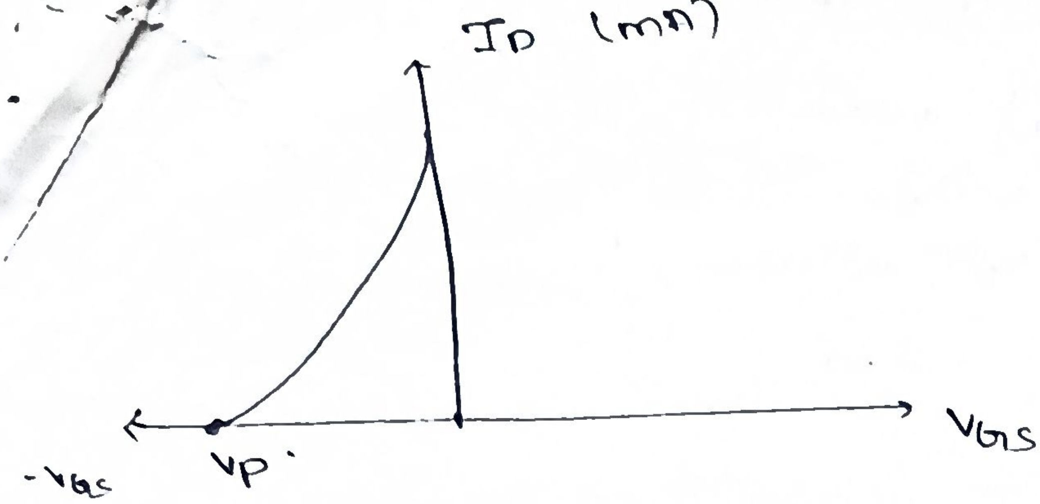
Transfer Characteristics

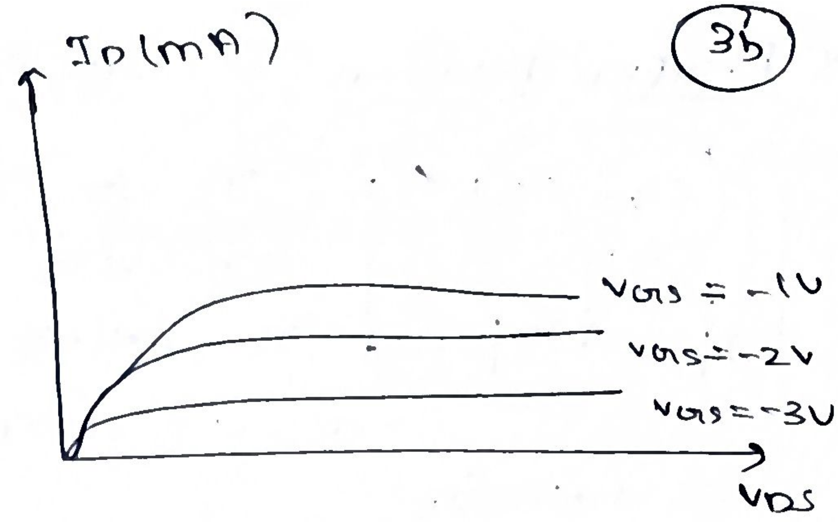


Depletion MOSFET



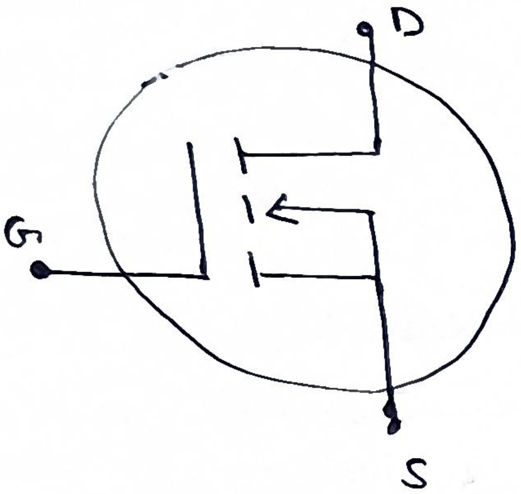
- A -ve voltage is applied at the gate.
- Holes from the substrate are attracted towards the gate.
- They begin to flow in the n channel.
- The holes recombine w/ the electrons being repelled by the gate, thereby reducing the concentration of electrons in the channel.
- This results in a reduction in the saturation current $I_{D(sat)}$.
- If V_{GS} is made more & more -ve, at $V_{GS} = V_P$, the channel pinches off.



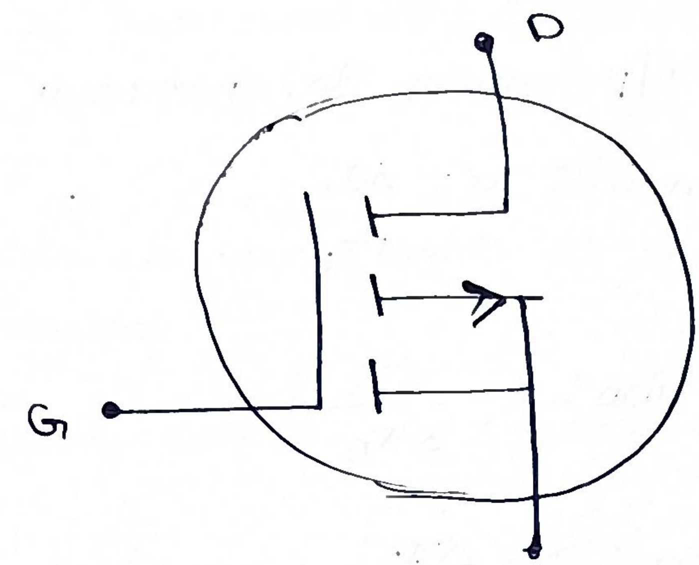


Symbol

Enhancement mode

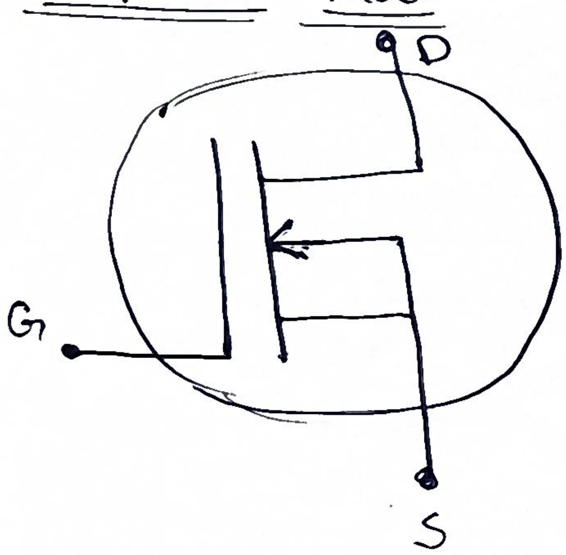


n-channel



p-channel

Depletion mode



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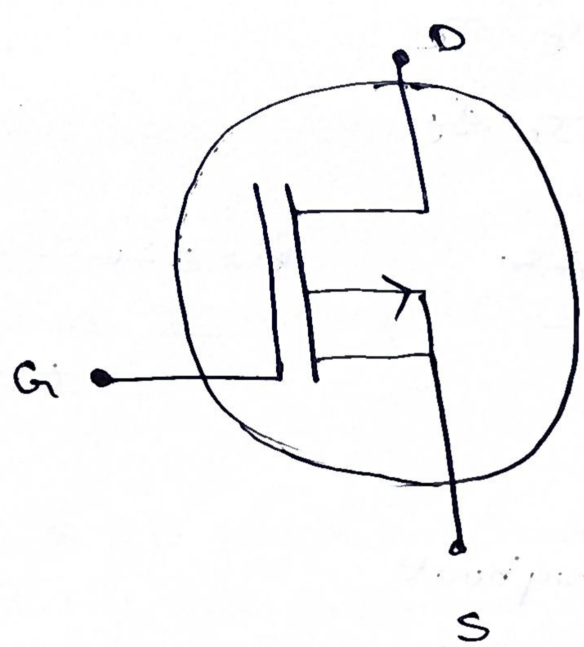
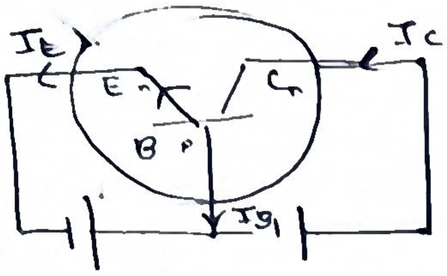


* Relation between I_C, I_B & I_{CBO} in a BJT



$I_E = -(I_C + I_B)$ ~~$+I_{CBO}$~~

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

$I_C = +\alpha(I_C + I_B) + I_{CBO}$

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

$I_C(1-\alpha) = \alpha I_B$

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

Current amplification factor

ratio of change in o/p current to change in input current

In the CB configuration : $\alpha = \frac{\Delta I_C}{\Delta I_E}$

In the CE configuration : $\beta = \frac{\Delta I_C}{\Delta I_B}$

In the CC configuration : $\gamma = \frac{\Delta I_E}{\Delta I_B}$

Relation between α, β and γ

$I_E = I_C + I_B$ $\qquad \gamma = \frac{\Delta I_E}{\Delta I_B}$

$\Delta I_B = \Delta I_E - \Delta I_E$,

$\frac{\Delta I_E}{\gamma} = \Delta I_E - \Delta I_C$

~~$\gamma = \frac{\Delta I_E - \Delta I_C}{\Delta I_E}$~~ $\qquad$ ~~$\gamma = \frac{\Delta I_E - \Delta I_C}{\Delta I_E}$~~

$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$

% by ΔI_E throughout

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