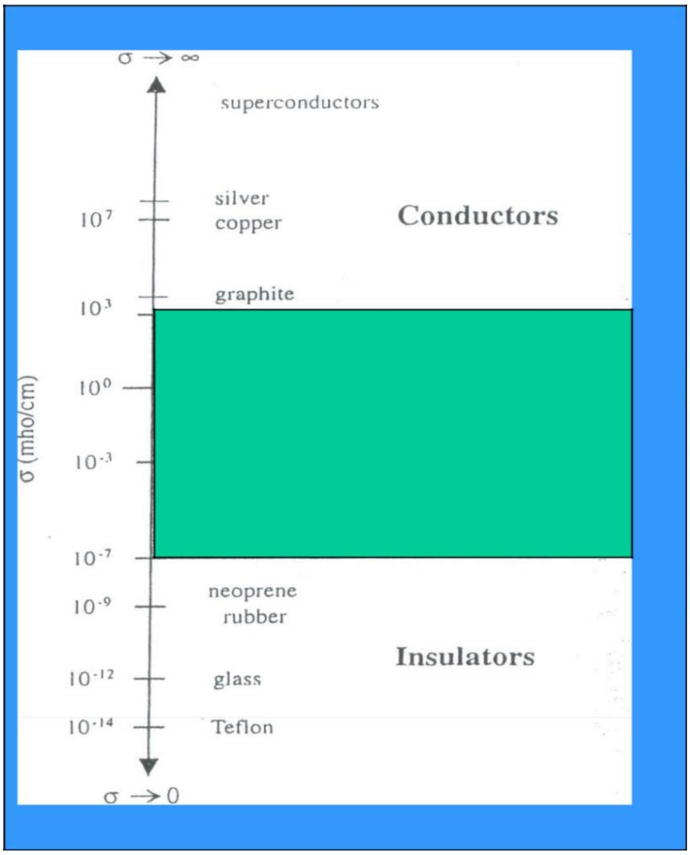
Semiconductors

•Materials that permit flow of electrons are called conductors
e.g., gold, silver, copper

•Materials that block flow of electrons are called insulators
e.g., rubber, glass, Teflon, mica

•Materials whose conductivity falls between those of conductors and insulators are called semiconductors.

•Semiconductors are “part-time” conductors whose conductivity can be controlled.



Semiconductor materials fall into one of two classes:

1. Single crystal: Single crystal semiconductor such as germanium (GE) and silicon (Si) have a repetitive crystal structure
2. Compound: compound semiconductors such as gallium arsenide (GaAs), cadmium sulphide (CdS), gallium nitride (GaN), and gallium arsenide phosphide (GaAsP)

are constructed of two or more semiconductor materials of different atomic structure.

The three semiconductors used most frequently in the construction of electronic device are Ge, Si, and GaAs.

Energy Band

The range of energies possessed by electrons of the same orbit in a solid is known as energy band.

Important Energy Bands in Solids

(i) **Valence Band:** The electrons in the outermost orbit of an atom are known as valence electrons. Under normal condition of an atom, valence band contains the electrons of highest energy. This band may be filled completely or partially. The energy band which possesses the valence electrons is called valence band.

(ii) **Conduction Band**: In some of the materials (e.g., metals), the valence electrons are loosely attached to the nucleus and can be detached very easily. These electrons are known as free electrons and are responsible for the conduction of current. For this reason, these electrons are known as conduction electrons. The energy band which possesses the conduction electrons is called conduction band.

(iii) **Forbidden Energy Gap:** The energy gap between the valence band and conduction band is known as forbidden energy gap.

Material Structure

Structure of Insulators

The substance (like, wood, glass, mica etc.) which do not allow the passage of current through them are known as insulators. The valence band of these substance is full, whereas the conduction band is completely empty. Moreover, the forbidden energy gap between valence band and conduction band is large (15ev nearly). Therefore, a large amount of energy i.e. a very high electric field is required to push the valence electrons to the conduction band. This is the reason why such materials under ordinary condition do not conduct at all and are designed as insulators.

Metals

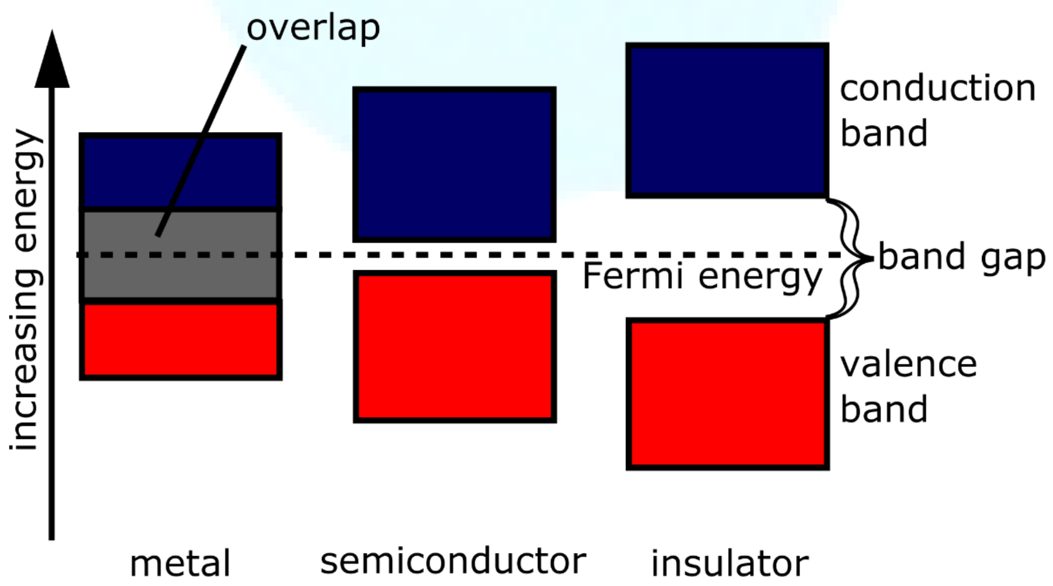
The substance (like copper, aluminium, silver etc.) which allow the passage of current through them are known as conductors. The valence band of these substance overlap the conduction band as shown in fig. 3.1. Due to this overlapping, a large number of free electrons are available for conduction. This the reason, why a slight potential difference applied across such substance causes a heavy flow of current through them

Semiconductors

The substance (like carbon, silicon, germanium etc.) whose electrical conductivity lies in between the conductor and insulators are known as semiconductors. Although the valence band of these substances is almost filled and conduction band is almost empty as in case of insulators.

The forbidden energy gap between valence band and conduction band is very small (nearly 1 eV).
Therefore comparatively a smaller electric field is required to push the valence electrons to the conduction band. This is the reason why such materials under ordinary conditions do not conduct current and behave as an insulator.

However even at room temperature some heat energy is imparted to the valence electrons and a few of them cross over to the conduction band imparting minor conductivity to the semiconductors. As the temperature is increased more valence electrons cross over to the conduction band and the conductivity of the material increases. Thus, these materials have negative temperature coefficient of resistance.



Intrinsic & Extrinsic Semiconductor

(i) Intrinsic Semiconductor

An **extremely pure** semiconductor is called **intrinsic semiconductor**.
On the basis of energy band phenomenon, an intrinsic semiconductor at absolute zero temperature, its valence band is completely filled and the conduction band is completely empty.
When some heat energy is supplied to it (i.e., its temperature is raised say to room temperature) some of the valence electrons are lifted to conduction band are free to move at random. The holes created in the crystal also move at random in the crystal.
The behaviour of semiconductor shows that they have negative temperature co-efficient of resistance i.e the resistivity decreases or conductivity increases with the rise in temperature.

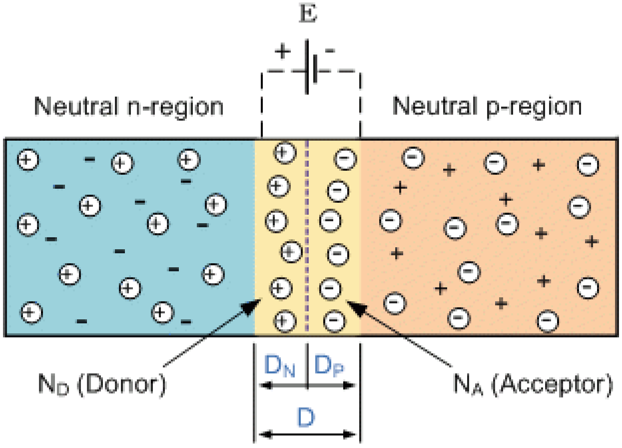
(ii) Extrinsic Semiconductor

Although an intrinsic semiconductor is capable to conduct a little current even at room temperature but as it is, it is not useful for the preparation of various electronic devices. To make it conductive a small amount of suitable impurity is added. It is then called extrinsic (impure) semiconductor.

Doping: The process by which an impurity is added to a semiconductor is known as doping. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, one impurity atom is added to 10^8 atoms of a semiconductor. Thus, a semiconductor to which an impurity at controlled rate is added to make it conductive is known as an extrinsic semiconductor.

Depending upon the type of impurity added extrinsic semiconductor may be classified as :

1. n- type semiconductor
2. p-type semiconductor



n- type semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor providing a large number of free electrons in it, the extrinsic semiconductor thus formed is known as n type semiconductor.

The addition of pentavalent impurities such as arsenic (atomic number 33) and antimony (atomic number 51) provide a large number of free electrons in the semiconductor crystal. Such impurities which produce n-type semiconductor are known as donor impurities because each atom of them donate one free electron to the semiconductor crystal as explained below:

When a small amount of pentavalent impurity like arsenic (atomic number 33: 2,8,18,5) having five valence electrons is added to germanium crystal each atom of the impurity fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms as shown. Whereas the fifth electron of the impurity (arsenic) atom finds no place in covalent bonds and is thus free. Hence each arsenic atom provides one free electron in the germanium crystal. Since, an extremely small amount of arsenic impurity has a large number of atoms, therefore it provides millions of free electrons for conduction

p- type semiconductors

When a small amount of trivalent impurity is added to a pure semiconductor providing a large number of free holes in it, the extrinsic semiconductor thus formed is known as p-type semiconductor.

The addition of trivalent impurities such as gallium (atomic number 31) and indium (atomic number 49) provide a large number of free holes in the semiconductor crystal. Such impurities which produce p-type semiconductor are known as acceptor impurities because each atom of them create one hole which can accept one electron from the semiconductor crystal as explained below.

When a small amount of trivalent impurity like gallium (atomic number 31: 2,8,18,3) having three valence electrons is added to germanium crystal each atom of the impurity fits in the germanium crystal in such a way that its three valence electrons form covalent bonds with four germanium atoms, in the fourth covalent bond, only germanium atom contributes one valence electron, while gallium atom has no valence electron to contribute, as all its three valence electron are already engaged in the covalent bonds. Hence the covalent bond is incomplete having one electron short. The amount of gallium impurity has a large number of atoms; therefore, it provides millions of holes in the semiconductor.

Drift Current

The flow of current in the semiconductor constituted by the drift electrons available in the conduction band and holes available in the valence band, which are formed due to external (heat) energy supplied to them, is known as drift current.

Diffusion Current

When the two pieces are joined together and suitably treated, they form a pn junction. The moment they form a pn junction, some of the conduction electrons from n- type material diffuse over to the p-type material and undergo electrons holes recombination with the holes available in the valence band. Simultaneously holes from p-type material diffuse over to the n-type material and undergo hole-electron combination with the electron available in the conduction band. This process is called diffusion.

Thus, the current which obtained while having diffusion is called diffusion current.

(a) Total Current

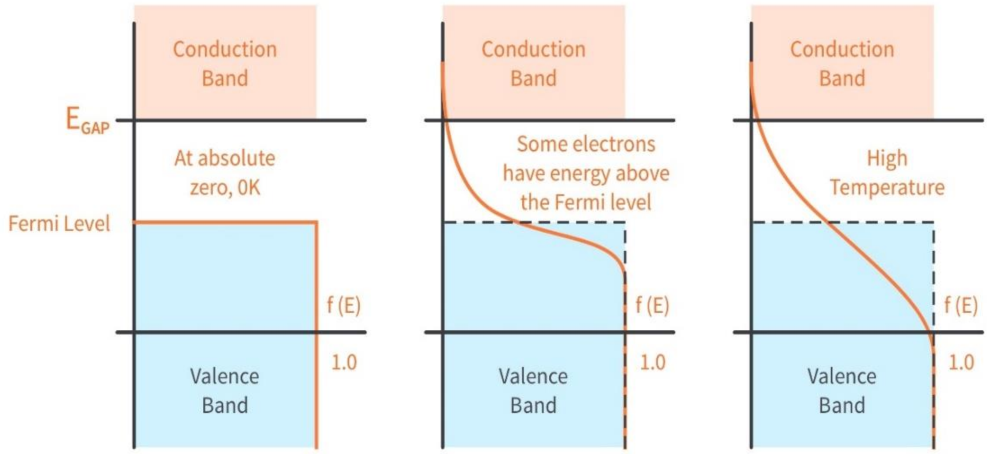
It is possible that a potential gradient and a concentration gradient may exist within semiconductor. In such a case the total current is the sum of drift current due to potential gradient and the diffusion current due to charge carrier concentration gradient.

(b) Mobility of Charges

The mobility of charge carriers (electrons and holes) varies as T^{-m} over a temperature range of 100 and 400 k. for silicon m = 2.5 for electrons and 2.7 for holes. For germanium m = 1.66 for electrons and 2.33 for holes.

The carriers' currents are also due to concentration gradients in the doped material which leads to diffusion of carriers from high concentration region to low concentration region.

Effects of Temperature on Conductivity of Semiconductor



The change in temperature changes the electrical conductivity of semiconductor appreciably.

No electrons can be above the valence band at OK, since none have energy above the Fermi level and there are no available energy states in the band gap

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

At absolute zero
At absolute zero temperature all the electrons of semiconductor are held tightly by their atom. The inner orbit electrons are bound to the nucleus whereas the valence electrons are bound by the forces of covalent bonds. Therefore, at this temperature no free electrons are available in semiconductor. Hence the semiconductor crystal behaves like a perfect insulator.

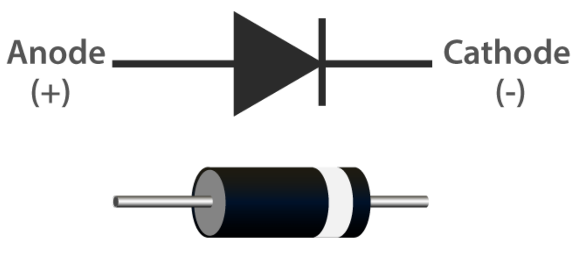
Above absolute zero

When a temperature of semiconductor is raised, some of its covalent bonds break due to the thermal energy supplied to it. The breaking of bonds sets those electrons free which were engaged in the formation of these bonds. Thus, at higher temperature few electrons exist in the semiconductor and they no longer behave as a perfect insulator.

Now if some potential difference is applied across the semiconductor a tiny current will flow through the circuit because of a minute quantity of free electrons existing in the semiconductor.

PN Junction Diode (Semiconductor Diode)

It is also known as crystal diode since it is grown out of a crystal (like germanium of silicon). A semiconductor diode has two terminals and acts as a one-way gate to electron flow. It conducts only when it is forward biased i.e., when terminal connected with overhead is at higher potential than the terminal connected to the bar.

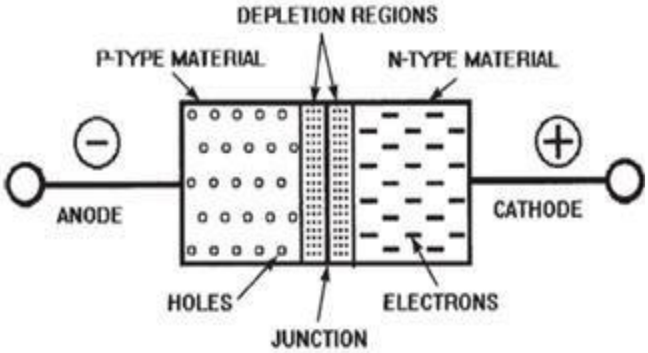


However, when it is reversed biased practically it does not conduct any current through it.

A pn-junction diode is formed by joining together n-type and p-type silicon. The p-side is called anode and the n-side is called cathode.

Depletion Layer

A region around the junction from which the charge carriers (free electrons and holes) are depleted is called depletion layer.



Potential Barrier

A potential difference built up across the pn junction which restricts further movement of charge carriers across the junction is known as potential barriers.

Biasing

When a pn junction is connected across an electric supply (potential difference) the junction is said to be under biasing. The type of biasing can be forward or reverse.

Forward Biasing

When the positive terminal of a D.C source or battery is connected to p-type and negative terminal is connected to n-type semiconductor of a pn junction, the junction is said to be in forward biasing.

when a junction is forward biased:

(i) The junction potential barrier is reduced and at some forward voltage (0.3 v for germanium and 0.7 v for silicon). It is eliminated altogether. (ii) The junction offers low resistance to the flow of current through it. (iii) The magnitude of flow of current through the circuit depends upon the applied forward voltage.

Reverse Biasing

When the positive terminal of a D.C source or battery is connected to n-type and negative terminal is connected to p-type semiconductor of a pn junction, the junction is said to be in reverse biasing.

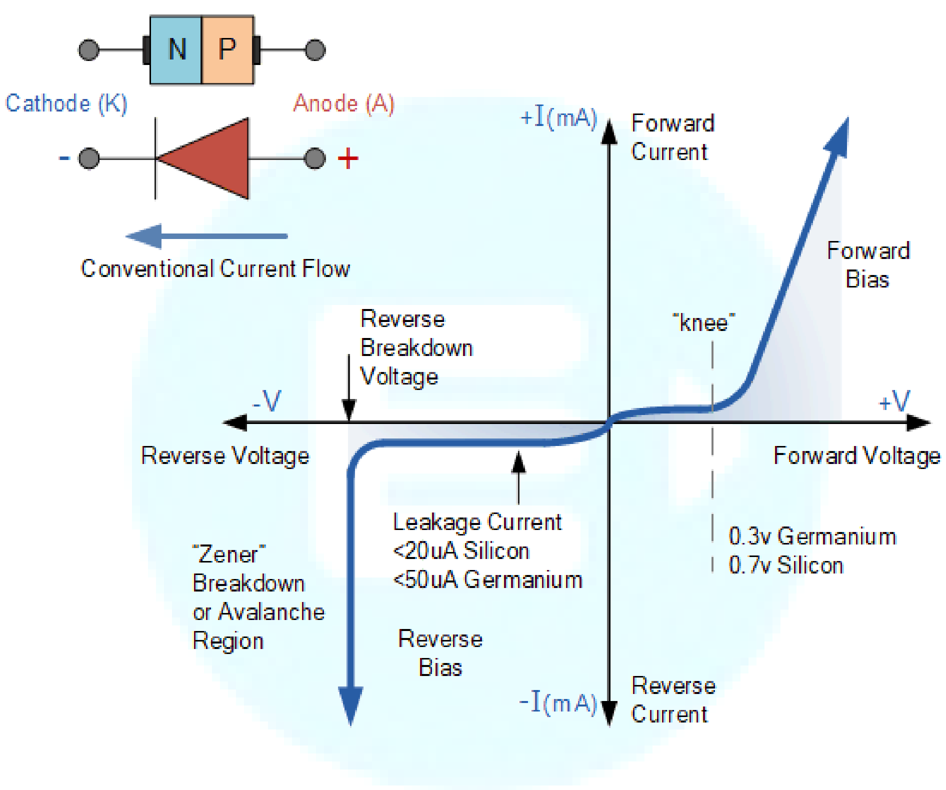
when a junction is forward biased:

(i) The junction potential barrier is strengthened.
(ii) The junction offers high resistance to the flow of current through it.

(iii) The magnitude of flow of current through the circuit depends upon the applied reverse voltage.

V-I Characteristic of Semiconductor

The volt ampere (V-I) characteristics of a pn-junction is just a curve between voltage across the junction and the circuit current. To draw the curve the circuit is arranged. In the circuit it is important to note that a resistor R is connected in series with the pn junction which limits the forward diode current from exceeding the permitted value. The characteristics are studied under three heads viz. zero external voltage, forward biasing and reverse biasing.



Zero External Voltage: When no external voltage is applied no current flow through the circuit. It is indicated by points 0 on the graph.

Forward Biasing: When key k is closed. the pn junction is forward biased as p-type semiconductor is connected to the positive terminal and n-type to the negative terminal of the supply. Now when supply voltage is increased by changing the variable resistor R the circuit current increases very slowly and the curve is nonlinear. The slow rise in current in this region is because the external applied voltage is used to overcome the potential barrier (0.3V for Ge and 0.7V for Si) of the pn junction

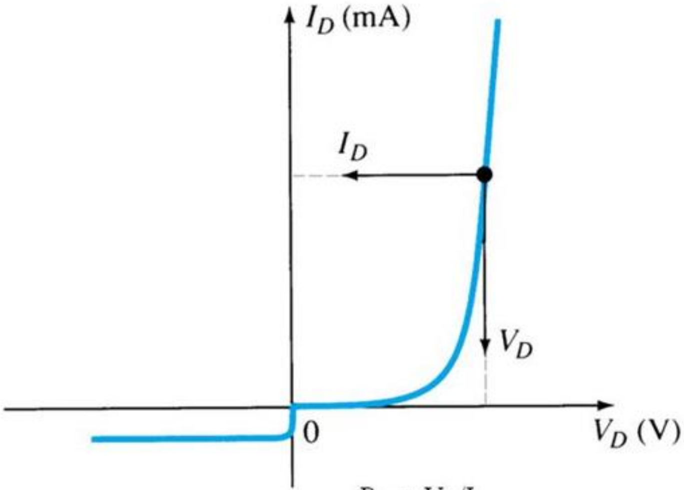
However, once the potential barrier is eliminated and external voltage is increased further the pn junction behaves like an ordinary conductor and the circuit current rises very sharply. At this instant the circuit current is limited by the series resistance R and a small value of the junction forward resistance R. The curve is almost linear. If the current rises more than the rated value of the diode the diode may change.

Reverse Biasing: When the double pole double throw switch is thrown to position 2, the pn junction is reverse biased as p- type semiconductor is connected to the negative terminal and n-type to the positive terminal of the supply. Under this condition the potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and practically no current flows through the circuit. However, in actual practice a very small current flows in the circuit as shown, this current is called reverse current and is due to minority carriers available at room temperature in the two types of semiconductors. The reverse bias appears as a forward biased for these undesirable minority carriers and thus they constitute a minor current in reverse direction. The reverse current increases slightly with the increase in reverse bias supply voltage.

The reverse voltage at which pn junction breaks in known as breakdown voltage.

Resistance Level

An actual diode offers a very small resistance when forward biased and is called a forward resistance whereas it offers a very high resistance when reverse biased and is called a reverse resistance.



$R_D = V_D/I_D$

Breakdown in Junction Diode

The breakdown of the pn junction can be of two types, these are

1. **Avalanche Breakdown**
2. **Zener Breakdown**

Avalanche Breakdown

Avalanche breakdown occurs in a pn junction diode which is moderately doped and has a thick junction (means its depletion layer width is high). Avalanche breakdown usually occurs when we apply a high reverse voltage across the diode (obviously higher than the Zener breakdown voltage, say V_Z). So, as we increase the applied reverse voltage, the electric field across junction will keep increasing.

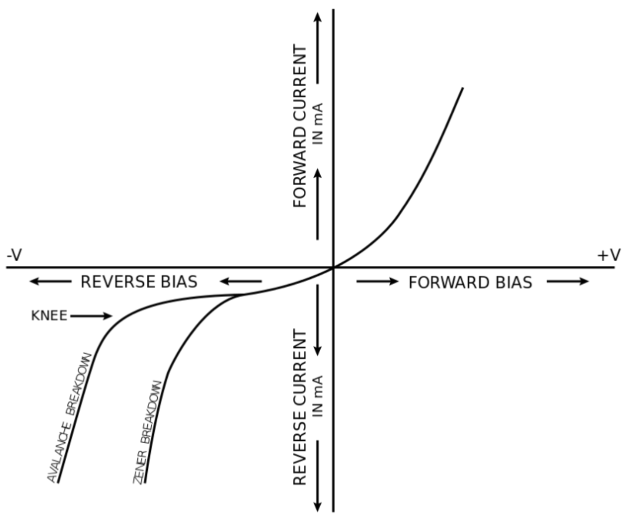
When the electric field existing in the depletion layer is sufficiently high, the velocity of the carriers (minority carriers) crossing the depletion layer increases. These carriers collide with the crystal atoms. Some collisions are so violent that electrons are knocked off the crystal atoms, thus creating electron hole pairs as the pair of electron hole is created in the midst of the high field, they quickly separate and attain high velocities to cause further pair generation through more collisions.

This is cumulative process and as we approach the breakdown voltage, the field becomes so large that the chain of collisions can give rise to an almost infinite current with very slight additional increase in voltage. The process is known as avalanche breakdown. Once this breakdown occurs, the junction cannot regain its original position. Thus, the diode is said to be burnt off.

Zener Breakdown

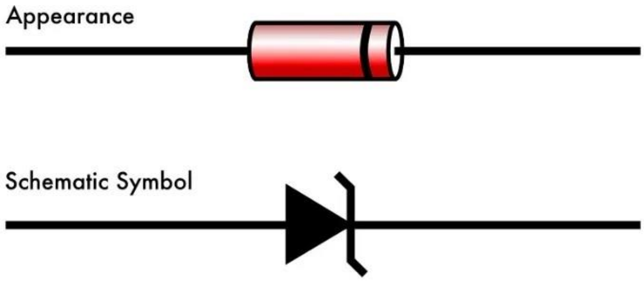
This breakdown takes place in a very thin junction i.e., when both sides of the junction are very heavily doped and consequently the depletion layer is narrow. In the Zener breakdown mechanism, the electric field becomes as high as 10^7 v/m in the depletion layer with only a small applied reverse bias voltage.

In his process it becomes possible for some electrons to jump across the barrier from the valence band in p- type material to some of the unfilled conduction band in n-material. This process is known as Zener breakdown. In this process the junction is not damaged.



Zener Diode

A specially designed silicon diode which is optimised to operate in the breakdown region is known as Zener diode.



Characteristics of Zener Diode

- Its characteristics are similar to an ordinary diode with the exception that it has a sharp (or distinct) breakdown voltage called Zener voltage V_Z
- It can be operated in any of the three regions i.e., forward, leakage or breakdown. But usually, it is operated in the breakdown region.
- The voltage is almost constant (V_Z) over the operating region.
- Usually, the value of V_Z at particular test current I_{zr} is specified in the data sheet.
- During operation it will not burn as long as the external circuit limits the current flowing through it below the burn out value i.e., I_{zm} (the maximum rated Zener current).

Applications

- Voltage Regulator
- Meter Protection
- Wave Shaping Circuit

Photo Diode

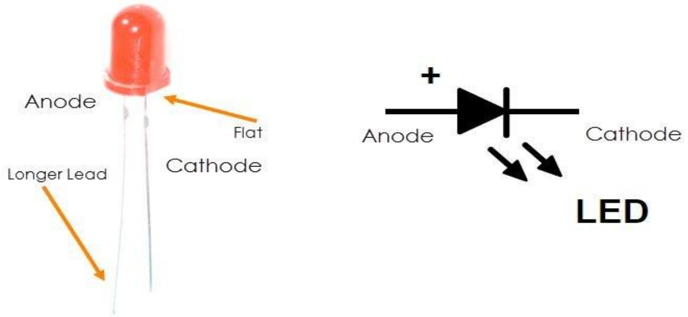
When a diode is reverse biased a minute current flow in the diode due to minority carriers. These carriers exist because of thermal energy which dislodge the valence electrons from their orbits producing free electrons and holes in the process.

When light energy falls on a pn junction, it also imparts energy to dislodge valence electron. In other words, the amount of light striking on the junction can control the reverse current in a diode.

A diode that is optimised for its sensitivity to light is known as photo diode.

LED (Light Emitting Diode)

When a diode is forward biased the potential barrier is lowered. The conduction band free electrons from n- region cross the barrier and enter the p-region, as these electrons enter the p- region they fall into the holes lying in the valence band. Hence, they fall from a higher energy level to a lower energy level in the process they radiate energy.



A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. The colour of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor. In LED the energy is radiated in the form of light and hence they glow. A manufacturer can produce LED that radiate red, green, yellow, blue, orange light.

Application
Instrument display, panel indicators, digital watches, calculator etc

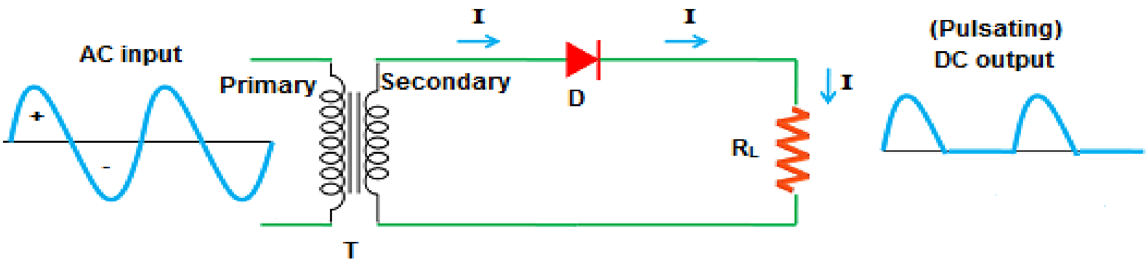
Diode as a Rectifier

The electrical power is generated transmitted and distributed as d.c. for economical reasons. As an alternating voltage is available at the mains. But most of the electronic circuit need d.c. voltage for their operation. Therefore, the rectifier is the heart of power supply. The rectifier can be of two types:

1. Half Wave Rectifier
2. Full Wave Rectifier

Half Wave Rectifier

In half wave rectifier when a.c supply is applied at the input only positive half cycle appears across the load, whereas the negative half cycle is suppressed.



Half wave rectifier

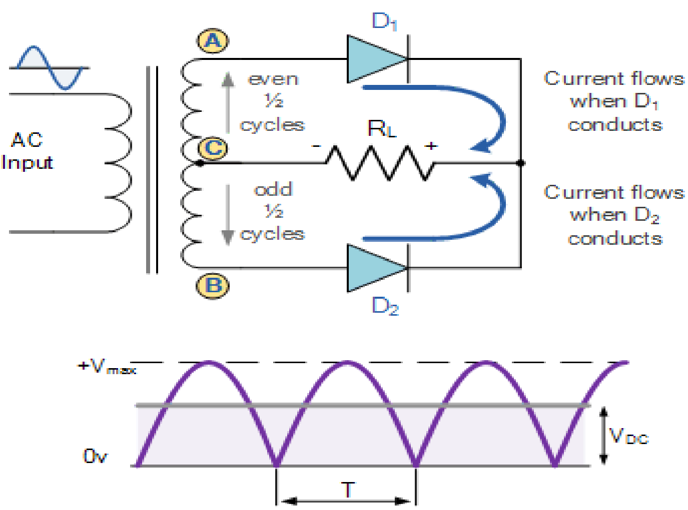
Circuit

For half wave rectification only one crystal diode is used. It is connected in the circuit as shown in the above figure, the a.c supply to be rectified is generally given through a transformer. The transformer is used to step down or step up as per requirement. It also isolates the rectifier circuit from power lines and thus reduce the risk of electric shock.

Operation

- A high AC voltage is applied to the primary side of the step-down transformer. The obtained secondary low voltage is applied to the diode.
- The diode is forward biased during the positive half cycle of the AC voltage and reverse biased during the negative half cycle.
- The final output voltage waveform is as shown in the figure above.

Full Wave Rectifier



Resultant Output Waveform

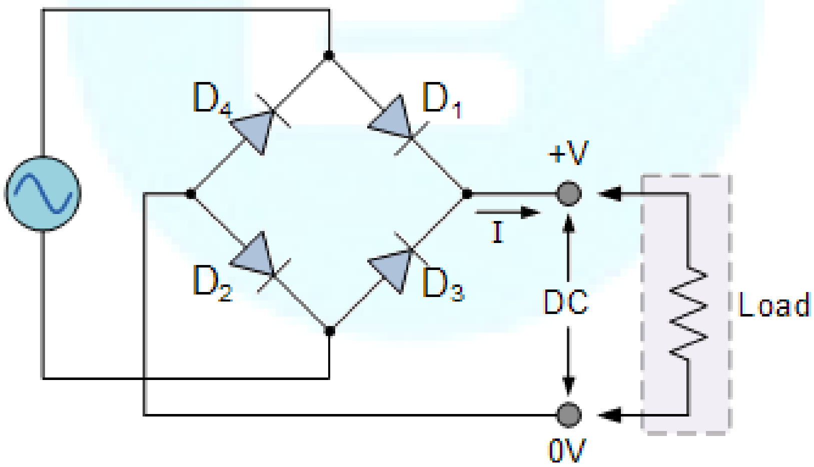
The full wave rectifier circuit consists of two power diodes connected to a single load resistance (RL) with each diode taking it in turn to supply current to the load. When point A of the transformer is positive with respect to point C, diode D1 conducts in the forward direction as indicated by the arrows.

When point B is positive (in the negative half of the cycle) with respect to point C, diode D2 conducts in the forward direction and the current flowing through resistor R is in the same direction for both half-cycles. As the output voltage across the resistor R is the phasor sum of the two waveforms combined, this type of full wave rectifier circuit is also known as a "bi-phase" circuit.

The Full Wave Bridge Rectifier

Another type of circuit that produces the same output waveform as the full wave rectifier circuit above, is that of the Full Wave Bridge Rectifier. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output.

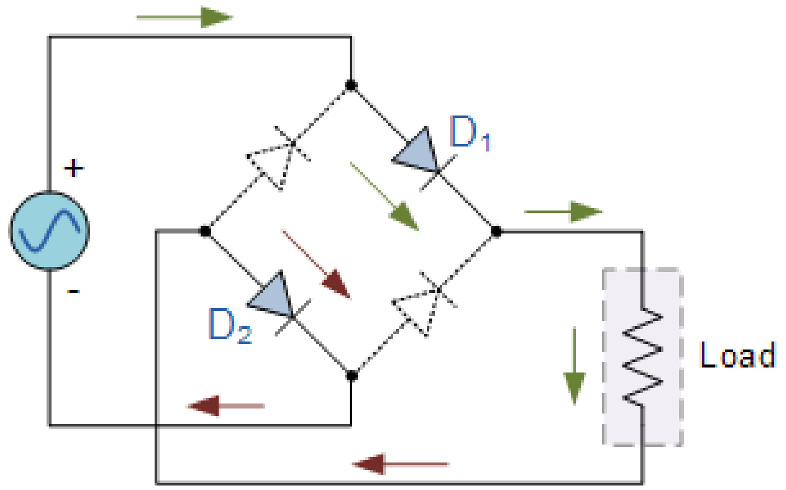
The main advantage of this bridge circuit is that it **does not require a special centre tapped transformer**, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below.



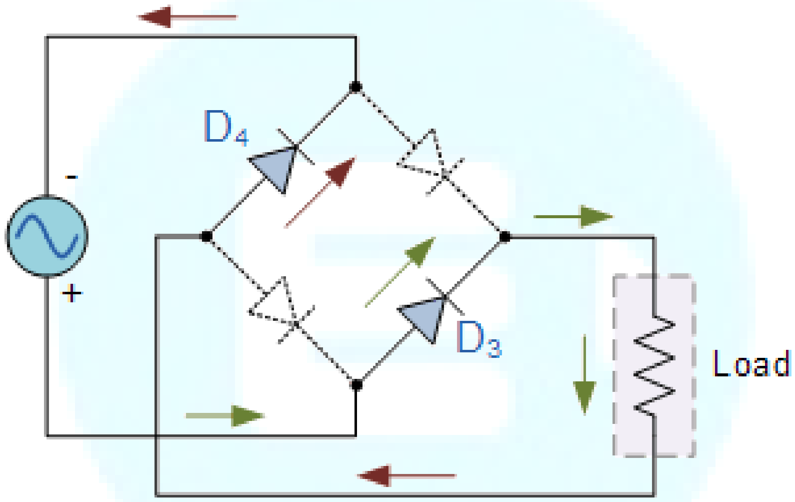
The four diodes labelled D1 to D4 are arranged in "series pairs" with only two diodes conducting current during each half cycle. During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown below.

The Positive Half-cycle

During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before.



The Negative Half-cycle

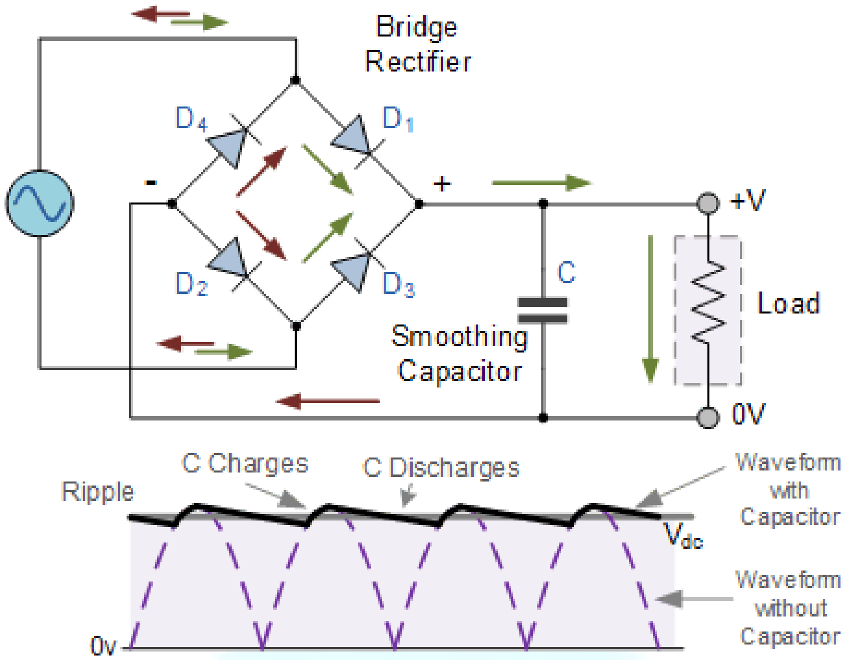


As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional the same as for the previous two diode full-wave rectifier, therefore the average DC voltage across the load is $0.637V_{max}$.

However, in reality during each half cycle the current flows through two diodes instead of just one so the amplitude of the output voltage is two voltage drops (2 x 0.7 = 1.4V) less than the input V_{MAX} amplitude. The ripple frequency is now twice the supply frequency (e.g., 100Hz for a 50Hz supply or 120Hz for a 60Hz supply.)

The Smoothing Capacitor

We can improve the average DC output of the rectifier while at the same time reducing the AC variation of the rectified output by using smoothing capacitors to filter the output waveform. Smoothing or reservoir capacitors connected in parallel with the load across the output of the full wave bridge rectifier circuit increases the average DC output level even higher as the capacitor acts like a storage device as shown below.



Resultant Output Waveform

The smoothing capacitor converts the full-wave rippled output of the rectifier into a smoother DC output voltage.

Bipolar Junction Transistor (BJT)

A Semiconductor device consisting of two PN junctions formed by sandwiching either p-type or n-type semiconductor between a pair of opposite types is known as a transistor thus it is also well known by the name bipolar junction transistor because its operation depends upon both the majority and minority carriers.

Accordingly, there are two types of transistors namely

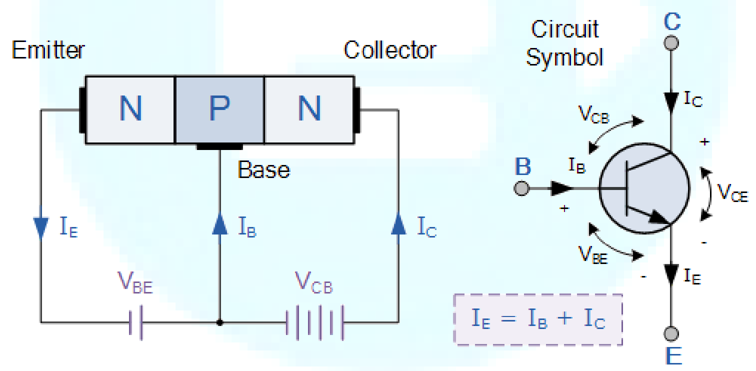
i. NPN Transistor
ii. PNP Transistor

NPN Transistor: A transistor in which two blocks of n-type semiconductor are separated by a thin layer of p-type semiconductor is known as NPN Transistor.

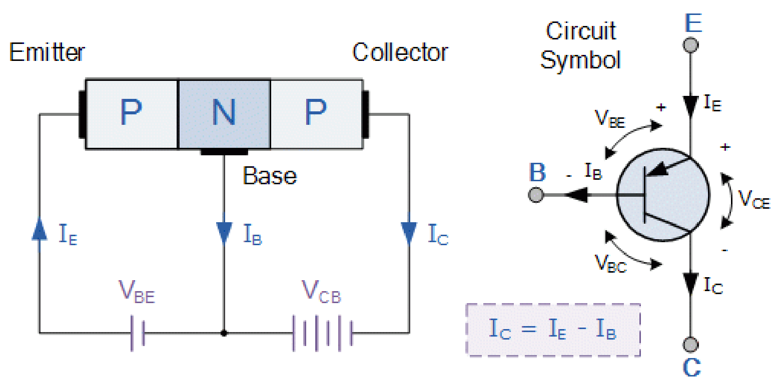
PNP Transistor: A transistor in which two blocks of p-type semiconductors are separated by a thin layer of n- type semiconductor is known as PNP Transistor.

NPN and PNP Transistor (Construction and Working)

Construction: or Transistor Terminals
Every transistor has three terminals called emitter, base and collector.



NPN Transistor



PNP Transistor

(i) **Emitter**

The Section on one side of the transistor that supplies a large number of majority carrier (electrons if emitter is n- type and holes if the emitter is of p-type) is called emitter. The emitter is always forward biased w.r.t base so that it can supply a large number of majority carriers to its junction with the base. The biasing of emitter base junction of NPN transistor and PNP transistor is shown in figures given above. Since emitter is to supply or inject a large amount of majority carriers into the base, it is heavily doped but moderate in size.

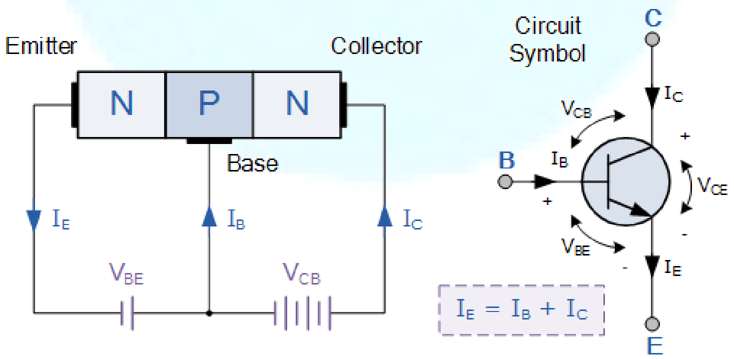
(ii) **Base**

The middle section which forms two pn junctions between emitter and collector is called base. The base form two circuits, one input circuit with emitter and other output circuit with collector. The base emitter junction is forward biased, providing low resistance to the emitter circuit. The base collector junction is reversed biased, offering high resistance path to the collector circuit. The base is lightly doped and very thin so that it can pass on most of the majority carriers supplied by emitter to the collector.

(iii) **Collector**

The section on the other side of the transistor that collects the major portion of the majority carriers supplied by the emitter is called collector. The collector base junction is always reverse biased. Its main function is to remove majority carriers (or charges) from its junction with base. The collector is moderately doped but larger in size so that it can collect most of the majority carriers supplied by the emitter.

Working of NPN Transistor

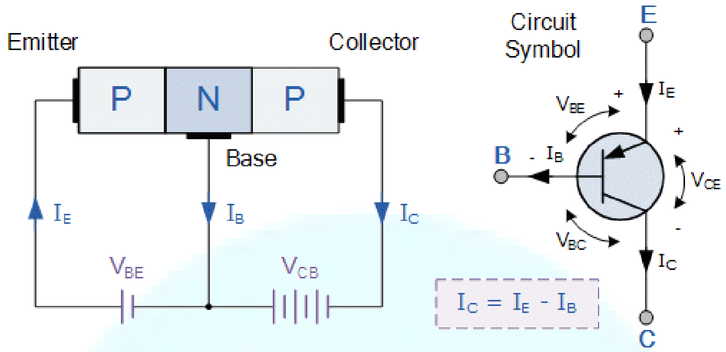


The npn transistor circuit is shown in above figure the emitter base junction is forward biased while collector base junction is reverse biased. The forward biased voltage V_{BE} is quite small, whereas reverse biased voltage for V_{CB} is considerably high.

As the emitter base junction is forward biased, a large number of electrons (majority carriers) in the emitter (N-TYPE) region are pushed toward the base. This constitutes the emitter current Ie. When these electrons enter the p-type material(base) they tend to combine with holes. Since the base is lightly doped and very thin, only a few electrons (less than 5 %) combine with holes to constitute base current I_b. The remaining electrons (more than 95%) diffuse across the thin base region and reach the collector space charge layer. These electrons then come under the influence of the positively biased n region and are attracted or collected by the collector. This constitutes the collector current Ic thus it is seen that almost the entire emitter current flows into the collector circuit. However, to be more precise the emitter current is the sum of collector current and base current.

Ie=Ic+Ib

Working of PNP Transistor

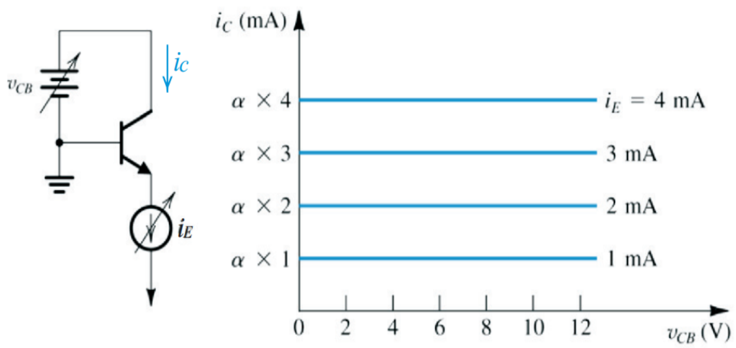


The pnp transistor circuit is shown above, the emitter base junction is forward biased while collector base junction is reverse biased. The forward biased voltage V_{BE} is quite small, whereas reverse biased voltage V_{CB} is considerably high.

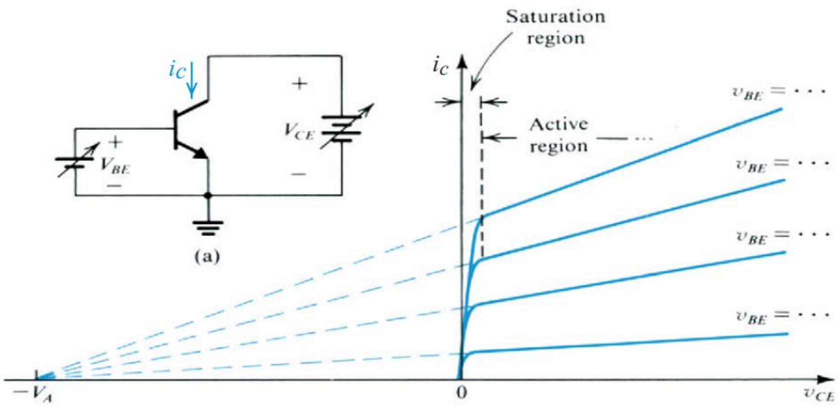
As the emitter base junction is forward biased, a large number of holes (majority carriers) in the emitter (P-TYPE) region are pushed toward the base. This constitutes the emitter current Ie. When these electrons enter the n-type material (base) they tend to combine with electrons. Since the base is lightly doped and very thin, only a few electrons (less than 5 %) combine with holes to constitute base current Ib. The remaining electrons (more than 95%) diffuse across the thin base region and reach the collector space charge layer. These holes then come under the influence of the negatively biased P-region and are attracted or collected by the collector. This constitutes the collector current Ic thus it is seen that almost the entire emitter current flows into the collector circuit. However, to be more precise the emitter current is the sum of collector current and base current.

Ie=Ic+Ib

Current Voltage Characteristics of BJT



The i_C V_{CB} Characteristics



The $i_C V_{CE}$ Characteristics

BJT Biasing

The process by which required condition such as proper flow of zero signal collector current and the maintenance of proper collector emitter voltage during the passage of signal are obtained is known as transistor biasing.

The basic procedure of transistor biasing is to keep the emitter junction forward biased and the collector junction properly reverse biased during the application of signal so that faithful amplification can be achieved. The biasing can be achieved either by using bias batteries Vbb and Vcc or by applying associating circuitry with the transistor. Generally, the latter method is employed since it is more efficient.

The circuitry which provides the necessary conditions of transistor biasing is known as biasing circuit. While designing a biasing circuit, various transistor rating such as maximum collector current I_{CMAX}, maximum collector emitter voltage V_{CEMAX} etc. are kept in view for safe operation of the transistor. In the amplifier circuits, a load resistance Rc is connected in the collector circuit, a load resistance Rc is connected in the collector circuit. The operating point will lie somewhere on this load line. Depending upon the base current, the operating point may lie at C, D or E.

When an a.c signal is applied at the input, the base current varies instant to instant. As a result of this, the current and collector voltage also vary with time. Thus an amplified signal is obtained at the output.

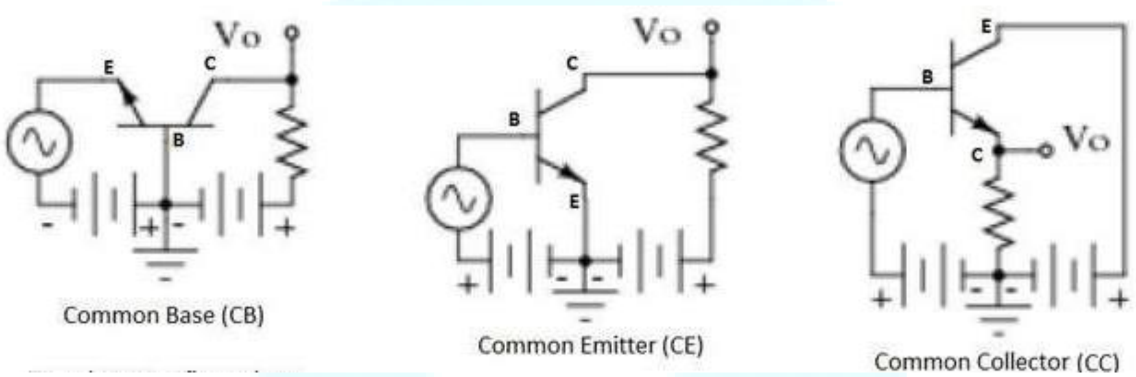
If point D is the as the operating point, the upper portion of the positive half will be clipped off as the point lies very near to the satisfaction region. On the other hand, if point E is selected as the operating point., the peak of negative half will be clipped off as this point lies very near to the cut off region. Thus, in both the cases, distorted signal is obtained at the output.

However, if point C is selected as the operating point, full cycle of the signal is obtained in the amplified form at the output in this case, signal is not distorted at all.

CB, CE and CC Configuration

A transistor has three leads, namely emitter, base and collector. However, to handle input and output four terminals are needed (two for input and two for output). Therefore, to connect transistor in the circuit, one lead or terminal is made common. The input is fed between common and one of the remaining terminals whereas, output is connected between the common and other terminal of the transistor. Accordingly, a transistor can be connected in the circuit in the following three ways:

(i) Common Base Connection (CB Configuration)
(ii) Common Emitter Connections (CE Configuration)
(iii) Common Collector Connection (CC Configuration)



It is important to note that transistor may be connected in any one of the above said three ways, the emitter base junction is always forward biased and collector base junction is always reverse biased to operate the transistor in active region.

Transistor CB (Common Base) configuration

It is transistor circuit in which base is kept common to the input and output circuits.

Current Amplification Factor (Alpha)

The ratio of output to input current is known as current amplification factor in a common base connection the output current is collector current Ic whereas the input current is emitter current Ie.

Thus, the ratio of change in collector current to the change in emitter current at constant collector base voltage Vcb is known as current amplification factor of transistor in common base configuration. It is generally represented by Greek letter (alpha).

Characteristics:

• It has low input impedance (on the order of 50 to 500 Ohms).

• It has high output impedance (on the order of 1 to 10 Mega Ohms).

• Current gain(alpha) is less than unity.

Transistor CE (Common Emitter) configuration

It is transistor circuit in which emitter is kept common to both input and output circuits.

Base Current Amplification Factor (Beta)

The ratio of output to input current is known as base current amplification factor. In a common emitter connection the output current is collector current Ic whereas the input current is base current Ib.

beta (bDC)

IC =bDCIB

Thus, the ratio of change in collector current to the change in base current is known as base current amplification factor of transistor in common emitter configuration.it is generally represented by Greek letter (beta).

Characteristics:

• It has high input impedance (on the order of 500 to 5000 Ohms).

• It has low output impedance (on the order of 50 to 500 Kilo Ohms).

• Current gain (Beta) is 98.

• Power gain is up to 37 dB.

• Output is 180 degrees out of phase.

Transistor CC (Common Collector) configuration

It is transistor circuit in which collector is kept common to both input and output circuits. It is also called as emitter follower.

Current Amplification Factor (Gama)

The ratio of output to input current is known as current amplification factor. In a common collector connection the output current is emitter current Ie whereas the input current is base current Ib.

Thus, the ratio of change in emitter current to the change in base current is known as current amplification factor of transistor in common collector configuration. It is generally represented by Greek letter (Gama)

Characteristics:

- It has high input impedance (on the order of about 150 to 600 Kilo Ohms).
- It has low output impedance (on the order of about 100 to 1000 Ohms).
- Current gain (Beta) is about 99.
- Voltage and power gain is equal to or less than one.

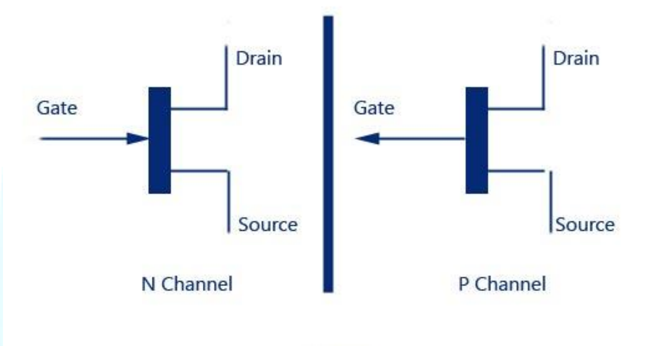
Parameter	Common Base	Common Emitter	Common Collector
Voltage Gain	High, Same as CE	High	Less than Unity
Current Gain	Less than Unity	High	High
Power Gain	Moderate	High	Moderate
Phase inversion	No	Yes	No
Input Impedance	Low (50 Ohm)	Moderate (1 K Ohm)	High (300 K Ohm)
Output Impedance	High (1 M Ohm)	Moderate (50 K)	Low (300 Ohm)

FIELD EFFECT DEVICES

Field Effect Transistor

A field effect transistor is a three terminal semiconductor device in which current conduction is by one type of carriers (i.e either electrons or holes) and is controlled by the effect of electric field.

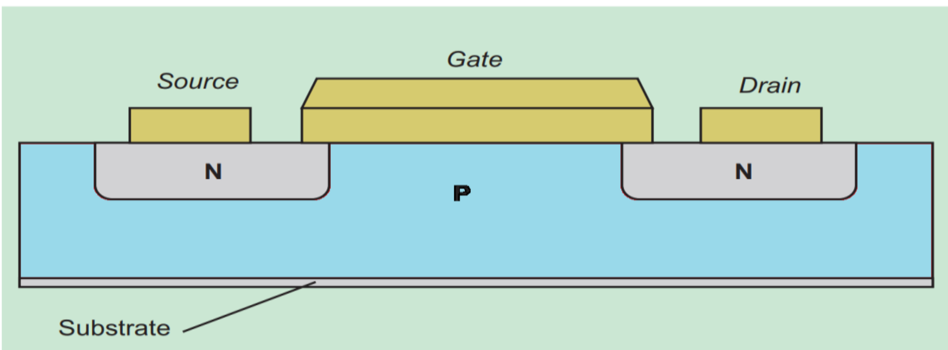
Unlike the usual transistor, its operation depends upon the flow of majority carriers only i.e. the current conduction in this case is either by electrons or holes. The flow of current is controlled by means of an electric field developed between the gate electrode and the conducting channel of the device. Although the working of FET was first given by Shockley in 1952 but it commercialised only in late 1960's.



FET

Construction

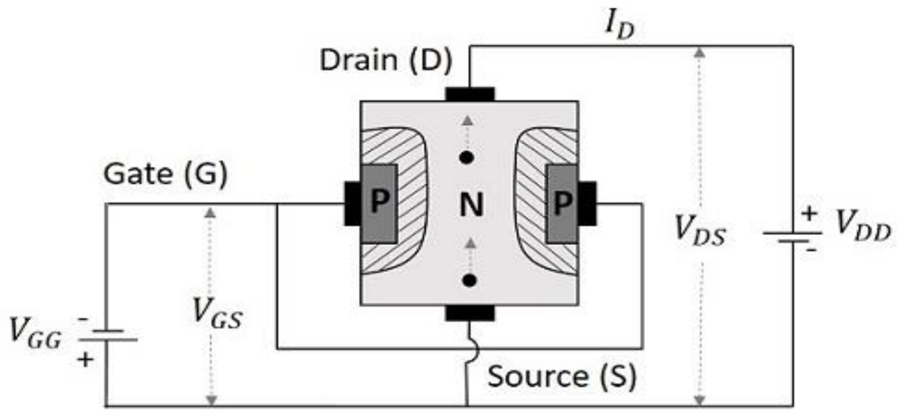
An n-channel field effect transistor is shown in below. It consists of an n-type silicon bar with two islands of p- type semiconductor material embedded in the sides, thus forming two pn junctions. The two-p region are connected with each other (externally or internally) and are called gate (G). Ohmic contacts are made at the two ends of the n- type semiconductor bar. One terminal is known as the source (S) through which the majority carriers (electrons in this case) enter the bar. The other terminal is known as the drain (D) through which these majority carriers leave the bar. Thus, a FET has essentially three terminals called gate(G), source(S) and drain(D)



Working of FET

The circuit diagram of an n- channel FET with normal polarities is shown. When a voltage Vds is applied across the drain and source terminals and voltage applied across the gate and source Vgs is zero (i.e gate circuit is open). The two pn junction establish a very thin depletion layer. Thus, a large number of electrons will flow from source to drain through a wide channel formed between the two depletion layers. When a reverse Vgs is applied across the gate and source as shown in fig. the width of the depletion layer is increased. This reduces the width of the conducting channel thereby decreasing the conduction (flow of electrons) through it. Thus, the current flowing from source to drain depends upon the width of the conducting channel which depends upon the thickness of depletion layer establish by the two pn junctions depends upon the voltage applied across the gate source terminals.

Hence it is clear that the current from source to drain can be controlled by the application of potential (electric field) on the gate. That is why the device is called field effect transistor. It may be noted that a p- channel FET also operates in the same manner as an n-channel FET except that the channel current carriers will be holes instead of electrons and all the polarities will be reversed.



Advantages

A FET is a voltage-controlled device. In which the output current (drain current) is controlled by the input (gate) voltage, therefore it has the following important advantages.

i. FET has a very high input impedance which shows a high degree of isolation between the input and output circuit.
ii. The operation of FET depends upon the majority carriers (i.e. electron in n-channel and holes in P-channel FET) which do not cross junctions. Therefore, the inherent noise of tubes (because of high temperature operation) and those of ordinary transistor are not present in a FET.
iii. In FET the risk of thermal runway is avoided since it has a negative temperature coefficient of resistance.
iv. A FET has smaller size, longer life and higher efficiency.

Disadvantage

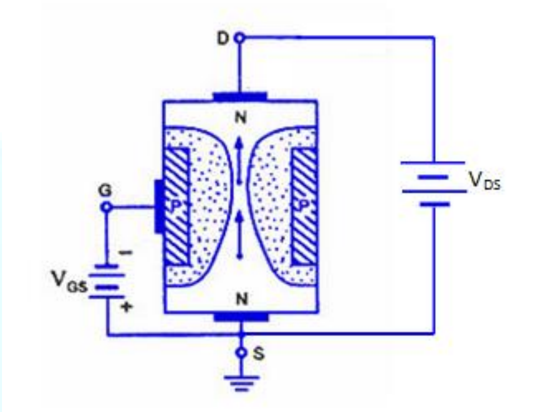
Since FET has high input impedance the gate voltage has less voltage and has less control over the drain current. Therefore, FET amplifier has much less voltage gain than a bipolar amplifier.

There are two major categories of field effect transistors namely:

1. Junction field effect transistors (JFET)
2. Metal oxide field effect transistor (MOSFET)

Construction and Characteristics of JFETs

JFET are of two types viz. N-channel JFET and P-channel JFETs. Generally N-channel JFET are preferred.



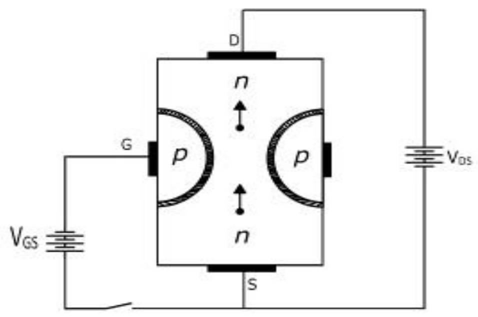
Basic Construction

In an N- channel JFET an N-type silicon bar, referred to as the channel, has two smaller pieces of P-type silicon material diffused on the opposite sides of its middle part, forming P-N junctions as shown in above figure. The two P-n junctions forming diodes or gates are connected internally and a common terminal called the gate terminal is brought out. Ohmic contacts are made at the two ends of the channel-one lead is called the source terminal S and the other drain terminal D.

The silicon bar behaves like a resistor between its two terminals D and S. The gate terminal is analogous to the base of an ordinary transistor (BJT). It is used to control the flow of current from source to drain. Thus, source and drain terminal are analogous to emitter and collector terminals respectively of a BJT.

Working Principle of JFET

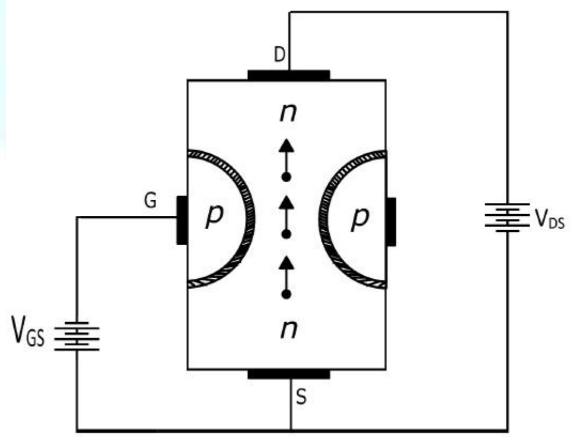
When voltage VDS is applied between the drain and source terminals and gate terminal voltage is zero, the two pn-junctions at the sides establishes depletion layers. The electrons flow from source to drain through the channel between the depletion layers. The width of these depletion layers determines the width of the channel and hence the current conduction through the bar.



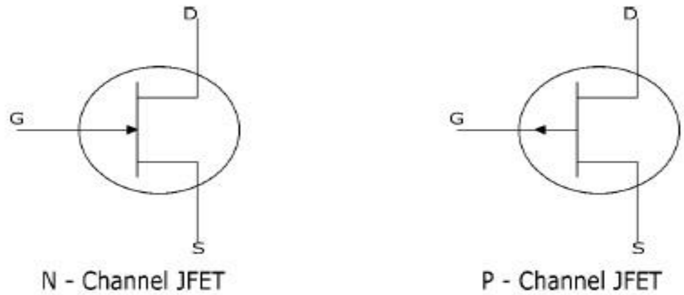
Now, when a reverse voltage V_{GS} is applied between the gate and the source terminals, the width of depletion layers is increased and this decreases the width of the conduction channel, thereby increasing the resistance of conduction channel. Consequently, the current from source to drain is decreased. On the other hand, when the reverse voltage V_{GS} is decreased the width of depletion layer also decreases. Hence, the width of conduction channel increases and the resulting source to drain current.

Therefore, the current from source to drain can be controlled by the application voltage (electric field) on the gate terminal. For this reason, it is known as Field Effect Transistor.

Hence, the JFET operates on the principle that the width and resistance of conduction channel can be varied by changing the reverse voltage V_{GS}

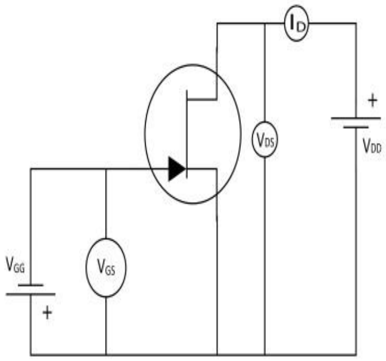


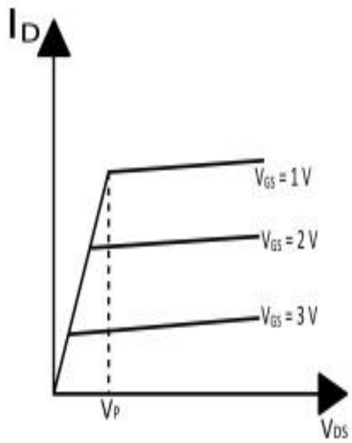
Schematic Symbol of JFET



ENTRI

Drain or Output Characteristics of JFET





The curve showing the relation between the drain current (I_D) and the drain-source voltage (V_{DS}) at constant gate-source voltage (V_{GS}) is known as the Output or Drain Characteristics of JFET.

The important points from the output characteristics are –

- At the start, the drain current (ID) increases rapidly with increase in drain-source voltage (VDS) but then becomes constant. The value of VDS above which the drain current becomes constant is called as **Pinch off Voltage (V_P)**.
- After pinch off voltage, the channel width becomes so narrow that the depletion layers touch each other. Therefore, after pinch off voltage the change in the drain current is small with change in the VDS. Hence, the drain current remains constant.
- After pinch off voltage, the channel width becomes so narrow that the depletion layers touch each other. Therefore, after pinch off voltage the change in the drain current is small with change in the VDS. Hence, the drain current remains constant.

Parameters of JFET

The JFET has parameters which determine the performance of it.

- **AC drain resistance (r_d)** – It is defined as the ratio of the change in the drain-source voltage (ΔV_{DS}) to the corresponding change in the drain current (ΔI_D) at constant gate-source voltage (V_{GS}).
  AC drain resistance(rd)=$\Delta V_{DS}/\Delta I_D$
- **Trans-conductance (g_m)** – It is defined as the ratio of change in drain current (ΔI_{DS}) to the change in gate – source voltage (ΔV_{GS}) at constant drain-source voltage.

The trans-conductance of JFET is expressed either in mA/V or micro siemens.

Transconductance(gm)=$(\Delta I_D)/(\Delta V_{GS})$

- **Amplification Factor (μ)** – It is defined as the ratio of change in drain-source voltage (ΔV_{DS}) to the change in gate-source voltage (Δ_{GS}) at constant drain current.

The amplification factor of JFET shows how much control the gate voltage has over the drain current.

Amplification Factor(μ)=$(\Delta V_{DS})/(\Delta V_{GS})$

Advantages of JFET

- It has the high input impedance. This permits high degree of isolation between input-output circuit.
- JFET has a negative resistance temperature coefficient. This avoids the risk of thermal runaway.
- A JFET has a very high-power gain.
- A JFET has smaller size, high efficiency and longer life.

Applications of JFET

- A JFET can be used as a switch.
- JFET can be used as an amplifier.
- JFET can be used as a chopper.
- JFET can be used as a buffer.
- JFET can be used as voltage-controlled resistors in the operational amplifiers.
- JFET is used in cascade amplifier and in RF amplifiers.
- JFET is used in communication devices.
- JFET is used in digital circuits.

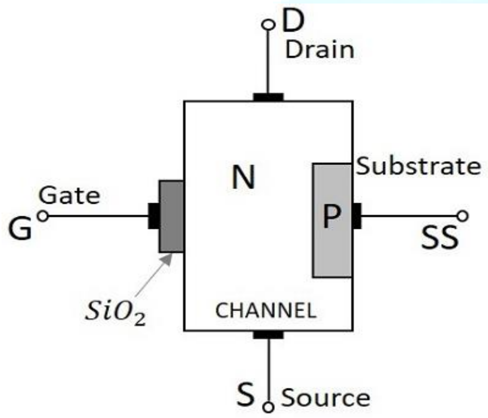
Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

A metal oxide semiconductor field effect transistor is a three terminal semiconductor device. The three terminals are source, gate and drain. Unlike a FET in this device the gate is insulate from the channel and therefore sometimes it is also known as insulated gate FET (IGFET). Because of this reason the gate current is very small whether the gate is positive or negative. The MOSFET can be used in any of the circuits covered for the FET. Therefore, all the equations apply equally well to MOSFET and FET in amplifier connections.

Construction of a MOSFET

The construction of a MOSFET is a bit similar to the FET. An oxide layer is deposited on the substrate to which the gate terminal is connected. This oxide layer acts as an insulator (sio2 insulates from the substrate), and hence the MOSFET has another name as IGFET. In the construction of MOSFET, a lightly doped substrate, is diffused with a heavily doped region. Depending upon the substrate used, they are called as P-type and N-type MOSFETs.

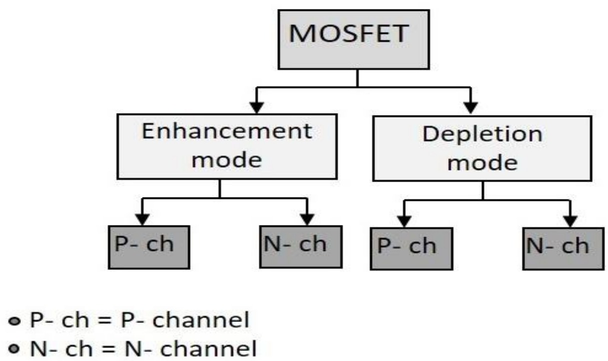
The following figure shows the construction of a MOSFET.



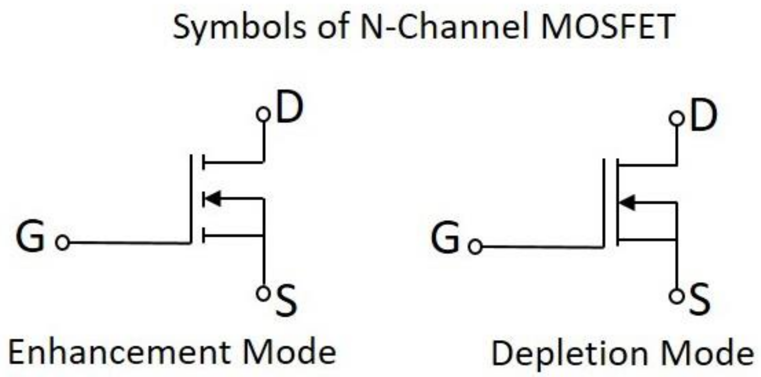
The voltage at gate controls the operation of the MOSFET. In this case, both positive and negative voltages can be applied on the gate as it is insulated from the channel. With negative gate bias voltage, it acts as **depletion MOSFET** while with positive gate bias voltage it acts as an **Enhancement MOSFET**.

Classification of MOSFETs

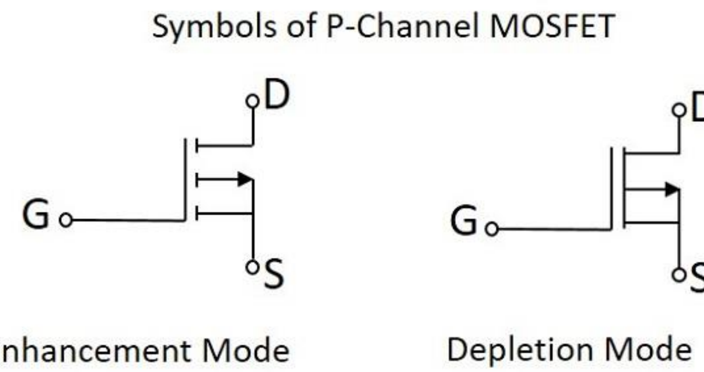
Depending upon the type of materials used in the construction, and the type of operation, the MOSFETs are classified as shown in the following figure.



The **N-channel MOSFETs** are simply called as **NMOS**.

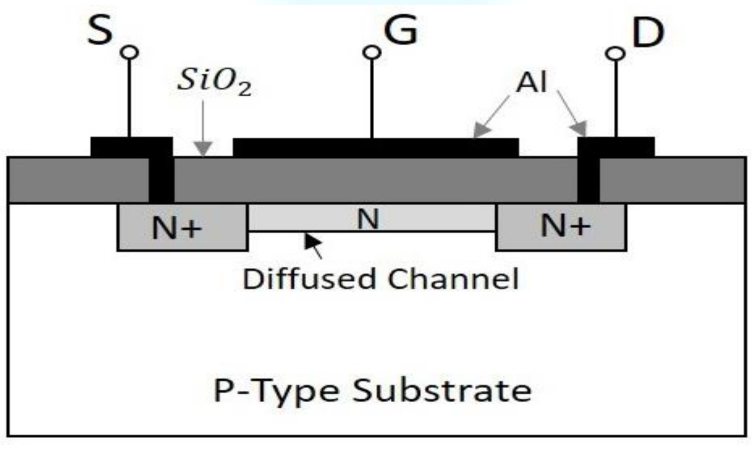


The **P-channel MOSFETs** are simply called as **PMOS**.



Construction of N- Channel MOSFET

A lightly doped P-type substrate is taken into which two heavily doped N-type regions are diffused, which act as source and drain. Between these two N+ regions, there occurs diffusion to form an N-channel, connecting drain and source.



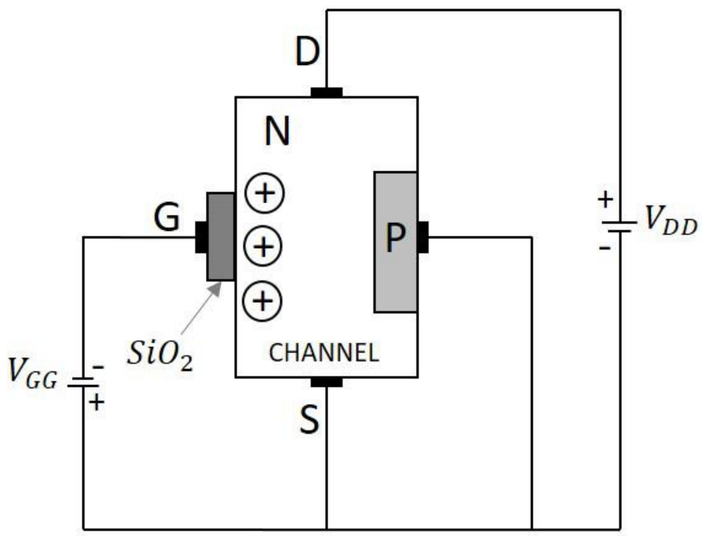
Structure of N-channel MOSFET

A thin layer of **Silicon dioxide (SiO_2)** is grown over the entire surface and holes are made to draw ohmic contacts for drain and source terminals. A conducting layer of **aluminium** is laid over the entire channel, upon this **SiO_2** layer from source to drain which constitutes the gate. The **SiO_2 substrate** is connected to the common or ground terminals.

Because of its construction, the MOSFET has a very less chip area than BJT, which is 5% of the occupancy when compared to bipolar junction transistor. This device can be operated in modes. They are depletion and enhancement modes. Let us try to get into the details.

Working of N Channel depletion mode MOSFET

If the NMOS has to be worked in depletion mode, the gate terminal should be at negative potential while drain is at positive potential, as shown in the following figure.



Working of MOSFET in depletion mode

When no voltage is applied between gate and source, some current flows due to the voltage between drain and source. Let some negative voltage is applied at **V_{GG}**. Then the minority carriers i.e. holes, get attracted and settle near **SiO_2** layer. But the majority carriers, i.e., electrons get repelled.

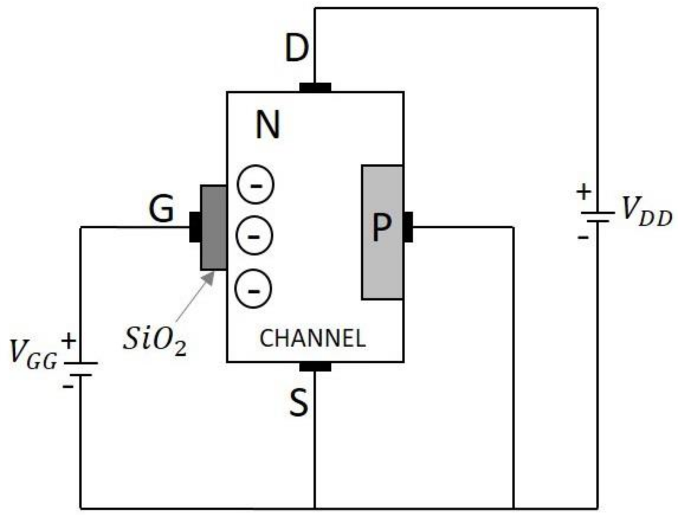
With some amount of negative potential at **V_{GG}** a certain amount of drain current **I_D** flows through source to drain. When this negative potential is further increased, the electrons get depleted and the current **I_D** decreases. Hence the more negative the applied **V_{GG}**, the lesser the value of drain current **I_D** will be.

The channel nearer to drain gets more depleted than at source like in FET and the current flow decreases due to this effect. Hence it is called as depletion mode MOSFET.

Working of N-Channel MOSFET

Enhancement Mode

The same MOSFET can be worked in enhancement mode, if we can change the polarities of the voltage $\mathbf{V_{GG}}$. So, let us consider the MOSFET with gate source voltage $\mathbf{V_{GG}}$ being positive as shown in the following figure.



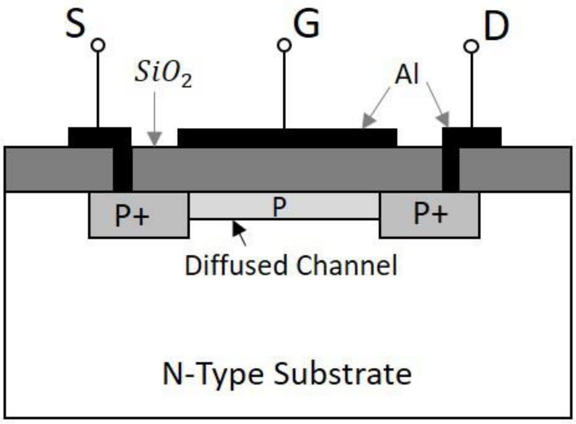
Working of MOSFET in Enhancement mode

When no voltage is applied between gate and source, some current flows due to the voltage between drain and source. Let some positive voltage is applied at $\mathbf{V_{GG}}$. Then the minority carriers i.e. holes, get repelled and the majority carriers i.e. electrons gets attracted towards the $\mathbf{SiO_2}$ layer.

With some amount of positive potential at $\mathbf{V_{GG}}$ a certain amount of drain current $\mathbf{I_D}$ flows through source to drain. When this positive potential is further increased, the current $\mathbf{I_D}$ increases due to the flow of electrons from source and these are pushed further due to the voltage applied at $\mathbf{V_{GG}}$. Hence the more positive the applied $\mathbf{V_{GG}}$, the more the value of drain current $\mathbf{I_D}$ will be. The current flow gets enhanced due to the increase in electron flow better than in depletion mode. Hence this mode is termed as **Enhanced Mode MOSFET**.

P - Channel MOSFET

The construction and working of a PMOS is same as NMOS. A lightly doped **n-substrate** is taken into which two heavily doped **P+ regions** are diffused. These two P+ regions act as source and drain. A thin layer of $\mathbf{SiO_2}$ is grown over the surface. Holes are cut through this layer to make contacts with P+ regions, as shown in the following figure.



Structure of P-channel MOSFET

Working of PMOS

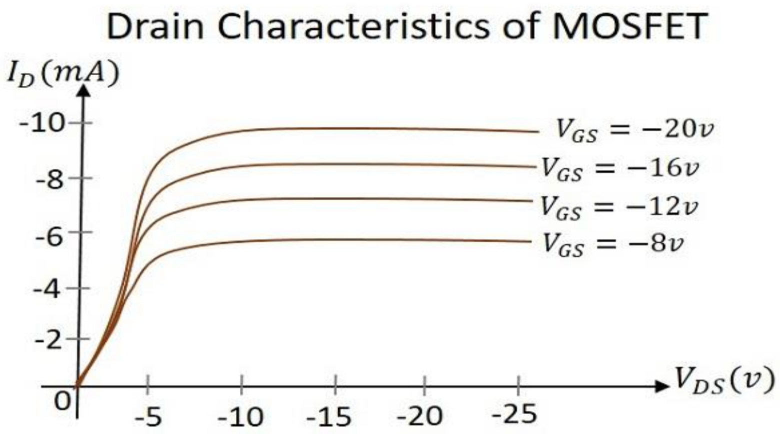
When the gate terminal is given a negative potential at $\mathbf{V_{GG}}$ than the drain source voltage $\mathbf{V_{DD}}$, then due to the P+ regions present, the hole current is increased through the diffused P channel and the PMOS works in **Enhancement Mode**.

When the gate terminal is given a positive potential at $\mathbf{V_{GG}}$ than the drain source voltage $\mathbf{V_{DD}}$, then due to the repulsion, the depletion occurs due to which the flow of current reduces. Thus, PMOS works in **Depletion Mode**. Though the construction differs, the working is similar in both the type of MOSFETs. Hence with the change in voltage polarity both of the types can be used in both the modes.

This can be better understood by having an idea on the drain characteristics curve.

Drain Characteristics

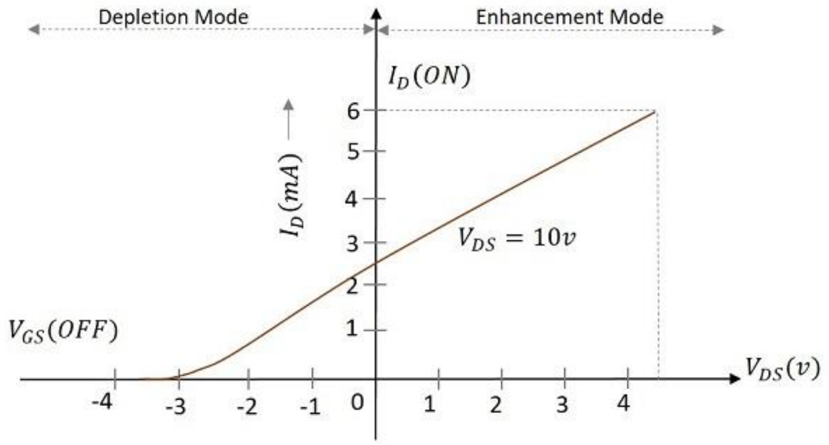
The drain characteristics of a MOSFET are drawn between the drain current $\mathbf{I_D}$ and the drain source voltage $\mathbf{V_{DS}}$. The characteristic curve is as shown below for different values of inputs.



Actually, when V_{DS} is increased, the drain current I_D should increase, but due to the applied V_{GS}, the drain current is controlled at certain level. Hence the gate current controls the output drain current.

Transfer Characteristics

Transfer characteristics define the change in the value of V_{DS} with the change in I_D and V_{GS} in both depletion and enhancement modes. The below transfer characteristic curve is drawn for drain current versus gate to source voltage.



Transfer Characteristics of a MOSFET

Comparison between BJT, FET and MOSFET

TERMS	BJT	FET	MOSFET
Device type	Current controlled	Voltage controlled	Voltage Controlled
Current flow	Bipolar	Unipolar	Unipolar
Terminals	Not interchangeable	Interchangeable	Interchangeable
Operational modes	No modes	Depletion mode only	Both Enhancement and Depletion modes
Input impedance	Low	High	Very high
Output resistance	Moderate	Moderate	Low
Operational speed	Low	Moderate	High
Noise	High	Low	Low
Thermal stability	Low	Better	High

Homojunction Semiconductor

A homojunction is a semiconductor device or interface that occur between the layer of similar materials with equal band gap but different doping concentration. Mostly, it occurs at the interface between an n-type (known as donor doped) and p-type (known as acceptor doped) semiconductor such as silicon.

For example, n-type to n-type junction would also be considered as homojunction even if the doping levels are unusual or different.

Heterojunction Semiconductor

The heterojunction is the interface that occurs between two-layer or regions of dissimilar material/crystalline semi-conductor or solid-state materials. The concentration of multiple heterojunctions together in a device is called a heterostructure.

To manufacture the heterojunction generally requires the use of molecular beam epitaxy (MBE) or chemical vapor deposition (CVD) technologies. Some of the specialized applications of heterojunction are:

- Solar Cells: - In 1983, the Heterojunction with Intrinsic Thin-Layer (HIT) solar cell structure was first developed. Intrinsic Thin-Layer (HIT) solar cells are now one of the most efficient single-junction silicon cells as it has a conversion efficiency of 26.7%.

- Lasers: - By the association of a smaller direct bandgap material like Gallium arsenide (GaAs) and between two larger bandgap layers like Aluminium arsenide (AlAs), carriers can be made very small so that lasing can occur at room temperature with low threshold currents. One of the major advantages of the use of semiconductor lasers is that heterostructures can be used as waveguides.

- Bipolar Transistors: - When a heterojunction is used in bipolar junction transistors, it will obtain extremely high forward gain and low reverse gain. This results in very good high-frequency operation (values in tens to hundreds of GHz) and has a low leakage current. Such a device is called a heterojunction bipolar transistor (HBT).

- Field-effect transistors: - It is used in high electron mobility transistors (HEMT) and it can be operated at significantly higher frequencies (over 500 GHz).