6.1 Semiconductor Diode

A pn junction is known as a **semi-conductor** *or* ***crystal diode**.

The outstanding property of a crystal diode to conduct current in one direction only permits it to be used as a rectifier. A crystal diode is usually represented by the schematic symbol shown in Fig. 6.1. The arrow in the symbol indicates the direction of easier conventional current flow.

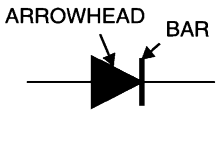
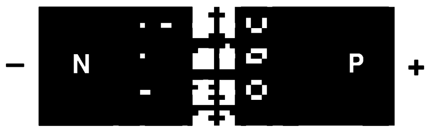


Fig. 6.1



A crystal diode has two terminals. When it is connected in a circuit, one thing to decide is whether the diode is forward or reverse biased. There is an easy rule to ascertain it. If the external circuit is trying to push the conventional current in the direction of arrow, the diode is forward biased. On the other hand, if the conventional current is trying to flow opposite to arrowhead, the diode is reverse biased. Putting in simple words :

(*i*) If *arrowhead* of diode symbol is *positive w.r.t. bar* of the symbol, the diode is forward biased.

(*ii*) If the *arrowhead* of diode symbol is *negative w.r.t. bar*, the diode is reverse biased.

Identification of crystal diode terminals. While using a crystal diode, it is often necessary to know which end is arrowhead and which end is bar. For this purpose, the following methods are available :

(*i*) Some manufacturers actually paint the symbol on the body of the diode *e.g. BY*127, *BY*114 crystal diodes manufactured by *BEL* [See Fig. 6.2 (*i*)].

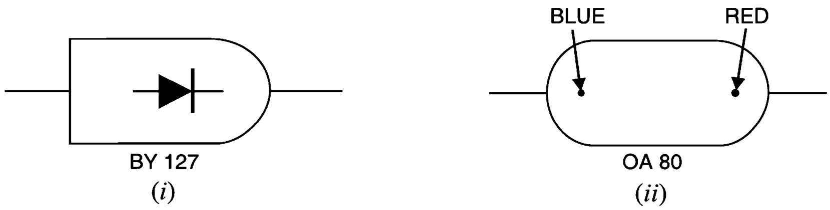


Fig. 6.2

(*ii*) Sometimes, red and blue marks are used on the body of the crystal diode. Red mark denotes arrow whereas blue mark indicates bar *e.g. OA80* crystal diode [See Fig. 6.2 (*ii*)].

6.2 Crystal Diode as a Rectifier

Fig. 6.3 illustrates the rectifying action of a crystal diode. The a.c. input voltage to be rectified, the diode and load R_L are connected in series. The d.c. output is obtained across the load as explained in the following discussion. During the positive half-cycle of a.c. input voltage, the arrowhead becomes positive *w.r.t.* bar. Therefore, diode is forward biased and conducts current in the circuit. The result is that positive half-cycle of input voltage appears across R_L as shown. However, during the negative half-cycle of input a.c. voltage, the diode becomes reverse biased because now the arrowhead is negative *w.r.t.* bar. Therefore, diode does not conduct and no voltage appears across load R_L. The result is that output consists of positive half-cycles of input a.c. voltage while the negative half-cycles are suppressed. In this way, crystal diode has been able to do rectification i.e. change a.c. into d.c. It may be seen that output across R_L is pulsating d.c.

* So called because *pn* junction is grown out of a crystal.

It is interesting to see that behaviour of diode is like a *switch*. When the diode is forward biased, it behaves like a closed switch and connects the a.c. supply to the load R_L. However, when the diode is reverse biased, it behaves like an open switch and disconnects the a.c. supply from the load R_L. This switching action of diode permits only the positive half-cycles of input a.c. voltage to appear across R_L.

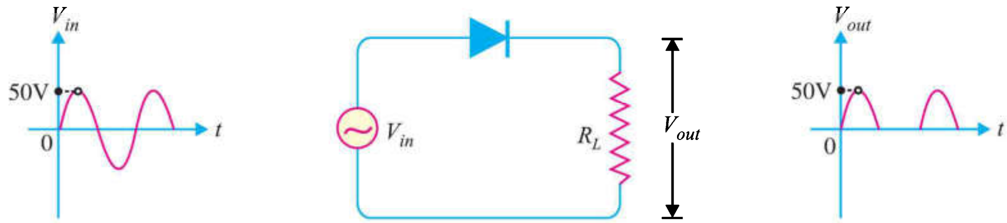


Fig. 6.3

Example 6.1. *In each diode circuit of Fig. 6.4, find whether the diodes are forward or reverse biased.*

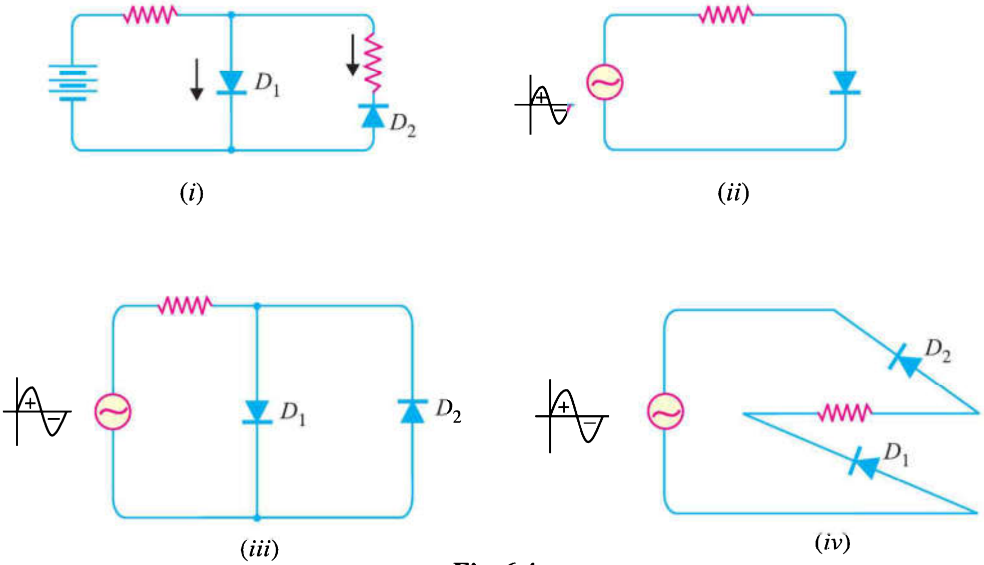


Fig. 6.4

Solution.

(*i*) Refer to Fig. 6.4 (*i*). The conventional current coming out of battery flows in the branch circuits. In diode D_1, the conventional current flows in the direction of arrowhead and hence this diode is forward biased. However, in diode D_2,the conventional current flows opposite to arrowhead and hence this diode is reverse biased.

(*ii*) Refer to Fig. 6.4 (*ii*). During the positive half-cycle of input a.c. voltage, the conventional current flows in the direction of arrowhead and hence diode is forward biased. However, during the negative half-cycle of input a.c. voltage, the diode is reverse biased.

(*iii*) Refer to Fig. 6.4 (*iii*). During the positive half-cycle of input a.c. voltage, conventional current flows in the direction of arrowhead in D_1 but it flows opposite to arrowhead in D_2. Therefore, during positive half-cycle, diode D_1 is forward biased and diode D_2 reverse biased. However, during the negative half-cycle of input a.c. voltage, diode D_2 is forward biased and D_1 is reverse biased.

(*iv*) Refer to Fig. 6.4 (*iv*). During the positive half-cycle of input a.c. voltage, both the diodes are reverse biased. However, during the negative half-cycle of input a.c. voltage, both the diodes are forward biased.

6.3 Resistance of Crystal Diode

It has already been discussed that a forward biased diode conducts easily whereas a reverse biased diode practically conducts no current. It means that *forward resistance* of a diode is quite small as compared with its *reverse resistance*.

1. Forward resistance. The resistance offered by the diode to forward bias is known as *forward resistance*. This resistance is not the same for the flow of direct current as for the changing current. Accordingly; this resistance is of two types, namely; *d.c. forward resistance* and *a.c. forward resistance*.

(*i*) *d.c. forward resistance*. It is the opposition offered by the diode to the direct current. It is measured by the ratio of d.c. voltage across the diode to the resulting d.c. current through it. Thus, referring to the forward characteristic in Fig. 6.5, it is clear that when forward voltage is OA, the forward current is OB.

$$\therefore \quad \text{d.c. forward resistance, } R_f = \frac{OA}{OB}$$

(*ii*) *a.c. forward resistance*. It is the opposition offered by the diode to the changing forward current. It is measured by the ratio of change in voltage across diode to the resulting change in current through it *i.e.*

$$\text{a.c. forward resistance, } r_f = \frac{\text{Change in voltage across diode}}{\text{Corresponding change in current through diode}}$$

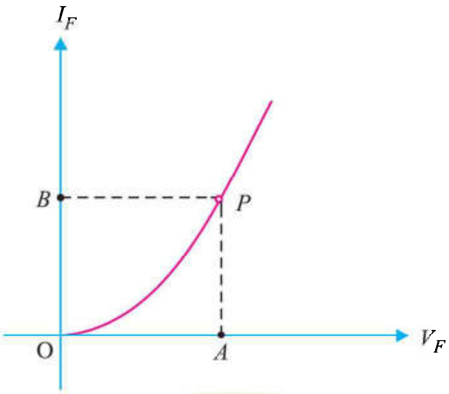


Fig. 6.5

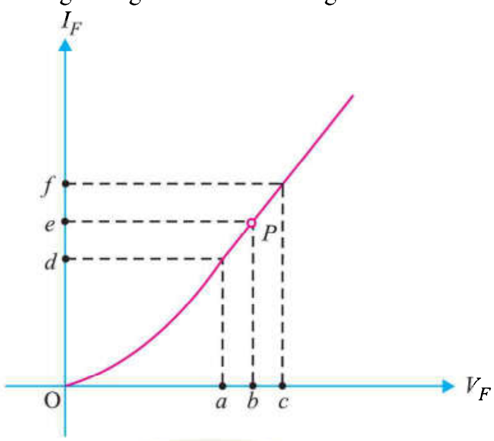


Fig. 6.6

The a.c. forward resistance is more significant as the diodes are generally used with alternating voltages. The a.c. forward resistance can be determined from the forward characteristic as shown in Fig. 6.6. If P is the operating point at any instant, then forward voltage is ob and forward current is oe. To find the a.c. forward resistance, vary the forward voltage on both sides of the operating point equally as shown in Fig. 6.6 where $ab = bc$. It is clear from this figure that :

For forward voltage oa, circuit current is od.

For forward voltage oc, circuit current is of.

$$\therefore \quad \text{a.c. forward resistance, } r_f = \frac{\text{Change in forward voltage}}{\text{Change in forward current}} = \frac{oc - oa}{of - od} = \frac{ac}{df}$$

It may be mentioned here that forward resistance of a crystal diode is very small, ranging from 1 to 25 Ω.

Referring to Fig. 6.50 (*ii*), it is easy to see that C_1 (charged to $V_{S\,(pk)}$)and the source voltage (V_S) now act as *series-aiding* voltage sources. Thus C_2 will be charged to the sum of the series peak voltages *i.e.* 2 $V_{S(pk)}$.

(*iii*) When V_S returns to its original polarity (*i.e.* negative half-cycle), D_2 is again turned off (*i.e.* reverse biased). With D_2 turned off, the only discharge path for C_2 is through the load resistance R_L. The time constant (= $R_L\,C_2$) of this circuit is so adjusted that C_2 has little time to lose any of its charge before the input polarity reverses again. During the positive half-cycle, D_2 is turned on and C_2 recharges until voltage across it is again equal to 2 $V_{S\,(pk)}$.

∴ D.C. output voltage, $V_{dc} = 2\ V_{S\,(pk)}$

Since C_2 barely discharges between input cycles, the output waveform of the half-wave voltage doubler closely resembles that of a filtered half-wave rectifier. Fig. 6.51 shows the input and output waveforms for a half-wave voltage doubler.

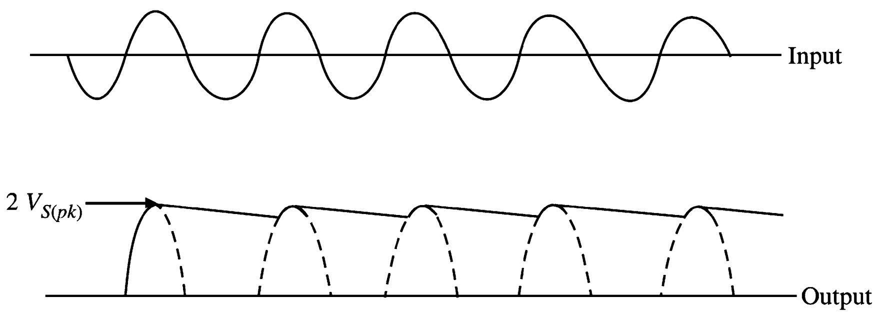


Fig. 6.51

The voltage multipliers have the disadvantage of poor voltage regulation. This means that d.c. output voltage drops considerably as the load current increases. Large filter capacitors are needed to help maintain the output voltage.

6.24 Voltage Stabilisation

A rectifier with an appropriate filter serves as a good source of d.c. output. However, the major disadvantage of such a power supply is that the output voltage changes with the variations in the input voltage or load. Thus, if the input voltage increases, the d.c. output voltage of the rectifier also increases. Similarly, if the load current increases, the output voltage falls due to the voltage drop in the rectifying element, filter chokes, transformer winding etc. In many electronic applications, it is desired that the output voltage should remain constant regardless of the variations in the input voltage or load. In order to ensure this, a voltage stabilising device, called voltage stabiliser is used. Several stabilising circuits have been designed but only *zener diode* as a voltage stabiliser will be discussed.

6.25 Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called *breakdown voltage* is reached where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig. 6.52. The satisfactory explanation of this breakdown of the junction was first given by the American scientist *C*. Zener. Therefore, the breakdown voltage is sometimes called *zener voltage* and the sudden increase in current is known as zener current.

The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called

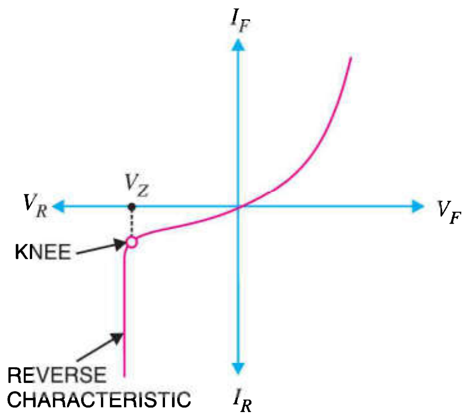


Fig. 6.52

a zener diode.

A properly doped crystal diode which has a sharp breakdown voltage is known as a **zener diode.**

Fig. 6.53 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into *z*-shape. The following points may be noted about the zener diode:

(*i*) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.

(*ii*) A zener diode is always reverse connected *i.e.* it is always reverse biased.

(*iii*) A zener diode has sharp breakdown voltage, called zener voltage V_Z.

(*iv*) When forward biased, its characteristics are just those of ordinary diode.

(*v*) The zener diode is not immediately burnt just because it has entered the *breakdown region. As long as the external circuit connected to the diode limits the diode current to less than *burn out* value, the diode will not burn out.

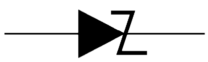
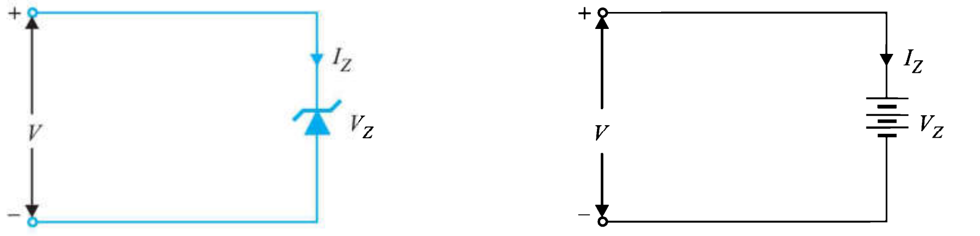


Fig. 6.53

6.26 Equivalent Circuit of Zener Diode

The analysis of circuits using zener diodes can be made quite easily by replacing the zener diode by its equivalent circuit.

(*i*) **"On" state.** When reverse voltage across a zener diode is equal to or more than break down voltage V_Z, the current increases very sharply. In this region, the curve is almost vertical. It means that voltage across zener diode is constant at V_Z even though the current through it changes. Therefore, in the breakdown region, an **ideal zener diode can be represented by a battery of voltage V_Z as shown in Fig. 6.54 (*ii*). Under such conditions, the zener diode is said to be in the "ON" state.



(*i*)
$V \geq V_Z$

(*ii*)
Equivalent circuit of zener for ''on'' state

Fig. 6.54

(*ii*) **"OFF" state.** When the reverse voltage across the zener diode is less than V_Z but greater than 0 V, the zener diode is in the "OFF" state. Under such conditions, the zener diode can be represented by an open-circuit as shown in Fig. 6.55 (*ii*).

* The current is limited only by both external resistance and the power dissipation of zener diode.

** This assumption is fairly reasonable as the impedance of zener diode is quite small in the breakdown region.

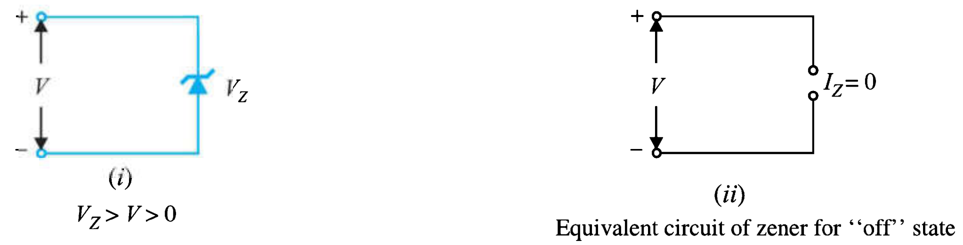


Fig. 6.55

6.27 Zener Diode as Voltage Stabiliser

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range. The circuit arrangement is shown in Fig. 6.56 (*i*). The zener diode of zener voltage V_Z is reverse connected across the load R_L across which constant output is desired. The series resistance R absorbs the output voltage fluctuations so as to maintain constant voltage across the load. It may be noted that the zener will maintain a constant voltage V_Z (= E_0) across the load so long as the input voltage does not fall below V_Z.

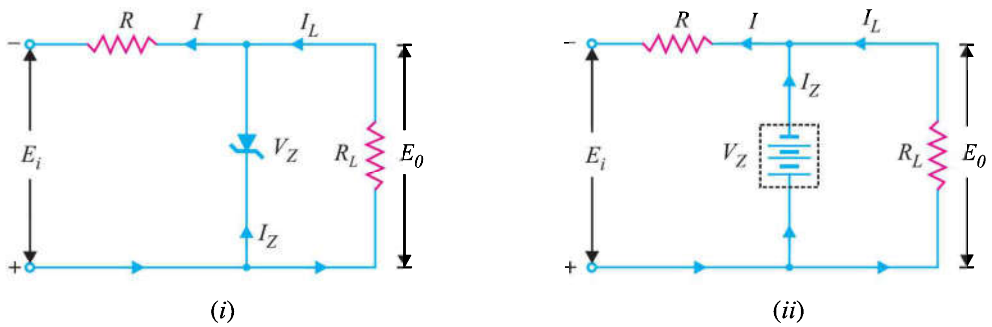


Fig. 6.56

When the circuit is properly designed, the load voltage E_0 remains essentially constant (equal to V_Z) even though the input voltage E_i and load resistance R_L may vary over a wide range.

(*i*) Suppose the input voltage increases. Since the zener is in the breakdown region, the zener diode is equivalent to a battery V_Z as shown in Fig. 6.56 (*ii*). It is clear that output voltage remains constant at V_Z (= E_0). The excess voltage is dropped across the series resistance R. This will cause an increase in the value of total current I. The zener will conduct the increase of current in I while the load current remains constant. Hence, output voltage E_0 remains constant irrespective of the changes in the input voltage E_i.

(*ii*) Now suppose that input voltage is constant but the load resistance R_L decreases. This will cause an increase in load current. The extra current cannot come from the source because drop in R (and hence source current I) will not change as the zener is within its regulating range. The additional load current will come from a decrease in zener current I_Z. Consequently, the output voltage stays at constant value.

$$\text{Voltage drop across } R = E_i - E_0$$
$$\text{Current through } R,\ I = I_Z + I_L$$

Applying Ohm's law, we have,

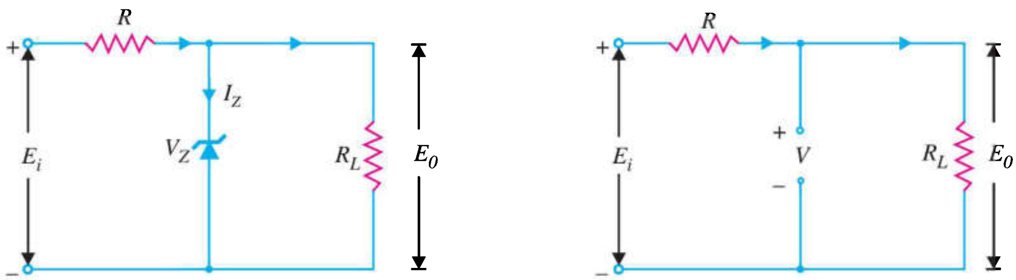
$$R = \frac{E_i - E_0}{I_Z + I_L}$$

6.28 Solving Zener Diode Circuits

The analysis of zener diode circuits is quite similar to that applied to the analysis of semiconductor diodes. The first step is to determine the state of zener diode *i.e.*, whether the zener is in the "on" state or "off" state. Next, the zener is replaced by its appropriate model. Finally, the unknown quantities are determined from the resulting circuit.

1. E_i and R_L fixed. This is the simplest case and is shown in Fig. 6.57 (*i*). Here the applied voltage E_i as well as load R_L is fixed. The first step is to find the state of zener diode. This can be determined by removing the zener from the circuit and calculating the voltage V across the resulting open-circuit as shown in Fig. 6.57 (*ii*).

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$



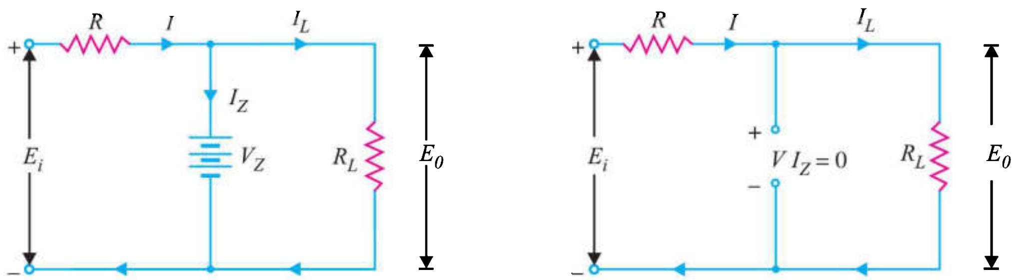
(*i*) (*ii*)

Fig. 6.57

If $V \geq V_Z$, the zener diode is in the "on" state and its equivalent model can be substituted as shown in Fig. 6.58 (*i*). If $V < V_Z$, the diode is in the "off" state as shown in Fig. 6.58 (*ii*).

(*i*) On state. Referring to circuit shown in Fig. 6.58 (*i*),

$$E_0 = V_Z$$



(*i*) (*ii*)

Fig. 6.58

7.1 Zener Diode

A zener diode is a special type of diode that is designed to operate in the reverse breakdown region. An ordinary diode operated in this region will usually be destroyed due to excessive current. This is not the case for the zener diode.

A zener diode is heavily doped to reduce the reverse breakdown voltage. This causes a very thin depletion layer. As a result, a zener diode has a sharp reverse breakdown voltage V_Z. This is clear from the reverse characteristic of zener diode shown in Fig. 7.1. Note that the reverse characteristic drops in an almost vertical manner at reverse voltage V_Z. As the curve reveals, two things happen when V_Z is reached :

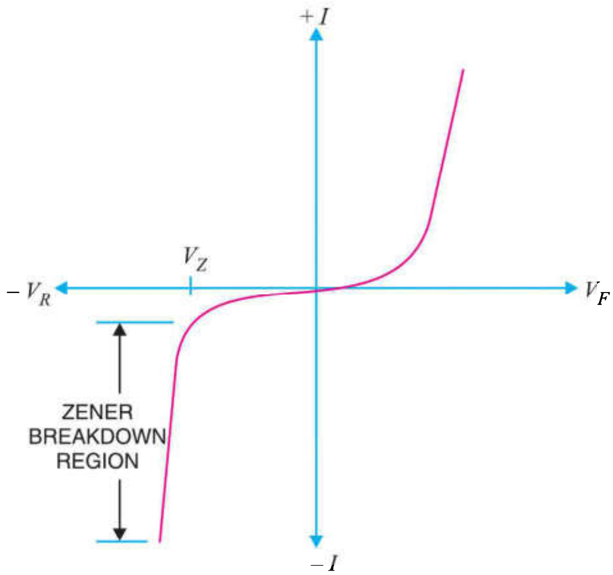


Fig. 7.1

(*i*) The diode current increases rapidly.

(*ii*) The reverse voltage V_Z across the diode remains almost constant.

In other words, *the zener diode operated in this region will have a relatively constant voltage across it, regardless of the value of current through the device.* This permits the zener diode to be used as a *voltage regulator.* For detailed discussion on zener diode, the reader may refer to chapter 6 of this book.

7.2 Light-Emitting Diode (LED)

A **light-emitting diode (LED)** *is a diode that gives off visible light when forward biased.*

Light-emitting diodes are not made from silicon or germanium but are made by using elements like gallium, phosphorus and arsenic. By varying the quantities of these elements, it is possible to produce light of different wavelengths with colours that include red, green, yellow and blue. For example, when a LED is manufactured using gallium arsenide, it will produce a red light. If the LED is made with gallium phosphide, it will produce a green light.

Light-emitting diode

Theory. When light-emitting diode (LED) is forward biased as shown in Fig. 7.2 (*i*), the electrons from the *n*-type material cross the *pn* junction and recombine with holes in the *p*-type material. Recall that these free electrons are in the conduction band and at a higher energy level than the holes in the valence band. When recombination takes place, the recombining electrons release energy in the form of heat and light. In germanium and silicon diodes, almost the entire energy is given up in the form of heat and emitted light is insignificant. However, in materials like gallium arsenide, the number of photons of light energy is sufficient to produce quite intense visible light.

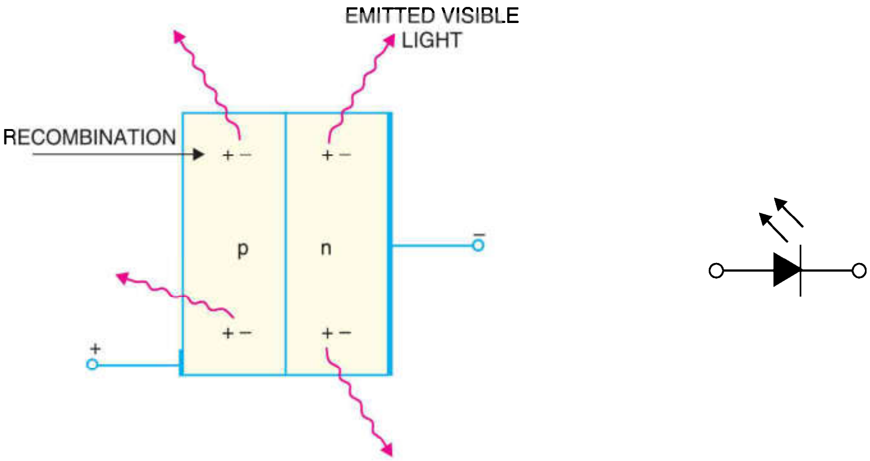


Fig. 7.2

Fig. 7.2 (*ii*) shows the schematic symbol for a LED. The arrows are shown as pointing away from the diode, indicating that light is being emitted by the device when forward biased. Although LEDs are available in several colours (red, green, yellow and orange are the most common), the schematic symbol is the same for all LEDs. There is nothing in the symbol to indicate the colour of a particular LED. Fig. 7.3 shows the graph between radiated light and the forward current of the LED. It is clear from the graph that the intensity of radiated light is directly proportional to the forward current of LED.

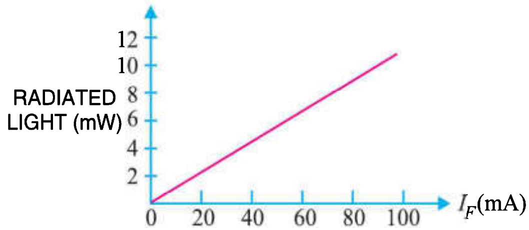


Fig. 7.3

7.3 LED Voltage and Current

The forward voltage ratings of most LEDs is from 1V to 3V and forward current ratings range from 20 mA to 100 mA. In order that current through the LED does not exceed the safe value, a resistor R_S is connected in series with it as shown in Fig. 7.4. The input voltage is V_S and the voltage across LED is V_D.

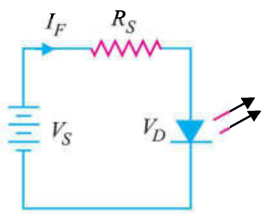


Fig. 7.4

∴ Voltage across $R_S = V_S - V_D$

∴ Circuit current, $I_F = \dfrac{V_S - V_D}{R_S}$

Example 7.1. *What value of series resistor is required to limit the current through a LED to 20 mA with a forward voltage drop of 1.6 V when connected to a 10V supply ?*

Solution.

Series resistor, $R_S = \dfrac{V_S - V_D}{I_F}$

Here $V_S = 10\text{ V}; \quad V_D = 1.6\text{ V}; \quad I_F = 20\text{ mA} = 20 \times 10^{-3}\text{ A}$

$$\therefore \qquad R_S = \frac{10 - 1.6}{20 \times 10^{-3}} = \mathbf{420\ \Omega}$$

Note that resistor R_S is also called *current-limiting resistor.*

Example 7.2. *What is current through the LED in the circuit shown in Fig. 7.5 ? Assume that voltage drop across the LED is 2 V.*

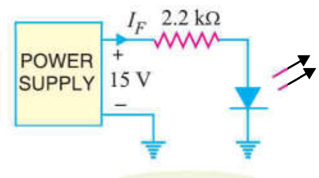


Fig. 7.5

Solution.

$$\text{Current through LED, } I_F = \frac{V_S - V_D}{R_S}$$

Here $V_S = 15$ V; $V_D = 2$ V; $R_S = 2.2\ \text{k}\Omega = 2.2 \times 10^3\ \Omega$

$$\therefore \qquad I_F = \frac{15 - 2}{2.2 \times 10^3} = 5.91 \times 10^{-3}\ \text{A} = \mathbf{5.91\ mA}$$

7.4 Advantages of LED

The light-emitting diode (LED) is a solid-state light source. LEDs have replaced incandescent lamps in many applications because they have the following advantages :

(*i*) Low voltage

(*ii*) Longer life (more than 20 years)

(*iii*) Fast on-off switching

Protecting LED against reverse bias. The LEDs have low reverse voltage ratings. For example, a typical LED may have a maximum reverse voltage rating of 3V. This means that if a reverse voltage greater than 3 V is applied to the LED, the LED may be destroyed. Therefore, one must be careful not to use LEDs with a high level of reverse bias. One way to protect a LED is to connect a rectifier diode in parallel with LED as shown in Fig. 7.6. If reverse voltage greater than the reverse voltage rating of LED is accidentally applied, the rectifier diode will be turned on. This protects the LED from damage.

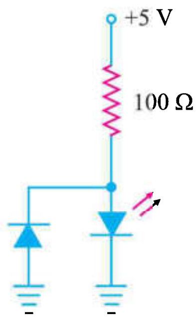


Fig. 7.6

7.5 Multicolour LEDs

A LED that emits one colour when forward biased and another colour when reverse biased is called a **multicolour LED.**

One commonly used schematic symbol for these LEDs is shown in Fig. 7.7. Multicolour LEDs

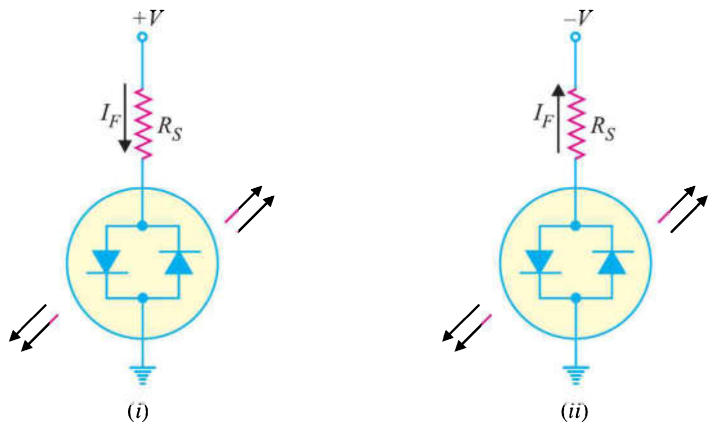


Fig. 7.7

actually contain two *pn* junctions that are connected in *reverse-parallel i.e.* they are in parallel with anode of one being connected to the cathode of the other. If positive potential is applied to the top terminal as shown in Fig. 7.7 (*i*), the *pn* junction on the **left** will light. Note that the device current passes through the left *pn* junction. If the polarity of the voltage source is reversed as shown in Fig. 7.7 (*ii*), the *pn* junction on the **right** will light. Note that the direction of device current has reversed and is now passing through the right *pn* junction.

Multicolour LEDs are typically *red* when biased in one direction and *green* when biased in the other. If a multicolour LED is switched fast enough between two polarities, the LED will produce a *third* colour. A red/green LED will produce a *yellow* light when rapidly switched back and forth between biasing polarities.

7.6 Applications of LEDs

The LED is a low-power device. The power rating of a LED is of the order of milliwatts. This means that it is useful as an indicator but not good for illumination. Probably the two most common applications for visible LEDs are (*i*) as a power indicator (*ii*) seven-segment display.

(*i*) **As a power indicator.** A LED can be used to indicate whether the power is on or not. Fig. 7.8 shows the simple use of the LED as a power indicator. When the switch *S* is closed, power is applied to the load. At the same time current also flows through the LED which lights, indicating power is on. The resistor R_S in series with the LED ensures that current rating of the LED is not exceeded.

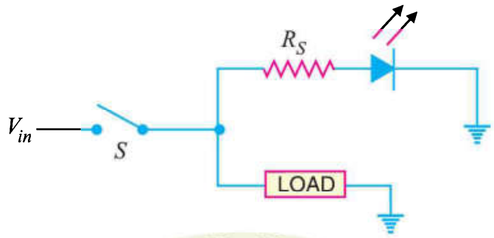


Fig. 7.8

(*ii*) **Seven-segment display.** LEDs are often grouped to form seven-segment display. Fig. 7.9 (*i*) shows the front of a seven segment display. It contains seven LEDs (*A, B, C, D, E, F* and *G*) shaped in a figure of *8. Each LED is called a **segment. If a particular LED is forward biased, that LED or segment will light and produces a bar of light. By forward biasing various combinations of seven LEDs, it is possible to display any number from 0 to 9. For example, if LEDs *A, B, C, D* and *G* are lit (by forward biasing them), the display will show the number 3. Similarly, if LEDs *C, D, E, F, A* and *G* are lit, the display will show the number *6*. To get the number 0, all segments except *G* are lit.

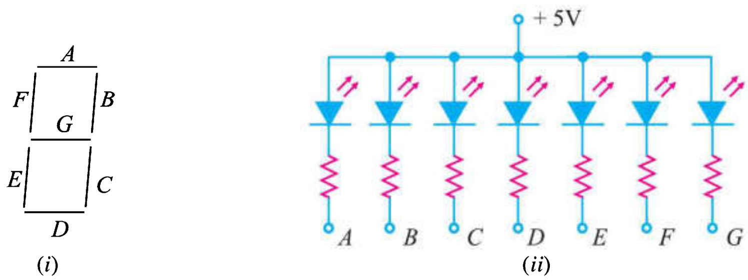


Fig. 7.9

Fig. 7.9 (*ii*) shows the schematic diagram of seven-segment display. External series resistors are included to limit currents to safe levels. Note that the anodes of all seven LEDs are connected to a

* Note that LEDs *A, B, C, D, E* and *F* are arranged clockwise from the top with LED *G* in the middle.

** Each LED is called a segment because it forms part of the character being displayed.