Contents

CHAPTER 2

Diodes and Applications

GOALS AND OBJECTIVES

- Discussion of various types of diodes
- Description of *PN*-junction diode
- Zener diode and its applications as voltage regulator
- Types of rectifiers—half wave, full wave and bridge rectifier
- Rectifier with centre tapped (CT) transformer
- Different types of wave shaping
- Explanation of special purpose diodes—Schottky, barrier and photodiode

2.1 INTRODUCTION

A diode is a two-layer (*PN*-junction) device which facilitates conduction in one direction and stops conduction in the other direction. It has a wide range of applications like rectification (converting ac to dc), voltage regulation, protection against high voltage and wave shaping. Furthermore, there are special purpose diodes, e.g. Zener diode, light-emitting diode and several others.

2.2 PN-JUNCTION DIODE

As shown in Fig. 2.1, the junction is formed when thin layers of *P*- and *N*-type semiconductor, are joined together that results in following phenomenon immediately.

- The majority holes from *P*-side diffuse into *N*-side and vice versa.
- Recombination of electrons and holes in a narrow region on both sides of the junction results in uncovered fixed positive ions on *N*-side and fixed negative ions on *P*-side.
- This is the *depletion region* where no free electrons and holes are present.
- The electric field set up by the positive and negative ions prevents further flow of electrons and holes.
- The electric field causes the movement of minority carriers in opposite direction that provides a minority carrier *drift* current.
- In steady-state, there is no net current flow across the junction.

The simplified diagram of an open-circuit *PN*-junction diode is drawn in Fig. 2.2 where V_o is a constant potential. The *P*-side terminal is called the *anode* and the *N*-side terminal is the *cathode*. The symbol of diode is shown in Fig. 2.3.

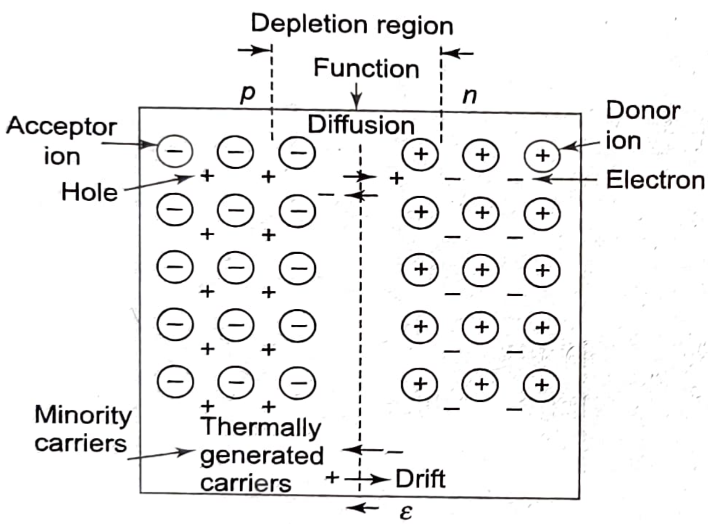

Fig. 2.1 Phenomenon at PN-junction

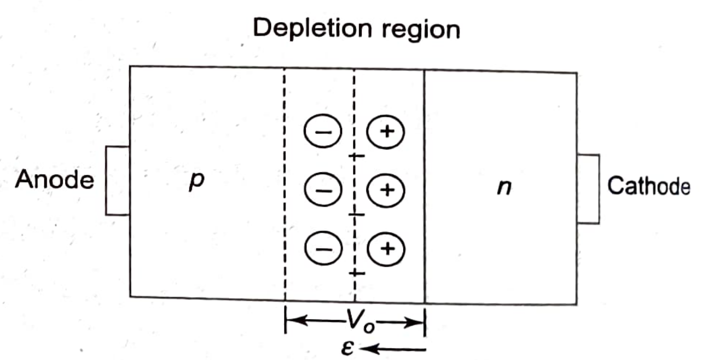

Fig. 2.2 An open-circuited PN-junction diode

2.2.1 Reverse Bias

In reverse bias, the positive terminal of the battery is connected to *N*-side (cathode) and negative terminal of the battery is connected to *P*-side (anode) as shown in Fig. 2.3.

As a result of reverse biasing, the majority of holes and electrons are pulled away from the junction. This causes the width of the depletion region to increase. Therefore, the majority carrier current cannot flow. However, the minority carrier drift current flows but stays at the saturation level I_s as the minority carrier concentrations are very low. I_s is known as the *reverse saturation current*, which is almost of negligible order (nA for Si and μA for Ge).

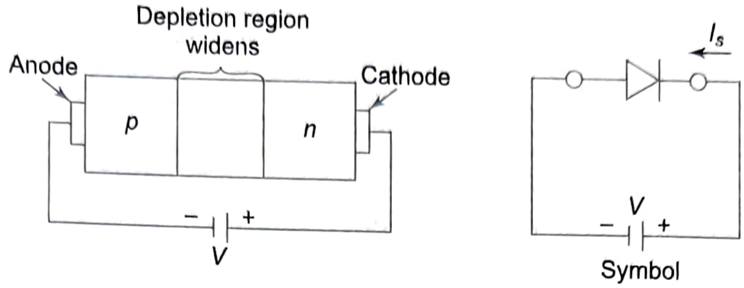

Fig. 2.3 Reverse-biased diode

2.2.2 Forward Bias

The positive terminal of the battery is connected to the anode (*P*-side) and negative terminal, to cathode (*N*-side). The holes from *P*-side and electrons from *N*-side get pushed towards the junction, thereby narrowing the depletion region. As a result, holes easily cross to *N*-side and electrons to *P*-side constituting the injunction current (I_i). The reverse saturation current I_s flows in the opposite direction. The net forward current $I_f = I_i - I_s$ increases sharply and is limited to a value determined by an external series resistance (load).

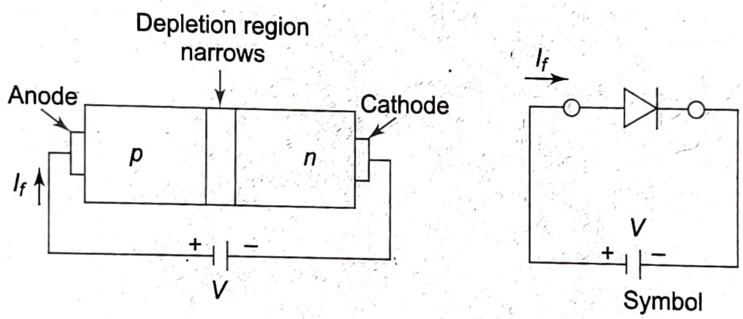

Fig. 2.4 Forward-biased diode

✦ Diode Relationship

$$I_D = I_s(e^{kV_D/T_k} - 1) \tag{2.1}$$

where I_s = reverse saturation current

k = $11{,}600/\eta$; $\eta = 1$ for Ge and $\eta = 2$ for Si for low current, below the knee of the curve and

η = 1 for both Ge and Si for higher level of current beyond the knee (see Fig. 2.5).

$T_k = T_c + 273°$, and

T_c = operating temperature (25°C)

The plots of Eq. (2.1) for Ge and Si diodes are drawn to scale in Fig. 2.5. The sharply rising part of the curve extended downward meets the V_D axis, which is indicated as

V_T = offset, threshold or firing potential.

It is quite accurate to assume that $I_D = 0$ up to V_T and then increases almost linearly at a sharp slope. The values of V_T are

V_T = 0.7 V for Si diode

$V_T = 0.3$ V for Ge diode

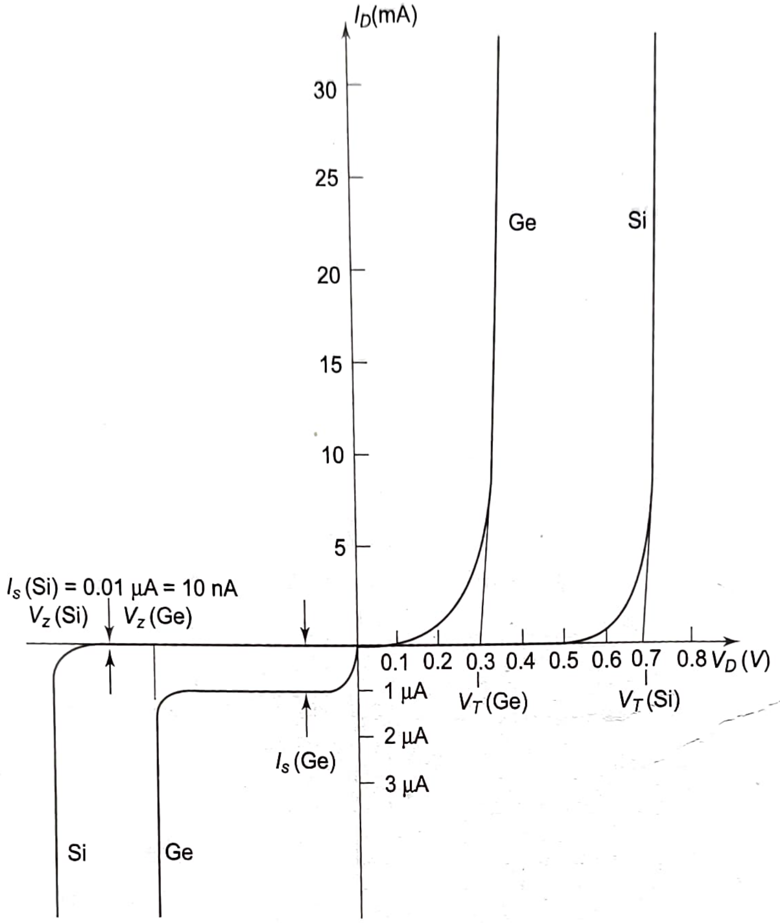

Fig. 2.5 Diode characteristics

EXAMPLE 2.1 An Si diode has I_s = 10 nA operating at 25°C. Calculate I_D for a forward bias of 0.6 V.

Solution We take $\eta = 2$

$$T_k = 25° + 273° = 298°$$

$$k = \frac{11,600}{2} = 5,800$$

$$kV_D/T_k = \frac{5800 \times 0.6}{298} = 11.68$$

$$e^{11.68} = 117930$$

Then $$I_D = 10\,(117930 - 1) = 10 \times 0.117929 \times 10^6 \text{ nA}$$
$$= 1.18 \text{ mA, negligible.}$$

This justifies the choice of $\eta = 2$

Note: The diode is to conduct current much larger than this value.
Therefore, $I_D = 1.18$ mA may be approximated as zero.

❑ ***Zener Region*** As the reverse-bias voltage is raised, the diode breaks down at voltage V_z, by *avalanche phenomenon*. The maximum negative voltage that a diode can withstand is at Peak Inverse Voltage (PIV rating).

❑ ***Zener Breakdown*** By heavily doping the *N*- and *P*-regions, the breakdown voltage V_z can be brought as low as –10 V, –5 V. This mechanism of breakdown is different from avalanche. This type of diode is called *zener diode*. When connected at a point in an electronic circuit, it does not allow the potential there to exceed the diode rated voltage.

2.2.3 Equivalent Circuit of Diode

✦ Ideal Diode

It conducts when $V_D > 0$ as shown in Fig. 2.6(a).

✦ Piecewise Linear Model

From the diode characteristic of Fig. 2.5, the piecewise linear characteristic follows and is drawn in Figs. 2.6(a), (b) and (c) along with its circuit model.

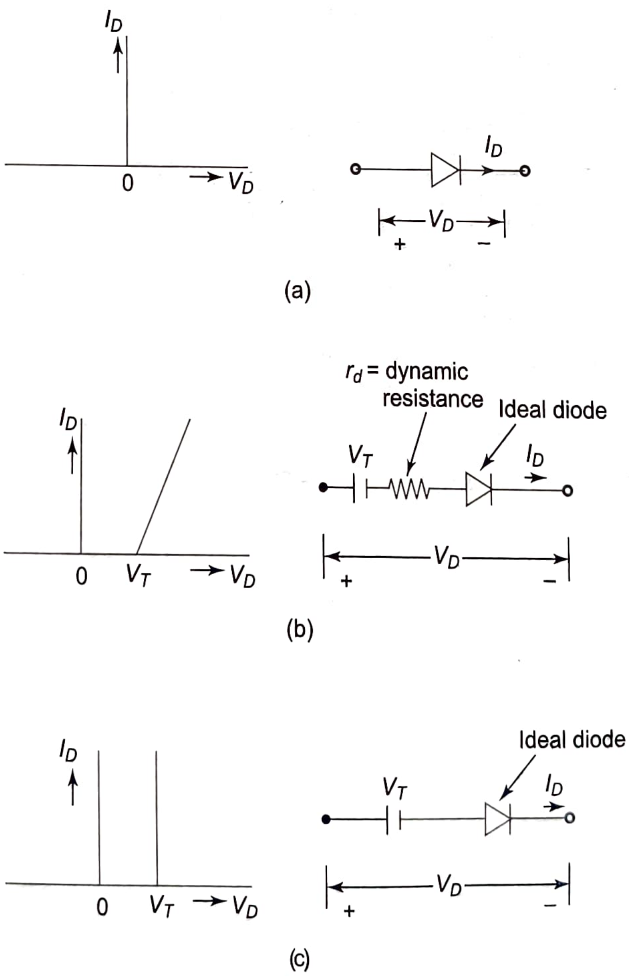

Fig. 2.6 (a) Ideal diode (b) Piecewise linear model (c) Approximate model

✦ Dynamic Resistance

$$r_d = \frac{dV_D}{dI_D} \text{ (average)}$$

It can be proved that dynamic resistance on any point of the actual IV characteristic of a diode is given by

$$r_d = \frac{26 \text{ mV}}{I_D \text{ (mA)}} \tag{2.2}$$

The dynamic resistance of r_d is quite small and order of few ohms.

❑ ***Approximate Model*** Assuming $r_d = 0$, the model characteristic and circuit are drawn in Fig. 2.6(c). This equivalent circuit of diode is used most often.

EXAMPLE 2.2 For the diode circuits of Fig. 2.7, find the value of *I*. Use approximate model of the diode.

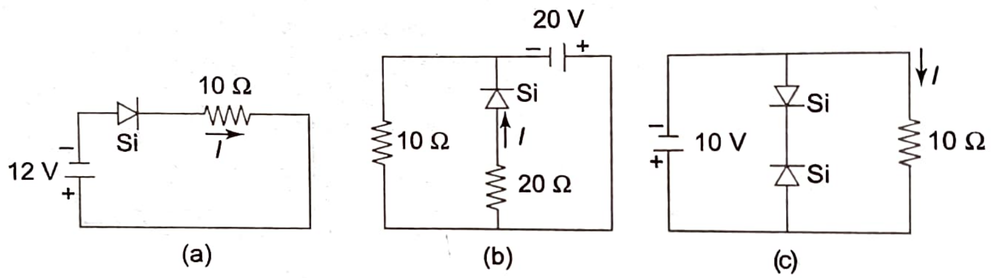

Fig. 2.7

Solution

(a) The Si diode is reverse biased by 12 V. So it does not conduct.

$$I = 0$$

(b) The voltage across diode branch is 20 V independent of 10 Ω resistance. Therefore, the diode conducts. As per equivalent circuit,

$$I = \frac{20 - 0.7}{20} = \frac{19.3}{20} = 0.965 \text{ A}$$

(c) The two diodes are in opposition and cannot conduct (open circuit).
Thus,

$$I = \frac{-10}{10} = -1 \text{A}$$

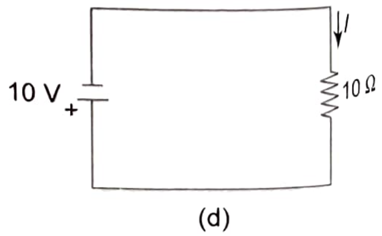

Fig. 2.7(d)

EXAMPLE 2.3 For the diode circuits of Fig. 2.8, determine I_D and V_o using approximate model of the diode.

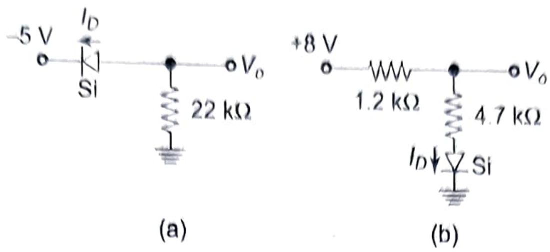

Fig. 2.8

Solution (a) The equivalent circuit is drawn in adjoining Fig. 2.9(a).

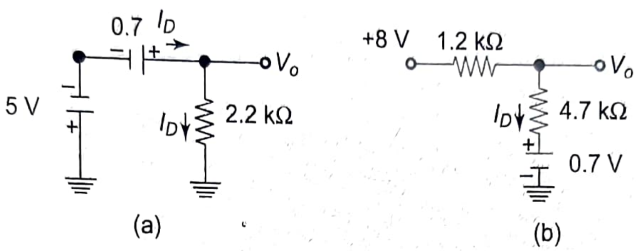

Fig. 2.9

$$I_D = \frac{5-0.7}{2.2} = \frac{4.3}{2.2} = 1.95 \text{ mA}$$

$$V_o = 2.2\, I_D = 2.2 \times \frac{4.3}{2.2} = 4.3 \text{ V}$$

or directly,

$$V_o = 5 - 0.7 = 4.3 \text{ V}$$

(b) The equivalent circuit is drawn in Fig. 2.9(b).

$$I_D = \frac{8-0.7}{1.2+4.7} = \frac{7.3}{5.9} = 1.237 \text{ mA}$$

$$V_o = 4.7 \times 1.237 + 0.7 = 6.51 \text{ V}$$

EXAMPLE 2.4 For the diode circuits of Fig. 2.10(a), determine V_o and I_D.

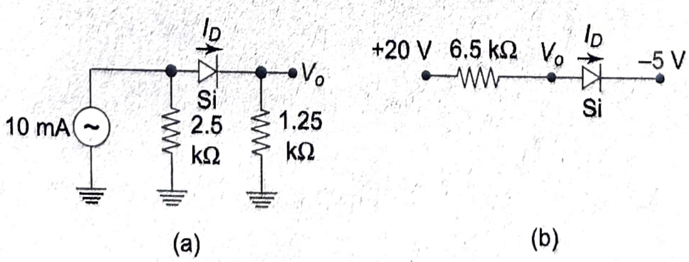

Fig. 2.10

(a) Converting current source to voltage source and diode by its circuit model, we get the circuit of the adjoining figure (Fig. 2.11).

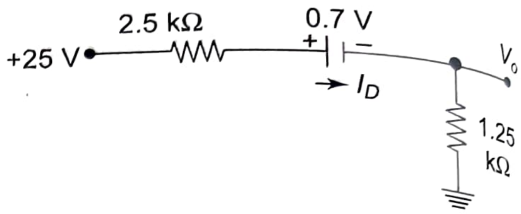

Fig. 2.11

$$I_D = \frac{25 - 0.7}{2.5 + 1.25} = 6.48 \text{ mA}$$

$$V_o = 1.25 \times 6.48 = 8.1 \text{ V}$$

(b) We can proceed directly.

$$I_D = \frac{20 - 0.7 + 5}{6.5} = 3.738 \text{ mA}$$

$$V_o = 20 - 3.738 \times 6.5 = -4.3 \text{ V}$$

or $$V_o = -5 + 0.7 = -4.3 \text{ V}$$

EXAMPLE 2.5 For the network of Fig. 2.12, determine V_{o1} and V_{o2}.

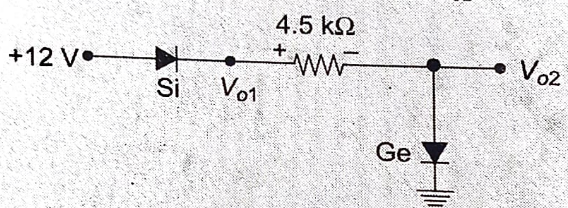

Fig. 2.12

Solution

$$V_{o2} = 0.3 \text{ V or } V_T(\text{Ge}) = 0.3 \text{ V when conducting}$$

$$V_{o1} = 12 - 0.7 = 11.3 \text{ V}$$

Note the result does not depend on 4.5 kΩ.

EXAMPLE 2.6 For the diode network of Fig. 2.13, determine V_o.

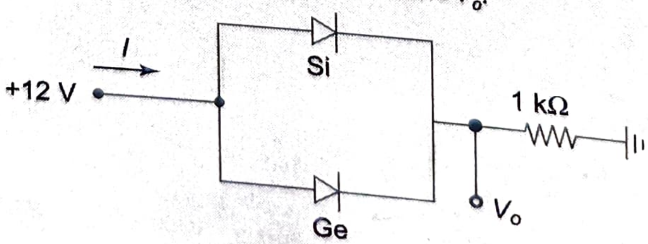

Fig. 2.13

Solution Diode Ge conducts, holding voltage at $V_T = 0.3$ V. Therefore, diode Si does not conduct as its $V_T = 0.7$ V

$$I = \frac{12 - 0.3}{1} = 11.7\text{mA}$$

$$V_0 = 1 \times 11.7 = 11.7 \text{ V}$$

EXAMPLE 2.7 Determine V_0 for the negative logic OR gate.

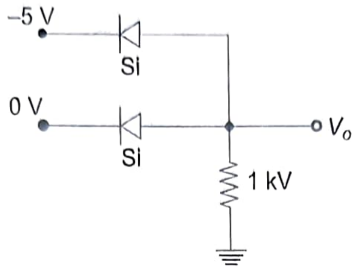

Fig. 2.14(a)

Solution Top diode conducts

$$V_o = -5 + 0.7 = -4.3 \text{ V}$$

Lower diode is negatively biased, so does not conduct.

The output will be $V_o = -4.3$ V (high of negative logic) for input –5 V at any one or both terminals. The output will be zero (low) if both inputs are zero. This is presented in tabular form in Fig. 2.14(b).

In		Out
0	0	0
0	1	1
1	0	1
1	1	1

0 ~ Low (0 V)

1 ~ High (–4.3 V)

Fig. 2.14(b)

EXAMPLE 2.8 Determine V_o for negative logic AND gate of Fig. 2.15.

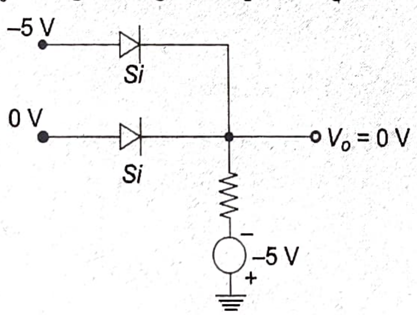

Fig. 2.15

Solution The lower diode will conduct.

$$V_o = 0 \text{ V (low, 0)}$$

If both inputs are 0 V, both diodes conduct. $V_o = 0$ V (low, 0). If both inputs are –5 V, both diodes do not conduct, $V_o = -5$ V (high, 1).

−5 V = high, 0 V = low, 0

The result is presented in the table below.

In		Out
0	0	0
1	0	0
0	1	0
1	1	1

This is negative, AND.

2.3 ZENER DIODE

A zener diode has zener breakdown in reverse bias as shown in *IV* characteristic of Fig. 2.16(a). The symbol of the zener diode is drawn in Fig. 2.16(b). Its equivalent circuit is drawn in Fig. 2.16(c). It is connected in a circuit such that it is reverse biased. It conducts only if reverse bias exceeds V_z. For positive bias, it acts as short circuit.

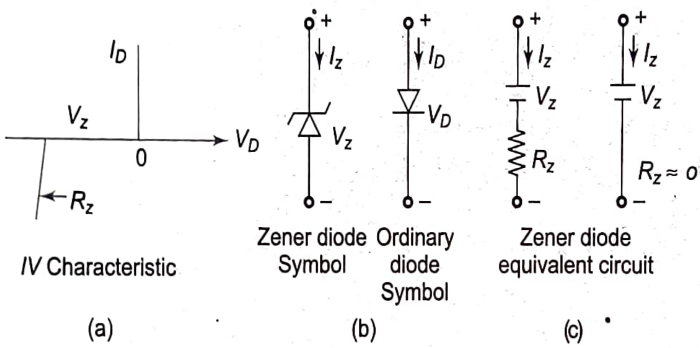

Fig. 2.16 Zener diode

2.3.1 Zener Diode as a Voltage Regulator

Voltage regulators are the devices used to maintain constant voltage across a load despite of fluctuations in the input voltage and load currents. The Zener diode in its reverse bias region is widely used as a voltage regulator as it continues to operate till the magnitude of current becomes less than $I_{Z(min)}$. The typical Zener voltage regulator is shown in Fig. 2.17. The Zener diode of breakdown voltage V_Z is connected to the input supply in reverse direction. For all the values of current within the breakdown region, the voltage across the diode will remain fixed at V_Z, giving a constant supply across its load.

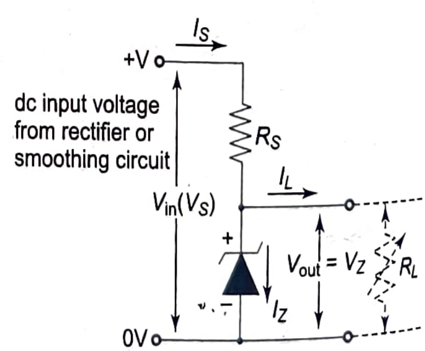

Fig. 2.17 Zener diode as a voltage regulator

The resistance R_S controls the current flowing in the circuit.

❑ ***Case I: When no load is connected ($I_L = 0$)***

The current flowing in the circuit entirely passes through Zener diode. The diode dissipates maximum power. Thus, utmost care must be taken while selecting the series resistor so as to maintain the power dissipation within the range of maximum power dissipating capability of the diode.

❑ ***Case II: When load resistance R_L is connected across the diode***

Here, since the load is parallel to Zener diode, the output voltage will be equal to V_Z. The Zener current must always be above $I_{z(\min)}$ (current for which the stabilisation of voltage is effective). The higher limit of current allowed to flow in the circuit depends upon the power dissipating capability of the components used.

The voltage regulation can be done through two techniques:

1. ***Line Regulation*** In this case, series resistance and load resistance are kept constant and it is assumed that all the variations in voltage arise due to fluctuations in input power supply. The regulated output voltage is achieved for input voltage above certain minimum level. The percentage of regulation is given by

$$\frac{\Delta V_0}{\Delta V_{IN}} \times 100$$

   where V_0 is the output voltage, V_{IN} is the input voltage, and ΔV_0 is the change in output voltage for a particular change in input voltage ΔV_{IN}.
2. ***Load Regulation*** In this, the input voltage is fixed while the load resistance is varied. The constant output voltage is obtained as long as the load resistance is maintained above a minimum value. The percentage of regulation is given by

$$\left(\frac{V_{NL} - V_{FL}}{V_{NL}}\right) \times 100$$

   where V_{NL} is the voltage across the Zener Diode when no load is applied and V_{NL} is the full load resistor voltage.

EXAMPLE 2.9 The circuit of Fig. 2.18 has a zener diode connected across the load.

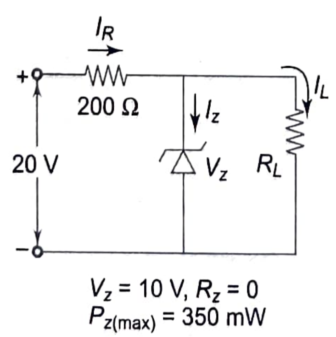

Fig. 2.18

(a) For $R_L = 180\ \Omega$, determine all currents and voltages.
(b) Repeat part (a) for $R_L = 450\ \Omega$.
(c) Find the value of R_L for the zener to draw maximum power.
(d) Find the minimum value of R_L for the zener to be just in on-state.

Solution

(a) As R_L is small, assume that the zener does not conduct,

i.e. $I_z = 0.$

Then, $$I_R = I_L = \frac{20}{200+180} = 52.6\text{ mA}$$

$$V_z = V_L = 20 - 200 \times 52.6 \times 10^{-3} = 9.48 < 10\text{ V}$$

So our assumption is correct.

(b) $$R_L = 450\ \Omega$$

Assume that the zener conducts.

$$V_L = V_z = 10\text{ V}$$

$$I_L = \frac{10}{450} \times 10^3 = 22.2\text{ mA}$$

$$I_R = \frac{20-10}{200} \times 10^3 = 50\text{ mA}$$

$$I_z = 50 - 22.2 = 27.8\text{ mA}$$

$$P_z = 27.8 \times 10 = 278\text{ mW} < 350\text{ mW (rating)}$$

(c) When the zener draws maximum power,

$$I_z = \frac{350}{10} = 35\text{ mA}$$

Then $$I_R = \frac{20-10}{200} \times 10^3 = 50\text{ mA}$$

$$I_L = I_R - I_z = 50 - 3.5 = 15\text{ mA}$$

$$R_L = \frac{10}{15} \times 10^{-3} = 667\ \Omega$$

(d) $$I_z = 0\text{ (just on state)}$$

$$I_R = 50\text{ mA} = I_L$$

$$V_L = V_z = 10\text{ V}$$

$$R_L\text{ (min)} = \frac{10}{50} \times 10^{-3} = 200\ \Omega$$

EXAMPLE 2.10 Determine the range of V_i in which the zener diode of Fig. 2.19 conducts.

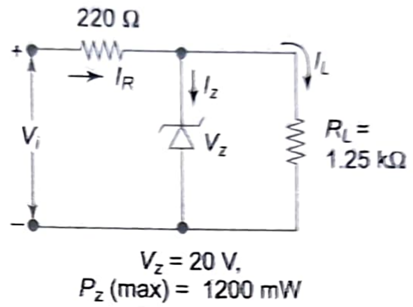

Fig. 2.19

Solution

(a) V_z just in conducting state

$$V_z = 20\text{ V}, I_z = 0$$

$$I_R = I_L = \frac{20}{1.25} = 16\text{ mA}$$

$$V_i = 20 + 220 \times 16 \times 10^{-3} = 23.52\text{ V}$$

(b)
$$I_z = I_z(\text{max}) = \frac{1200}{20} = 60\text{ mA}$$

$$I_L = 16\text{ mA}$$

$$I_R = 60 + 16 = 76\text{ mA}$$

$$V_i = 20 + 220 \times 76 \times 10^{-3} = 36.72\text{ V}$$

For input voltage from 23.52 V to 36.72 V, V_L will remain constant at 20 V.

EXAMPLE 2.11 For network of Fig. 2.20, determine the range of $R_L < I_L$ that will result in V_{R_L} being mentained at 10 V. Also determine wattage rating of diode.

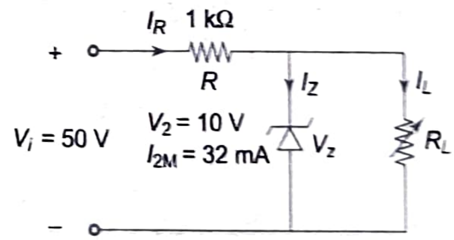

Fig. 2.20

Solution Value of R_L that will turn Zener diode on

$$R_{L_{min}} = \frac{RV_2}{V_i - V_2} = \frac{1000 \times 10}{50 - 10} = 250\ \Omega$$

Voltage across R, i.e., $V_R = V_i - V_2 = 50 - 10 = 40$ V

$$I_R = \frac{V_R}{R} = \frac{40}{1000} = 40 \text{ mA} \Rightarrow I_{L_{min}} = I_R - I_{2M} = 8 \text{ mA}$$

So,
$$R_{L_{max}} = \frac{V_2}{I_{2_{min}}} = \frac{10}{8 \text{ mA}} = 1.2 \text{ k}\Omega$$

$$P_{max} = V_i I_{2M} = 320 \text{ mW}$$

2.4 RECTIFICATION

The diode is an ideal and simple device to convert ac to dc. The process is called rectification. We shall focus our attention on some performance measures of a rectifier: dc voltage, ripple factor, power conversion efficiency, PIV, and voltage regulation.

2.4.1 Half-wave Rectification (Sinusoidal Input)

The half-wave rectification is carried out by the simple circuit of Fig. 2.21 with a single diode. The diode conducts during positive half-cycles of input voltage and cuts off during negative half-cycle. The input and output waveforms are shown in the Fig. 2.21.

The *dc output voltage* can be expressed as

$$V_{dc} = \frac{1}{2\pi}\left[V_m \int_0^{\pi} \sin \omega t \, d\omega + 0\right] = \frac{V_m}{\pi} = 0.318\, V_m \quad (2.3)$$

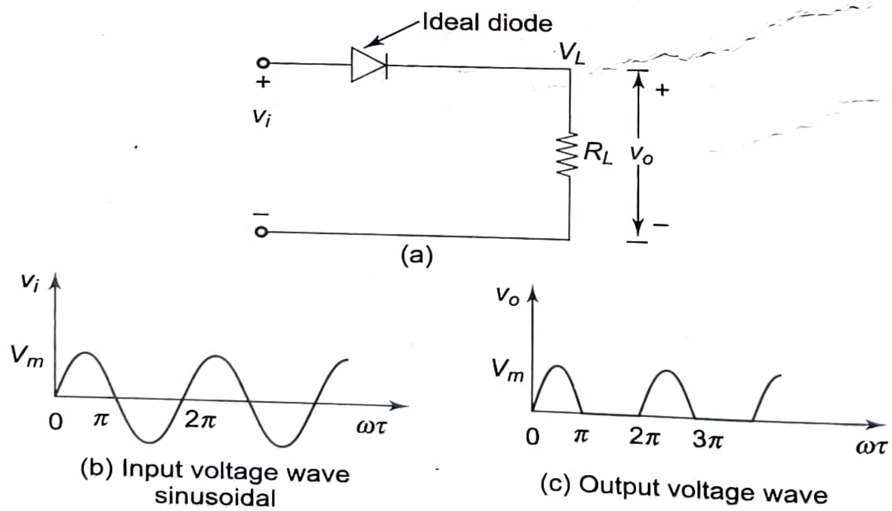

Fig. 2.21 Input/output waveforms of half-wave rectification

Then
$$I_{dc} = \frac{V_m}{\pi} \cdot \frac{1}{R_L} = \frac{I_m}{\pi} = 0.318\, I_m \quad (2.4)$$

PIV—During negative half, the input voltage reverse biases the diode. So PIV = V_m

✦ Ripple Factor

Ripple is the variation of output voltage about dc, which is quite large in a half-rectified wave. It has a two times frequency to the frequency of the input voltage.

Ripple factor is defined as

$$\gamma = \frac{\text{rms value of the ac component of load (output) voltage}}{\text{dc component of load voltage}} \tag{2.5}$$

We can write the equality

$$V_{L\,\text{rms}} = \left[V^2_{L\,\text{ac rms}} + V^2_{L\text{dc}}\right]^{1/2}$$

or

$$\gamma = \left[\frac{V^2_{L\text{rms}}}{V^2_{L\text{dc}}} - 1\right]^{1/2} \tag{2.6}$$

$$V_{L\,\text{rms}} = \text{rms of half sine wave } (0-\pi) \text{ over } (0-2\pi)$$

$$V_{L\,\text{rms}} = \sqrt{\left(\frac{V_m}{\sqrt{2}}\right)^2 \times \frac{1}{2}} = \frac{V_m}{2}$$

Then

$$\gamma = \left[\frac{(V_m/2)^2}{(V_m/\pi)^2} - 1\right]^{1/2} = \left[\left(\frac{\pi}{2}\right)^2 - 1\right]^{1/2} = 1.21 \tag{2.7}$$

We find that ripple factor of a half-wave rectifier is quite high, which is unacceptable.

The value of V_{dc} can be adjusted by providing V_i from a transformer of appropriate turn ratio.

For small values of V_m, we need to replace V_m by $(V_m - V_T)$ in all the above relationships.

✦ Power Conversion Efficiency

It is defined as

$$\eta = \frac{\text{dc power output}}{\text{ac power input}}$$

Assuming the diode to be ideal in a half-wave rectifier,

$$\text{dc output} = I^2_{\text{dc}} R_L$$

$$\text{ac input} = I^2_{\text{rms}} R_L$$

$$I_{\text{rms}} = \sqrt{\left(\frac{I_m}{\sqrt{2}}\right)^2 \div 2} = \frac{I_m}{2}$$

$$\eta = \left(\frac{I_{\text{dc}}}{I_{\text{rms}}}\right)^2 = \left(\frac{I_m/\pi}{I_m/2}\right)^2 = \left(\frac{2}{\pi}\right)^2 = 0.405 \text{ or } 40.5\% \text{ (ideal)} \tag{2.8}$$

2.4.2 Full-wave Rectification

In order to reduce the ripple factor and raise the dc voltage level, we switch to full-wave rectification in which the phase of the second half of the wave is reversed. The full-wave rectified waveform is drawn in Fig. 2.22.

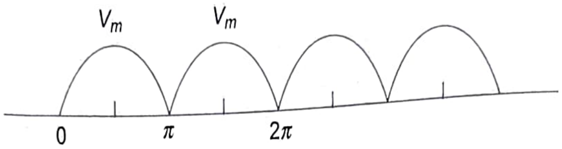

Fig. 2.22 Full-wave rectified waveform

Obviously,

$$V_{dc} = \frac{2V_m}{\pi} = 0.637\, V_m \text{ (double of half-wave)} \tag{2.9}$$

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

- **Ripple Factor**

$$V_{i\,\text{rms}} = \frac{V_m}{\sqrt{2}}$$

Substituting in Eq. (2.7),

$$\gamma = \left[\left(\frac{V_m/\sqrt{2}}{2V_m/\pi}\right)^2 - 1\right] = \left[\left(\frac{\pi^2}{8}\right) - 1\right]^{1/2} = 0.482 \tag{2.10}$$

The ripple factor is reduced from 1.21 to 0.482.

- **Power Conversion Efficiency**

$$\text{dc output} = I_{dc}^2\, R_L$$

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

$$\text{ac input} = I^2_{\text{rms}}\, R_L$$

$$\eta = \left(\frac{I_{dc}}{I_{\text{rms}}}\right)^2 = \left(\frac{2I_m/\pi}{I_m/\sqrt{2}}\right)^2 = \left(\frac{2\sqrt{2}}{\pi}\right)^2 = 0.81 \text{ or } 81\% \text{ (ideal)} \tag{2.11}$$

We shall now take up two full-wave rectification circuits.

2.4.3 Bridge Rectifier

It is a bridge of four diodes as shown in Fig. 2.23. In positive half-cycle of input v_i, diodes D and D_3 conduct through the load R_L. The conduction path is shown by a solid line. During