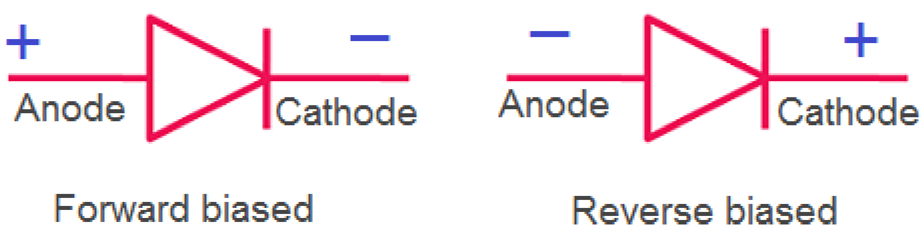
P-N junction semiconductor diode

What is p-n junction semiconductor diode?

A p-n junction diode is two-terminal device, which allows the electric current in only one direction while blocks the electric current in opposite or reverse direction. If the diode is forward biased, it allows the electric current flow. On the other hand, if the diode is reverse biased, it blocks the electric current flow. P-N junction semiconductor diode is also called as p-n junction semiconductor device. When the n-type semiconductor is joined with the p-type semiconductor, a p-n junction is formed. The p-n junction, which is formed when the p-type and n-type semiconductors are joined, is called as p-n junction diode.

- The p-n junction diode is made from the semiconductor materials such as silicon (Si), germanium (Ge), and gallium arsenide (GaAs).

The basic symbol of p-n junction diode under forward bias and reverse bias is shown in the below figure:



In the above figure, arrowhead of a diode indicates the conventional direction of electric current when the diode is forward biased (from positive terminal to the negative terminal). The holes which move from positive terminal (anode) to the negative terminal (cathode) is the conventional direction of current.

The free electrons moving from negative terminal (cathode) to the positive terminal (anode) actually carry the electric current. However, due to the convention we have to assume that the current direction is from positive terminal to the negative terminal.

- Conventionally, the direction of current is defined as the direction of flow of positive charges but the current carriers are electrons which are negatively charged. So, the real current is in a direction opposite to the conventional current.

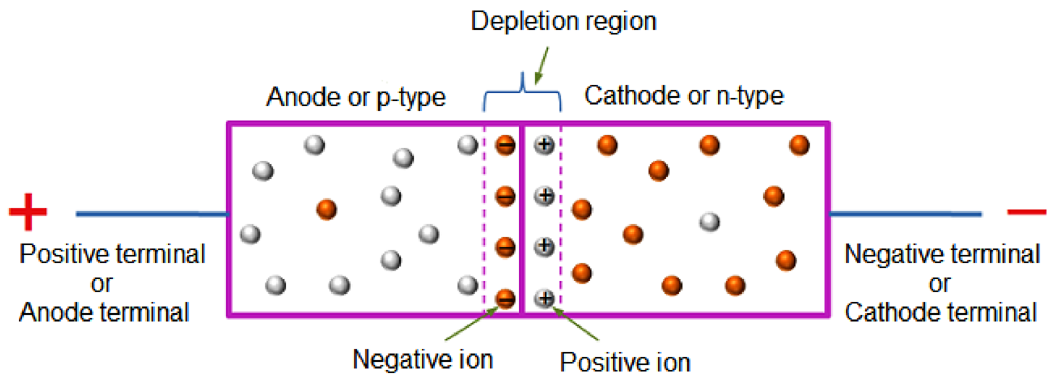
Biasing of p-n junction semiconductor diode

The process of applying the external voltage to a p-n junction semiconductor diode is called biasing. External voltage to the p-n junction diode is applied in any of the two methods: forward biasing or reverse biasing.

If the p-n junction diode is forward biased, it allows the electric current flow. Under forward biased condition, the p-type semiconductor is connected to the positive terminal of battery whereas; the n-type semiconductor is connected to the negative terminal of battery.

If the p-n junction diode is reverse biased, it blocks the electric current flow. Under reverse biased condition, the p-type semiconductor is connected to the negative terminal of battery whereas; the n-type semiconductor is connected to the positive terminal of battery.

- In forward biased p-n junction diode (p-type connected to positive terminal and n-type connected to negative terminal), anode terminal is a positive terminal whereas cathode terminal is negative terminal. Anode terminal is a positively charged electrode, which supplies holes to the p-n junction. Cathode is the negatively charged electrode or conductor, which supplies free electrons to the p-n junction.

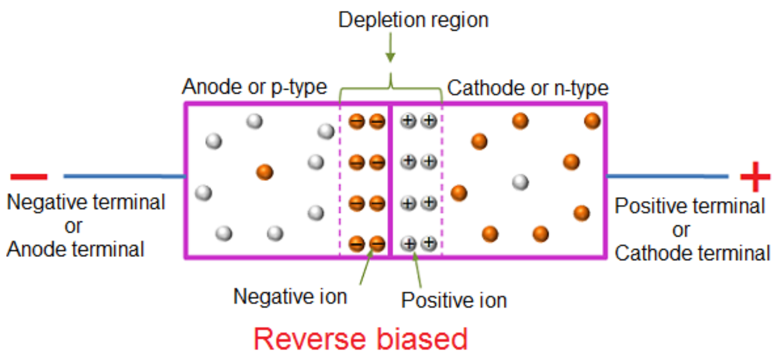


Forward biased

The positive terminal repels the holes of the p-type region and the negative terminal repels the free electrons of the n-type region. Due to this a pressure acts on the junction which causes the junction to shrink. As a result, the depletion region narrows down. It can cause the flow of current in the forward direction as soon as the forward bias voltage is above the specified voltage (for Si the voltage is 0.7volts and for Ge the voltage is 0.3volts).

Terminals of diode under reverse bias

- If the diode is reverse biased (p-type connected to negative terminal and n-type connected to positive terminal), the anode terminal becomes a negative terminal whereas the cathode terminal becomes a positive terminal.



If the external reverse voltage applied on the p-n junction diode is increased, the free electrons from the n-type semiconductor and the holes from the p-type semiconductor are moved away from the p-n junction. This increases the width of depletion region. on the other words, the negative terminal attracts the holes of p-type region and the positive terminal attracts the free electrons of n-type region. This causes the p-n junction to get wider and increases the depletion layer. Thus the flow of free electrons from n-type to p-type and the flow of holes from p-type to n-type are hampered which means flow of current is also restricted in reverse bias region.

Silicon and germanium semiconductor diodes

- For designing the diodes, silicon is more preferred over germanium.
- The p-n junction diodes made from silicon semiconductors works at high temperature than the germanium semiconductor diodes.
- Forward bias voltage for silicon semiconductor diode is approximately 0.7 volts whereas for germanium semiconductor diode is approximately 0.3 volts.
- Silicon semiconductor diodes do not allow the electric current flow, if the voltage applied on the silicon diode is less than 0.7 volts.
- Silicon semiconductor diodes start allowing the current flow, if the voltage applied on the diode reaches 0.7 volts.
- Germanium semiconductor diodes do not allow the electric current flow, if the voltage applied on the germanium diode is less than 0.3 volts.
- Germanium semiconductor diodes start allowing the current flow, if the voltage applied on the germanium diode reaches 0.3 volts.
- The cost of silicon semiconductors is low when compared with the germanium semiconductors.

Advantages of p-n junction diode

P-n junction diode is the simplest form of all the semiconductor devices. However, diodes plays a major role in many electronic devices.

- A p-n junction diode can be used to convert the alternating current (AC) to the direct current (DC). These diodes are used in power supply devices.

- If the diode is forward biased, it allows the current flow. On the other hand, if it is reverse biased, it blocks the current flow. In other words, the p-n junction diode becomes on when it is forward biased whereas the p-n junction diode becomes off when it is reversed biased (I.e. it acts as switch). Thus, the p-n junction diode is used as electronic switch in digital logic circuits.

V-I CHARACTERSTICS OF P-N JUNCTION DIODE:

Forward V-I characteristics of p-n junction diode

If the positive terminal of the battery is connected to the p-type semiconductor and the negative terminal of the battery is connected to the n-type semiconductor, the diode is said to be in forward bias. In forward biased p-n junction diode, V_F represents the forward voltage whereas I_F represents the forward current.

- **Forward V-I characteristics of silicon diode**

If the external voltage applied on the silicon diode is less than 0.7 volts, the silicon diode allows only a small electric current. However, this small electric current is considered as negligible. When the external voltage applied on the silicon diode reaches 0.7 volts, the p-n junction diode starts allowing large electric current through it. At this point, a small increase in voltage increases the electric current rapidly. The forward voltage at which the silicon diode starts allowing large electric current is called cut-in voltage. The cut-in voltage for silicon diode is approximately 0.7 volts.

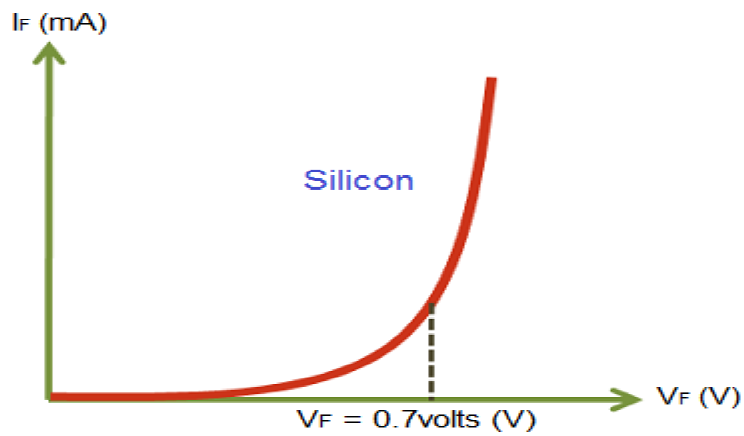


Fig: Forward characteristics of silicon diode

If the external voltage applied on the germanium diode is less than 0.3 volts, the germanium diode allows only a small electric current. However, this small electric current is considered as negligible. When the external voltage applied on the germanium diode reaches 0.3 volts, the germanium diode starts allowing large electric current through it. At this point, a small increase in voltage increases the electric current rapidly. The forward voltage at which the germanium diode starts allowing large electric current is called cut-in voltage. The cut-in voltage for germanium diode is approximately 0.3 volts.

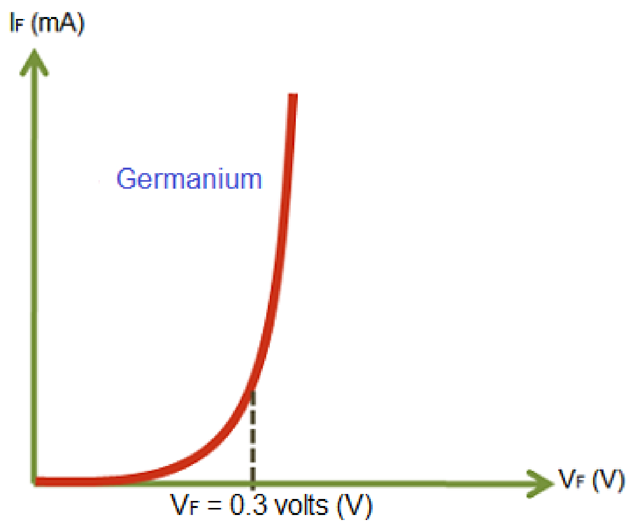


Fig: Forward characteristics of germanium diode

- **Reverse V-I characteristics of p-n junction diode**

If the negative terminal of the battery is connected to the p-type semiconductor and the positive terminal of the battery is connected to the n-type semiconductor, the diode is said to be in reverse bias. In reverse biased p-n junction diode, V_R represents the reverse voltage whereas I_R represents the reverse current.

The wide depletion region of reverse biased p-n junction diode completely blocks the majority charge carrier current. However, it allows the minority charge carrier current. The free electrons (minority carriers) in the p-type semiconductor and the holes (minority carriers) in the n-type semiconductor carry the electric current. The electric current, which is carried by the minority charge carriers in the p-n junction diode, is called reverse current.

In n-type and p-type semiconductors, very small number of minority charge carriers is present. Hence, a small voltage applied on the diode pushes all the minority carriers towards the junction. Thus, further increase in the external voltage does not increase the electric current. The voltage or point at which the electric current reaches its maximum level and further increase in voltage does not increase the electric current is called reverse saturation current.

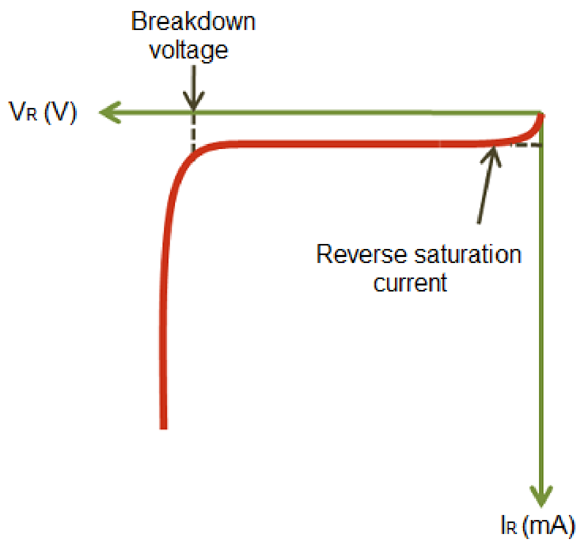


Fig: Reverse characteristics of diode

The reverse saturation current is depends on the temperature. If temperature increases the generation of minority charge carriers increases. Hence, the reverse current increases with the increase in temperature. However, the reverse saturation current is independent of the external reverse voltage. Hence, the reverse saturation current remains constant with the increase in voltage. However, if the voltage applied on the diode is increased continuously, the p-n junction diode reaches to a state where junction breakdown occurs and reverse current increases rapidly.

In germanium diodes, a small increase in temperature generates large number of minority charge carriers. The number of minority charge carriers generated in the germanium diodes is greater than the silicon diodes. Hence, the reverse saturation current in the germanium diodes is greater than the silicon diodes.

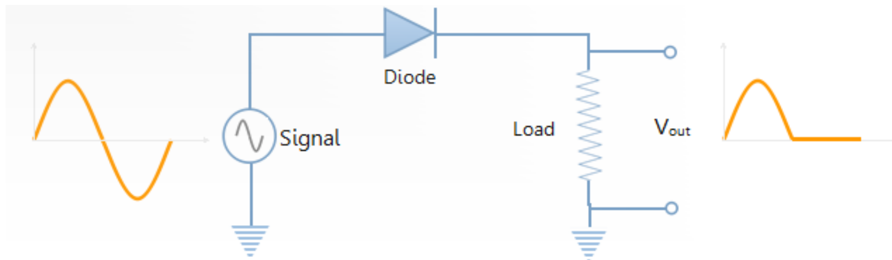
- **JUNCTION BREAKDOWN**-- When the voltage applied across the reversed biased diode is increased, a point comes where the current increases rapidly. This is called junction breakdown.
- **BREAKDOWN VOLTAGE**-- The reverse voltage at which current increases abruptly is known as breakdown voltage.

RECTIFIER: Rectifier is an electronic device which converts the alternating current to unidirectional current, in other words rectifier converts the AC voltage to DC voltage.

TYPES: 1) HALF WAVE RECTIFIER. &

2) FULL WAVE RECTIFIER.

HALF WAVE RECTIFIER:

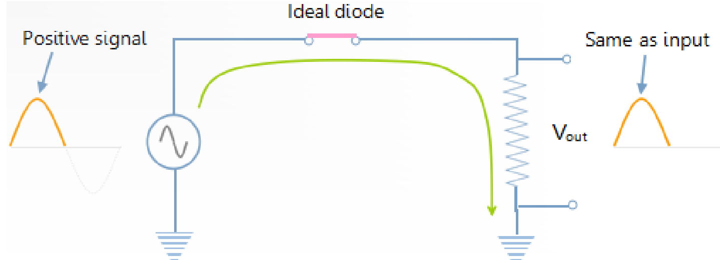


Half wave rectifier

The circuit of half wave rectifier only consists of a diode and a load resistor. The voltage is measured across the load resistor. To understand the working of half wave rectifier, we analyse the circuit in two parts.

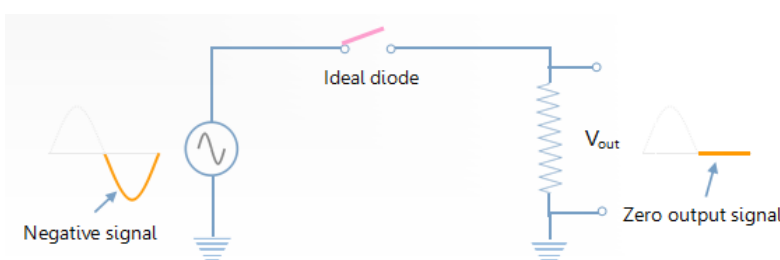
1. First we analyse the circuit for the positive values of input.
2. We analyse the circuit when the input voltage goes negative

When the input signal is positive, the anode of the diode is at a higher potential than the cathode. This makes the diode forward biased. We know from the discussion on diode biasing that a forward biased diode acts as closed switch. Thus a forward biased diode allows the current to pass through. As the diode allows the current to pass through, this current flows through the load resistor and constitutes output voltage. This is shown graphically in the figure below:



Half wave rectifier
Diode (ideal) acts as a closed switch for positive half cycle

Now as soon as the input voltage goes negative, the anode of the diode is at lower potential than the cathode. This makes the diode reverse biased. A reverse biased diode acts as an open switch. Hence the current stops flowing in the circuit. As there is no current flowing through the diode and load resistor, the output voltage becomes zero. This is shown in the figure below:



Half wave rectifier
Diode (ideal) acts as an open switch for negative half cycle

Thus the output of half wave rectifier is a pulsating DC.

FULL WAVE RECTIFIERS: Rectifiers that rectify both the positive as well as negative pulses of the input waveform, then they are called Full-Wave Rectifiers.
2 TYPES

1) Center Tapped Full Wave Rectifier.

2) Full wave bridge rectifier.

Center Tapped Full Wave Rectifier:

Figure 1 shows such a rectifier designed using a multiple winding transformer whose secondary winding is equally divided into two parts with a provision for the connection at its central point (and thus referred to as the centre-tapped transformer), two diodes (D_1 and D_2) and a load resistor (R_L).

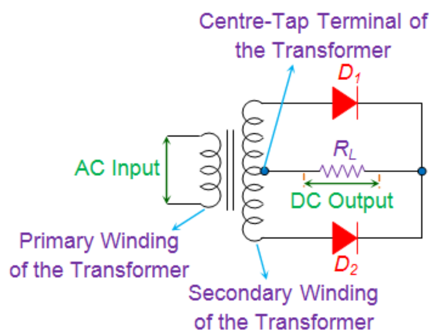


Figure 1 Full Wave Rectifier

Figure 2a shows the case where the AC pulse is positive in nature i.e. the polarity at the top of the primary winding is positive while its bottom will be negative in polarity. This causes the top part of the secondary winding to acquire a positive charge while the common centre-tap terminal of the transformer will become negative.

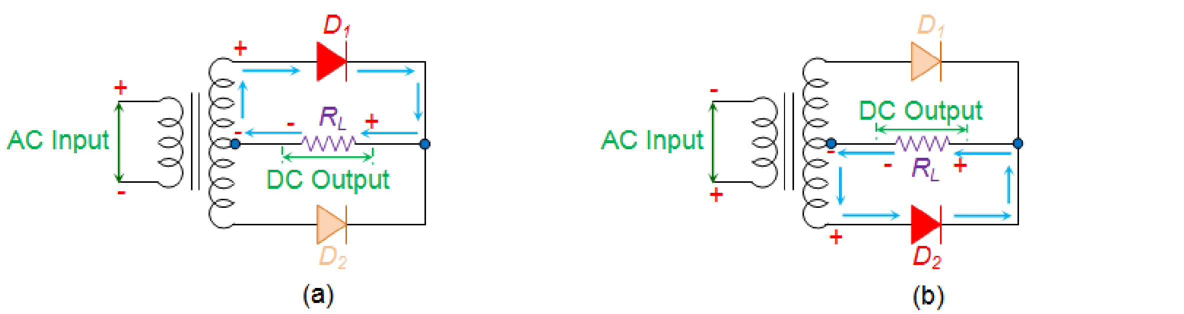


Figure 2 Conduction Path of Full Wave Rectifier for (a) Positive Input Pulse (b) Negative Input Pulse

This causes the diode D_1 to be forward biased which inturn causes the flow of current through R_L along the direction shown in Figure 2a. However at the same time, diode D_2 will be reverse biased and hence acts like an open circuit. This causes the appearance of positive pulse across the R_L, which will be the DC output. Next, if the input pulse becomes negative in nature, then the top and the bottom of the primary winding will acquire the negative and the positive polarities respectively. This causes the bottom of the secondary winding to become positive while its centre-tapped terminal will become negative. Thus the diode D_2 gets forward biased while the D_1 will get reverse biased which allows the flow of current as shown in the Figure 2b. Here the most important thing to note is the fact that the direction in which the current flows via R_L will be identical in either case (both for positive as well as for negative input pulses). Thus we get the positive output pulse even for the case of negative input pulse (Figure 3), which indicates that both the half cycles of the input AC are rectified.

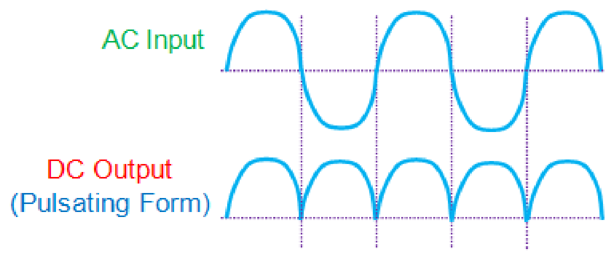


Figure 3 input & output waveshape

FULL WAVE BRIDGE RECTIFIER: Figure 1 shows such a bridge rectifier composed of four diodes D_1, D_2, D_3 and D_4 in which the input is supplied across two terminals A and B in the figure while the output is collected across the load resistor R_L connected between the terminals C and D.

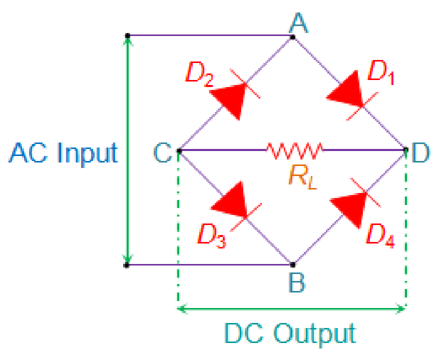


Figure 1 Bridge Rectifier

Now consider the case wherein the positive pulse appears at the AC input i.e. the terminal A is positive while the terminal B is negative. This causes the diodes D_1 and D_3 to get forward biased and at the same time, the diodes D_2 and D_4 will be reverse biased. As a result, the current flows along the short-circuited path created by the diodes D_1 and D_3 (considering the diodes to be ideal), as shown by Figure 2a. Thus the voltage developed across the load resistor R_L will be positive towards the end connected to terminal D and negative at the end connected to the terminal C.

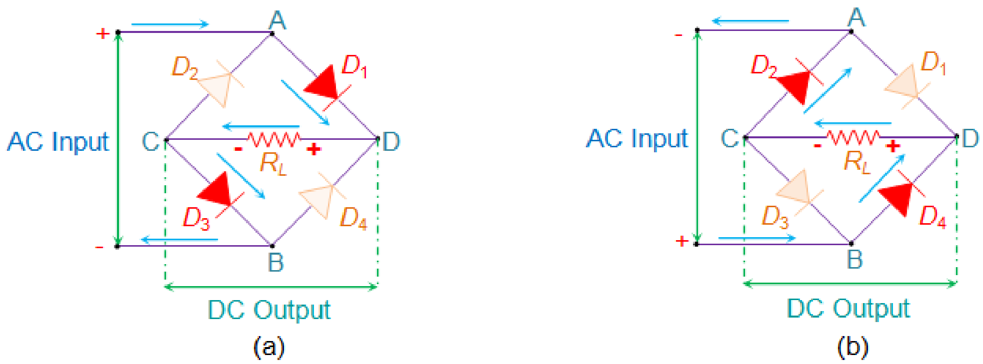


Figure 2 Current Path Through the Bridge Rectifier for (a) Positive half-cycle (b) Negative Half-Cycle

Next if the negative pulse appears at the AC input, then the terminals A and B are negative and positive respectively. This forward biases the diodes D_2 and D_4, while reverse biasing D_1 and D_3 which causes the current to flow in the direction shown by Figure 2b. At this instant, one has to note that the polarity of the voltage developed across R_L is identical to that produced when the incoming AC pulse was positive in nature. This means that for both positive and negative pulse, the output of the bridge rectifier will be identical in polarity as shown by the wave forms in Figure 3.

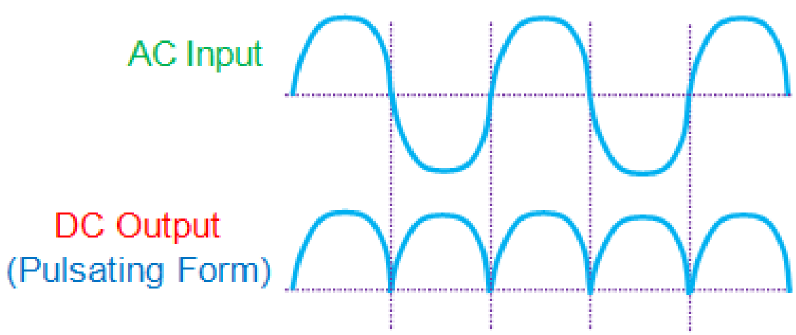


Figure 3 Input-Output Waveforms of a Bridge Rectifier

A p-type semiconductor material in contact with an n-type semiconductor material forms a p-n junction in which a depletion region occurs around the plane of contact. The width of this depletion region is seen to vary depending on the bias applied at the terminals of the p-n junction i.e. an increase in the applied voltage reduces the width of the depletion region in case of forward bias, while it increases the depletion region width for the case of reverse bias. Further the span of the depletion region is found to be more for a lightly doped material when compared to that of a heavily doped material. Figure 1 shows the I-V characteristics of such a p-n junction both for the case of forward- as well as reverse-bias. From the figure, it is clear that the current through the semiconductor rises with an increase in the magnitude of the applied voltage when the p-n junction is forward biased. Further it is seen that there will be a certain amount of minimum current flowing through the p-n junction under the reverse bias condition. This current is referred to as the reverse saturation current (I_S) and is due to the minority charge carriers in the semiconductor device.

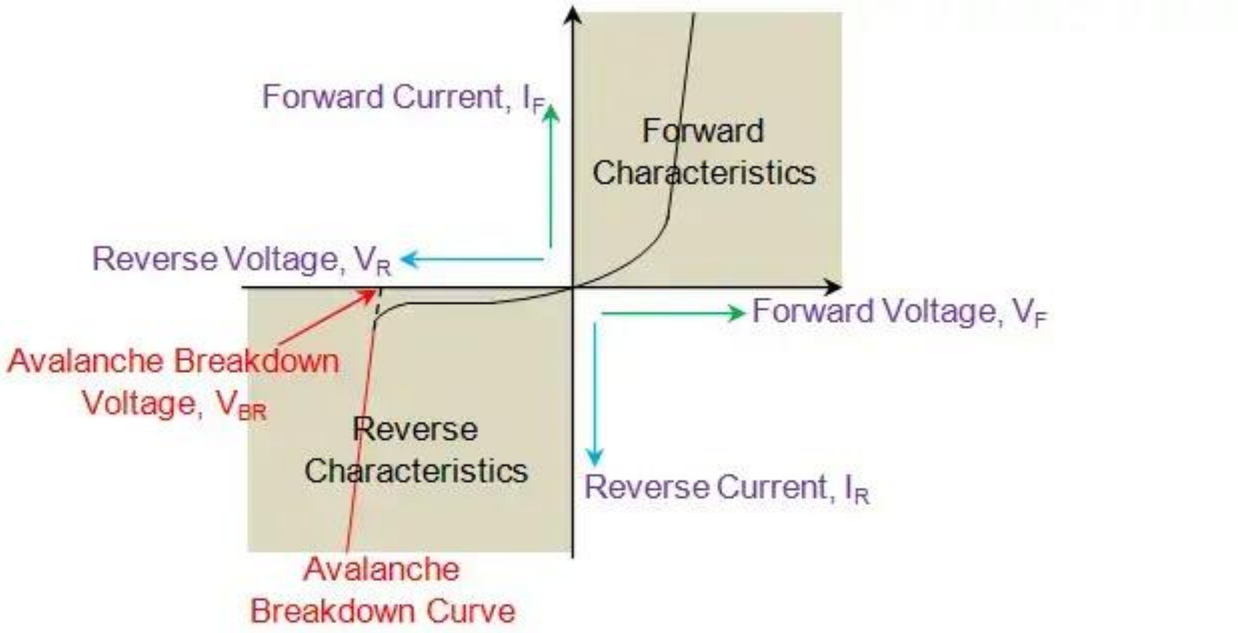


Figure 1 I-V Curve for a P-N Junction Depicting Avalanche Breakdown Phenomenon

Moreover I_S is observed to be almost independent of the applied voltage at its initial stage. However after reaching a particular point, the junction breaks-down leading to the heavy flow of reverse current through the device. This is because, as the magnitude of the reverse voltage increases, the kinetic energy of the minority charge carriers also increase. These fast moving electrons collide with the other atoms in the device to knock-off some more electrons from them.

The electrons so released further release much more electrons from the atoms by breaking the covalent bonds. This process is termed as carrier multiplication and leads to a considerable increase in the flow of current through the p-n junction. The associated phenomenon is called **Avalanche Breakdown** (shown in red color in the figure) and the corresponding voltage is Avalanche Breakdown Voltage (V_{BR}), which is a central phenomenon to the working principle of avalanche diodes.

Avalanche breakdown occurs in lightly doped p-n junctions when the reverse voltage increases beyond 5 V. Further, it is difficult to control this phenomenon as the number of charge carriers generated cannot be directly controlled. Moreover the Avalanche breakdown voltage has positive temperature coefficient meaning which the **Avalanche breakdown** voltage increases with the increase in the junction temperature.

Diode equation:

The general equation linking the diode current, I_D with the applied voltage V_D is:

$$I_D = I_s e^{\frac{V_D}{\eta V_T}} - 1$$

Where, I_S = Saturation Current

VT = Thermal Voltage = kT/q ≈ 25mV @ 20°C

≈ 26mV @ 25°C

k = Boltzmann's Constant (1.38 x 10-23 J / K)

T = Absolute Temperature (K)

q = Charge of an Electron (1.6 x 10^{-19} C)

Ideality Factor ((n)):
The ideality factor indicates how closely the diode behaves compared to an ideal diode. For an ideal diode, (n) is 1. As the deviation from ideal behavior increases, (n) also increases. Typical values are 1 for germanium diodes and 2 for silicon diodes, but it can vary based on factors like doping level, manufacturing technique, and material purity.

Approximate Form $I_D \approx I_S\ e\ V_D / nV_T$

Problem 1: A Si diode has diode saturation current 10 nA at 25°C. Determine diode current for a forward bias voltage of 0.6 V.

Sol: I_S= 10X 10^{-9} A, T= 25 °C= 25+273=298K, V_D= 0.6 V, k= 1.38 x 10-23 J / K, q= 1.6 x 10^{-19} C

$\eta = 2$

$$I_D = I_s e^{\frac{V_D}{\eta V_T}} - 1$$

$T = 298K$

⇨ $I_D = 10X\ 10^{-9} X e^{\frac{0.6}{2*\frac{kT}{q}}} - 1 = 1.17\ mA$

Problem 2: A Ge diode is used in a rectifier circuit and is operating at 25°C with a reverse saturation current of 1000 uA. Calculate the value of forward current if it is forward biased by 0.22 V.

I_s 1000×10^{-6} A

$= 10^{-3}$ A

$\eta = 1$

V_D