Chapter 5

Semiconductor Devices

We have discussed in the previous chapter that a p-n junction diode conducts only when it is forward biased and does not conduct when reverse biased. Thus current flow takes place in one direction only. This unidirectional property of diode is used in several applications such as rectifiers, clipping circuits, clamping circuits, etc.

5.1 Rectifiers

Rectifiers are used for converting AC into DC. The *unidirectional property* of a diode enables it to be used as a rectifier. It may be broadly categorized as the following two types.

1) Half wave rectifier and 2) Full wave rectifier

5.1.1 Half Wave Rectifier

Half wave rectifier is a circuit with a single diode that conducts only in one half cycle of the input ac cycle.

The circuit diagram of a half wave rectifier is shown in Figure 5.1. A transformer is used at the input side to step down the voltage. In the circuit, the secondary of transformer is connected to a single diode in series with a load resistance (R_L).

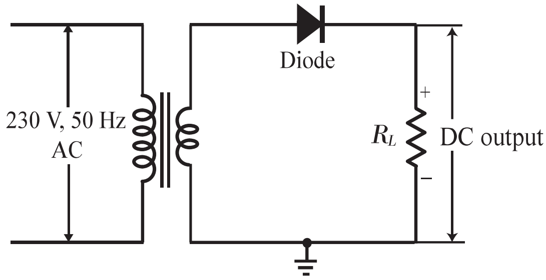

Figure 5.1: Half wave rectifier circuit

During the positive half cycle of the ac input voltage, the diode is forward biased (since upper side of the transformer secondary is positive with respect to lower end). Hence the diode conducts so that a current i flows through the load resistor and a voltage ($i \times R_L$) is developed across it. So, we get an output voltage during the positive half cycle. (When diode conducts, it produces a very small voltage drop across it; 0.3 V for Ge and 0.7 V for Si and hence the voltage across the load is practically same as the input voltage).

During the negative half cycle, the polarity of voltage on the secondary transformer is reversed. Therefore the diode is reverse biased and it does not conduct. There is no current through the load and no output voltage. So, there is no output in the negative half cycle of the input.

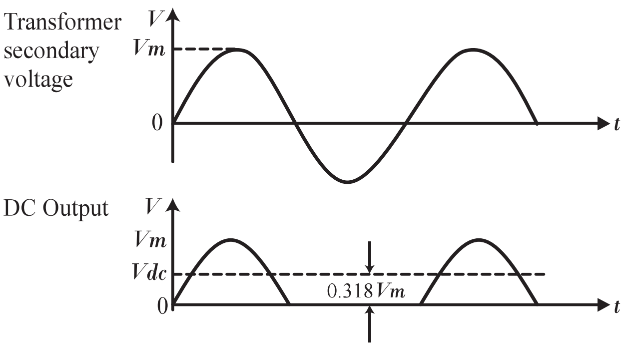

Figure 5.2: Input and output waveforms of a half wave rectifier

Thus a half wave rectifier produces output voltage only in one half cycle of the input voltage. Hence the name half wave rectifier. The input and output waveforms are shown in Figure 5.2. It is also clear that the output voltage is not a pure DC. But it is a pulsating dc which contains ac components (called *ripples*) having frequency equal to the input frequency. If we measure the output voltage by a dc voltmeter, it will indicate average value of the output voltage.

Average and RMS values of Half Wave Rectifier Output

Let the instantaneous value of sinusoidal ac voltage at the secondary is given by $v = V_m \sin \omega t$ where $V_m =$ Maximum value of secondary voltage.

The average or dc value of half wave rectified output voltage is given by the relation

$$V_{dc} = \frac{V_m}{\pi} = 0.318V_m$$

This indicates that average value of output voltage is 31.8% of the maximum value as shown in Figure 5.2.

Similarly, the average or dc value of the load current is

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{V_m}{\pi R_L}$$

Since $I_m = \dfrac{V_m}{R_L}$, we have $I_{dc} = \dfrac{I_m}{\pi} = 0.318I_m$

Also rms value of output voltage is given by the relation

$$V_{rms} = \frac{V_m}{2} = 0.5V_m$$

Similarly, rms value of load current is

$$I_{rms} = \frac{I_m}{2} = 0.5I_m$$

Peak Inverse Voltage of a diode in half wave rectifier

We have discussed that in half wave rectifier, during the negative cycle of the input, the diode is reverse biased. There is no current flow through the load and hence no output voltage. As a result, whole of the input voltage appears across the diode. When the input voltage reaches its maximum value (V_m), in the negative half cycle, the voltage across the diode is also maximum. This maximum reverse voltage is known as the Peak Inverse

Voltage (PIV). *It is the maximum voltage the diode must withstand during the reverse bias*.

For a half wave rectifier,

$$\text{PIV} = V_m$$

Disadvantages of Half Wave Rectifier

- Filtering is required to produce steady DC because the current in the load contains ac component.

- The output power is very low since output is obtained only half of the time.

5.1.2 Full Wave Rectifier

A full wave rectifier is a circuit which produces unidirectional current during the entire input cycle. Thus a pulsating DC (DC having ac components) is obtained during both half cycles of the input. In half wave rectifier, output is obtained only in one half cycle only. There are two types of full wave rectifiers. They are centre-tapped full wave rectifier and bridge rectifier.

5.1.3 Centre-Tapped Full Wave Rectifier

The circuit of a centre-tapped full wave rectifier is shown in Figure 5.3. A centre-tapped transformer is used in this circuit to step down the input voltage. There are two diodes D_1 and D_2 connected to the secondary of the transformer. The centre-tap on the secondary winding of the transformer is usually taken as the ground or zero voltage reference point. The voltage between the centre-tap and either end of the secondary winding is half of the secondary voltage. The operation of a centre-tapped full wave rectifier is described below.

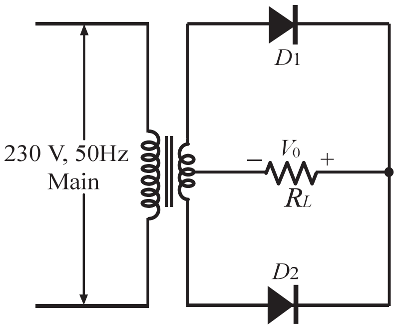

Figure 5.3: Full wave rectifier circuit

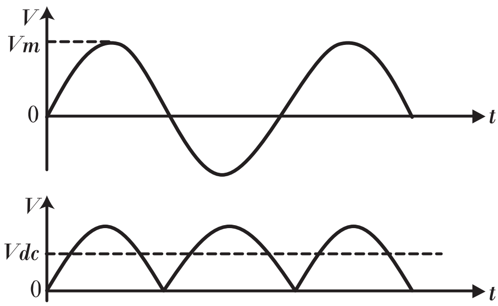

Figure 5.4: Input and output waveforms of a full wave rectifier

During the positive half cycle of the input voltage, the diode D_1 is forward biased and D_2 is reverse biased. D_1 conducts and D_2 becomes open. The current flows through the diode D_1, the load resistor R_L and the upper half of the winding as shown in Figure 5.5.

During the negative half cycle of the input, the polarities of the secondary voltage are as shown in Figure 5.6. Thus the diode D_1 is reverse biased and the diode D_2 is forward biased. D_2 conducts and D_1 becomes open. The current flows through D_2, load resistor R_L and lower half of the winding.

It is important to note that current through the load flows in the same direction during both the positive and negative half cycles of the input. As a result, the output voltage developed across the load resistor is of same polarity and magnitude. The input and output waveform are shown in Figure 5.4.

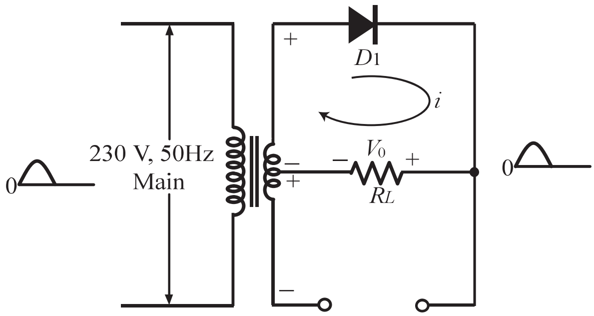

Figure 5.5: Current flow when diode D_1 ON and D_2 OFF

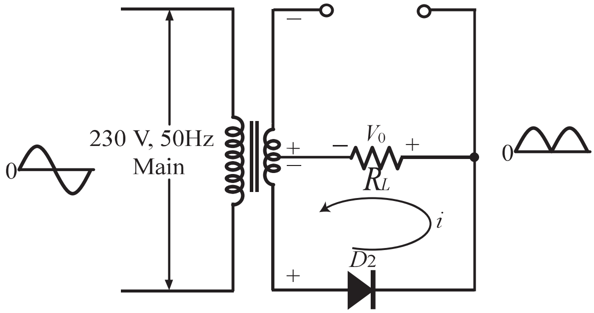

Figure 5.6: Current flow when diode D_2 ON and D_1 OFF

PIV of a Diode in Full Wave Rectifier

We know that PIV is the maximum voltage the diode can withstand during the reverse bias. In centre-tapped full wave rectifier, at positive half cycle of the input voltage, the diode D_1 is conducting while the diode D_2 is open. Let V_m represents the maximum voltage across each half of secondary winding. The whole of the voltage across the upper half winding appears across the load resistor R_L. Therefore the reverse voltage across the non conducting diode D_2 is the sum of the voltage across the lower half winding and the voltage across the load R_L. That is $V_m + V_m = 2V_m$.

Hence, for a centre-tapped full wave rectifier, PIV $= 2V_m$

5.1.4 Bridge Rectifier

Circuit diagram of a bridge rectifier is shown in Figure 5.7. The bridge rectifier circuit is made of four diodes D_1, D_2, D_3, D_4, and a load resistor R_L. The four diodes are connected in a closed-loop configuration to efficiently convert the alternating current (AC) into direct current (DC). The main advantage of this configuration is the absence of the expensive centre-tapped transformer. Therefore, the size and cost are reduced.

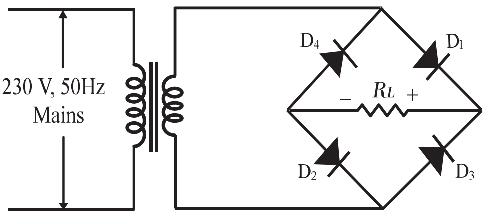

Figure 5.7: Bridge rectifier circuit

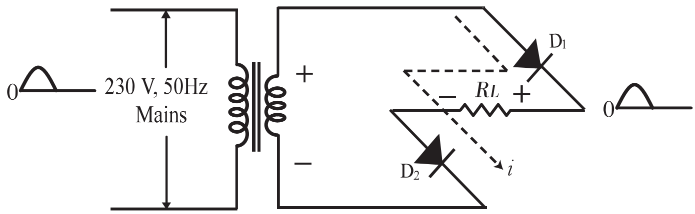

Figure 5.8: Current flow when diodes D_1 and D_2 are ON

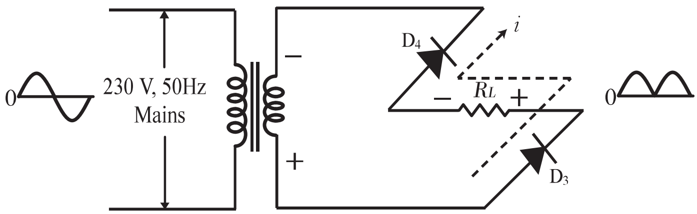

Figure 5.9: Current flow when diodes D_3 and D_4 are ON

During the positive half cycle of the input, diodes D_1 and D_2 conduct and diodes D_3 and D_4 do not conduct. Therefore current flows through the secondary winding, diode D_1, load resistor R_L and diode D_2 as shown in Figure 5.8.

During the negative half cycle, diodes D_3 and D_4 conduct while D_1 and D_2 do not conduct. Hence current flows through the secondary winding, diode D_3, load resistor R_L and diode D_4 as indicated in Figure 5.9.

In both cases, current flow through the load is in the same direction. As a result, a full wave rectified (unidirectional) voltage is developed across the load resistor R_L.

PIV of a Diode in Bridge Rectifier

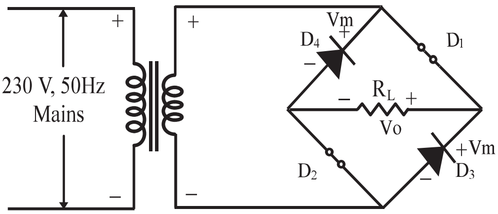

Figure 5.10: PIV of a diode in bridge rectifier

Consider a bridge rectifier circuit shown in Figure 5.10. The polarities of primary and secondary windings during the positive half cycle are indicated. Under this condition, diodes D_1 and D_2 are conducting and these diodes are shown as shorted points in the figure. Also, diodes D_3 and D_4 are reverse biased and have a maximum reverse voltage equal to the maximum secondary voltage (V_m). Hence, PIV of a diode in a bridge rectifier,

$$\text{PIV} = V_m$$

Average and RMS values of Full Wave Rectifier Output

Let the instantaneous value of sinusoidal ac voltage at the secondary is given by $v = V_m \sin \omega t$ where $V_m =$ Maximum value of secondary voltage.

The average or dc value of the output voltage is given by the relation

$$V_{dc} = \frac{2V_m}{\pi} = 0.636V_m$$

This indicates that average value of output voltage is 63.6% of the maximum value.

Similarly, the average or dc value of the load current is

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi} \qquad \because \; I_m = \frac{V_m}{R_L}$$

$$= 0.636 I_m$$

Also rms value of output voltage is given by the relation

$$V_{rms} = \frac{V_m}{\sqrt{2}} = 0.707 V_m$$

Similarly, rms value of load current is

$$I_{rms} = \frac{I_m}{\sqrt{2}} = 0.707 I_m$$

Ripple Factor

The output voltage of a rectifier is not a pure dc. It contains dc component as well as ac components. *The ac components present in the output are called ripples*. The ripple factor is a measure of purity of the dc output of a rectifier and is given by,

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

or

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

Ripple Factor of a Half Wave Rectifier

We know that the rms and average value of load current in a half wave rectifier are

$$I_{rms} = \frac{I_m}{2} \text{ and } I_{dc} = \frac{I_m}{\pi}$$

Substituting the values of I_{dc} and I_{rms} in the expression for ripple factor

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1} = 1.21$$

If the ripple factor is expressed in percentage, its value is 121%. This shows that the amount of ac component present in the output of a half wave rectifier is 121% of dc output voltage. Hence the half wave rectifier is not very good in converting the current from ac to dc.

Ripple Factor of a Full Wave Rectifier

We know that the rms and average values of load current in a full wave rectifier are

$$I_{rms} = \frac{I_m}{\sqrt{2}} \text{ and } I_{dc} = \frac{2I_m}{\pi}$$

Substituting the values of I_{dc} and I_{rms} in the expression for ripple factor

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2I_m/\pi}\right)^2 - 1} = 0.482$$

Thus the ripple factor of a full wave rectifier is 0.482. It is much smaller than that of a half wave rectifier. Hence full wave rectifier is more commonly used.

5.1.5 Efficiency of a Rectifier

Efficiency of a rectifier can be defined as *the ratio of dc power delivered to the load to the ac input power from the secondary winding of the transformer*. Mathematically, the rectifier efficiency,

$$\eta = \frac{\text{dc power delivered to the load}}{\text{ac input power from the transformer secondary}} = \frac{P_{dc}}{P_{ac}} \tag{5.1}$$

$$\begin{aligned} \text{We know,}\ P_{dc} &= I_{dc}^2 \times R_L \\ P_{ac} &= I_{rms}^2 \times (r_f + R_L) \\ \text{where}\ R_L &= \text{Load resistance, and} \\ r_f &= \text{Forward resistance of a diode.} \end{aligned}$$

Substituting the values of P_{dc} and P_{ac} in equation 5.1,

$$\eta = \frac{I_{dc}^2 \times R_L}{I_{rms}^2 \times (r_f + R_L)}$$

Efficiency of Half Wave Rectifier

$$\eta = \frac{I_{dc}^2 \times R_L}{I_{rms}^2 \times (r_f + R_L)} \tag{5.2}$$

We know that for a half wave rectifier,

$$I_{dc} = \frac{I_m}{\pi} \ \text{and} \ I_{rms} = \frac{I_m}{2}$$

Substituting the values of I_{dc} and I_{rms} in equation 5.2,

$$\eta = \frac{\left(\frac{I_m}{\pi}\right)^2 \times R_L}{\left(\frac{I_m}{2}\right)^2 \times (r_f + R_L)} = \frac{4}{\pi^2} \times \frac{R_L}{r_f + R_L} = \frac{0.406}{1 + \frac{r_f}{R_L}}$$

The efficiency is maximum when $R_L >> r_f$. Thus the maximum efficiency of a half wave rectifier is 40.6%.

Efficiency of Full Wave Rectifier

Rectifier efficiency is given by the relation,

$$\eta = \frac{I_{dc}^2 \times R_L}{I_{rms}^2 \times (r_f + R_L)} \tag{5.3}$$

We know that for a full wave rectifier,

$$I_{dc} = \frac{2I_m}{\pi} \text{ and } I_{rms} = \frac{I_m}{\sqrt{2}}$$

Substituting the values of I_{dc} and I_{rms} in equation 5.3,

$$\eta = \frac{\left(\frac{2I_m}{\pi}\right)^2 \times R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 \times (r_f + R_L)} = \frac{8}{\pi^2} \times \frac{R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

The efficiency is maximum when $R_L >> r_f$. Thus the maximum efficiency of a full wave rectifier is 81.2 % which is twice that of a half wave rectifier.

5.1.6 Comparison of Rectifiers

The comparison of various parameters of different rectifiers is given in Table 5.1.

No.	Item	Half wave	Full wave	
			Centre-tap	Bridge
1	Number of diodes	1	2	4
2	Peak Inverse Voltage of diode	V_m	$2V_m$	V_m
3	DC output voltage	$0.318V_m$	$0.636V_m$	$0.636V_m$
4	Ripple factor	1.21	0.482	0.482
5	Ripple frequency	f_{in}	$2f_{in}$	$2f_{in}$
6	Transformer utilization factor	0.287	0.693	0.812
7	Maximum efficiency	40.6%	81.2%	81.2%

f_{in} = Frequency of input signal

Table 5.1: Comparison of various parameters of different rectifiers

5.2 Zener Diode

Zener diode is a semiconductor diode specially designed to operate in the breakdown region of the reverse bias.

Zener diode is *heavily doped* and hence depletion region is very *thin*.

When the reverse voltage across is increased, the *electric field* across the junction becomes *very high* and this field exerts a force on the electrons in the outermost shell. When this field is about 3×10^7 V/m, these valence electrons are pulled away from the parent nuclei and become free carriers. Thus a large number of electron-hole pairs are produced and reverse current increases sharply. This effect is known as *zener breakdown*.

The circuit symbol for zener diode is shown in Figure 5.11.

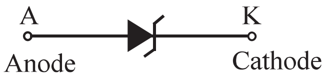

Figure 5.11: Symbol for zener diode

The breakdown voltage of a Zener diode is set by controlling the doping level during manufacture. If the diode is heavily doped, depletion layer will be thin and thus the breakdown of the junction will occur at lower reverse voltages. On the other hand, for a lightly doped diode the breakdown voltage is higher.

V-I characteristics of a Zener Diode

Zener diode is operated in the *reverse bias* region. V-I characteristics of a zener diode is as shown in Figure 5.12.

The forward biased characteristics of Zener diode is similar to normal pn junction diode.

When it is reversed biased, a small reverse saturation current flows across the diode. This current is due to thermally generated minority carriers present in the diode. The reverse bias voltage sets up a strong electric field across the narrow depletion layer. This field is strong enough to break the covalent bonds of atoms. Therefore, there is a generation of a large number of electron-hole pairs, leading to a sharp increase in the reverse current. When reverse bias is increased, up to a certain voltage called as breakdown voltage, the diode starts conducting heavily and the reverse current increases sharply. This voltage is called *Zener breakdown voltage (V_z)*. If the applied voltage is increased beyond V_z, a constant voltage is maintained across its terminals.

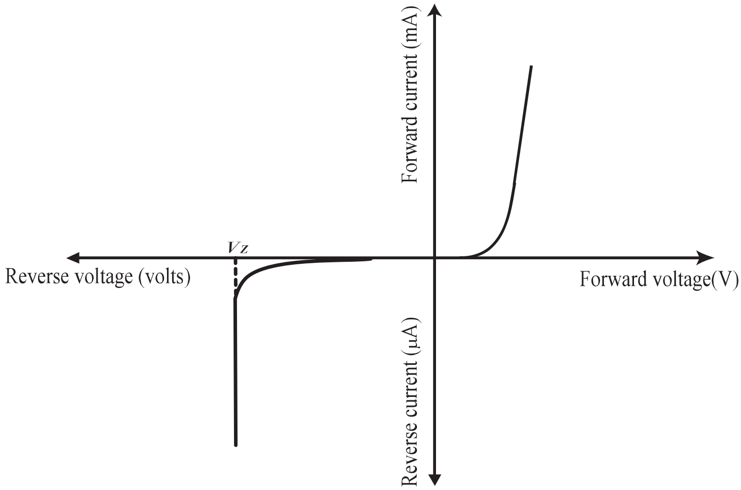

Figure 5.12: V-I characteristic of zener diode

Applications of Zener Diode

Some of the applications of Zener diodes are listed here.

- **Zener diode as a voltage regulator**
  We know that when the ac input voltage of a rectifier fluctuates, its rectified output also fluctuates. To get a constant dc voltage from the dc unregulated output of a rectifier, we use a Zener diode. The circuit diagram of a voltage regulator is as shown in Figure 5.13.

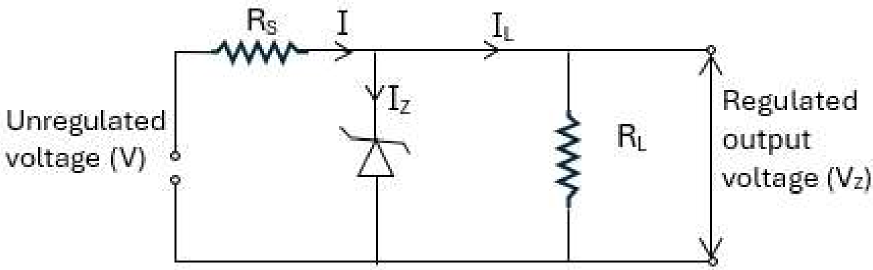

Figure 5.13: Zener diode as voltage regulator

The unregulatd dc voltage is connected to the Zener diode through a series resistance R_s such that the Zener diode is reverse biased. If input voltage increase, the current through R_s and Zener diode also increases. This increases the voltage drop across R_s without any change in voltage across Zener diode. This is because in the breakdown region, Zener voltage remains constant even though the current through the Zener diode changes.

Similarly, if input voltage decreases, the current through R_s and Zener diode also decreases. The voltage drop across R_s decreases without any change in voltage across the Zener diode.

Thus any increase or decrease in the input voltage results in increase or decrease of voltage drop across R_s without any change in voltage drop across the Zener diode. Thus Zener diode acts as a voltage regulator.

- They provide precise reference voltages for analog circuits, such as operational amplifiers and comparators.

- Zener diodes are used in circuits to protect sensitive components from voltage spikes. When the voltage exceeds the Zener voltage, the diode conducts heavily, shunting the excess current away from the protected circuit.

- Zener diodes are used in clipping circuits.

- Zener diodes are used in combination with other components (like transistors) in switching circuits.

- Zener diodes are used to protect measuring instruments and meters (such as voltmeters or ammeters) from over voltage conditions.

- Zener diodes can be used in noise filtering circuits to attenuate unwanted high-frequency noise.

- Zener diodes can be used as temperature sensors due to their temperature dependent breakdown voltage.

Difference between pn Junction Diode and Zener Diode

SL.No	pn Junction Diode	Zener Diode
1	In pn junction diode, the current is allowed to flow only in one direction when it is in forward biased condition.	In Zener diode, the current flows in both direction when it is in forward biased as well as in reverse biased condition.
2	The width of the depletion region is large in pn junction diode because the p and n region is lightly doped.	The width of the depletion region is narrow in Zener diode because the p and n region is heavily doped.
3	The breakdown occurs at higher voltage in a pn junction diode.	The breakdown occurs at lower voltage in a Zener diode
4	pn junction diode operates under forward biased condition.	Zener diode operates when it is reverse biased.
5	pn junction diode is used for rectification	Zener diode is used for voltage regulation.

Table 5.2: Difference between pn junction diode and Zener diode

5.2.1 Zener Breakdown and Avalanche Breakdown

Zener breakdown and avalanche breakdown are two primary mechanisms by which a Zener diode can conduct current in reverse bias. While both result in a sudden increase in current, they differ in their underlying physical processes.

Zener Breakdown

Zener breakdown occurs at lower reverse voltage, especially in heavily doped Zener diodes.

Zener breakdown occurs due to the strong electric field in the depletion region when a reverse bias voltage is applied. This high electric field is

strong enough to pull electrons from their covalent bonds in the semiconductor material, generating electron-hole pairs through quantum mechanical tunneling. This is a quantum effect known as *Zener tunneling* .
The breakdown voltage decreases with increasing temperature.

Avalanche Breakdown

This typically occurs at higher reverse voltages, especially in lightly doped Zener diodes.

Avalanche breakdown occurs when the reverse bias voltage is high enough to impart enough kinetic energy to free electrons. These electrons collide with atoms in the depletion region, knocking more electrons free, which further accelerates and causes more collisions in a chain reaction. This is known as impact ionization.

The breakdown voltage increases slightly with temperature.

In many practical Zener diodes, both mechanisms contribute to the breakdown. However, one mechanism may dominate depending on the doping level and other characteristics of the diode. Understanding the differences between zener and avalanche breakdown is crucial for selecting the appropriate Zener diode for specific applications, such as voltage regulation, clipping, and surge protection.

Difference Between Zener Breakdown and Avalanche Breakdown

The main difference between zener breakdown and avalanche breakdown is their mechanism of occurrence.Let us look at the other differences between them in the below table.

SL.No	Zener Breakdown	Avalanche Breakdown
1	It will occur in the diodes that are highly doped.	It will occur in the diodes that are lightly doped.
2	The VI characteristics of a Zener breakdown has a very sharp curve.	The VI characteristics of an Avalanche breakdown do not have a very sharp curve.
3	The increase in temperature decreases the breakdown voltage.	The increase in temperature increases the breakdown voltage.
4	Zener breakdown occurs only because of the high electric field in reverse bias condition.	Avalanche breakdown occurs because of the collision of free electrons with the atoms.
5	This is observed in Zener diodes having Zener breakdown voltage V_z. between 5 to 6 volts.	This is observed in Zener diodes having Zener breakdown voltage V_z greater than 6 volts.

Table 5.3: Difference between zener Breakdown and Avalanche Breakdown

5.3 Tunnel Diode

A tunnel diode, also known as an Esaki diode, is a heavily doped pn junction diode that exhibits a region of *negative resistance* (as the voltage increases, the current decreases) between peak point voltage and valley point voltage in forward biased condition. This phenomenon is due to a quantum mechanical effect called *tunneling*.

Symbol of Tunnel Diode

The symbol of tunnel diode is as shown in figure 5.14.

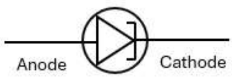

Figure 5.14: Tunnel Diode

In tunnel diode, the p-type and n-type semiconductor is heavily doped which means a large number of impurities are introduced into the p-type and n-type semiconductor. This heavy doping process produces an extremely narrow depletion region. This causes many valence electrons to have their energy levels raised closer to the conduction region. Therefore, only small forward voltage is required to start conduction. The movement of valence electrons from valence energy band to the conduction band with little or no forward bias voltage is called tunnelling. In a similar way, holes tunnel from the valence band of p-region to the conduction band of n-region.

At small forward voltages, tunneling further occurs, leading to an increase in current. As the voltage increases further, current reaches a peak value (called peak current, I_p). Again on increasing the forward voltage, the current starts to decrease, which is the negative resistance region. If the applied voltage is further increased, the tunneling current drops and this minimum current is called *valley current* I_v. At this point, the conduction band and valence band no longer overlaps and hence no tunnelling occurs. Further increase in forward biasing will lead to complete vanishing of tunnelling current and the tunnel diode operates in the same manner as a normal pn junction diode.

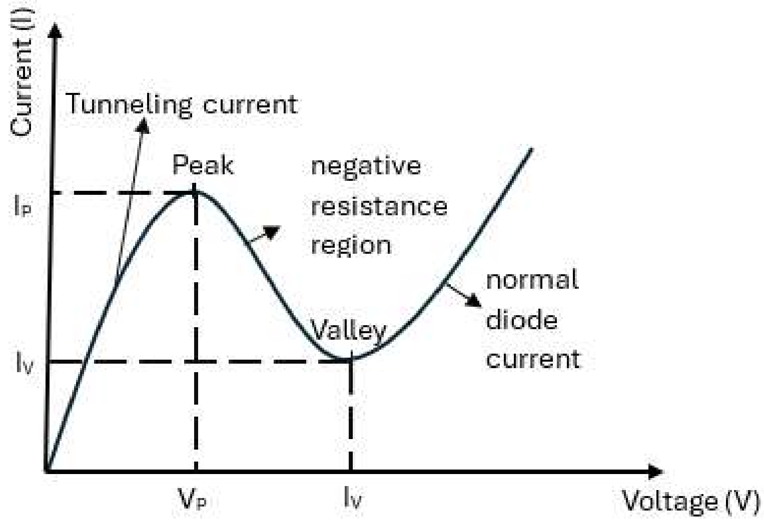

Figure 5.15: V-I characteristics of tunnel diode

Applications

- Due to their high-speed operation and ability to generate oscillations in the gigahertz (GHz) range, tunnel diodes are used in microwave and high-frequency oscillators.
- Tunnel diodes are used in radio frequency (RF) and microwave amplifiers.
- Tunnel diodes are used as microwave detectors and mixers in RF applications due to their high sensitivity and efficiency in detecting weak signals.
- In satellite communications and radar, tunnel diodes can be used in frequency conversion circuits where they shift frequencies from one range to another.
- In pulse and waveform generator circuits, tunnel diodes can produce rapid pulses due to their negative resistance region, making them useful in time-sensitive electronic systems.

5.4 Semiconductor Laser

A semiconductor laser is a heavily doped p-n junction device which emits coherent light in forward bias condition.

Semiconductor laser was invented in 1962 by R.N. Hall and his co-workers. Laser diodes are very popular for their compactness and operational efficiency. The fibre communication systems are realized because of the availability of laser diodes.

Construction

A typical schematic diagram of a semiconductor laser diode is as shown in Figure (5.16). The semiconductor laser diodes are made of direct band semiconductors like Gallium Arsenide. A junction is formed between p-type and n-type semiconductors.

The depletion region is the *active medium* in semiconductor laser. The thickness of depletion layer is very small about 1μm. Under the influence of forward biased electric field, conduction electrons will be injected from n-side into the junction area, while holes will enter junction area from p-side. Thus there will be recombination of holes and electrons in depletion region and hence this region becomes thinner. The direct conversion method is used as *pumping method*.

The two faces of semiconductor which are perpendicular to junction are polished which makes a *resonant cavity*.The other two opposite faces are roughened to prevent lasing action in that direction.

The top and bottom faces are metallised and ohmic contacts are provided to pass current through the diode.

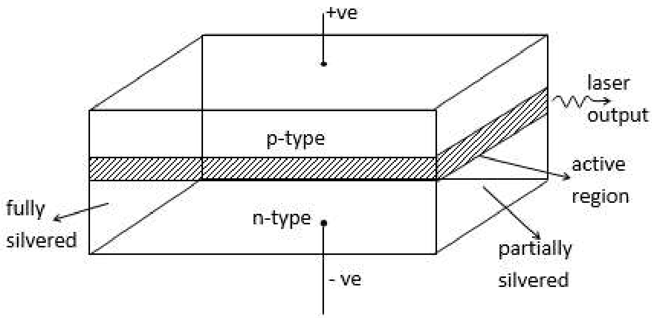

Figure 5.16: Schematic diagram of semiconductor laser

Working

When no voltage is applied, the Fermi levels of p-type semiconductor and n-type semiconductor lies in the same horizontal line as shown in figure (5.17).

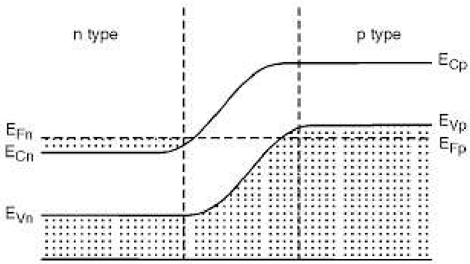

Figure 5.17: Energy level diagram of semiconductor laser with no biasing

When a forward bias voltage V is applied to the diode, the two Fermi levels become separated by an amount given by $\Delta E = eV$. The new distribution is as shown in figure (5.18).

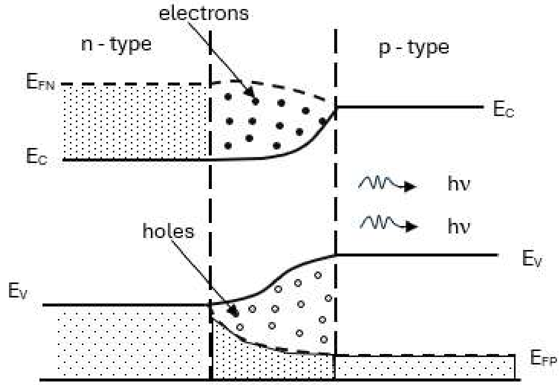

Figure 5.18: Energy level diagram of semiconductor laser with forward biasing

When pn junction diode is forward biased, there will be injection of electrons into the conduction band along n-side and production of more holes in valence band along p-side into active region of the diode. Thus, there will be more number of electrons in conduction band compared to valence band, and hence population inversion is achieved.
The radiative emission occurs when an electron in the conduction band recombines with the hole in the valence band. The frequency of the emitted radiation has a frequency corresponding to the frequency of the band gap energy. In GaAs laser, the photons emitted have a wavelength 8200Å to 9000Å in IR region.

Applications

Laser diodes are very popular for their compactness and operational efficiency. The fibre communication systems are realized because of the availability of laser diodes. Some of the applications of semiconductor lasers are given below.

- Used in CD players, laser discs etc.

- Used for laser printing, laser type setting, laser pointers.
- Used in fibre optic communications.
- Used in barcode scanners.
- Used in laser welding and laser cutting.
- Used in laser ranging systems to measure distances accurately.
- Used in lidar systems for remote sensing and mapping.
- Semiconductor lasers can be used for various surgical procedures, such as eye surgery and laser skin resurfacing. They are also used in diagnostic tools like flow cytometry and Laser Doppler velocimetry.

5.5 Photonic Devices

Photonics is the science and technology of generating, controlling, and detecting light. It's essentially the study of light and its applications. Unlike traditional electronics, which use electrons to process information, photonics utilizes photons, the particles of light.

Devices that run on light have a number of advantages over those that use electricity. Light travels at about 10 times the speed that electricity does, which means that data transmitted photonically can travel long distances in a fraction of the time. Furthermore, visible light and IR rays, unlike electric current, pass through each other without interaction, so they don't cause interference. A single optical fibre has the capacity to carry three million telephone calls simultaneously. Photonics explores a wider variety of wavelengths from gamma rays to radio including X-rays, UV and IR light.

Photonics is everywhere, in consumer electronics (barcode scanners, remote TV control), telecommunications (internet), health (eye surgery medical instruments), manufacturing industry (laser cutting and machining), defense and security (infrared camera, remote sensing), entertainment (holography and laser shows) etc.

Solid State Lighting: Light applications that use light emitting diodes (LEDs), organic light emitting diodes (OLEDs) or light emitting polymers are commonly referred as solid state lighting (SSL). This type of lighting has higher efficiency, reliability and environmentally friendly technology compared to the conventional incandescent lighting.

5.6 Photodetectors

The process of conversion of optical power into electrical power is called photo-detection. The device, which converts light power incident on it into electrical power is called *photo-detector*.

A photo detector has a pn junction which converts light into electrical current. These devices are widely used in optical communication systems. It is operated in photovoltaic mode or photo conductive mode.

In *photovoltaic mode*, photovoltaic effect is used. i.e., *Photovoltaic effect* is the production of an emf across the junction of two semiconductors when light is incident at that junction. They are suitable for fibre optic communication systems.

In *photoconductive mode*, when light is incident on a semiconducting material, electron – hole pairs are formed and as a result photo current is produced. They are used in devices like remote control devices etc.

5.6.1 Junction Photodiode

It is a semiconductor device that converts light into current. It is a pn junction diode usually sealed in a transparent plastic so that its junction region may be exposed to light of suitable intensity and frequency. It is operated in the reverse bias as shown in figure 5.19.

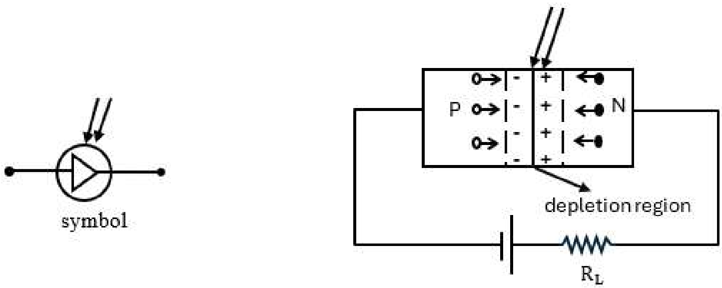

Figure 5.19: Symbol and block diagram of Photo detectors

In the absence of light, when the diode is in the reverse bias condition, a small current is produced due to the flow of minority carriers from p and n sides. This current is called dark current.

When light falls on depletion region $(h\nu \geq \Delta E_g)$ photons get absorbed by the bound electrons of immobile ions and large number of new electron – hole pairs are created. These newly generated electrons moved towards the n- side and holes towards the p-side by the reverse bias. As a result large reverse current flows through the junction diode known as photo current.

Magnitude of photo current is proportional to the intensity of light incident on it.

Applications

Some of the applications of photodiodes are given below.

- Photodiodes are commonly used in fiber-optic networks for high-speed data transmission.
- Photodetectors are used in systems that detect air and water quality through light-based measurements.
- Used in light controlled relays, optical reader, CD players, smoke detectors, remote control devices.
- Photodiodes are widely used in medical field. For example, it is used in instruments to analyse samples, detectors for computed tomography and also used in blood gas monitors.

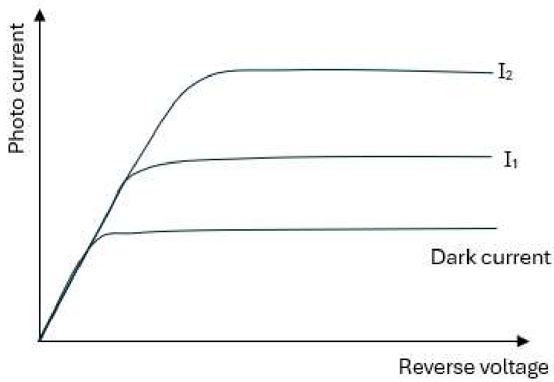

Figure 5.20: VI characteristics of photodiode

5.6.2 P-I-N Photodiode (P-type – intrinsic – N-type)

In PIN photodiode, a thick intrinsic (pure or lightly doped) semiconducting layer is inserted between heavily doped p and n region as shown in Figure 5.21. The large resistance of intermediate intrinsic layer provides larger electric field between p and n regions and therefore, charge carriers drift towards their majority carrier side.

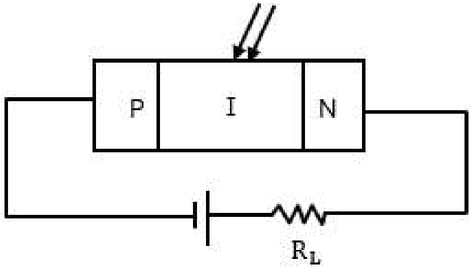

Figure 5.21: PIN Photodiode

When reverse bias is applied and increased gradually, width of depletion region increases at a certain reverse voltage. Width extends to almost entire region of intrinsic layer. Now region of intrinsic layer becomes the absorption region where most of the absorption of photons occur.

When light is incident in this region, electrons are excited from the valence band to the conduction band producing a large number of electron – hole pairs. Because of its large width, the intrinsic layer absorbs very large number of incoming photons compared to the p and n regions.

Due to the electric field created by the reverse bias, these carriers are separated: electrons moves towards n region and holes moves towards p region. This movement of charge carriers creates a current, which is the electrical signal corresponding to the incident light. The large width of the intrinsic layer increases the photocurrent and improves the efficiency, speed and sensitivity compared to that in photodiode.

The advantage of PIN photodiode from photodiodes are its high speed, making them suitable for high-speed optical communication systems. They can detect light over a broad wavelength range.They generate minimal current in the absence of light.

Applications:

- PIN diodes are used in the RF and microwave switches and variable attenuators.
- PIN diodes are used in optical communication.
- PIN diodes are used to detect X-ray and gamma rays photons.
- PIN diodes are also used in solar cells, optical sensors, image sensors etc.

5.7 Solar Cells

Solar cell is the photovoltaic device that converts the sun light into electrical energy. This device works on the principle of *photovoltaic effect*.

Photovoltaic Effect: The generation of voltage across the p-n junction in a semiconductor due to the absorption of light radiation is called photovoltaic effect. The device based on this effect is called *photovoltaic device*.

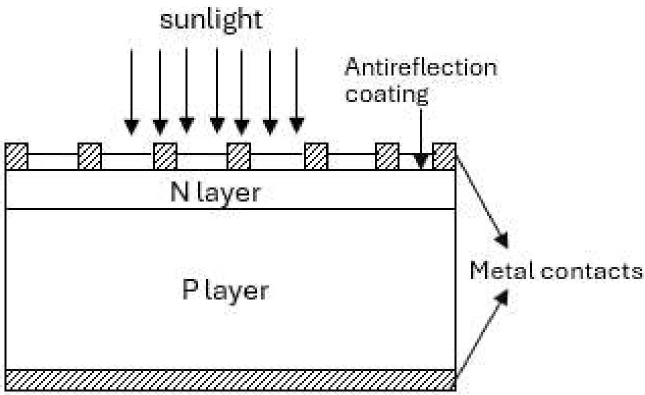

Figure 5.22: Solar cell

Construction

Solar cell consists of a heavily doped p-n junction. It has a large surface area to receive large amount of sunlight. Top N-layer is very thin, to allow solar radiations to reach the p-n junction as shown in the Figure 5.22.

The pn junction is very narrow because of high doping. Connections are made from bottom P-layer(anode) and top N-layer (cathode) using metal contacts. An antireflection coating is provided on the top layer to prevent loss of light by reflection.

Working

Solar cell is a p-n junction diode under zero bias.

At zero bias, free electrons flow from n-region to p-region. These free electrons will recombine with holes in the p-region and become bound electrons. When solar radiation are incident at pn junction, more electron-hole pairs are formed producing an electric current in the external circuit. Thus solar energy is converted into electrical energy. Total output voltage can be increased by connecting a number of solar cells in series. A solar panel is an array of a number of solar cells connected together.

5.7.1 V-I characteristics of Solar Cell

Consider a solar cell connected with an ammeter, voltmeter and a load resistance as shown in figure (5.23) and it is exposed to sunlight.

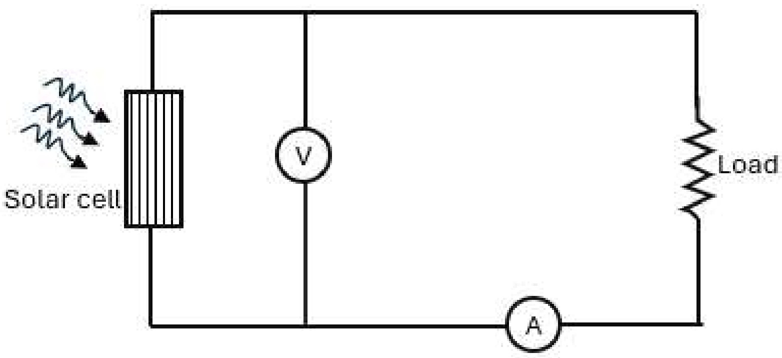

Figure 5.23: V-I characteristics of solar cell

If there is no load connected with the solar cell, an open circuit voltage V_{oc} is produced without a current. *The open-circuit voltage,* V_{oc}, is the maximum voltage available from a solar cell,and this occurs at zero current.

The open circuit voltage corresponds to the amount of forward bias on the solar cell junction due to illumination.

If the terminal of the solar panels are shorted together, the short circuit current I_{sc} flows without an output voltage. (*Short circuit current* is the current through the solar cell when the voltage across the solar cell is zero. The short-circuit current is due to the generation and collection of light-generated carriers.The short-circuit current is the largest current which may be drawn from the solar cell. The short circuit current depends on various factors like area of the solar cell, the power of incident light source etc. In both the cases, no power is delivered by the solar cell.

When a load is connected, a voltage is developed, a current flows in the circuit and there is an output power. Let V_m and I_m be the voltage and current corresponding to the maximum power. Maximum power is the condition under which solar cell generates its maximum power P_m. The power of the solar cell equals to the product of the diode voltage and current.

$$P_m = V_m I_m$$

V-I characteristics of solar cell is given in the figure 5.24.

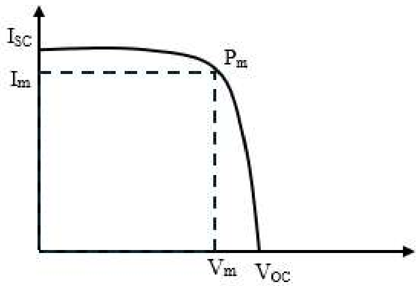

Figure 5.24: V-I characteristics of solar cell

5.7.2 Efficiency of Solar Cell

Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.

$$\text{Efficiency, } \eta = \frac{\text{Electrical power delivered}}{\text{Solar power incident}}$$

$$\eta = \frac{V_m I_m}{P_{in}}$$

$$\text{Also,} \quad \eta = \frac{P_{max}}{\text{light intensity} \times \text{area of the solar cell}}$$

Fill factor (FF) is the ratio of the maximum power from the actual solar cell to the maximum power from a ideal solar cell.

$$FF = \frac{\text{Maximum power from real cell}}{\text{Maximum power from ideal cell}} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Then efficiency can be written as

$$\eta = \frac{V_{oc} I_{sc} \times FF}{P_{in}}$$

5.7.3 Stringing of Solar Cells to Solar Panel

Stringing of solar cells to form a solar panel refers to the process of connecting individual photovoltaic (PV) cells in a specific configuration to create a solar module or panel. This process is crucial because individual solar cells generate relatively low voltage and current, and by stringing them together, we can increase the overall power output of the solar panel.

To achieve higher voltage and current outputs, solar cells are connected in series and parallel configurations, depending on the desired output power. Stringing can help optimize the overall efficiency of the solar panel by reducing losses due to resistive elements.

Series Connection: Solar cells are connected end-to-end, where the positive terminal of one cell is connected to the negative terminal of the next cell. This increases the voltage while the current remains the same.

Parallel Connection: Solar cells are connected such that their positive terminals are connected together, and their negative terminals are connected together. This increases the current while the voltage remains the same.

Advantages

Solar cells offer lots of benefits, making them a popular choice for renewable energy solutions. Here are some key advantages.

- **Renewable energy source:** Solar energy is abundant and freely available, ensuring a long-term, sustainable energy source.
- **Clean energy:**Solar energy produces no harmful emissions, reducing greenhouse gas contributions which causes climate change.
- **Low maintenance:** Solar panels require minimal maintenance, such as occasional cleaning, making them a hassle-free energy solution.
- **Versatility:** Solar cells can be installed on various surfaces, including rooftops, ground mounts, and even portable systems for camping or off-grid applications.

Applications

Solar cells, or photovoltaic cells, convert sunlight into electricity and have a wide range of applications across different fields.

- **Telecommunication stations:** Solar cells power remote communication towers, weather stations, and satellites where conventional power sources are impractical.
- **Solar-powered vehicles:** Solar cells are integrated into cars, boats, and even airplanes to supplement power or, in some cases, serve as the primary energy source.
- **Satellites:** Solar panels power satellites, space stations, and spacecraft, providing a continuous energy supply in space where traditional fuels are impractical.
- **Solar water pumps:** In areas where grid electricity is unavailable, solar cells power water pumps for irrigation and livestock.
- **Solar farms:** Large-scale solar power plants use vast arrays of solar cells to produce electricity that is fed into the grid, helping to power cities and industries.
- **Rural electrification:** Solar cells are used to provide electricity to remote villages in developing countries.

5.8 Light Emitting Diode (LED)

LED is a heavily doped pn junction diode of suitable materials that emits light when it is forward biased. The symbol of LED is given in Figure 5.25.

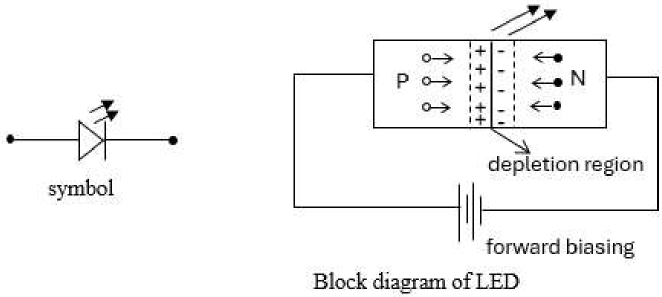

Figure 5.25: Symbol and block diagram of LED

During forward bias, free electrons from conduction band of n region combines with the holes from valence band of p region crossing the barrier at p-n junction. During recombination, electromagnetic radiation is emitted with energy equal to band gap energy of semiconducting material. Some semiconducting materials like GaAs, GaP, GaAsP etc have band gap energy ΔE_g in the range of about 1.5 – 3.0 eV, which provides radiation in the visible/ infrared region.

$$\Delta E_g = h\nu = \frac{hc}{\lambda}$$

where ν is frequency, c is the velocity of light and λ is the wavelength.

$$\nu = \frac{\Delta E_g}{h}$$

The band gap energy determines the colour or wavelength of the emitted light. The intensity of the light emitted due to recombination process is directly proportional to the rate of (electron-hole) recombinations at the junction.

Now-a-days, Organic Light Emitting Diodes (OLEDs) and Polymer Light Emitting Diodes (PLEDs) are also available. LEDs are increasingly using quantum dots to enhance color accuracy and energy efficiency. Quantum dot LEDs (QLEDs) embeds nanoscale semiconductor particles into

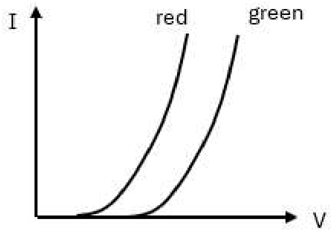

Figure 5.26: VI characteristics of LED

LEDs, enabling them to produce a wider and more vibrant color spectrum, particularly useful for high-quality displays. It also help reduce energy consumption.

Applications

Light emitting diodes are widely used in small indicators, warning lights and in alphanumeric display devices like calculators etc.

It is used in optical communication.

It is used for fancy light and decoration.

LEDs with invisible radiation are used in remote control devices, burglar alarm systems etc.

Advantages of LED

Light Emitting Diodes (LED) have several advantages over traditional lighting technologies like incandescent and fluorescent lights. Here are some key benefits:

- **Energy efficiency:** LEDs consume significantly less energy compared to traditional light sources. They convert more energy into light rather than heat, which reduces power consumption.

- **Long lifespan:** LEDs have a much longer operational life, often lasting up to 50,000 hours or more.

- **Directional lighting:** LEDs emit light in a specific direction, which reduces the need for reflectors and diffusers and ensures more efficient use of light.

- **Low heat emission:** Unlike incandescent bulbs that release 90% of their energy as heat, LEDs emit very little heat. This makes them safer to handle and reduces the need for additional cooling.
- **Durability:** LEDs are highly durable and can withstand rough conditions such as vibrations and impacts better than other lighting technologies, making them suitable for outdoor and industrial use.

5.9 Solved Numerical Problems

Example 5.9.1 The applied input a.c. power to a half-wave rectifier is 100 watts. The d.c. output power obtained is 40 watts. What is the rectification efficiency ?

Solution

Rectifier efficiency,

$$\eta = \frac{\text{dc outpower}}{\text{ac outpower}} = \frac{40}{100} = 0.4 = 40\%$$

Example 5.9.2 An input voltage $v_i = 10 \sin \omega t$ is applied to a half wave rectifier with a diode having forward resistance 15 Ω and load resistance 600 Ω. Determine

1. Maximum value of current, dc current and rms value of current.
2. ac power input and dc power output.
3. Efficiency of rectification.

Solution

Given input voltage, $v_i = 10 \sin \omega t$
Comparing with standard form, $v_i = V_m \sin \omega t$, $V_m = 10$ V
Forward resistance of diode, $r_f = 15\ \Omega$ and load resistance, $R_L = 600\ \Omega$

1. Maximum value of current, $I_m = \dfrac{V_m}{r_f + R_L}$

$$= \frac{10 \text{ V}}{15 \ \Omega + 600 \ \Omega}$$

$$= 16.3 \text{ mA}$$

dc current, $I_{dc} = \frac{I_m}{\pi} = \frac{16.3 \text{ mA}}{\pi} = 5.2 \text{ mA}$

rms current, $I_{rms} = \frac{I_m}{2} = \frac{16.3 \text{ mA}}{2} = 8.15 \text{ mA}$

2. ac power, $P_{ac} = I_{rms}^2 (r_f + R_L)$

$$= (8.15 \times 10^{-3})^2 (15 + 600) = 0.041 \text{ watts}$$

dc power output, $= (I_{dc}^2) R_L$

$$= (5.2 \times 10^{-3})^2 \times 600 = 0.016 \text{ watts}$$

3. Rectification efficiency, $= \frac{P_{dc}}{P_{ac}} \times 100$

$$= \frac{0.016}{0.041} \times 100 = 39\%$$

Example 5.9.3 The input voltage applied to the primary of a 4:1 step down transformer of a full wave center-tap rectifier is 230 V, 50 Hz. If the load resistance is 600 Ω and forward resistance is 20 Ω. Determine the following parameters of the full wave rectifier.

1. dc power output
2. Rectification efficiency
3. PIV

Solution

rms value of primary voltage, $V_1 = 230$ V

rms value of secondary voltage, $V_2 = V_1 \times \frac{N_2}{N_1} = 230 \times \frac{1}{4} = 57.5$ V rms value of voltage between centre tap and each side of secondary

$$V = \frac{V_2}{2} = \frac{57.5}{2} = 28.75 \text{ V}$$

Then maximum value of voltage $V_m = \sqrt{2} \times 28.75 = 40.7$ V

Maximum value of current, $I_m = \dfrac{V_m}{r_f + R_L} = \dfrac{40.7}{20 + 600} = 65.64$ mA

dc current, $I_{dc} = \dfrac{2I_m}{\pi} = \dfrac{2 \times 65.64 \text{ mA}}{\pi} = 41.79$ mA

rms current, $I_{rms} = \dfrac{I_m}{\sqrt{2}} = \dfrac{65.64}{\sqrt{2}} = 46.41$ mA

Ac input power, $P_{ac} = I_{rms}^2(r_f + R_L)$

$$= (46.41 \times 10^{-3})^2(20 + 600) = 1.335 \text{ W}$$

1. dc output power $= I_{dc}^2 R_L = (41.79 \times 10^{-3})^2 600 = 1.047$ W

2. Rectification efficiency $= \dfrac{P_{dc}}{P_{ac}} \times 100 = \dfrac{1.047}{1.335} \times 100 = 78.4\%$

3. PIV of full wave rectifier $= 2V_m = 2 \times 40.7 = 81.4$ V

Example 5.9.4 A solar cell with an area of $100cm^2$ has an open-circuit voltage of 0.6 V and a short-circuit current of 3 A. If the solar irradiance is $1000W/m^2$, calculate the efficiency of the solar cell if its fill factor is 0.75.

Solution

Given area of the solar cell is $100cm^2 = 0.01m^2$

Solar power input is $1000W/m^2 \times 0.01m^2$ = 10 W

$$\text{Efficiency, } \eta = \frac{\text{Electrical power delivered}}{\text{Solar power incident}}$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

$$= \frac{0.6 \times 3 \times 0.75}{10} = 0.135$$

Therefore, the efficiency of the solar cell is 13.5

Example 5.9.5 A light emitting diode is made of GaAsP having a band gap of 1.9eV. Determine the wavelength and colour of radiation emitted.

Solution

$$\lambda = \frac{hc}{E_g} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{1.9 \times 1.6 \times 10^{-19}} = 652.6nm$$

5.10 Exercises

1. A single solar cell of dimension (10cm x 10cm) produces a voltage of 0.5V and current 2.5 A. The intensity of light absorbs by cell is 800 W/m^2. What is the efficiency of cell?
Hint: $\eta = 15.6\%$

2. Given that a solar cell has V_{OC} = 4.2V, $I_{SC} = 45mA$, and FF=60%, what is the efficiency? If the solar irradiance is $1000W/m^2$ and the area of the cell is $50cm^2$.
Hint: $\eta = 2.27\%$

3. At room temperature, the voltage across an LED was measured to be 1.67 V. What is the band gap of this semiconductor, and what wavelength of light is emitted?
Hint: E_g = 1.67eV and λ = 744nm in red part of the visible spectrum

4. A semiconductor diode laser has a peak emission wavelength of 1.55 μm. Find its band gap in eV.
Hint: $E_g = 0.8eV$