Chapter 14
Semiconductor Electronics:
Materials, Devices and Simple Circuits Introduction

14.1 Introduction

Semiconductors are the basic materials used in the present solid state electronic devices like diode, transistor, ICs, etc. Lattice structure and the atomic structure of constituent elements decide whether a particular material will be insulator, metal or semiconductor.

14.2 Classification of Metals, Conductors and Semiconductors

On the basis of conductivity:

On the basis of the relative values of electrical conductivity (σ) or resistivity ($\rho = 1/\sigma$), the solids are broadly classified as:

(i) Metals: They possess very low resistivity (or high conductivity).

$$\rho \sim 10^{-2} - 10^{-8}\ \Omega\ \text{m}$$
$$\sigma \sim 10^{2} - 10^{8}\ \text{S m}^{-1}$$

(ii) Semiconductors: They have resistivity or conductivity intermediate to metals and insulators.

$$\rho \sim 10^{-5} - 10^{6}\ \Omega\ \text{m}$$
$$\sigma \sim 10^{5} - 10^{-6}\ \text{S m}^{-1}$$

(iii) Insulators: They have high resistivity (or low conductivity).

$$\rho \sim 10^{11} - 10^{19}\ \Omega\ \text{m}$$
$$\sigma \sim 10^{-11} - 10^{-19}\ \text{S m}^{-1}$$

Semiconductors which could be:

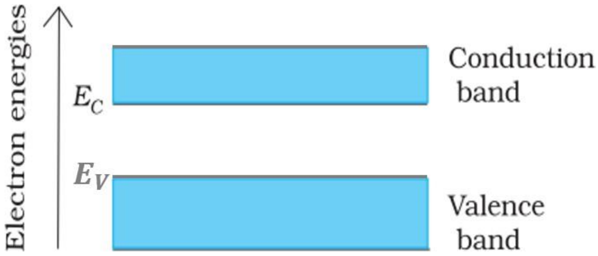
(i) Elemental semiconductors: Si and Ge

(ii) Compound semiconductors: Examples are:

- Inorganic: CdS, GaAs, CdSe, InP, etc.
- Organic: anthracene, doped pthalocyanines, etc.
- Organic polymers: polypyrrole, polyaniline, polythiophene, etc.

Most of the currently available semiconductor devices are based on elemental semiconductors Si or Ge and compound inorganic semiconductors.

Energy Bands In Solids



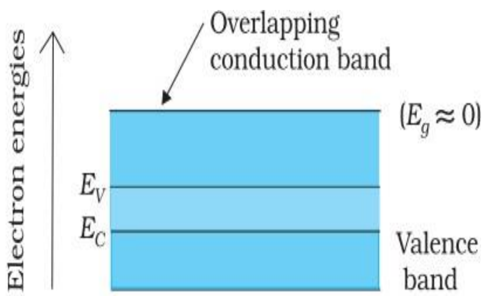
- Inside the crystal each electron will have a different energy level. These different energy levels with continuous energy variation form energy bands.
- The energy band which includes the energy levels of the valence electrons is called the valence band.
- The energy band which includes the energy levels of conduction electrons is called the conduction band.
- The conduction band is above the valence band .Normally the conduction band is empty and valence band is occupied.
- The gap between the top of the valence band and bottom of the conduction band is called the energy band gap (Energy gap E_g). It is measured in electron volt.

Classification of Metals, Conductors and Semiconductors

On the basis of energy bands

(i) metals

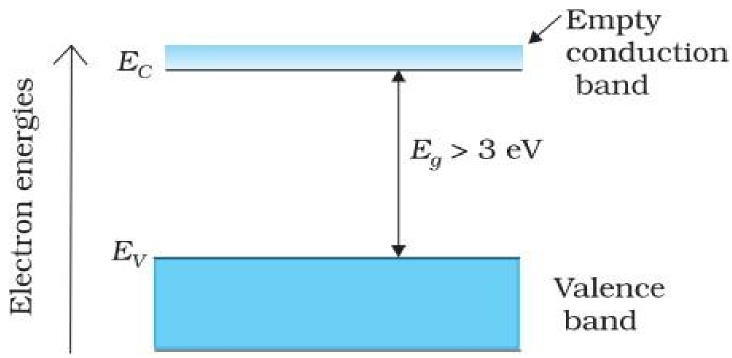
(i)



(ii)

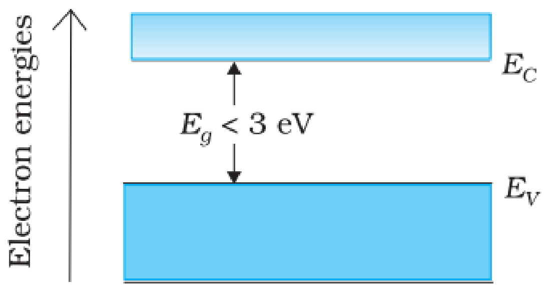
In some metals, the conduction band is partially filled and the valence band is partially empty with small energy gap and in some others the conduction and valance bands overlap. When there is overlap electrons from valence band can easily move into the conduction band. Therefore, the resistance of such materials is low or the conductivity is high.

(ii) Insulators



In insulators a large band gap , $E_g > 3$ eV. There are no electrons in the conduction band, and therefore no electrical conduction is possible. The energy gap is so large that electrons cannot be excited from the valence band to the conduction band by thermal excitation.

(iii) Semiconductors

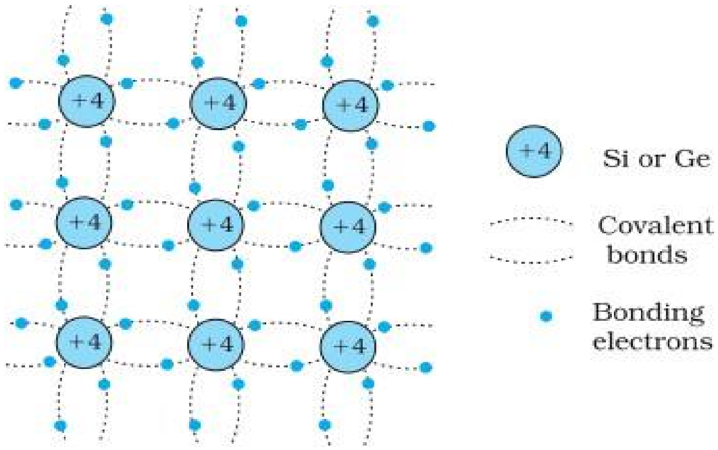


In semiconductors a finite but small band gap ($E_g < 3$ eV) exists. Because of the small band gap, at room temperature some electrons from valence band can acquire enough energy to cross the energy gap and enter the conduction band. These electrons (though small in numbers) can move in the conduction band. Hence, the resistance of semiconductors is lower than that of insulators.

When the electrons from valence band move to the conduction band vacant energy levels will be created in the valence band . This vacancy of electrons is called hole. Other valence electrons can move to this hole thereby producing hole current.

14.3 Intrinsic Semiconductor

Pure semiconductors are called 'intrinsic semiconductors'.
Si and Ge have four valence electrons. In a pure Si or Ge crystal ,each atom make covalent bond with four neighbouring atoms and share the four valence electrons.

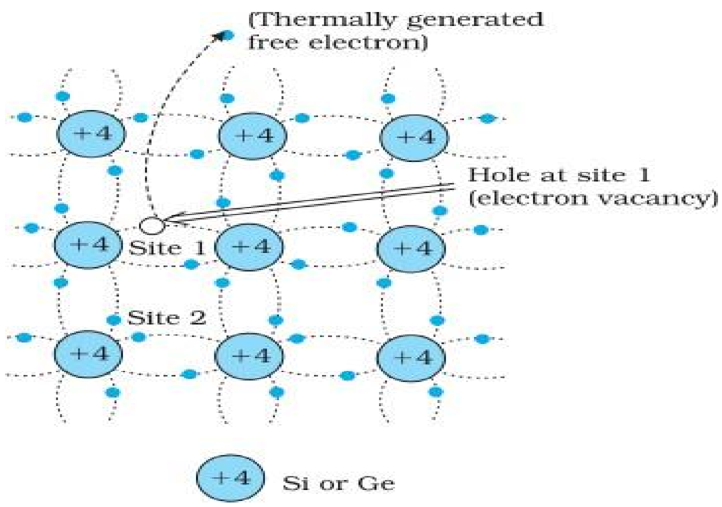


As the temperature increases, these electrons get more thermal energy , break–away the covalent bonds and become free electrons contributing to conduction. These free electrons (with charge –q) leaves a vacancy with an effective charge (+q). This vacancy with the effective positive electronic charge is called a hole.

In intrinsic semiconductors, the number of free electrons, n_e is equal to the number of holes, n_h.

$$n_e = n_h = n_i$$

where n_i is called intrinsic carrier concentration.

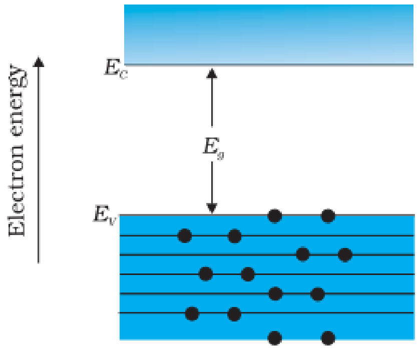


The free electrons move as conduction electron and gives rise to an electron current, I_e under an applied electric field. Under the action of an electric field, the holes move towards negative potential giving the hole current, I_h. The total current, I is thus the sum of the electron current I_e and the hole current I_h:

$$I = I_e + I_h$$

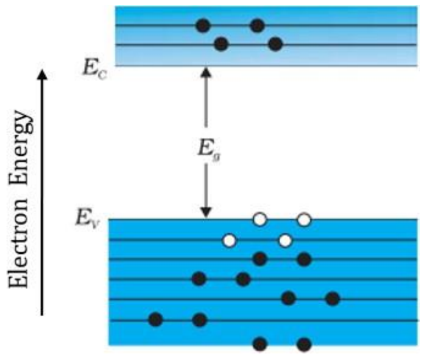
Energy-Band Diagram of an Intrinsic Semiconductor at T=0K

An intrinsic semiconductor will behave like an insulator at T = 0 K .



Energy-Band Diagram of an Intrinsic Semiconductor at T > 0K

At temperatures (T > 0K), some electrons are excited from the valence band to the conduction band, leaving equal number of holes there.



14.4 Extrinsic Semiconductor

When a small amount of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased . Such materials are known as extrinsic semiconductors or impurity semiconductors.

The deliberate addition of a desirable impurity is called doping and the impurity atoms are called dopants. Such a material is also called a doped semiconductor.

There are two types of dopants used in doping Si or Ge:

(i)Pentavalent (valency 5)

Eg: Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

(ii)Trivalent (valency 3)

Eg: Indium (In), Boron (B), Aluminium (Al), etc.

Depending on the type of impurities added, there are two types of semiconductors –

(i) n-type semiconductor
(ii) p-type semiconductor

n-type semiconductor

n-type semiconductor is obtained by doping Si or Ge with pentavalent atoms (donors) like As, Sb, P, etc. The four valence electrons of pendavalent impurity atom bond with the four silicon neighbours ,while the fifth one is free to move in the lattice of the semiconductor ,at room temperature. Thus, the pentavalent dopant is donating one extra electron for conduction and hence is known as donor impurity.

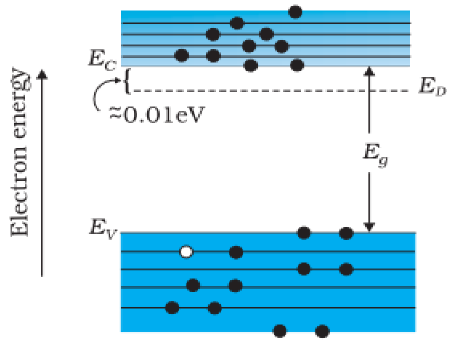
For n-type semiconductors, $n_e >> n_h$

Here electrons become the majority carriers and holes the minority carriers.

The electron and hole concentration in a semiconductor in thermal equilibrium is given by

$$n_e n_h = n_i^2$$

Energy bands of n-type semiconductor at T > 0K



(a) $T > 0K$

For n-type Si semiconductor ,the donor energy level E_D ,is slightly below the bottom E_C of the conduction band .The electrons from this level move into the conduction band with very small supply of energy.

p-type semiconductor

p-type semiconductor is obtained when Si or Ge is doped with a trivalent impurity like *Al*, B, In, etc. The dopant has only 3 valence electrons and can form covalent bonds with neighbouring three Si atoms but does not have any electron to offer to the fourth Si atom. This vacancy of electron creates a hole. As the pendavalent impurities creates holes ,which can accept electrons from neighbouring atom, these impurities are called acceptor impurities.

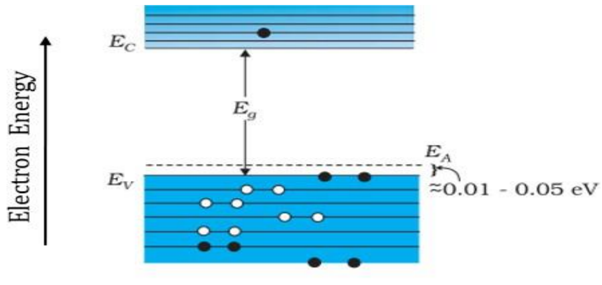
For p-type semiconductors, $n_h >> n_e$

Here holes become the majority carriers and electrons the minority carriers.

The electron and hole concentration in a semiconductor in thermal equilibrium is given by

$$n_e n_h = n_i^2$$

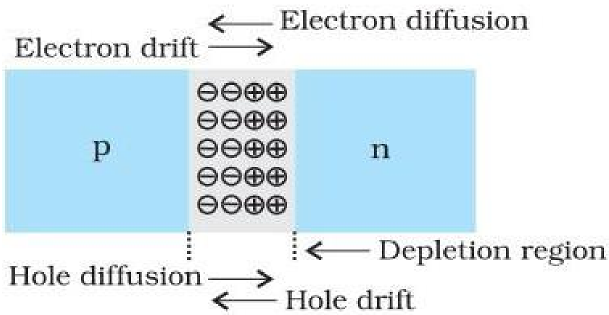
Energy bands of p-type semiconductor at T > 0K



(b) T > 0K

For p-type semiconductor, the acceptor energy level E_A is slightly above the top E_V of the valence band . With very small supply of energy an electron from the valence band can jump to the level E_A and ionise the acceptor .
negatively.

14.5 p-n junction



A p-n junction can be formed by adding a small quantity of pendavalent impurity to a p-type semiconductor or by adding a small quantity of trivalent impurity to an n-type semiconductor.

Two important processes occur during the formation of a p-n junction: diffusion and drift.

1.Diffusion

The holes diffuse from p-side to n-side (p → n) and electrons diffuse from n-side to p-side (n → p). This motion of charge carriers give rise to Diffusion current across the junction.
Due to diffusion, a layer of positive charge (or positive space-charge region) is developed on n-side of the junction and a layer of negative charge (or negative space-charge region) is developed on the p-side of the junction .

Depletion region (Depletion layer)

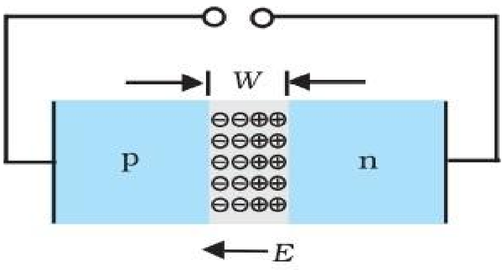
The space-charge region on either side of the junction together is known as depletion region. The depletion layer consist of immobile ion-cores and no free electrons or holes. This is responsible for a junction potential barrier.

2.Drift

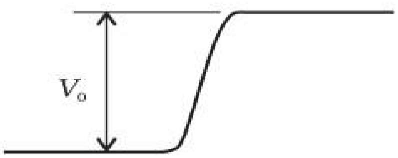
The positive charge on n-side of the junction and negative charge on p-side of the junction develops an electric field. Due to this field, an electron(minority carrier) on p-side of the junction moves to n-side and a hole(minority carrier) on n- side of the junction moves to p-side. The motion of charge carriers due to the electric field is called drift.

Initially, diffusion current is large and drift current is small. As the diffusion process continues, the electric field strength increases and hence drift current also increases. This process continues until the diffusion current equals the drift current.. Thus in a p-n junction under equilibrium there is no net current.

Barrier Potential

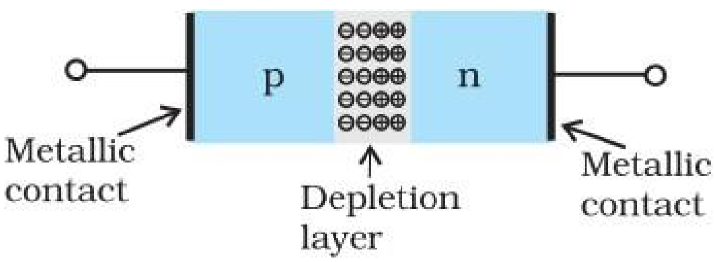


(a)



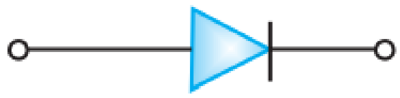
The loss of electrons from the n-region and the gain of electron by the p-region causes a difference of potential across the junction of the two regions. Since this potential tends to prevent the movement of electron from the n region into the p region, it is often called a barrier potential. The barrier potential of a Ge diode is 0.2Vand that of a Si diode is 0.7V.

14.6 Semiconductor Diode

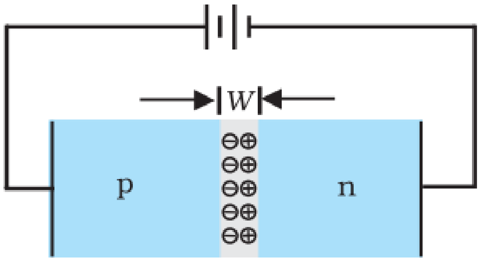


A semiconductor diode is basically a p-n junction with metallic contacts provided at the ends for the application of an external voltage. It is a two terminal device.

Symbol of a p-n junction Diode



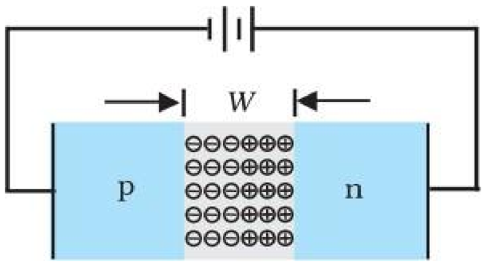
p-n junction diode under forward bias



If p-side of the diode is connected to the positive terminal and n-side to the negative terminal of the battery, it is said to be forward biased.

- The direction of the applied voltage (V) is opposite to barrier potential V_0. As a result, the depletion layer width decreases and the barrier height is reduced.
- The effective barrier height under forward bias is (V_0 – V).
- At high applied voltage, electrons from n-side cross the depletion region and reach p-side . Similarly, holes from p-side cross the junction and reach the n-side.
- This motion of majority carriers on either side gives rise to diffusion current.
- The magnitude of this current is usually in mA.

p-n junction diode under reverse bias

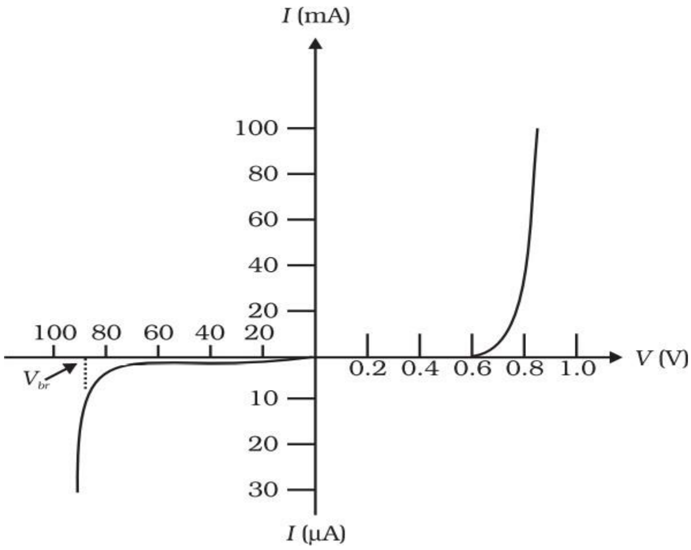


If n-side of the diode is connected to the positive terminal and p-side to the negative terminal of the battery, it is said to be reverse biased.

- The direction of the applied voltage (V) is same as barrier potential V_0. As a result, the depletion layer width increases and the barrier height is incresaed.
- The effective barrier height under reverse bias is (V_0 + V).
- The flow of electrons from n → p and holes from p → n is suppressed. Thus, diffusion current, decreases enormously compared to the diode under forward bias.

- The electricfield of the junction is such that the minority carriers are drifted to majority zone which gives rise to drift current.
- The drift current is of the order of a few μA.

V-I characteristics of a silicon diode.



- In forward bias, the current first increases very slowly, till the voltage across the diode crosses a certain value. . This voltage is called the threshold voltage or cut-in voltage (0.2V for germanium diode and 0.7 V for silicon diode).
- After threshold voltage, the diode current increases significantly , even for a very small increase in the diode bias voltage.
- For the diode in reverse bias, the current is very small (~μA) and almost remains constant with change in bias. It is called reverse saturation current. However, at very high reverse bias called break down voltage V_{br}, the current suddenly increases. The general purpose diode are not used beyond the reverse saturation current region.

Threshold Voltage

The forward voltage beyond which the diode current increases significantly is called threshold voltage or cut-in voltage.

Break down Voltage

The reverse voltage at which the reverse current increases suddenly is called break down voltage.

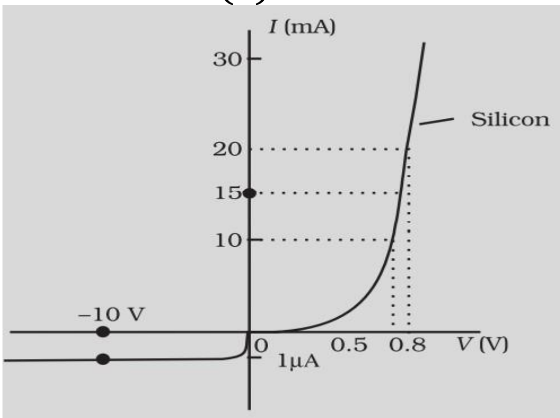
Dynamic Resistance(r_d)

Dynamic resistance is defined as the ratio of small change in voltage ΔV to a small change in current ΔI.

$$r_d = \frac{\Delta V}{\Delta I}$$

Example

The V-I characteristic of a silicon diode is shown in the Figure. Calculate the resistance of the diode at (a) $I_D = 15$ mA and (b) $V_D = -10$ V.



(a) From the curve, at I = 20 mA, V = 0.8 V

I = 10 mA, V = 0.7 V

$$r_{\text{forwrd bias}} = \frac{\Delta V}{\Delta I} = \frac{0.1}{10\text{x}10^{-3}} = 10\ \Omega$$

(b) From the curve at V = −10 V, I = −1 μA,

$$r_{\text{reverse bias}} = \frac{10}{1\text{x}10^{-6}} = 1.0 \times 10^{7}\ \Omega$$

14.7 Application of Junction Diode as a Rectifier

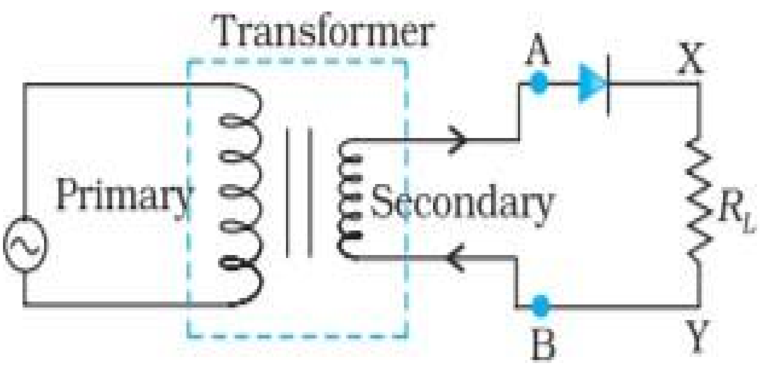
The diode allows current to pass only when it is forward biased.

If an alternating voltage is applied across a diode the current flows only in that part of the cycle when the diode is forward biased. This property is used to rectify alternating voltages .

Rectifier

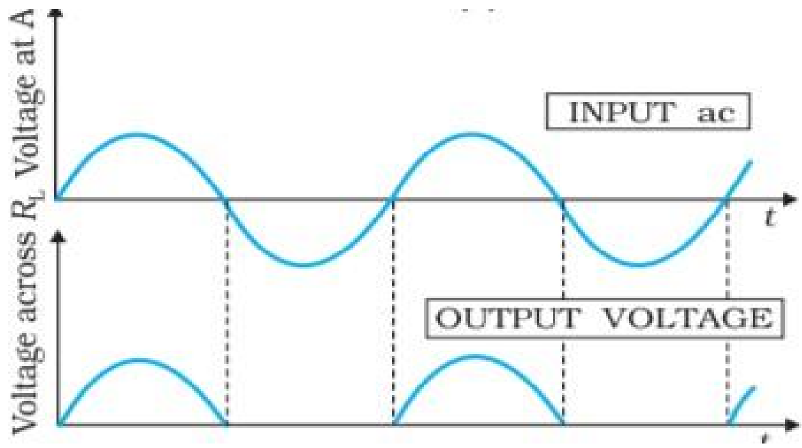
The process of conversion of ac voltage to dc voltage is called rectification and the circuit used for rectification is called rectifier.

Half wave Rectifier

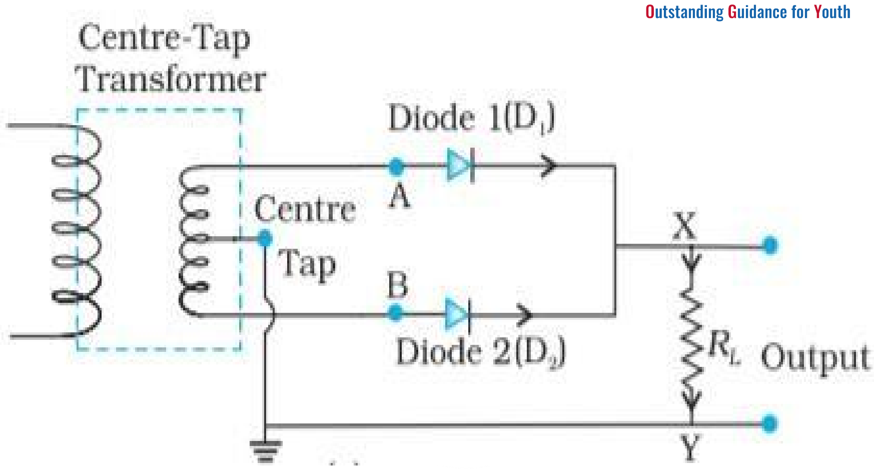


In the positive half-cycle of ac there is a current through the load resistor R_L and we get an output voltage, whereas there is no current in the negative half cycle. Since the rectified output of this circuit is only for half of the input ac wave it is called as half-wave rectifier.

Input ac voltage and output voltage waveforms from the rectifier circuit.

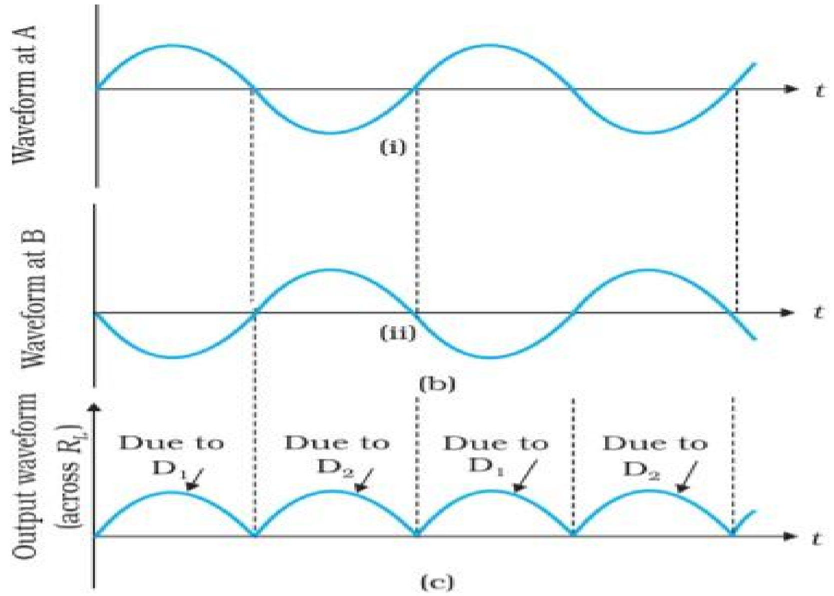


Full wave rectifier



- For a full-wave rectifier the secondary of the transformer is provided with a centre tapping and so it is called centre-tap transformer.
- During this positive half cycle, diode D_1 gets forward biased and conducts ,while D_2 being reverse biased is not conducting. Hence we get an output current and a output voltage across the load resistor R_L.
- During negative half cycle, diode D_1 would not conduct but diode D_2 conducts, giving an output current and output voltage across R_L in the same directionas in positive half.
- Thus, we get output voltage during both the positive as well as the negative half of the cycle. This is a more efficient circuit for getting rectified voltage or current than the halfwave rectifier.

Input ac voltage and output voltage waveforms from the rectifier circuit.



Filters

To get steady dc output from the pulsating voltage a capacitor is connected parallel to the output terminals.

The cicuits that filter out the ac ripple and give a pure dc voltage are called filters.