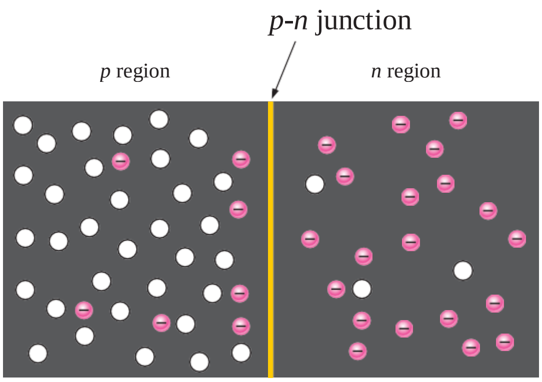
1–4 *P-N* Junction and Application

In the P type semiconductor there are a large no of majority charge carrier hole and small no of minority charge carrier electron. Similarly, in N type semiconductor there are a large no of majority charge carrier electron and a small no of minority charge carrier holes. But they are electronically neutral and such a piece of extrinsic material is not of practical use. A pure block of intrinsic semiconductor can be so doped by a special manufacturing process that one half of it becomes P type and the other part with becomes N type to produce P-N junction diode that are the building block of all electronic gadgets we use today.

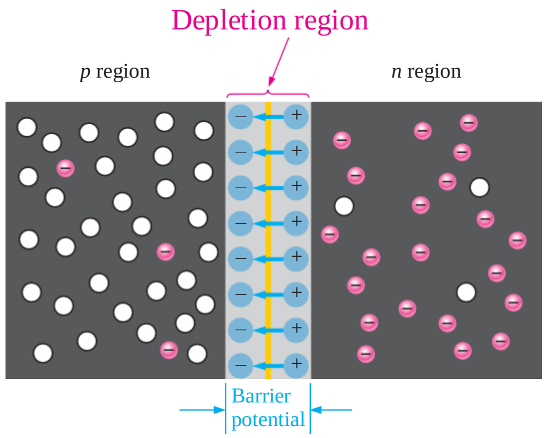
After completing this section, we should be able to

- **Describe how a *p-n* junction is formed**
  - Discuss diffusion across a *p-n* junction
  - Explain the formation of the depletion region
  - Define *barrier potential* and discuss its significance
- **Working principle of *p-n* junction under forward and reverse bias**
  - Half wave and Bridge rectifier

If a piece of intrinsic silicon is doped so that part is *n*-type and the other part is *p*-type, a ***p-n* junction** forms at the boundary between the two regions and a diode is created, as indicated in Figure 1–20(a). The *p* region has many holes (majority carriers) from the impurity atoms and only a few thermally generated free electrons (minority carriers). The *n* region has many free electrons (majority carriers) from the impurity atoms and only a few thermally generated holes (minority carriers).



(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *p-n* junction begin to defuse across the junction and fall into holes near the junction in the *p* region. Besides this, there are negatively charged **Acceptor** atom in P region and positively charged **Donor** atom in the N region.



(b) Every electron that defuses across the junction combines with a hole to make it neutral in the p region of the junction. As a result, there are only negatively charged **Acceptor** atom in the *p* region and positively charged **Donor** atom left in the *n* region at the vicinity of the junction that produce electric potential across it. This potential repels the charge carriers to defuse further. This part of the junction region consists of blue arrows showing in Figure 1-20(b), is called depletion region and the electric field produced across it is called barrier potential.

▲ **FIGURE 1–20**

Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

Formation of the depletion Region

Free electrons in the *n* region are randomly drifting in all directions. At the instant of the *p-n* junction formation, those electrons near the junction in the *n* region begin to diffuse across the junction into the *p* region where they combine with holes, as shown in Figure 1–20(b).

Electron defuses across the boundary of the *p* and *n* region and combines with a hole to make it neutral in the *p* region of the junction. So the *n* region loses some electrons and the *p* region loses some holes near the junction. As a result, a layer of *n* region at the vicinity of the interface contains only a no of positively charged pentavalent **donor** ions that creates positive potential. Similarly, the layer of *p* region near the junction consists of only a no of negatively charged trivalent **acceptor** ions producing negative positive potential. These two layers of positive and negative immovable ions form electric field across it, form **depletion region,** as shown in Figure 1–19(b). The term ***depletion*** refers to the fact that this region near the *p-n* junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. This electric field that opposes the diffusion of charge carriers further, is called barrier potential or potential barrier. Keep in mind that the depletion region is formed very quickly and is very thin (of the order of 10^{-6} m) compared to the *n* region and *p* region.

HISTORY NOTE

After invention of the electric light bulb, Edison continued to experiment and in 1883 found that he could detect electrons flowing through the vacuum from the lighted filament to a metal plate mounted inside the bulb. This discovery became known as the *Edison effect*.

An English physicist, John Fleming, took up where, Edison left off and found that the Edison effect could also, be used to detect radio waves and convert them to electrical signals. He went on to develop a two-element vacuum tube called the *Fleming valve*, later known as the *diode*. It was a device that allowed current in only one direction. Modern *p-n* junction devices are an outgrowth of this.

Barrier Potential

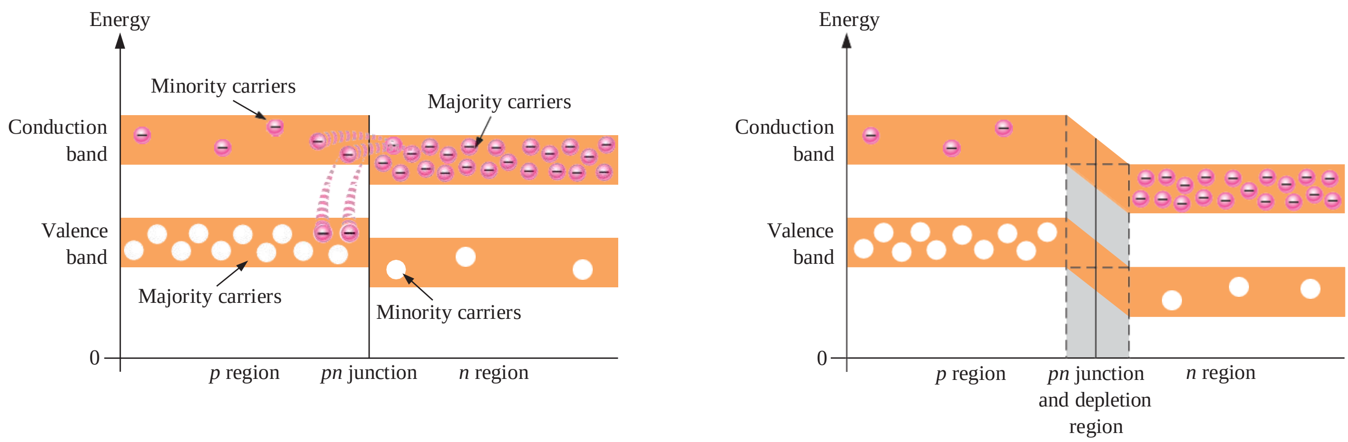
In the depletion region there are many positive ions in *n* region and many negative ions in *p* region of the *pn* junction. The forces between the opposite ions form an *electric field*, as illustrated in Figure 1–20(b) by the blue arrows. This electric field offers a barrier to the freely movable electrons in the *n* region defuse further. The potential difference across the depletion region is called the **barrier potential** and is expressed in volts.

Therefore, external electric potential across the depletion region equal to the barrier potential with the proper polarity must be applied to provide energy to the electrons to move across the barrier. But on the other hand, it is noticed that the internal electric field enables the minority carriers (electrons in *p* region and holes in *n* regions) to flow across the junction. Thus a very small drift current flows in the reverse direction.

The barrier potential of a *p-n* junction depends on several factors, including the type of semiconductive material, the amount of doping, and the temperature. The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 258C.

HISTORY NOTE

Russell Ohl, working at Bell Labs in 1940, stumbled on the semiconductor *pn* junction. Ohl was working with a silicon sample that had an accidental crack down its middle. He was using an ohmmeter to test the electrical resistance of the sample when he noted that when the sample was exposed to light, the current between the two sides of the crack made a significant jump. This discovery was fundamental to the work of the team that invented the transistor in 1947.



(a) At the instant of junction formation

(b) At equilibrium

▲ **FIGURE 1–21**

Energy diagrams illustrating the formation of the *pn* junction and depletion region.

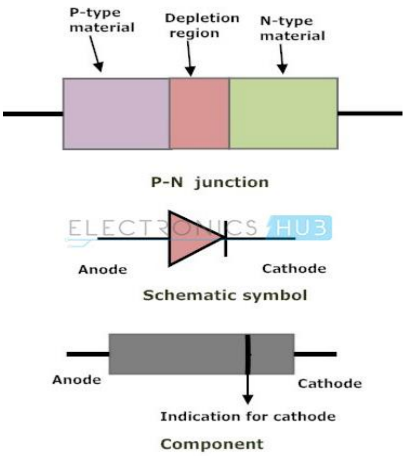
Energy diagrams of the *P-N* Junction and depletion Region

The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material. Recall that *p*-type material has trivalent impurities and *n*-type material has pentavalent impurities. The trivalent impurities exert lower forces on the outer-shell electrons than the pentavalent impurities. The lower forces in *p*-type materials mean that the electron orbits are slightly larger and hence, have greater energy than the electron orbits in the *n*-type materials.

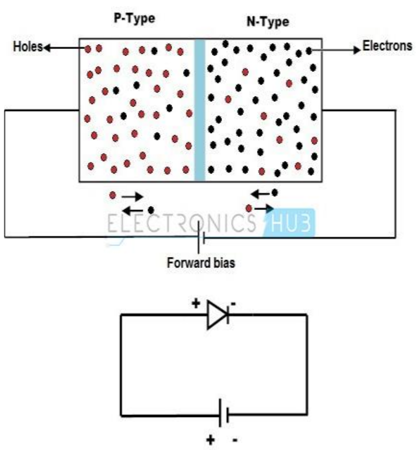
An energy diagram for a *p-n* junction at the instant of formation is shown in Figure 1–20(a). As we can see, the energy level of the valence and conduction bands in the *n* region are slightly, lower than those in the *p* region, but, there is a significant amount of overlapping.

The free electrons in the *n* region that occupy the upper part of the conduction band in terms of their energy can easily, diffuse across the junction (they do not have to gain additional energy) and temporarily, become free electrons in the lower part of the conduction band of *p*-region. After crossing the junction, the electrons quickly, lose some energy and fall into the holes in the valence band of the *p*-region as indicated in Figure 1–21(a).

At the time of formation of depletion region, the energy level of the conduction band of the *n*-region decreases due to the loss of the higher-energy electrons diffused across the junction. Soon, diffusion ceases as, there are no electrons left with enough energy to get across the boundary to the conduction band of the *p*-region, as indicated by the alignment of the top of the conduction band of *n*-region and the bottom of the *p*-region conduction band in Figure 1–20(b). At this point, the junction is at equilibrium; and the formation of depletion region is complete. There is an energy gradient across the depletion region, which acts as an "energy hill" that an *n*-region electron must climb to get to the *p* region.



▲ **FIGURE 1–22**
Symbol of P–N junction **Diode**



▲ **FIGURE 1–23**

Biasing of P-N Junction Diode

P-N junction semiconductor crystals is widely used in electronic devices and serve as a semiconductor counter part of vacuum tube diode which became obsolete after invention of it. So, it is also named P-N junction diode. It is basically a p-n with metallic contacts at its ends for the application of external potential difference. The symbolic representation of p-n junction diode is shown in figure 1-22. The p end and n are called **Anode** and **Cathode** respectively. The black ring at one end of a diode indicates the cathode. Now let us see, how it can be connected with the external potential on the basis of which it is of two types--

a) Forward bias and b) Reverse bias

Forward Bias

When the positive terminal and the negative terminal of an external potential source is connected with *p* and *n* region respectively this type of connection is called ***forward bias***. Hence, it is opposite to the internal field i.e barrier potential. In this connection, the net potential against the depletion layer will be reduced that produces negative potential against the junction as long as the external potential is less than the barrier potential. In this situation, the charge carriers do not have enough energy to get through the depletion layer.

Now, if the external potential increases so that, the net potential against the junction becomes positive, the depletion layer will be virtually abolished. In this situation, it is possible for the net positive potential to push the majority charge carriers i.e free electrons and the holes towards the interface and they cross the barrier.

After diffusion through the depletion layer, electrons recombine with the holes in the *p* region and reduce the concentration of the holes in the *p* region. At that time, same no of electrons enter the positive terminal of the external potential from the electron-hole pair of the covalent bond that produce hole to maintain the previous concentration of the hole in *p* region. Similarly, positive holes defuse the depletion layer to recombine with the electrons in the *n* region that reduce the concentration of the electrons. To compensate it, electrons enter the n region from the negative terminal of the external source. Thus a continuous current I flows in the conventional direction (from *p* to *n*) as shown in figure 1-23.

The drift current produced by the minority carriers, however, remain unchanged and small, because the rate of formation of electron-hole pair is independent of the electric field, unless it is very large.

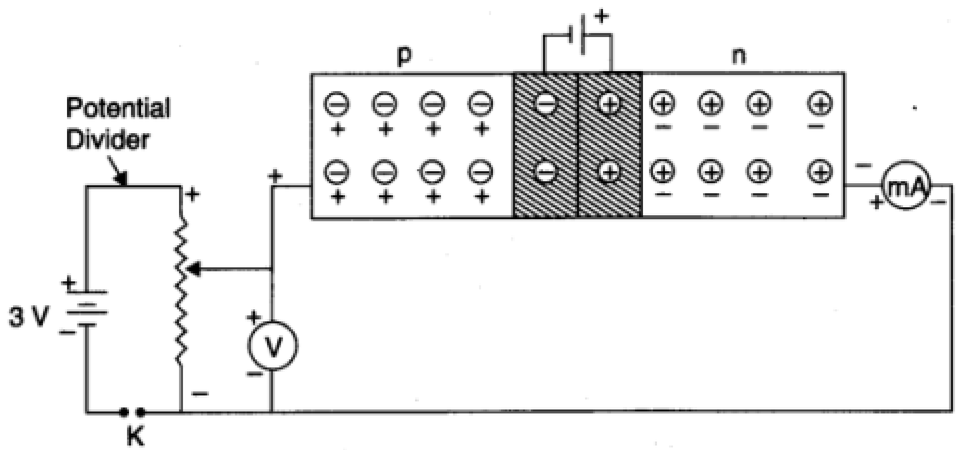


Fig. *p-n* **junction diode—forward biased.**

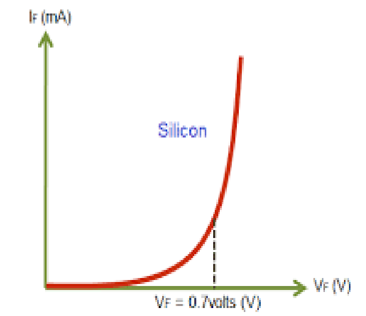


Fig: Forward characteristics of silicon diode

FIGURE 1-24

Forward Bias Characteristics

If the external potential increases from zero the net potential against depletion layer increases from negative net potential and no forward current will flow as shown in figure 1-24. But, when external positive potential exceeds (the barrier potential 0.3 V for Ge and 0.7 V for Si, 1.2V for GaAs), the barrier becomes virtually, abolished as net potential becomes zero. This potential is called knee potential or threshold or offset voltage.

After that, by supplying greater external voltage to produce positive net voltage, the electrons get enough energy to overcome the potential barrier (depletion layer) and cross the junction. The same thing happens with the holes as well. In this situation, the junction becomes forward biased and forward current increases with the increases of external potential. Then, the diode current flows rapidly with very small increase of voltage which follows nonlinear curve as shown in figure 1-24. This is forward characteristics of *p-n* diode. In this non-linear region the dynamic resistance can be defined as, $R_d = \frac{\Delta V}{\Delta I}$.

Reverse Bias

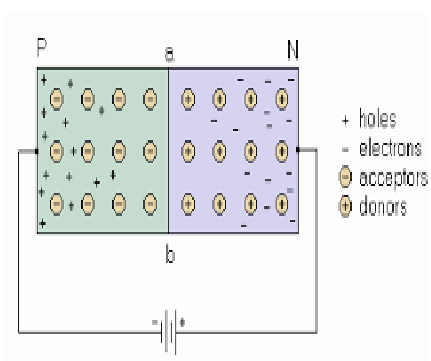


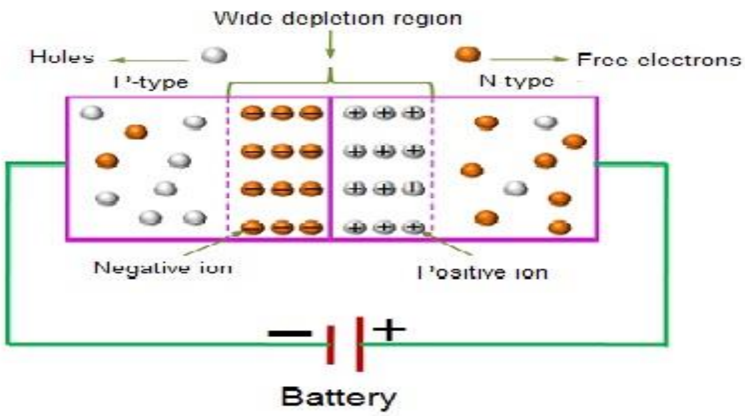
FIGURE-1-25
Reverse Bias

When the positive terminal and the negative terminal of an external potential source is connected with *n* and *p* region respectively, this type of connection is called ***reverse bias*** as shown in figure 1-25. In this situation, the net potential against the diode corresponds to the more negative potential. The width of the depletion layer will virtually be wider and the majority charge carriers (electron in *n* and hole in *p* region) do not have enough energy to get through the depletion layer.

The drift current carried by the minority carriers (electron in *p* and hole in *n* region) however, is not affected. Electrons in *p* and hole in *n* region can flow in the direction of the field from *n* to *p*. But, the number of minority carriers being very small, the drift current is very small (of the order of microampere) compared to current under forward bias.

Therefore, the conduction current is contributed by the majority charge carrier in forward bias but by the minority carrier in the reverse bias. The situation is entirely different in a conductor. In a conductor, only free electrons take part in electric current nor the holes. Therefore, the same current can flow in the opposite direction, when the voltage is reversed.

Therefore, it can be concluded that, *p-n* diode acts like a valve, which opens only in one direction. Current can flow through the *p-n* diode only in the direction from p to n under forward bias and practically, no current flows in opposite direction under reverse bias condition.



Reverse Bias characteristics

The direction of reverse bias potential and barrier potential are same and along *n* side to *p* side. Therefore, if the bias potential increases from zero, the net potential against the junction increases. The layer becomes, virtually, wider that opposes the flow of majority charge carriers. In this situation, very feeble current of the order of μA flows due to the flow of minority charge carriers (electrons in *p* and holes in *n* region) in the reverse direction as shown in figure 1-26. This current remains constant with the increase of reverse voltage. This current is called **reverse saturation current**.

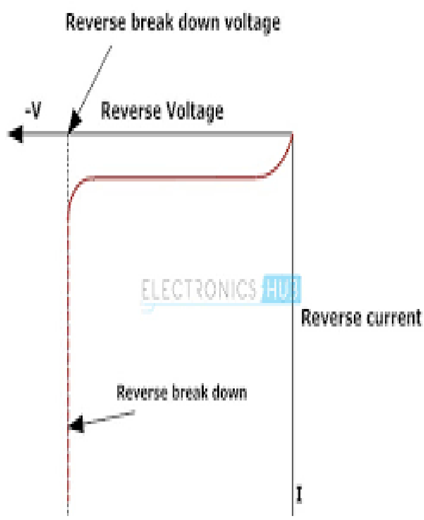


FIGURE-1-26
Reverse Bias Characteristic

As the reverse bias potential increases, the majority carrier, electrons of the *n* region and holes of *p* region, are attracted respectively, towards positive terminal and negative terminal of the external potential. Therefore, majority carrier start accumulating at the opposite ends of the diode, as a result, the deletion width at the surface of separation becomes extended to a large extent. In this situation, both electrons and holes are bound together with Coulomb attraction.

But, a large no of electron-hole pair will be produced when a certain large reverse voltage is applied. Huge no of electrons will be released through the *n* side end due to the large attraction by the positive terminal. Similarly, same no of electrons will enter the *p* region from the negative terminal and recombine with the hole that results huge reverse current. It seems that electron flows from *p* to *n* region that results abruptly high current along reverse direction. This phenomenon is called ***Reverse Break down*** (Avalanche and Zener break down) held at ***breakdown voltage*** and in this situation, diode gets destroyed.

Diode as rectifier

Rectification means conversion of alternating voltage (or current) to direct voltage. An *n-p* diode can be used as a rectifier. There are two types of Rectifier----a) Half wave rectifier, and b) Full wave rectifier

Half wave rectifier

From the previous explanation, it is clear that diode operates in forward bias and it remains inoperative in reverse bias condition. The necessary circuit diagram of half wave rectifier is given below in figure-1-27(b).

The alternating voltage to be rectified is applied across the primary of a suitable transformer and the secondary of the transformer is connected to the *p-n* junction diode D through a load resistance R_L. The output is obtained across R_L with alternative interruption.

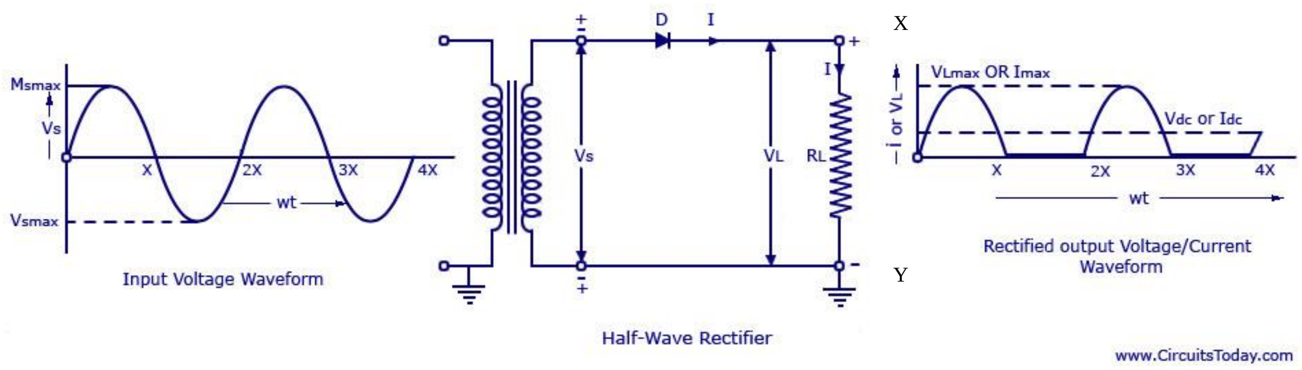


FIGURE-1-27(a)
Input Waveform

FIGURE-1-27(b)
Circuit Diagram of Halfwave Rectifier

FIGURE-1-27(c)
Output Waveform

Explanation

The transformer converts the alternating voltage of the source to the required voltage in the secondary. The secondary provides alternating potential to the diode D. The wave form of the input is represented by the figure 1-27(a). Therefore, the diode D gets positive and negative potential alternatively. During positive half cycle, the diode is forward biased and conducts electricity. This current flows through the load resistance R_L from top to bottom and returns back to the secondary winding of the transformer. But during negative half cycle, being reverse biased the diode don't conduct current. So, one directional interrupted output current flows through the load R_L from X to Y only, during alternate half-cycle. The output wave form is shown in figure 1-27(c).

The dc value of the output is the same as the average value which is

$V_{dc} = \frac{V_0}{\pi} = 0.318V_0$, where V_0 =peak value of the input voltage. Thus the average dc value of the output is 31.85 of peak value.

Full wave rectifier

If we like to get a rectified voltage during both the half cycles of an input AC voltage, we require a full wave rectifier in which output power is receive uninterruptedly against load resistance R_L. This type of rectifier is called full wave rectifier. It is of two types—

i) Center tapped full wave rectifier
ii) Full wave Bridge rectifier

Center tapped full wave rectifier

The alternative voltage source is connected at the input primary of a transformer and the secondary is connected with two *p-n* junction diodes D_1 and D_2 as shown in figure 1-28. Then, the center tapped point and the common point of the two diodes are joined with a load resistance against which unidirectional uninterrupted output voltage can be received as shown in figure 1-28.

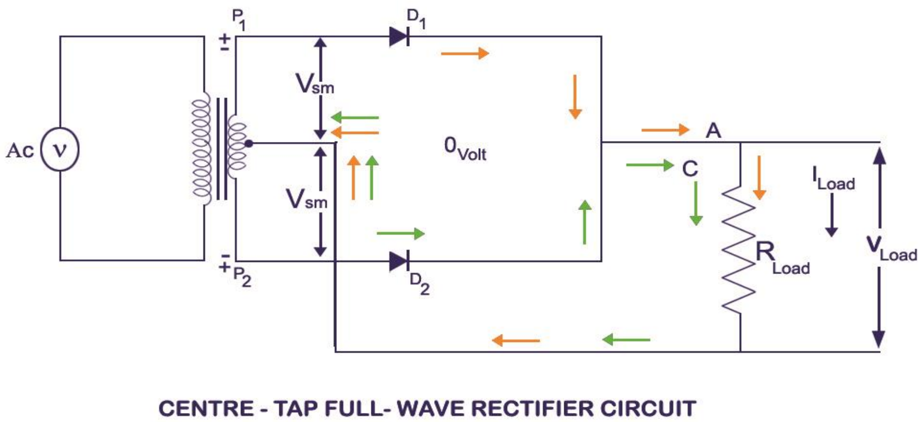


FIGURE 1-28

Explanation

The alternating voltage at P_1 and P_2 with respect to the central tap point are out of phase (phase difference = π) with each other. Therefore, during positive half-cycle, diode D_1 is forward biased and conducts current through load resistance R_{Load} from top to bottom indicated by orange arrow in the figure 1-28 while the other diode D_2 is inoperative having been reverse biased.

Similarly, during negative half cycle, diode D_2 is forward biased and conducts current through the load resistance R_{Load} along same direction indicated by green arrow while the other diode D_1 is inoperative having been reverse biased.

Therefore, D_1 and D_2 operate alternatively and so, a unidirectional uninterrupted current can be achieved against the load for both the cycles of the input voltage. The output wave form is shown in figure 1-29.

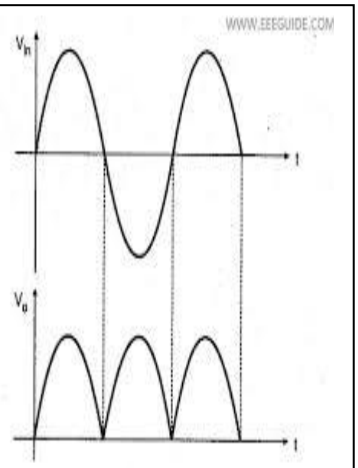


FIGURE 1-29

Full wave Bridge rectifier

In this type of full wave rectifier, four diodes are necessary and connected in a bridge. The transformer need not be center tapped at the secondary. So, the peak value of the input ac voltage at the secondary of the transformer is fed to the input MN of the bridge rectifier containing diodes D_1, D_2, D_3 and D4 as shown in figure 1-30(a).

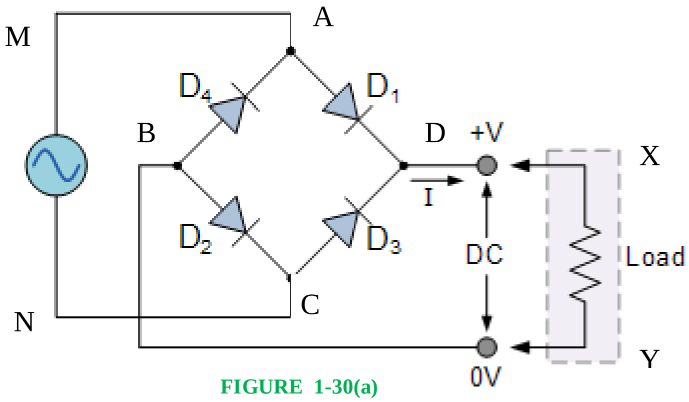


FIGURE 1-30(a)
Full wave Bridge rectifier

During positive input half cycle, M is positive and N is negative. Hence, D_1 and D_3 become forward biased and start conducting. But, D_2 and D_4 having been reverse biased, become inoperative. Hence, current flows along the path MADXYBCN. Similarly, during negative input half cycle, N is positive and M is negative. Hence, D_2 and D_4 become forward biased and start conducting. But, D_1 and D_3 having been reverse biased, become inoperative. Hence, current flows along the path NCDXYBAM.

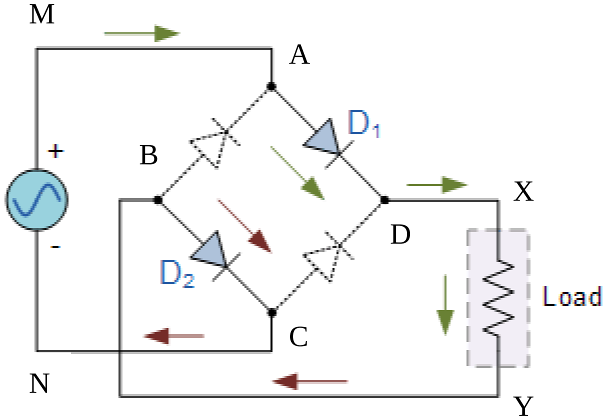


FIGURE 1-30(b)
Full wave Bridge rectifier in
Positive half cycle

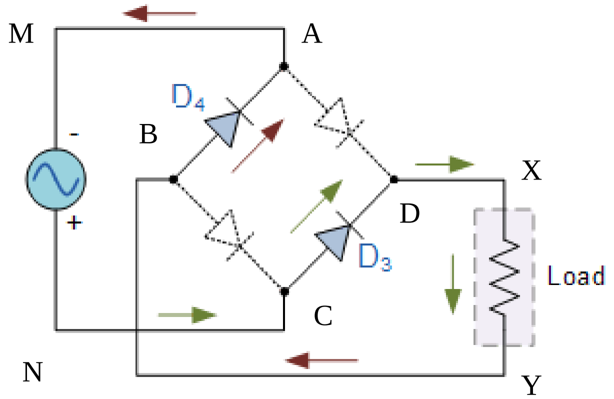
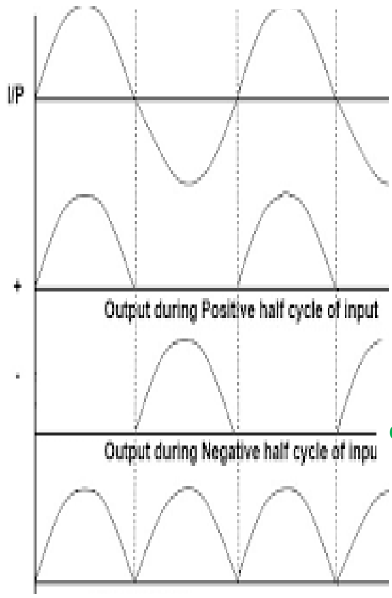


FIGURE 1-30(c)
Full wave Bridge rectifier in
negative half cycle

Input Waveform



Output waveform for full cycle

FIGURE 1-31

Therefore, current flows through the load from X to Y during both cycle of the input voltage and unidirectional uninterrupted output voltage can be received at the output. The output wave form corresponding to the input potential is shown in figure 1-31.

Check up

1. What is a *p-n* junction?
2. Explain diffusion.
3. Describe the depletion region.
4. Explain what the barrier potential is and how it is created.
5. What is the typical value of the barrier potential for a silicon diode?

Difference between Center tapped and Bridge rectifier

	Center Tapped Rectifier	Bridge Rectifier
Description	Center tapped rectifier as the name suggest is requires a center tapped transformer (secondary winding).	No center tapped transformer is required in bridged rectifier.
Peak Inverse Voltage	The peak inverse voltage (PIV) of diode in center tapped full wave rectifier is twice the transformer secondary terminal voltage.	Peak inverse voltage PIV of diode is equal to the transformer secondary voltage. Thus this type of rectifier can be used for high voltage application.
Number Of Diodes	Center tapped rectifier uses only two diodes in its circuit.	Bridge rectifier uses four diodes in its circuit. This result to increment in the circuit complexity in case of the bridge rectifier.
Transformer Utilization Factor (TUF)	The transformer utilization factor (TUF) is equal to 0.672	The transformer utilization factor (TUF) is equal to 0.810 for bridge rectifier.
Voltage Drop Across	Voltage drop across the two diodes of center tapped rectifier is less when compared to bridge rectifier.	The voltage drop across the 4 diodes of bridge rectifier is more than the voltage drop across center tapped rectifier.
Size Of Transformer (kVA rating)	The transformer required in center tapped rectifier is bigger.	The transformer required in bridge rectifier is smaller than that required in center tapped rectifier in terms of kVA rating.
Economic Efficiency	Center tapped transformer is economically efficient since it uses only two diodes in its circuit.	Bridge rectifier is economically inefficient since it uses four diodes in its circuit.