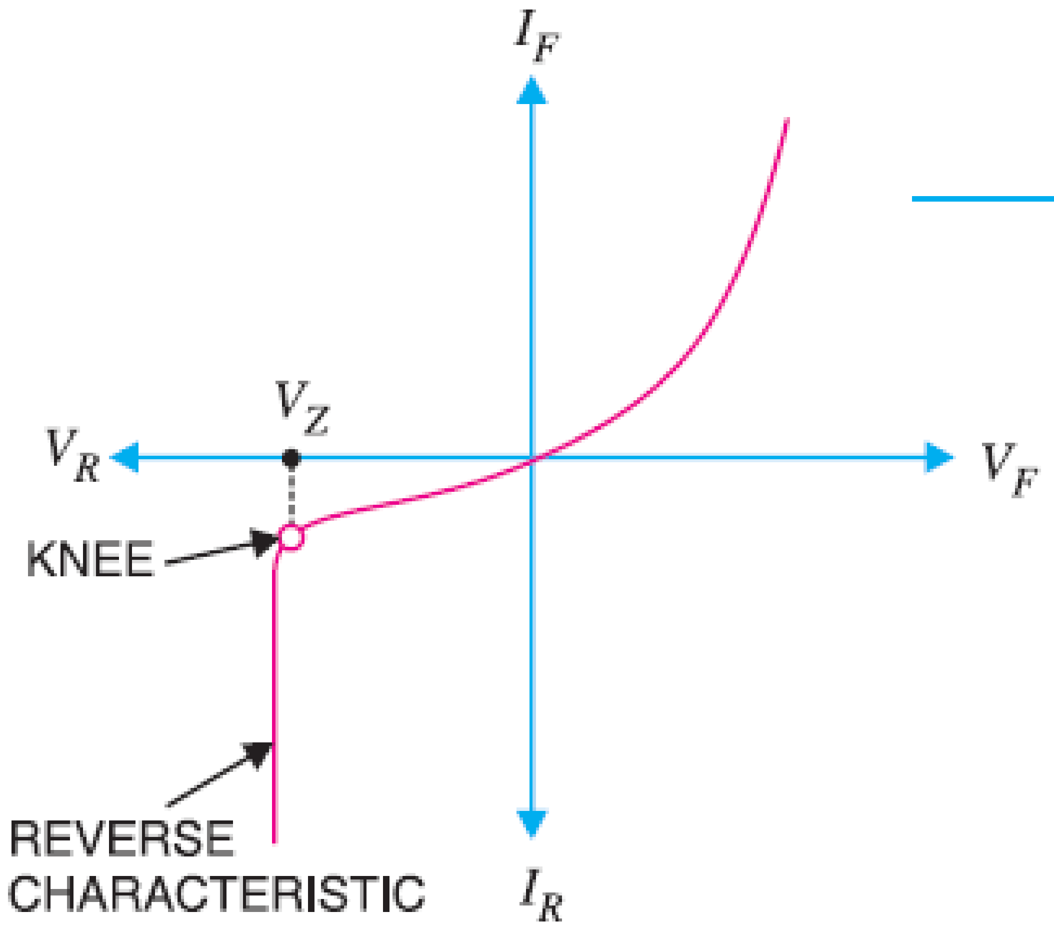
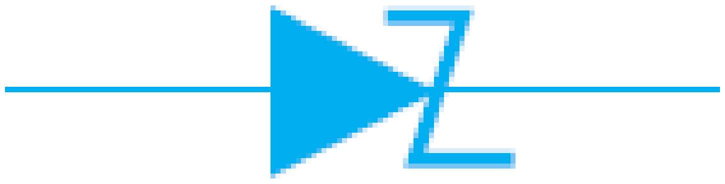
ZENER DIODE

- 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.
- 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.

Zener Diode Characteristics





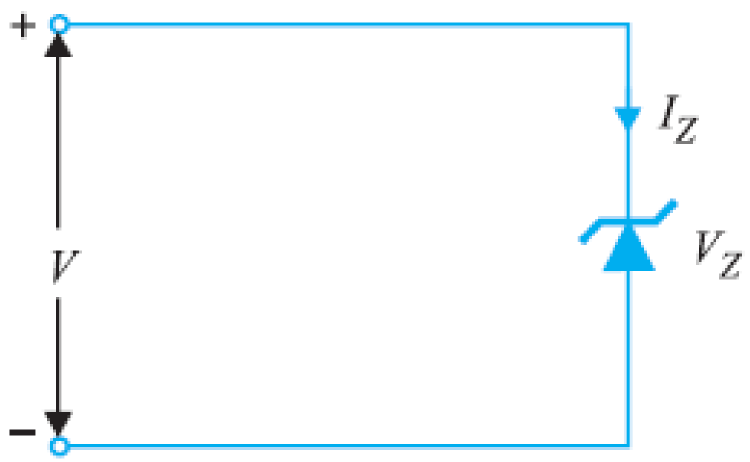
- The breakdown or zener voltage depends upon the amount of doping.
- If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage.
- On the other hand, a lightly doped diode has a higher breakdown voltage.
- When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called a zener diode.
- *"A properly doped crystal diode which has a sharp breakdown voltage is known as 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:
- A Zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.
- A Zener diode is always reverse connected *i.e.* it is always reverse biased.
- A Zener diode has sharp breakdown voltage, called Zener voltage *VZ*.
- When forward biased, its characteristics are just those of ordinary diode.
- 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.

Equivalent Circuit of Zener diode

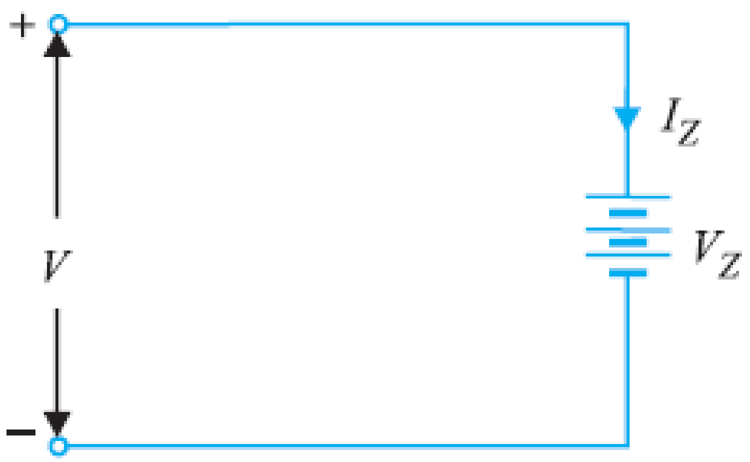
- The analysis of circuits using Zener diodes can be made quite easily by replacing the Zener diode by its equivalent circuit.
- ON STATE: When reverse voltage across a Zener diode is equal to or more than break down voltage *VZ*, the current increases very sharply. In this region, the curve is almost vertical.
- It means that voltage across Zener diode is constant at *VZ* even though the current through it changes.
- Therefore, in the breakdown region, an ideal Zener diode can be represented by a battery of voltage *VZ* as shown in Fig Under such conditions, the Zener diode is said to be in the "ON" state.

ON STATE



(i)

$V \geq V_Z$

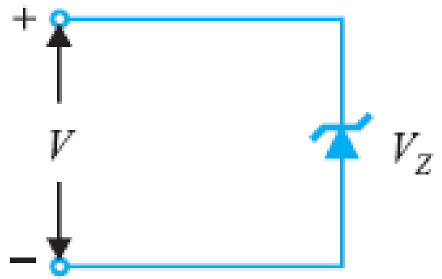


(ii)

Equivalent circuit of zener for "on" state

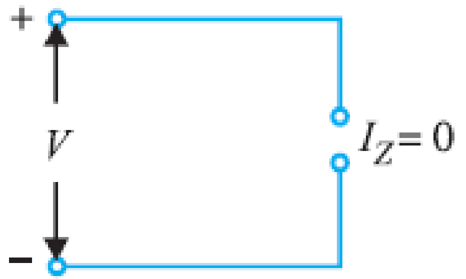
OFF STATE

- When the reverse voltage across the Zener diode is less than *VZ* 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.



(*i*)

$V_Z > V > 0$



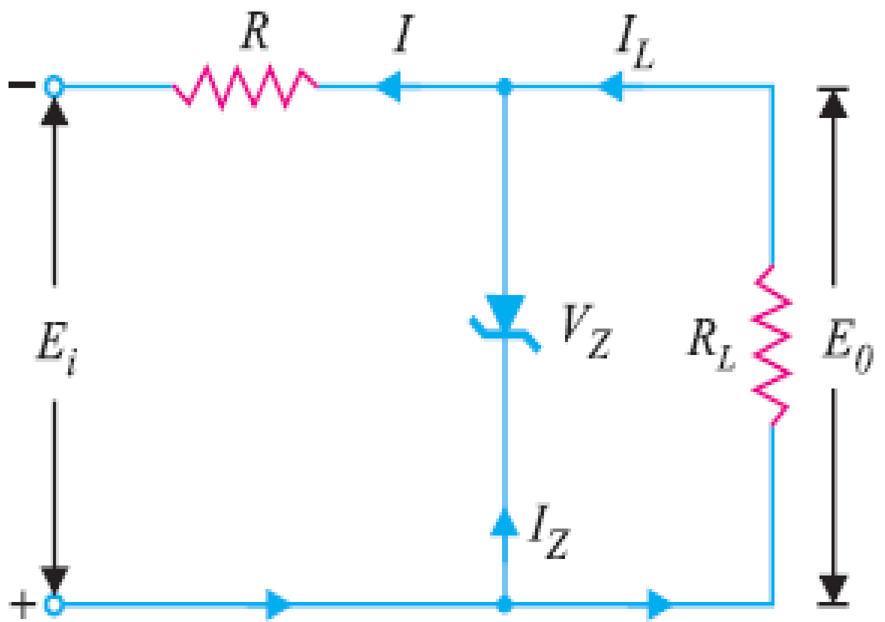
(*ii*)

Equivalent circuit of zener for ‘‘off’’ state

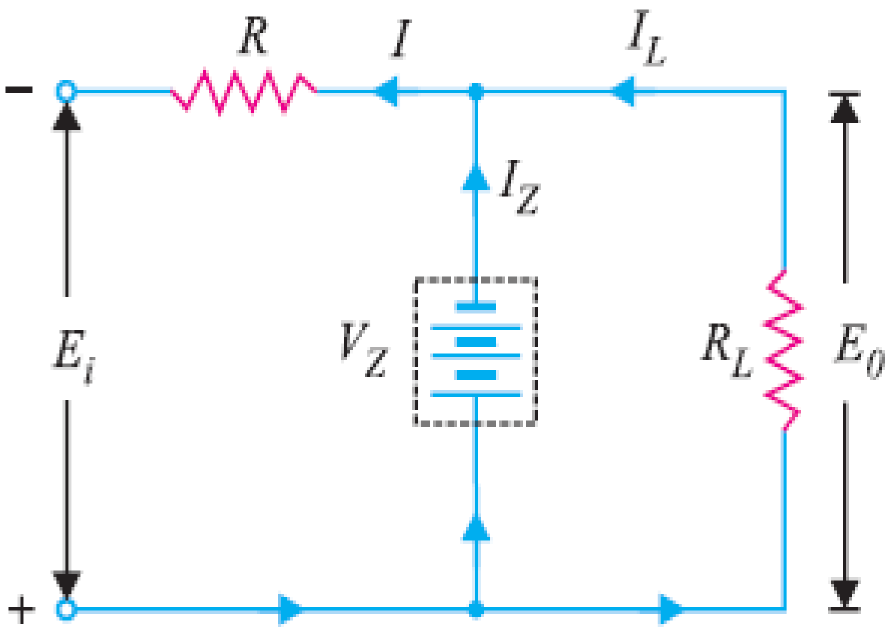
Zener Diode as Voltage Stabilizer

- 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 shown in fig
- The Zener diode of Zener voltage *VZ* is reverse connected across the load *RL* 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 *VZ* (= *E*0) across the load so long as the input voltage does not fall below *VZ*.
- When the circuit is properly designed, the load voltage *E*0 remains essentially constant (equal to *VZ*) even though the input voltage *Ei* and load resistance *RL* may vary over a wide range.

Zener Diode as Voltage Stabilizer



(i)



(ii)

- I) Suppose the input voltage increases. Since the Zener is in the breakdown region, the Zener diode is equivalent to a battery VZ as shown in Fig. 6.56 (*ii*).
- It is clear that output voltage remains constant at VZ (= $E0$). 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 $E0$ remains constant irrespective of the changes in the input voltage Ei.

- II) Now suppose that input voltage is constant but the load resistance *RL* 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 *IZ*. Consequently, the output voltage stays at constant value.

Voltage drop across $R = E_i - E_0$

Current through R, $I = I_Z + I_L$

Applying Ohm's law, we have,

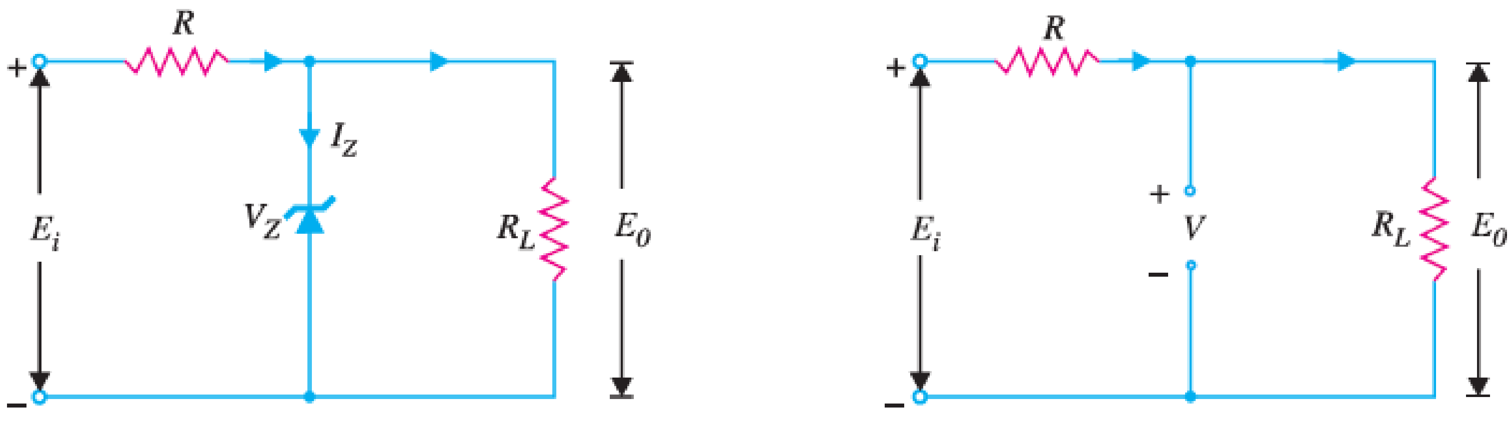
$$R = \frac{E_i - E_0}{I_Z + I_L}$$

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.

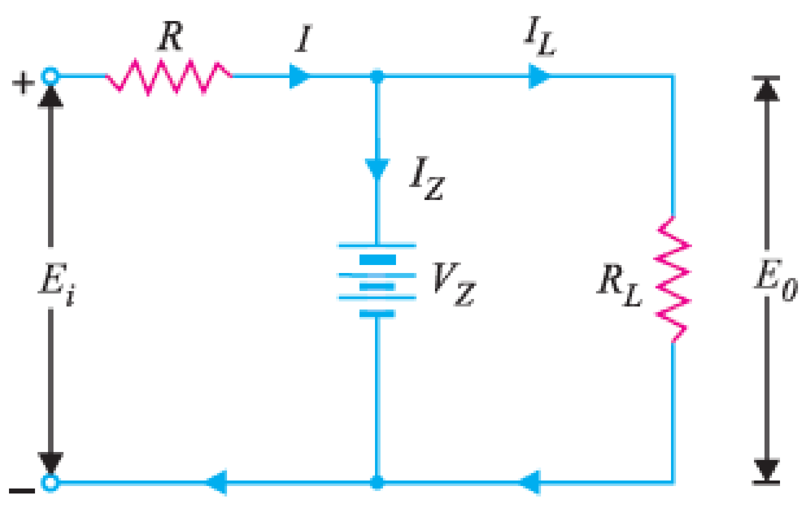
- **1) . Ei and RL fixed.** This is the simplest case and is shown in Fig. 6.57 (*i*). Here the applied
- voltage *Ei* as well as load *RL* is fixed. The first step is to find the state of zener diode. This can be determined by removing the zener from the circuit and calculating the voltage *V* across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

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

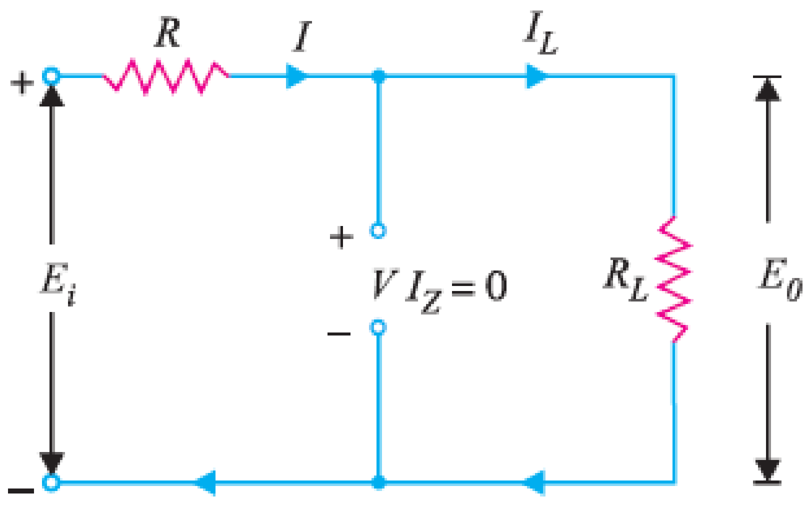


(*i*) (*ii*)

- If *V* >*VZ*, the Zener diode is in the "on" state and its equivalent model can be substituted as shown in Fig. 6.58
- (*i*). If *V* < *VZ*, 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*),



(*i*)



(*ii*)

$$I_Z = I - I_L \quad \text{where } I_L = \frac{E_0}{R_L} \text{ and } I = \frac{E_i - E_0}{R}$$

Power dissipated in zener, $P_Z = V_Z I_Z$

(*ii*) **Off state.** Referring to the circuit shown in Fig. 6.58 (*ii*),

$$I = I_L \quad \text{and} \quad I_Z = 0$$

$$V_R = E_i - E_0 \quad \text{and} \quad V = E_0 \quad (V < V_Z)$$

$$\therefore \quad P_Z = V I_Z = V(0) = 0$$

2. Fixed Ei and Variable RL. This case is shown in Fig. Here the applied voltage (*Ei*) is fixed while load resistance *RL* (and hence load current *IL*) changes.

Note that there is a definite range of *RL* values (and hence *IL* values) which will ensure the Zener diode to be in "on" state. Let us calculate that range of values.

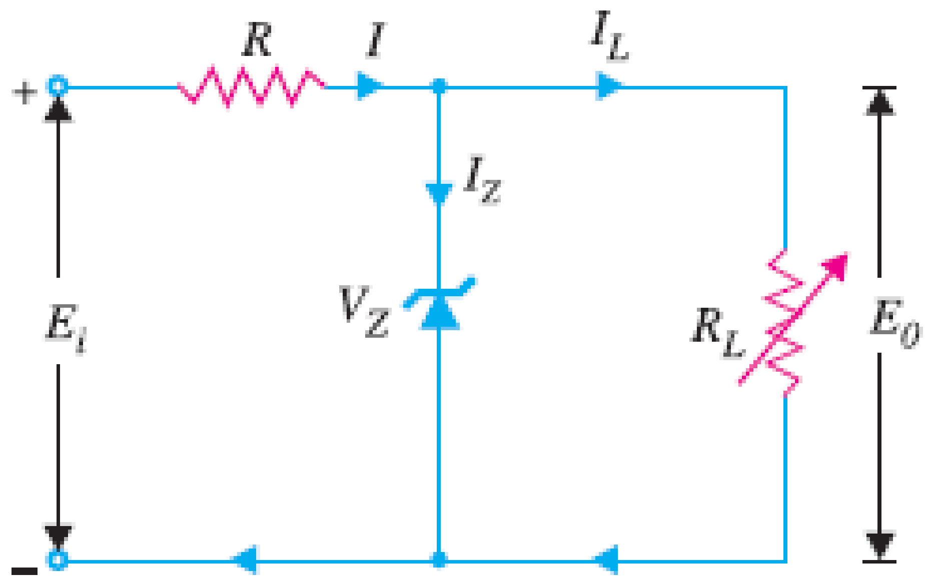


Fig. 6.59

(*i*) RLmin and ILmax. Once the zener is in the "on"

state, load voltage *E*0 (= *VZ*) is constant. As a result, when load resistance is minimum (*i.e.*, *RLmin*), load currentwill be maximum (*IL* = *E*0/*RL*).

In order to find the minimum load resistance that will turn the zener on, we simply calculate the value of *R*

L that will result in *E*0 = *VZ*

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

$$R_{Lmin} = \frac{R V_Z}{E_i - V_Z}$$

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

$$R_{Lmin} = \frac{R \ V_Z}{E_i - V_Z}$$

This is the minimum value of load resistance that will ensure that zener is in the "on" state. Any value of load resistance less than this value will result in a voltage *E*0 across the load less than *VZ* and the zener will be in the "off" state.

$$I_{Lmax} = \frac{E_0}{R_{Lmin}} = \frac{V_Z}{R_{Lmin}}$$

$$R_{Lmax} = \frac{E_0}{I_{Lmin}} = \frac{V_Z}{I_{Lmin}}$$

If the load resistance exceeds this limiting value, the current through Zener will exceed *IZM* and the device may burn out.

3. Fixed RL and Variable Ei. This case is shown in Fig. 6.60. Here the load resistance *RL* is fixed while the applied voltage (*Ei*) changes. Note that there is a definite range of *Ei* values that will ensure that zener diode is in the "on" state. Let us calculate that range of values.

(*i*) Ei (*min*). To determine the minimum applied voltage that will turn the zener on, simply calculate the value of *Ei* that will result in load voltage *E0* = *VZ*

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

$$\therefore \qquad E_{i\,(min)} = \frac{(R + R_L)\,V_Z}{R_L}$$

(*ii*) E_i (*max*)

Now, current through R, $I = I_Z + I_L$

Since I_L $(= E_0/R_L = V_Z/R_L)$ is fixed, the value of I will be maximum when zener current is maximum *i.e.*,

$$I_{max} = I_{ZM} + I_L$$

Now $\qquad E_i = I\,R + E_0$

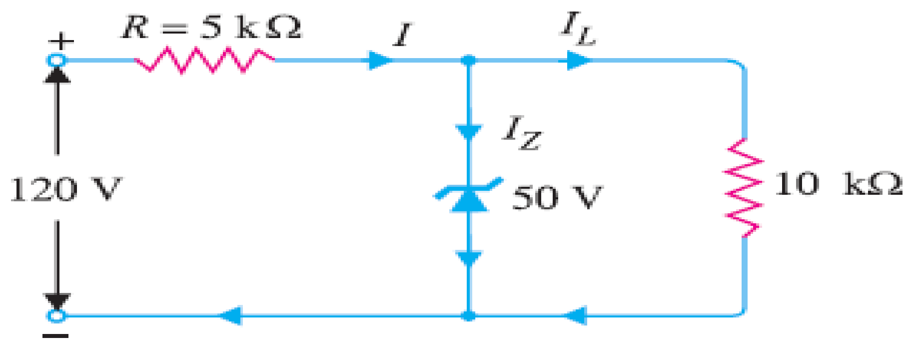
Since E_0 $(= V_Z)$ is constant, the input voltage will be maximum when I is maximum.

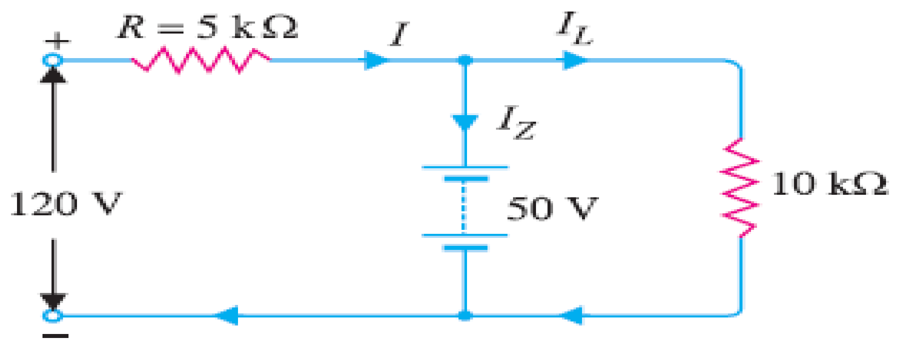
$$\therefore \qquad E_{i\,(max)} = I_{max}\,R + V_Z$$

Example 6.25. *For the circuit shown in Fig. 6.61 (i), find :*

(i) the output voltage *(ii) the voltage drop across series resistance*

(iii) the current through zener diode.





Solution. If you remove the zener diode in Fig. 6.61 (*i*), the voltage V across the open-circuit is given by :

$$V = \frac{R_L E_i}{R + R_L} = \frac{10 \times 120}{5 + 10} = 80 \text{ V}$$

Since voltage across zener diode is greater than V_Z (= 50 V), the zener is in the "on" state. It can, therefore, be represented by a battery of 50 V as shown in Fig. 6.61 (*ii*).

(*i*) Referring to Fig. 6.61 (*ii*),

$$\text{Output voltage} = V_Z = \mathbf{50\ V}$$

(*ii*) $$\text{Voltage drop across } R = \text{Input voltage} - V_Z = 120 - 50 = \mathbf{70\ V}$$

(*iii*) $$\text{Load current, } I_L = V_Z/R_L = 50 \text{ V}/10 \text{ k}\Omega = 5 \text{ mA}$$

$$\text{Current through } R,\ I = \frac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$$

$$\text{Applying Kirchhoff's first law, } I = I_L + I_Z$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9\ mA}$$

Example 6.27. *A 7.2 V zener is used in the circuit shown in Fig. 6.63 and the load current is to vary from 12 to 100 mA. Find the value of series resistance R to maintain a voltage of 7.2 V across the load. The input voltage is constant at 12V and the minimum zener current is 10 mA.*

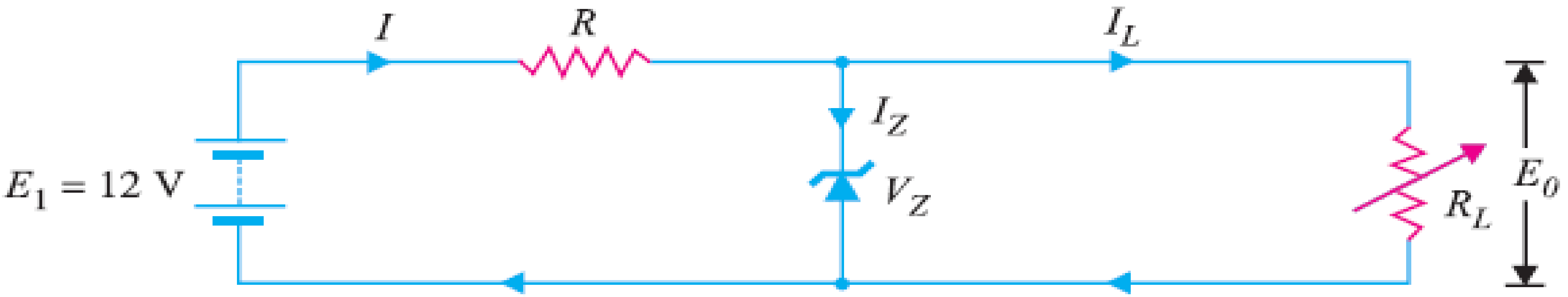


Fig. 6.63

Solution.

$$E_i = 12 \text{ V} ; \quad V_Z = 7.2 \text{ V}$$

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

The voltage across R is to remain constant at $12 - 7.2 = 4.8$ V as the load current changes from 12 to 100 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{12 \text{ V} - 7.2 \text{ V}}{(10 + 100) \text{ mA}} = \frac{4.8 \text{ V}}{110 \text{ mA}} = \mathbf{43.5\ \Omega}$$

If $R = 43.5\ \Omega$ is inserted in the circuit, the output voltage will remain constant over the regulating range. As the load current I_L decreases, the zener current I_Z will increase to such a value that $I_Z + I_L =$ 110 mA. Note that if load resistance is open-circuited, then $I_L = 0$ and zener current becomes 110 mA.

Example 6.28. *The zener diode shown in Fig. 6.64 has $V_Z = 18$ V. The voltage across the load stays at 18 V as long as I_Z is maintained between 200 mA and 2 A. Find the value of series resistance R so that E_0 remains 18 V while input voltage E_i is free to vary between 22 V to 28V.*

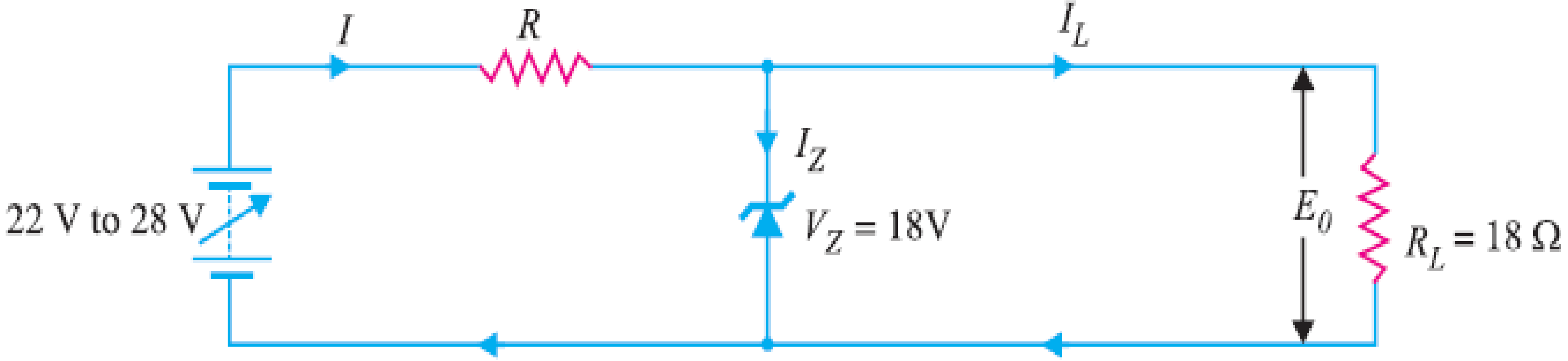


Fig. 6.64

Solution. The zener current will be minimum (*i.e.* 200 mA) when the input voltage is minimum (*i.e.* 22 V). The load current stays at constant value $I_L = V_Z / R_L = 18\text{ V}/18\ \Omega = 1\text{ A} = 1000$ mA.

$$\therefore \qquad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(22-18)\text{ V}}{(200+1000)\text{ mA}} = \frac{4\text{ V}}{1200\text{ mA}} = \mathbf{3.33\ \Omega}$$

Example 6.29. *A 10-V zener diode is used to regulate the voltage across a variable load resistor [See fig. 6.65]. The input voltage varies between 13 V and 16 V and the load current varies between 10 mA and 85 mA. The minimum zener current is 15 mA. Calculate the value of series resistance R.*

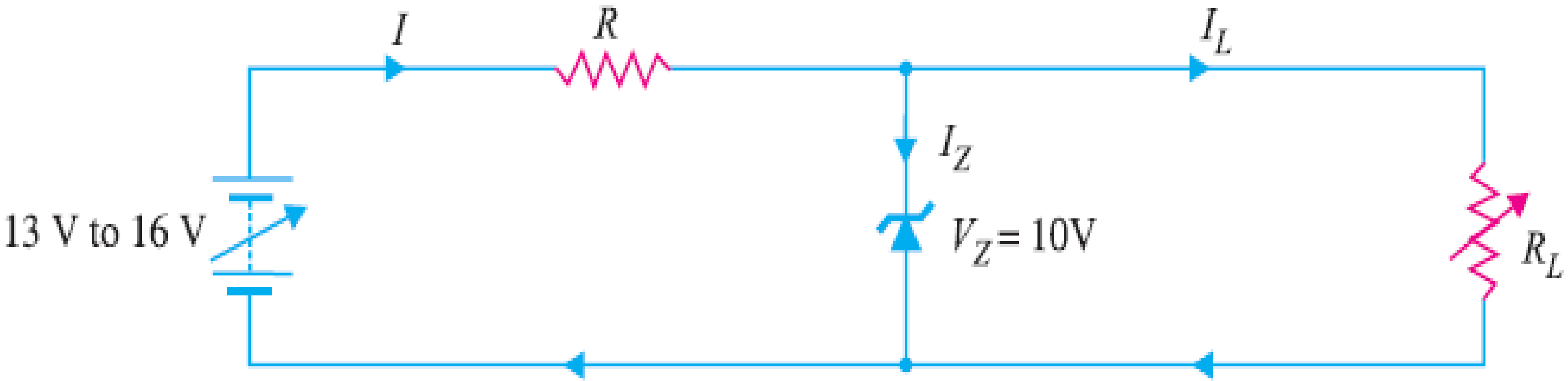


Fig. 6.65

Solution. The zener will conduct minimum current (*i.e.* 15 mA) when input voltage is minimum (*i.e.* 13 V).

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(13-10)\text{ V}}{(15+85)\text{ mA}} = \frac{3\text{ V}}{100\text{ mA}} = 30\ \Omega$$

Example 6.30. *The circuit of Fig. 6.66 uses two zener diodes, each rated at 15 V, 200 mA. If the circuit is connected to a 45-volt unregulated supply, determine :*

(i) The regulated output voltage *(ii) The value of series resistance R*

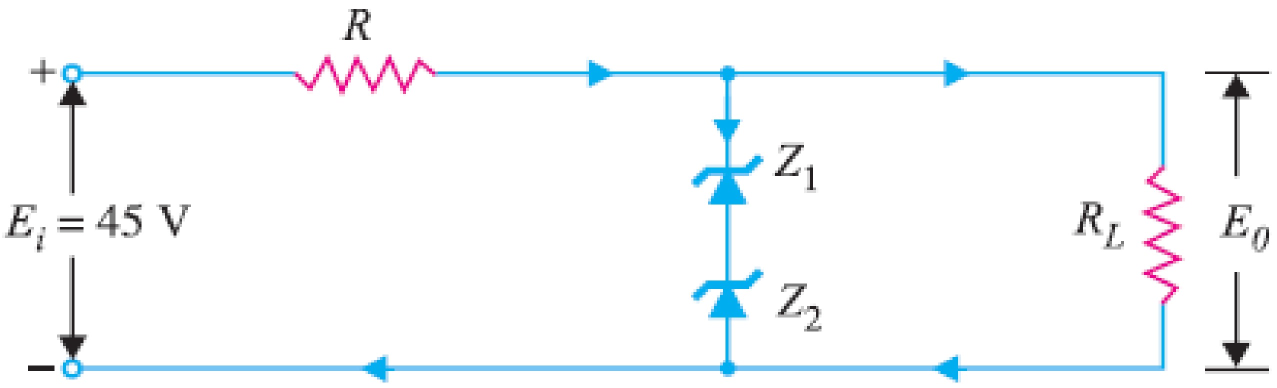


Fig. 6.66

Solution. When the desired regulated output voltage is higher than the rated voltage of the zener, two or more zeners are connected in series as shown in Fig. 6.66. However, in such circuits, care must be taken to select those zeners that have the same current rating.

Current rating of each zener, $I_Z = 200$ mA

Voltage rating of each zener, $V_Z = 15$ V

Input voltage, $E_i = 45$ V

(i) Regulated output voltage, $E_0 = 15 + 15 = \mathbf{30\ V}$

(ii) Series resistance, $R = \dfrac{E_i - E_0}{I_Z} = \dfrac{45 - 30}{200 \text{ mA}} = \dfrac{15 \text{ V}}{200 \text{ mA}} = \mathbf{75\ \Omega}$

Example 6.31. *What value of series resistance is required when three 10-watt, 10-volt, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45 volt d.c. power source ?*

Solution. Fig. 6.67 shows the desired circuit. The worst case is at no load because then zeners carry the maximum current.

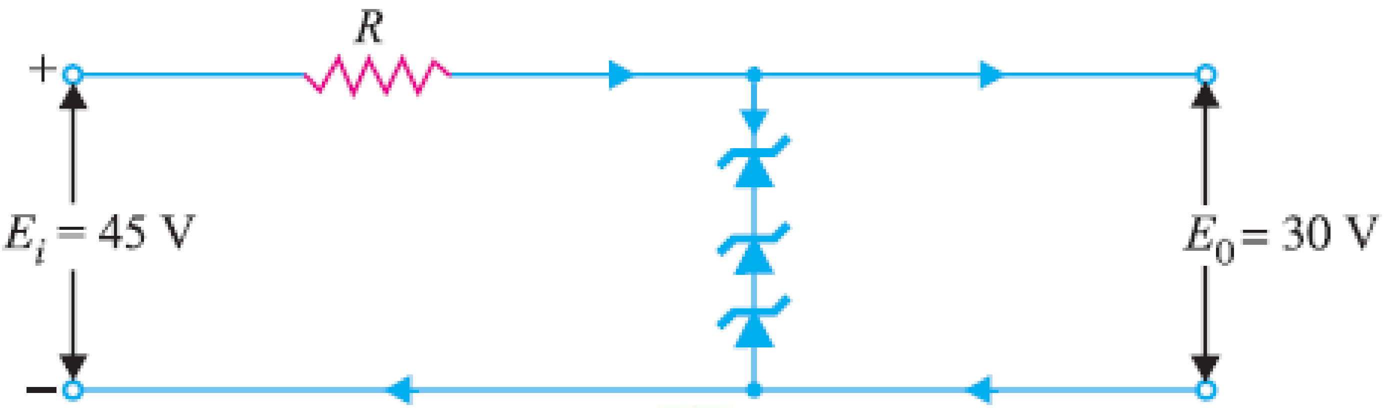


Fig. 6.67

$$\text{Voltage rating of each zener, } V_Z = 10\text{ V}$$
$$\text{Current rating of each zener, } I_Z = 1000\text{ mA}$$
$$\text{Input unregulated voltage, } E_i = 45\text{ V}$$
$$\text{Regulated output voltage, } E_0 = 10 + 10 + 10 = 30\text{ V}$$

Let R ohms be the required series resistance.

$$\text{Voltage across } R = E_i - E_0 = 45 - 30 = 15\text{ V}$$

$$\therefore \quad R = \frac{E_i - E_0}{I_Z} = \frac{15\text{ V}}{1000\text{ mA}} = 15\ \Omega$$

Example 6.32. *Over what range of input voltage will the zener circuit shown in Fig. 6.68 maintain 30 V across 2000 Ω load, assuming that series resistance R = 200 Ω and zener current rating is 25 mA ?*

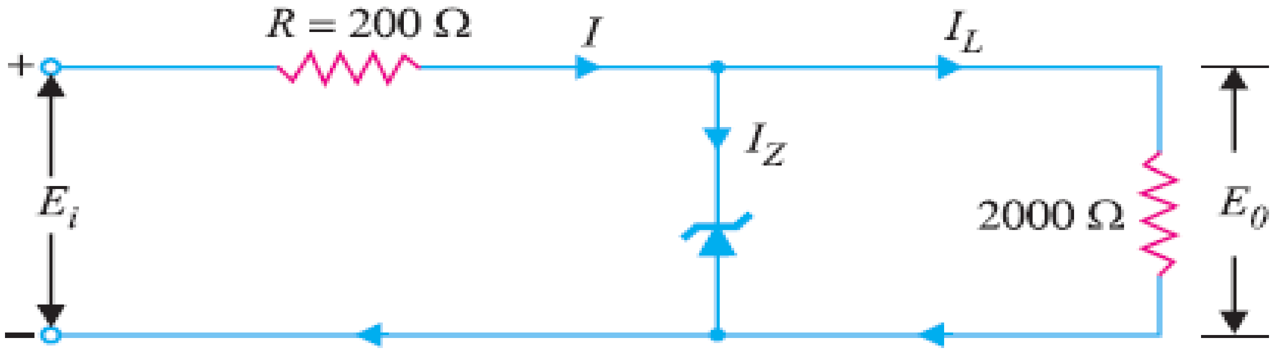


Fig. 6.68

Solution. The minimum input voltage required will be when $I_Z = 0$. Under this condition,

$$I_L = I = \frac{30\text{ V}}{2000\ \Omega} = 15\text{ mA}$$

$$\therefore \quad \text{Minimum input voltage} = 30 + IR = 30 + 15\text{ mA} \times 200\ \Omega$$

$$= 30 + 3 = \mathbf{33\ V}$$

The maximum input voltage required will be when $I_Z = 25$ mA. Under this condition,

$$I = I_L + I_Z = 15 + 25 = 40\text{ mA}$$

$$\therefore \quad \text{Max. input voltage} = 30 + IR$$

$$= 30 + 40\text{ mA} \times 200\ \Omega$$

$$= 30 + 8 = \mathbf{38\ V}$$

Therefore, the input voltage range over which the circuit will maintain 30 V across the load is **33 V to 38 V.**

Example 6.33. *In the circuit shown in Fig. 6.69, the voltage across the load is to be maintained at 12 V as load current varies from 0 to 200 mA. Design the regulator. Also find the maximum wattage rating of zener diode.*

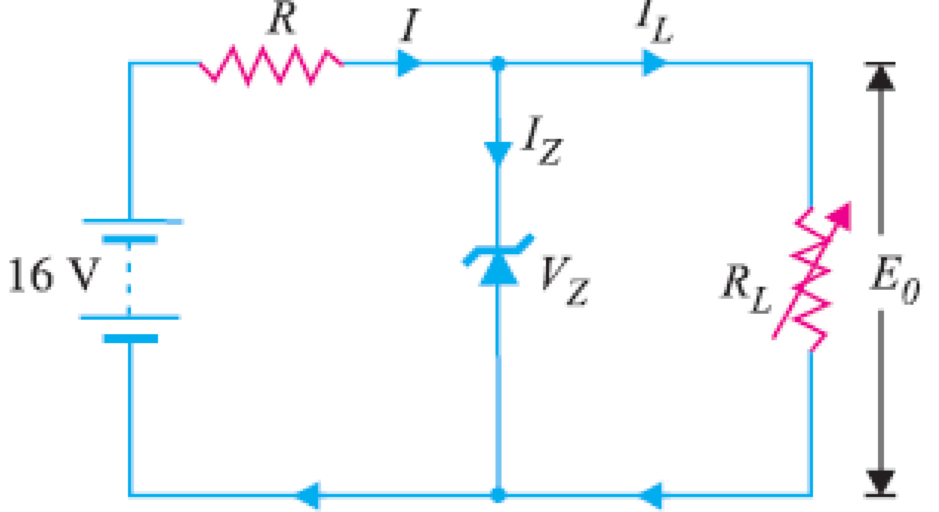


Fig. 6.69

Solution. By designing the regulator here means to find the values of V_Z and R. Since the load voltage is to be maintained at 12 V, we will use a zener diode of zener voltage 12 V *i.e.*,

$$V_Z = \mathbf{12\ V}$$

The voltage across R is to remain constant at 16 − 12 = 4 V as the load current changes from 0 to 200 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{16 - 12}{(0 + 200)\text{ mA}} = \frac{4\text{ V}}{200\text{ mA}} = \mathbf{20\ \Omega}$$

Maximum power rating of zener is

$$P_{ZM} = V_Z I_{ZM} = (12\text{ V})(200\text{ mA}) = \mathbf{2.4\ W}$$

Crystal Diode Versus Vacuum Diode

- **Advantages :**
- **(*i*)** They are smaller, more rugged and have a longer life.
- **(*ii*)** They are simpler and inherently cheaper.
- **(*iii*)** They require no filament power. As a result, the produce less heat than the equivalent vacuum diodes.

- **Disadvantages :**
- **(*i*)** They are extremely heat sensitive. Even a slight rise in temperature increases the current appreciably.
- Should the temperature exceed the rated value of the diode, the increased flow of current may produce enough heat to ruin the *pn* junction.
- On the other hand, vacuum diodes function normally over a wide range of temperature changes.
- It may be noted that silicon is better than germanium as a semiconductor material. Whereas a germanium diode should not be operated at temperatures higher than 80ºC, silicon diodes may operate safely at temperatures upto about 200ºC.
- **(*ii*)** They can handle small currents and low inverse voltages as compared to vacuum diodes.
- **(*iii*)** They cannot stand an overload even for a short period. Any slight overload, even a transient pulse, may permanently damage the crystal diode. On the other hand, vacuum diodes can stand an overload for a short period and when the overload is removed, the tube will generally recover.