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CHAPTER

52

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P-N JUNCTION DIODE

Chemist, led the research for the molecular diode (In the semiconductor industry, called p-n junctions)

52.1. P-N Junction Diode

(*a*) Construction

It is a two-terminal device consisting of a P-N junction formed either in Ge or Si crystal. Its circuit symbol is shown in Fig. 52.1 (*a*). The *P*-and *N*-type regions are referred to as anode and cathode respectively. In Fig. 52.1 (*b*), arrowhead indicates the conventional direction of current flow when forward-biased. It is the same direction in which hole flow takes place.

Commercially available diodes usually have some means to indicate which lead is *P* and which lead is *N*. Standard notation consists of type numbers preceded by 'IN' such as IN 240 and IN 1250. Here, 240 and 1250 correspond to colour bands. Fig. 52.2 (*a*) shows typical diodes having a variety of physical structures whereas Fig. 52.2 (*b*) illustrates terminal identifications. Also refer to the picture of two commercial diodes shown in Fig 52.1(*c*).

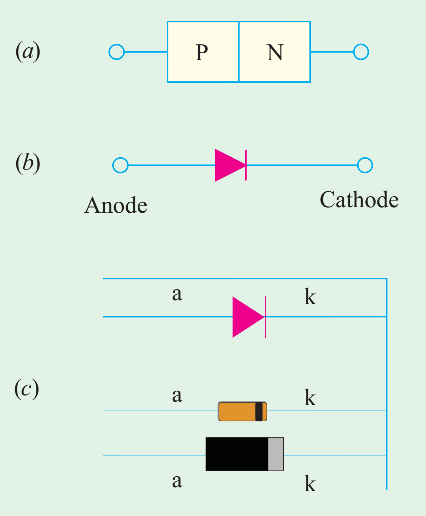


Fig. 52.1

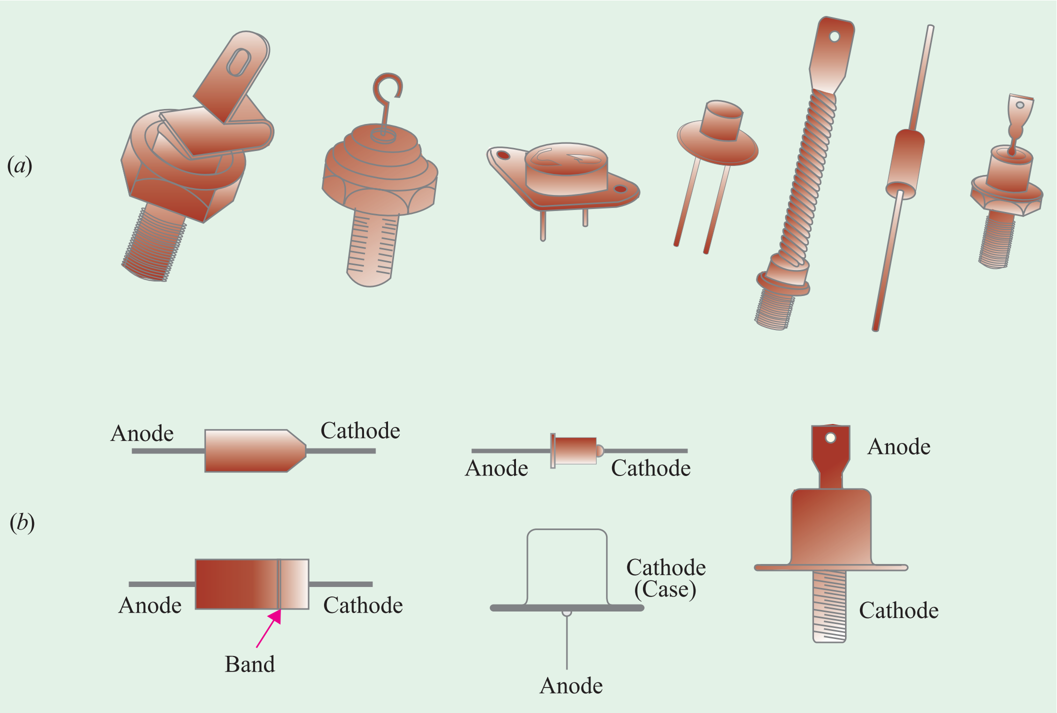


Fig. 52.2

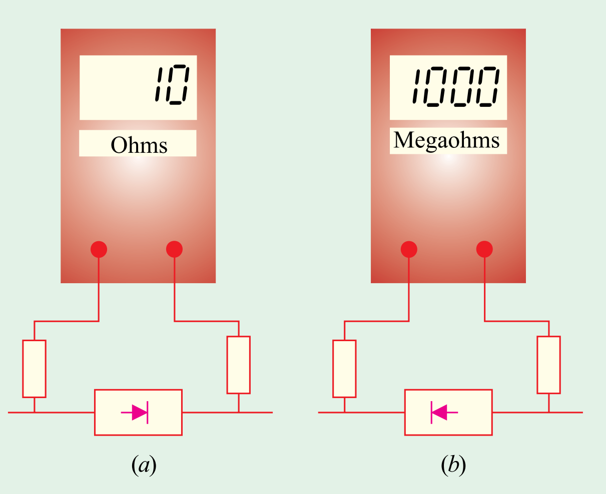
The low-current diodes whose body is about 3 mm long can carry a forward current of about 100 mA, have saturation current of 5 μA at room temperature (25ºC) and can withstand a reverse voltage of 75 V without breaking down. The medium-current diodes can pass a forward current of about 500 mA and can withstand a reverse voltage of 250 V. The high-current diodes or power diodes can pass a forward current of many amperes and can survive several hundred volts of reverse voltage.

(*b*) Diode Mounting

Low and medium-current diodes are usually mounted by soldering their leads to the connecting terminals. The heat generated by these diodes (when operating) is small enough to be carried away by air convection and conduction along the connecting leads. However, high-current stud-mounted diodes generate large amounts of heat for which air convection is totally inadequate. For coolong, they need heat sinks made of metals such as copper or aluminium which are good conductors of heat. The sink absorbs heat from the device and then transfers it to the surrounding air by convection and radiation since it has large surface area.

(*c*) Working

A P-N junction diode is one-way device offering low resistance when forward-biased [Fig. 52.3 (*a*)] and behaving almost as an insulator when reverse-biased [Fig. 52.3 (*b*)]. Hence, such diodes are mostly used as rectifiers *i.e.* for converting alternating current into direct current.



(*a*) (*b*)

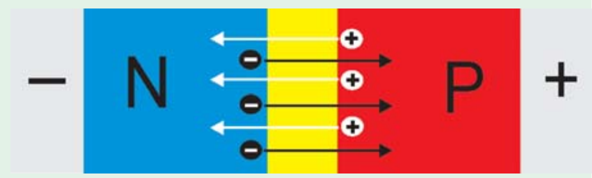
Fig. 52.3

(*d*) V/I Characteristic

Fig. 52.4 shows the static voltage-current characteristics for a low-power P-N junction diode.

1. Forward Characteristic

When the diode is forward-biased and the applied voltage is increased from zero, hardly any current flows through the device in the beginning. It is so because the external voltage is being opposed by the internal barrier voltage V_B whose value is 0.7 V for Si and 0.3 V for Ge. As soon as V_B is neutralized, current through the diode increases rapidly with increasing applied battery voltage. It is found that as little a voltage as 1.0 V produces a forward current of about 50 mA. A burnout is likely to occur if forward voltage is increased beyond a certain safe limit.



Forward biased diode.

2. Reverse Characteristic

When the diode is reverse-biased, majority carriers are blocked and only a small current (due to minority carriers) flows through the diode. As the reverse voltage is increased from zero, the reverse current very quickly reaches its maximum or saturation value I_0 which is also known as ***leakage current***. It is of the order of nanoamperes (nA) for Si and microamperes (μA) for Ge. The value of I_0 (or I_s) is independent of the applied reverse voltage but depends on (*a*) temperature, (*b*) degree of doping and (*c*) physical size of the junction.

Reverse biased diode.

As seen from Fig. 52.4, when reverse voltage exceeds a certain value called break-down voltage V_{BR} (or Zener voltage V_z), the leakage current suddenly and sharply increases, the curve indicating zero resistance at this point. Any further increase in voltage is likely to produce burnout unless protected by a current-limiting resistor.

When P-N junction diodes are employed primarily because of this breakdown property as voltage regulators, they are called Zener diodes (Art. 54.1).

3. Equation of the Static Characteristic

The volt-ampere characteristics described above are called ***static*** characteristics because they describe the d.c. behaviour of the diode. The forward and reverse characteristics have been combined into a single diagram of Fig. 52.4.

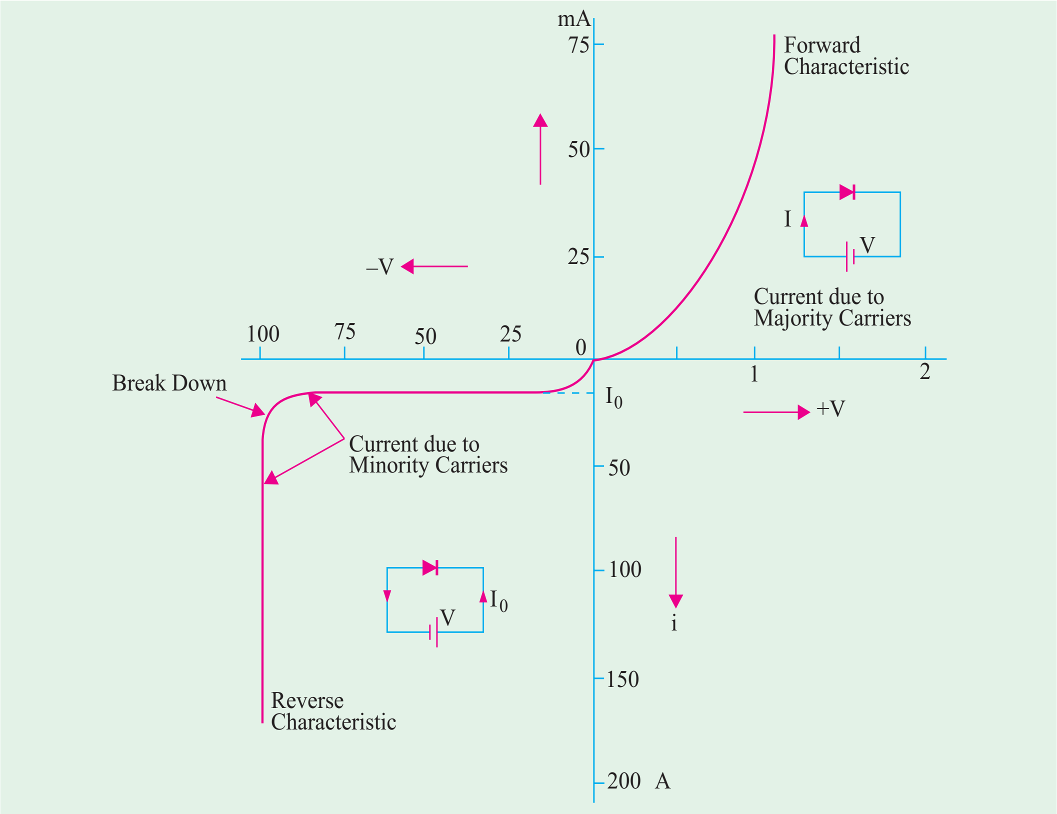


Fig. 52.4

These characteristics can be described by the analytical equation called ***Boltzmann diode equation*** given below :

$$I = I_0 \left(e^{\frac{eV}{kT}} - 1\right) \text{ ampere}$$

where I_0 = diode reverse saturation current
V = voltage across junction – positive for forward bias and negative for reverse bias.
k = Boltzmann constant = 1.38×10^{-23} J/°K
T = crystal temperature in °K
η = 1 – for germanium
= 2 – for silicon

Hence, the above diode equation becomes

$$I = I_0 (e^{eV/kT} - 1). \quad \text{– for germanium}$$
$$I = I_0 (e^{eV/2kT} - 1) \quad \text{– for silicon}$$

Now, $e/k = 11{,}600$ and putting $T/11{,}600 = V_T$, the above equation may be written as

$$I = I_0 (e^{11{,}600V/\eta T} - 1) = I_0 (e^{V/\eta V_T} - 1) \text{ ampere}$$

Now, at room temperature of (273 + 20) = 293°K, $V_T = 293/11{,}600 = 0.025$ V = 25 mV. Substituting the value of η, we have

$$I = I_0\,(e^{40\,V-1}) \qquad \text{– for Ge}$$
$$\cong I_0\,e^{40\,V} \qquad \text{– if } V > 1 \text{ volt}$$
$$I = I_0\,(e^{20\,V-1}) \qquad \text{– for Si}$$
$$\cong I_0\,e^{20\,V} \qquad \text{– if } V > 1 \text{ volt}$$

We may also write the above diode equation as under

$$I = I_0\,(e^{V_f/\eta V_T - 1}) \qquad \text{– forward bias}$$
$$= I_0\,(e^{V_R/\eta V_T - 1}) \qquad \text{– reverse bias}$$

(*e*) Diode Parameters

The diode parameters of greatest interest are as under :

1. Bulk resistance (r_B)

It is the sum of the resistance values of the P-and N-type semiconductor materials of which the diode is made of.

$$\therefore \qquad r_B = r_P + r_N \qquad \text{– Fig. 52.5}$$

Usually, it is very small. It is given by

$$r_B = (V_F - V_B)/I_F$$

It is the resistance offered by the diode well above the barrier voltage *i.e.* when current is large. Obviously, this resistance is offered in the forward direction.

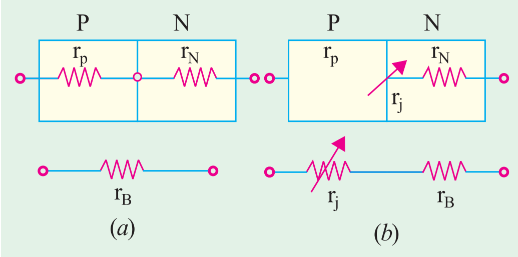


Fig. 52.5

2. Junction resistance (r_j)

Its value for forward-biased junction depends on the magnitude of forward *dc* current.

$$r_j = 25\text{ mV}/I_F\,(\text{mA}) \qquad \text{– for Ge}$$
$$= 50\text{ mV}/I_F\,(\text{mA}) \qquad \text{– for Si}$$

Obviously, it is a *variable* resistance.

3. Dynamic or ac resistance

$$r_{ac} \text{ or } r_d = r_B + r_j$$

For large values of forward current, r_j is negligible. Hence, $r_{ac} = r_B$. For small values of I_F, r_B is negligible as compared to r_j. Hence $r_{ac} = r_j$.

4. Forward voltage drop

It is given by the relation

$$\text{forward voltage drop} = \frac{\text{power dissipated}}{\text{forward dc current}}$$

5. Reverse saturation current (I_0). It has already been discussed in Art. 52.42.

6. Reverse breakdown voltage (V_{BR}). It is discussed in Art. 51.3.

7. Reverse dc resistance R_R $= \dfrac{\text{reverse voltage}}{\text{reverse current}}$

(*f*) Applications

The main applications of semiconductor diodes in modern electronic circuitry are as under :

1. As power or rectifier diodes. They convert ac current into dc current for dc power supplies of electronic circuits.
2. As signal diodes in communication circuits for modulation and demodulation of small signals.
3. As Zener diodes in voltage stabilizing circuits.
4. As varactor diodes–for use in voltage-controlled tuning circuits as may be found in radio and TV receivers. For this purpose, the diode is deliberately made to have a certain range of junction capacitance. The capacitance of the reverse-biased diode is given by $C = K/\sqrt{V_R}$

where V_R is the reverse voltage.

5. In logic circuits used in computers.

Example 52.1. *Using approximate Boltzmann's diode equation, find the change in forward bias for doubling the forward current of a germanium semiconductors at 290ºK.*

(Basic Electronics, Osmania Univ. 1993)

Solution. The approximate Boltzmann's diode equation is given by $I = I_0 \exp(eV/kT)$

$$\therefore \quad I_1 = I_0 \exp(eV_1/kT) \text{ and } I_2 = I_0 \exp(eV_2/kT)$$

$$\therefore \quad \frac{I_2}{I_1} = \exp\left[\frac{e}{kT}(V_2 - V_1)\right]$$

$$\text{or} \quad (V_2 - V_1) = \frac{kT}{e} \ln\left(\frac{I_2}{I_1}\right) = 25 \ln\left(\frac{I_2}{I_1}\right) \text{ mV}$$

$$\text{Since} \quad I_2 = 2I_1 \quad \text{or} \quad I_2 / I_1 = 2$$

$$\therefore \quad (V_2 - V_1) = 25 \ln 2 = 25 \times 0.693 = \mathbf{17.3\ mV}$$

Example 52.2. *A certain P-N junction diode has a leakage current of 10^{-14} A at room temperature of 27ºC and 10^{-9} A at 125ºC. The diode is forward-biased with a constant-current source of 1 mA at room temperature. If current is assumed to remain constant, calculate the junction barrier voltage at room temperature and at 125ºC.*

Solution. As given in Art. 52.1,

$$I = I_0 \exp(eV/kT - 1) \quad \text{or} \quad (I/I_0) + 1 = \exp(eV/kT)$$

Taking logarithm of both sides and solving for V, we get

$$V = \frac{kT}{e} \ln\left(\frac{I}{I_0} + 1\right)$$

Now, at 27ºC or (273 + 27) = 300ºK

$$\therefore \quad kT/e = 1.38 \times 10^{-23} \times 300 / 1.6 \times 10^{-19} = 26 \text{ mV}$$

$$\text{At} \quad (273 + 125) = 398\text{ºK},$$

$$kT/e = 1.38 \times 10^{-23} \times 398 \times (1.6 \times 10^{-19}) = 36 \text{ mV}$$

$$\text{Hence, at 27ºC,} \quad V_B = 26 \ln\left(\frac{10^{-3}}{10^{-14}} + 1\right) = 660 \text{ mV} = \mathbf{0.66\ V}$$

$$\text{At 125ºC,} \quad V_B = 36 \text{ In}\left(\frac{10^{-3}}{10^{-9}} + 1\right) = 500 \text{ mV} = \mathbf{0.5\ V}$$

52.2. Derivation of Junction Resistance

Junction resistance is also known as ***incremental* or *dynamic resistance*** and is an important parameter particularly in connection with small-signal operations of the diode.

$$r_j = dV/dI \quad \text{or} \quad g_j = dI/dV$$

$$\text{Now,} \quad I = I_0(e^{V/\eta V_T} - 1) = I_0 e^{V/\eta V_T} - I_0$$

$$\therefore \quad g_j = \frac{dI}{dV} = \frac{I_0 e^{V/\eta V_T}}{\eta V_T} = \frac{I + I_0}{\eta V_T}$$

(*a*) Reverse bias

When reverse bias is greater than a few tenths of a volt *i.e.* when $|V/\eta V_T| \gg |$, then g_j is extremely small so that r_j is very large. That high value is also represented by R_R.

(*b*) Forward bias

Again, for a forward bias greater than a few tenths of a volt, $I \gg I_0$, hence, $g_j = I/\eta V_T$ and $r_j = \eta V_T/I$.

Now, at room temperature of 293ºK, $V_T = T/11{,}600 = 293/11{,}600 = 25$ mV. Also $\eta = 1$ for Ge and 2 for Si.

$$\therefore \quad r_j = 25\,\text{mV}/I\,\text{mA} \quad \text{– for germanium}$$
$$= 50\,\text{mV}/I\,\text{mA} \quad \text{– for silicon}$$

Example 52.3. *A silicon diode has a forward voltage drop of 1.2 V for a forward dc current of 100 mA. It has a reverse current of 1 μA for a reverse voltage of 10 V. Calculate*

(a) *bulk and reverse resistance of the diode*

(b) *ac resistance at forward dc current of* **(i)** *2.5 mA and* **(ii)** *25 mA.*

Solution. (a) $r_B = \dfrac{V_F - V_B}{I_F} = \dfrac{1.2\text{ V} - 0.7\text{ V}}{100\text{ mA}} = 5\ \Omega$

$R_R = V_R / I_R = 10\text{ V}/1\ \mu\text{A} = \mathbf{10\ M}$

(b) (i) $r_j = 25\text{ mV}/2.5\text{ mA} = 10\ \Omega \qquad r_{ac} = r_B + r_j = 5 + 10 = \mathbf{15\ \Omega}$

(ii) $r_j = 25\text{ mV}/25\text{ mA} = 1\ \Omega \quad \therefore \quad r_{ac} = 5 + 1 = \mathbf{6\ \Omega}$

Example 52.4. *Using analytical expression for diode current, calculate the dynamic slope resistance of a germanium diode at 290 K when forward biased at current of* **(i)** *10 μA and* **(ii)** *5 mA.*
(Electronics-I, Mysore Univ. 1992)

Solution. $I = I_0\,(e^{eV/kT} - 1) \approx I_0 e^{eV/kT}$

$$\therefore \quad dI = \frac{e}{kT}\, I_0\,[e^{eV/kT}]\, dV = \frac{e}{kT}\, I\, dV$$

$$\therefore \quad r_d = \frac{dV}{dI} = \frac{kT}{eI} = \frac{25\times10^{-3}}{I} \quad \text{– } I \text{ in ampere}$$

(i) Now, $I = 10\ \mu\text{A} = 10\times10^{-6} = 10^{-5}$ A

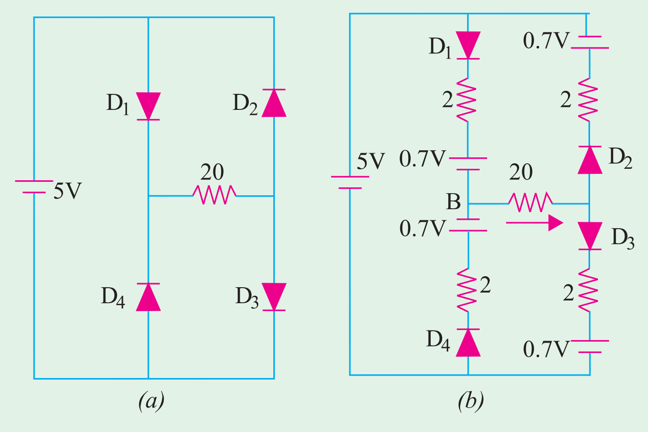
$r_d = 25\times10^{-3} / 10^{-5} = \mathbf{2500\ \Omega}$

(ii) Now, $I = 5\text{ mA} = 5\times10^{-3}$ A

$\therefore \quad r_d = 25\times10^{-3}/5\times10^{-3} = \mathbf{5\ \Omega}$

Example 52.5. *Find the current through the 20 Ω resistor shown in Fig. 52.6 (a). Each silicon diode has a barrier potential of 0.7 V and a dynamic resistance of 2 Ω. Use the diode equivalent circuit technique.* **(Semiconductor Devices, Gujarat BTE, 1993)**

Solution. In Fig. 52.6 (*b*) each diode has been replaced by its equivalent circuit. It is seen that diodes D_1 and D_3 are forward-biased by 5 V battery whereas D_2 and D_4 are reverse-biased. Hence, the current will flow from point *A* to *B*, then to *C* via 20 Ω resistance and then back to the negative terminal of the 5 V battery.



(*a*) (*b*)

Fig. 52.6

The net voltage in the equivalent circuit is

$V_{net} = 5 - 0.7 - 0.7 = 3.6$ V

Total resistance seen by this net voltage is

$R_T = 2 + 20 + 2 = 24\ \Omega$

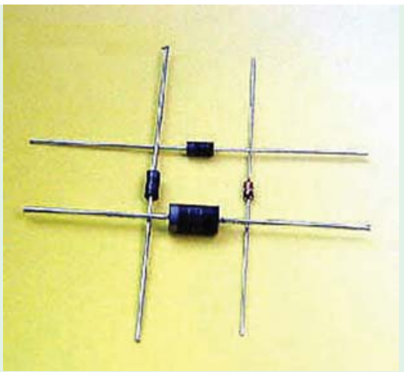
The circuit current $I = V_{net}/R_T = 3.6/24 = \mathbf{0.15\ A}$

52.3. Junction Breakdown

If the reverse bias applied to a *P-N* junction is increased, a point is reached when the junction breaks down and reverse current rises sharply to a value limited only by the external resistance connected in series with the junction (Fig. 52.7). This critical value of the voltage is known as **breakdown voltage** (V_{BR}). It is found that once breakdown has occured, very little further increase in voltage is required to increase the current to relatively high values. The junction itself offers almost zero resistance at this point.

The breakdown voltage depends on the width of the depletion region which, in turn, depends on the doping level.

The following two mechanism are responsible for breakdown under increasing reverse voltage:



Zener diodes

1. Zener Breakdown

This form of breakdown occurs in junctions which, being heavily doped, have narrow depletion layers. The breakdown voltage sets up a very strong electric field (about 10^8 V/m) across this narrow layer. This field is strong enough to ***break or rupture the covalent bonds*** thereby generating electron-hole pairs. Even a small further increase in reverse voltage is capable of producing large number of current carriers. That is why the junction has very low resistance in the break-down region.

2. Avalanche Breakdown

This form of breakdown occurs in junctions which being lightly-doped, have wide depletion layers where the electric field is not strong enough to produce Zener breakdown. Instead, the minority carriers (accelerated by this field) collide with the semiconductor atoms in the depletion region. Upon collision with valence electrons, covalent bonds are broken and electron-hole pairs are generated. These newly-generated charge carriers are also accelerated by the electric field resulting in more collisions and hence further production of charge carriers. This leads to an avalanche (or flood) of charge carriers and, consequently, to a very low reverse resistance. The two breakdown phenomena are shown in Fig. 52.7

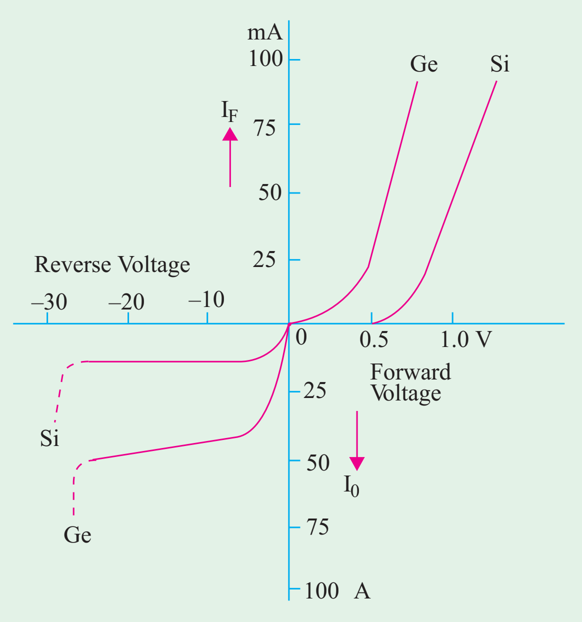


Fig. 52.7

52.4. Junction Capacitance

Capacitive effects are exhibited by *P-N* junctions when they are either forward-biased or reverse-biased.

(*a*) Transition Capacitance (C_T) or Space-charge Capacitance

When a *P-N* junction is reverse-biased, the depletion region acts like an insulator or as a dielectric material essential for making a capacitor. The *P*- and *N*-type regions on either side have low resistance and act as the plates. We, therefore, have all the components necessary for making a parallel-plate capacitor. This junction capacitance is called ***transition or space charge*** capacitance (C_{pn} or C_T). It may be calculated by the usual formula $C = \in A/d$. Its typical value is 40 pF. Since thickness of depletion (or transition) layer depends on the amount of reverse bias, capacitance C_T can be controlled with the help of applied bias. This property of variable capacitance possessed by a reverse-biased *P-N* junction is used in the construction of a device known as ***varicap or varactor***.

This capacitance is voltage dependent as given by the relation

$$C_T = \frac{K}{(V_K + V_R)^n}$$

where V_K = knee voltage ; V_R = applied reverse voltage

K = constant depending on semiconductor material

$n = \frac{1}{2}$ – for alloy junction and = $\frac{1}{3}$ –for diffused junction

The voltage-variance capacitance of a reverse-biased *P-N* junction is used in many circuits one of which is automatic frequency control (AFC) in an FM tuner. Other applications include self-balancing bridge circuits, special type of amplifiers known as ***parametric*** amplifiers and electronic tuners in TV.

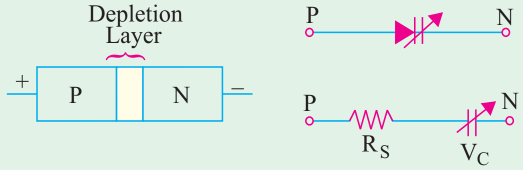


Fig. 52.8

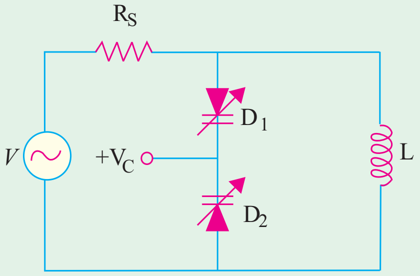


Fig. 52.9

When used in such a role, the diodes are called ***varactors, varicaps or voltacaps***. The symbol of these diodes when used in this role is shown in Fig. 52.8 along with its equivalent circuit.

When used in a resonant circuit, varactor acts as a variable capacitor and allows the resonant frequency to be adjusted by a variable voltage level. In Fig. 52.8, two varactors have been used to provide total variable capacitance in a parallel resonant circuit. Here V_C is a variable dc voltage that controls the reverse bias and hence the capacitance of the diodes.

(*b*) Diffusion or Storage Capacitance (C_D)

This capacitive effect is present when the junction is ***forward-biased***. It is called diffusion capacitance to account for the time delay in moving charges across the junction by diffusion process.* Due to this fact, this capacitance cannot be identified in terms of a dielectric and plates. It varies directly with the magnitude of forward current as explained below in more details.

Consider a forward-biased junction which is carrying a forward current I_F. Suppose the applied voltage is suddently reversed, then I_F ceases suddenly but leaves lot of majority charge carriers in the depletion region. These charge carriers must get out of the region which, to their bad luck, becomes wider under the reverse bias. Hence, it is seen that when a forward-biased *P-N* junction is suddenly reverse-biased, a reverse current flows which is large initially but gradually decreases to the level of saturation current I_0. This effect can be likened to the discharging current of a capacitor and is, therefore, rightly represented by a capacitance called ***diffusion capacitance*** C_D. Since the number of charge carriers left in depletion layer is proportional to forward current, C_D is direcly proportional to I_F. Its typical value is 0.02 µF which is 5000 times C_T.

The capacitance assumes great significance in the operation of devices which are required to switch rapidly from forward to reverse bias. If C_D is large, this switchover cannot be rapid. It will delay both the switch-on and the switch-off. This effect of C_D is variously known as ***recovery time*** or carrier storage.

---

* In the case of forward bias, the diode current is almost entirely due to diffusion (drift current being negligible).

If τ is mean lifetime of charge carriers, then a flow of charge Q yields a diode current of

$$I = \frac{Q}{\tau} = I_0\,(e^{V/\eta V_T} - 1) \cong I_0\, e^{V/\eta V_T},\; Q = I\tau = \tau\, I_0\, e^{V/\eta V_T}$$

$$\therefore \qquad C_D = \frac{dQ}{dV} = \frac{\tau\, I_0}{\eta\, V_T}\, e^{V/\eta V_T} \cong \frac{\tau\, I}{\eta\, V_T}$$

52.5. Equivalent Circuit of a P-N Junction

We have seen from above that a forward-biased junction offers ac resistance r_{ac} and possesses diffusion capacitance C_D (which comes into the picture only when frequency of the applied voltage is very high). Hence, it can be represented by the equivalent circuit of Fig. 52.10 (*a*). An opposing battery has been connected in series with r_{ac} to account for the junction barrier potential.

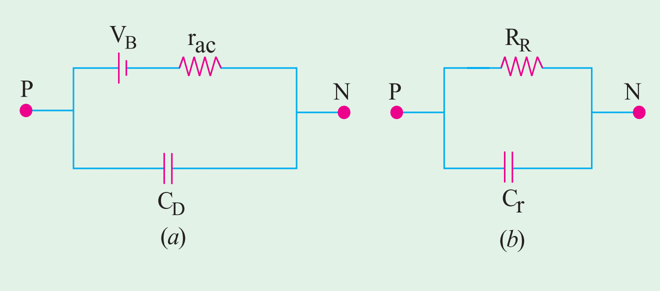


Fig. 52.10

As seen from Fig. 52.10 (*b*), a reverse-biased junction can be simply represented by a reverse resistance R_R connected in *parallel* with a capacitance C_T or C_{pn}.

Example 52.6. *Calculate the barrier potential for Si junction at (a) 100ºC and (b) 0ºC if its value at 25ºC is 0.7 V.*

Solution. As seen from Art. 1.38.

$$\Delta V = -0.002.\quad \Delta t = -0.002\,(t_2 - t_1)$$

(*a*) $\Delta t = (100 - 25) = 75ºC \qquad \therefore \Delta V = -0.002 \times 75 = -0.15$ V

$\therefore \quad V_B$ at 100ºC $= 0.7 + (-0.15) =$ **0.55 V**

(*b*) $\Delta t = (0 - 25) = -25ºC \qquad \therefore \Delta V = -0.002 \times (-25) = 0.05$ V

$\therefore \quad V_B$ at 0ºC $= 0.7 + 0.05 =$ **0.75 V**

Example 52.7. *A germanium diode draws 40 mA with a forward bias of 0.25 V. The junction is at room temperature of 293ºK. Calculate the reverse saturation current of the diode.*

Solution. $I = I_0\,(e^{40V} - 1)$ or $40 \times 10^{-3} = I_0\,(e^{40 \times 0.25} - 1)$

$\therefore \quad I_0 = 40 \times 10^{3}/(22{,}027 - 1) =$ **1.82 μ A**

Example 52.8. *Calculate forward current in Ge diode at 20ºC when forward voltage is 0.3 V. Compare this value with that after a temperature rise of 50ºC. Assume that reverse saturation current doubles for every 10ºC rise in temperature.* **(Electronics-I, Mysore Univ. 1991)**

Solution. According to Boltzmann's diode equation

$$I_{20} = I_0\,(e^{40V} - 1) = I_0\,(e^{40 \times 0.3} - 1) = I_0\,(e^{12} - 1) = 162{,}755\, I_0$$

At, $t = (20 + 50) = 70ºC$ or $T = 70 + 273 = 343ºK$

$$V_T = 343/11{,}600 = 0.0296\text{ V} \cong 0.03\text{ V, hence, } V/\eta\, V_T = 0.3/1 \times 0.03 = 10$$

The value of I_0 at 70ºC is $I_0' = 2^5 \times I_0 = 32\, I_0$ because it doubles for every 10ºC rise in temperature.

$$\therefore \quad I_{70} = I_0'\,(e^{10} - 1) = 32\, I_0\,(22{,}026 - 1) = 704{,}800\, I_0$$

It means that $I_{70} = (704{,}800,\ 162{,}755)\, I_{20} = 4.3\, I_{20}$ *i.e.* forward current has increased only 4.3 times whereas I_0 has increased 32 times for the same rise in temperature.

Example 52.9. *The capacitance of a varactor varies from 5 to 50 pF. Two such varactor diodes are used in the tuning circuit of Fig. 52.11. If L = 10 mH, determine the tuning range of the circuit.*

Solution. It should be noted that the two varactor capacitances are connected in series (Fig. 52.11).

$$C_{T(min)} = 5/2 = 2.5 \text{ pF} ; C_{T(max)} = 50/2 = 25 \text{ pF}$$

$$f_{r(max)} = 1/2\,\pi\,\sqrt{LC} = 1/2\pi\sqrt{10\times10^{-3}\times2.5\times10^{-12}}$$

$$= \mathbf{1\ MHz}$$

$$f_{r(min)} = 1/2\,\pi\,\sqrt{10\times10^{-3}\times25\times10^{-12}} = \mathbf{318\ KHz}$$

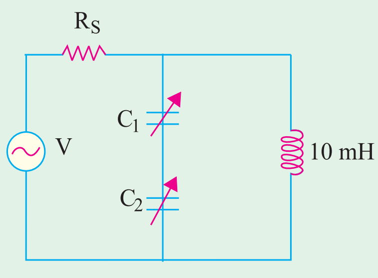
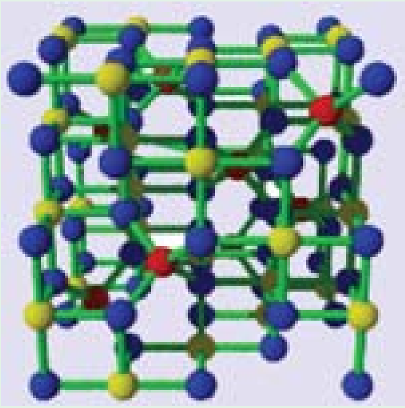


Fig. 52.11

52.6. Diode Fabrication

The electrical characteristics of a semiconductor diode depend on two factors ***(i)*** the material employed and ***(ii)*** the type of *P-N* junction used.



Polycrystalline structures

The two most commonly-used materials are germanium (Ge) and silicon (Si). Since Ge has higher electrical conduction than Si, it is often used in low- and medium-power diodes. On the other hand, Si has been found more suitable for high-power applications because it can be operated at higher temperatures than Ge. A new material called gallium-arsenide (GaAs) is found to combine desirable features of both Ge and Si and is finding ever-increasing use in many new applications.

The *P-N* junction may be produced by any one of the following methods :

1. grown junction
2. alloy junction
3. diffused junction
4. epitaxial growth
5. point contact junction.

The first step in the manufacture of any semiconductor device is to obtain the semiconductor material in an extremely pure form. The accepted impurity level is less than one part of impurity in one billion (10^9) parts of the semiconductor material. To begin with, the raw material is subjected to a series of chemical reactions and then to a zone refining process which employs induction heating to reduce the impurity level of the polycrystalline structure. Next, the Czochralski or floating zone technique is used to form single crystals of Ge or Si for fabrication of diodes. These crystals are then cut into wafers as thin as 0.025 mm (nearly one fourth the thickness of this paper).

Now, we will briefly discuss the four basic processes commonly used in the manufacture of semiconductor diodes.

52.7. Grown Junction

Such junctions are produced by employing either the Czochralski or floating zone technique. The apparatus used for Czochralski technique is shown in Fig. 52.12. A single crystal seed of the desired impurity level is immersed in the molten semiconductor material contained in a crucible. Then, it is gradually withdrawn while the shaft holding the seed is slowly turning. When crystal is being pulled out, impurities of *P*- and *N*-type are alternately added to produce a *P-N* junction. This large area crystal is then cut into a large number of smaller-area diodes.

52.8. Alloy Junction

The alloy process produces junction diodes that have high PIV and current ratings but which have large junction capacitance due to their large junction area.

In this process, a tiny dot (or pellet) of indium (or any other *P*-type impurity) is placed on the surface of an *N*-type silicon wafer and the two are heated well above the melting temperature of indium (about 150ºC) as shown in Fig. 52.13 (*a*). Consequently, indium melts and dissolves some of the silicon. The temperature is then lowered and silicon refreezes to form a single crystal having a *P*-*N* junction as shown in Fig. 52.13 (*b*).

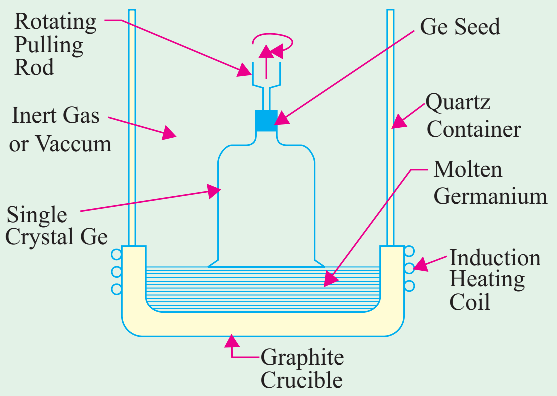
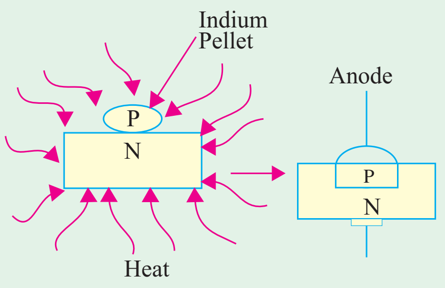


Fig. 52.12



(*a*) (*b*)

Fig. 52.13

52.9. Diffused Junction

The diffusion process employs either solid or gaseous diffusion. This process takes more time than alloy process but is relatively cheaper and more accurately controllable. In this process, particles from an area of high concentration drift to surrounding region of lesser concentration.

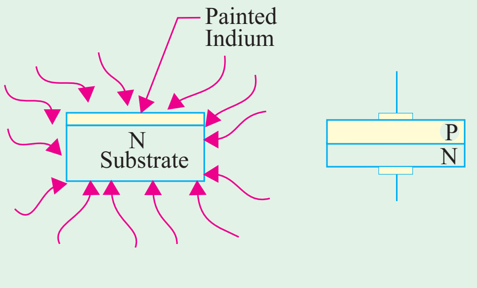


Fig. 52.14

(*i*) Solid Diffusion

The solid diffusion process starts with the 'painting' of a *P*-type impurity (say, indium) on an *N*-type substrate and heating the two until the impurity (say, indium) on an *N*-type substrate and heating the two until the impurity diffuses a short distance into the substrate to form *P*-type layer (Fig. 52.14).

(*ii*) Gaseous Diffusion

In the gaseous diffusion process, an *N*-type material is heated in a chamber containing a high concentration of an acceptor impurity in vapour form (Fig. 52.15). Some of the acceptor atoms are diffused (or absorbed) into the *N*-type substrate to form the *P*-type layer thus creating a *P*-*N* junction. By exposing only part of the *N*-type material during the diffusion process (the remainder being covered by a thin coating of SiO_2), the size of the *P*-region can be controlled. Finally, metal contacts are electroplated on the surface of each region for connecting the leads.

The diffusion technique enables simultaneous fabrication of many hundreds of diodes on one small disc of a semiconductor material. That is why it is the most frequently-used technique not only for the manufacture of semi-conductor diodes but also for the production of transistors and integrated circuits etc.

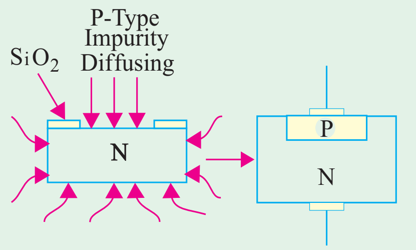


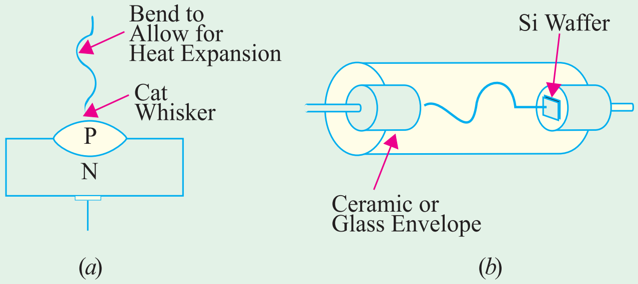
Fig. 52.15

52.10. Epitaxial Junction

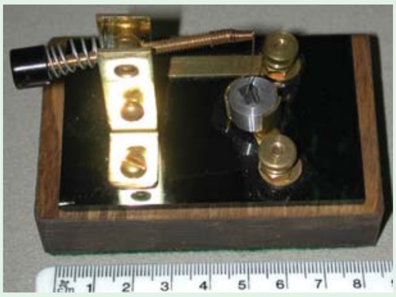
This junction differs from the diffusion junction only in the manner in which the junction is fabricated. Such junctions are grown on top of an *N*-type wafer in a high temperature chamber. The growth proceeds atom by atom and hence is exactly similar to the crystal lattice of the wafer on which it is grown. Such junctions have the advantage of low resistance.

52.11. Point Contact Junction

It consists of an *N*-type germanium or silicon wafer about 1.25 mm square by 0.5 mm thick, one face of which is soldered to a metal base by radio-frequency heating as shown in Fig. 52.16 (*a*). The other face has a phosphor bronze (or tungsten) spring (called a cat's whisker) pressed against it. The *P-N* junction is formed by passing a large current for a second or two through the wire while the crystal face with wire point is kept positive. The heat so produced drives away some of the electrons from the atoms in the small region around the point of contact thereby leaving holes behind. This small region of the *N*-type material is, consequently, converted into *P*-type material as shown in Fig. 52.16 (*a*). The small area of the *P-N* junction results in very low junction capacitance as mentioned earlier.



(*a*) (*b*)



Cat's whisker.

Fig. 52.16

52.12. The Ideal Diode

There is no such thing as an ***ideal*** diode or perfect diode. The existence of such a diode is visualized simply as an aid in analysing the diode circuits.

An ideal diode may be defined as a two-terminal device which

(*a*) conducts with zero resistance when forward-biased, and

(*b*) appears as an infinite resistance when reverse-biased.

In other words, such a device acts as a short-circuit in the forward direction and as an open-circuit in the reverse direction as shown in Fig. 52.17.

Also, in the forward direction, there is no voltage drop (even though current is there) since a short has zero resistance. On the other hand, there is no reverse current because reverse resistance is infinite.

It is helpful to think of an ideal diode as a bistable switch which is closed in the forward direction and open in the reverse direction. Hence, it has two stable states : ON or OFF.

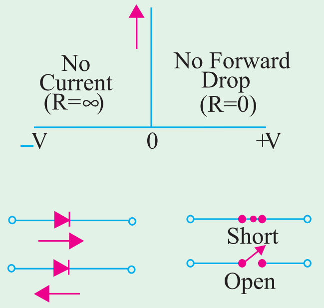


Fig. 52.17

Ideal diode

Example 52.10. *Calculate the circuit current and power dissipated in the* **(a)** *ideal diode* **(b)** *6 Ω resistor of the circuit shown in Fig. 52.18 (a).*

Solution. The diode is an ideal one and is forward-biased. Hence, it can be replaced by a short (closed switch) as shown in Fig. 52.18 (*b*). The circuit current, as given by Ohm's law, is

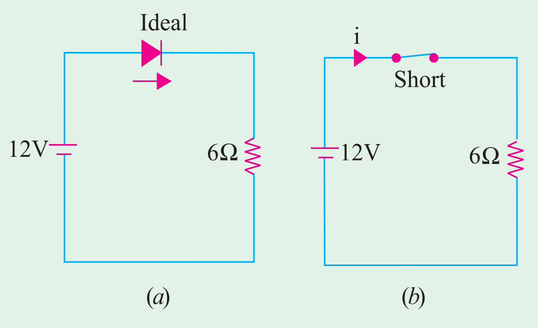
$$I = 12/6 = \mathbf{2\ A}$$

(*a*) Since there is no voltage drop across the diode, power consumed by it is **zero**.

As we know, there is no power when either the voltage or current is zero. In the forward direction, there is current but no voltage drop, hence power dissipated by the ideal diode is zero. In the reverse direction, there is voltage but no current. Hence, power dissipated by the diode is again zero. In fact, an ideal diode never dissipates any power.

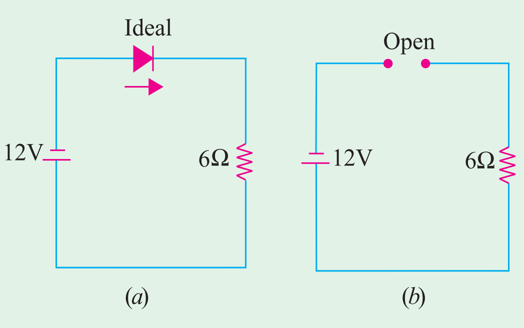
(*b*) power consumed by 6 Ω resistor = $2^2 \times 6$ = **24 W.**

Example 52.11. *Calculate the current in the circuit of Fig. 52.19 (a).*



(*a*) (*b*)

Fig. 52.18



(*a*) (*b*)

Fig. 52.19

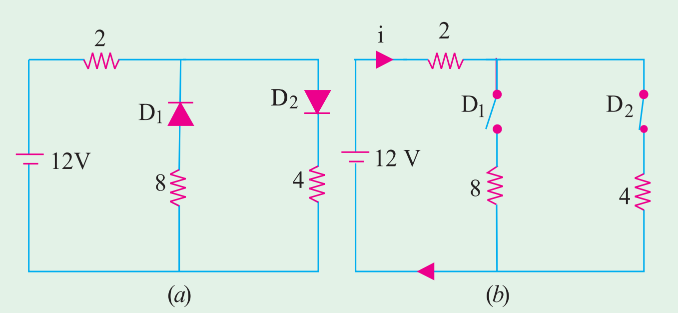
Solution. As seen from the polarity of the battery terminals, the diode is reverse-biased.

Hence, it acts like an open switch as shown in Fig. 52.18 (*b*). Obviously, current in such a circuit is zero.

Example 52.12. *Find the current, if any flowing in the circuit of Fig. 52.20 (a) which uses two oppositely-connected ideal diodes in parallel.*

Solution. The diode D_1 is reverse-biased and acts as an open switch as shown in Fig. 52.20 (*b*). So, there is no current through D_1 and the 8 Ω resistor.

However, D_2 is forward-biased and acts like a short-current or closed switch. The current drawn is $I = 12/(2 + 4)$ = **2 A**.



(*a*) (*b*)

Fig. 52.20

Example. 52.13. *A sinusoidal voltage of peak value 50 V is applied to a diode as shown in Fig. 52.21. Sketch the waveform of voltage* V_O *treating the diode as an ideal one.*

Solution. First, consider the positive half-cycle of the input signal. The diode acts as a short in the forward direction and the moment V_{in} exceeds battery voltage of 10 V, current will start flowing through the circuit. The value of V_O will remain steady at 10 V, the balance of 40 V dropping across 5 K resistance. It is seen that value of V_O is set by the battery voltage.

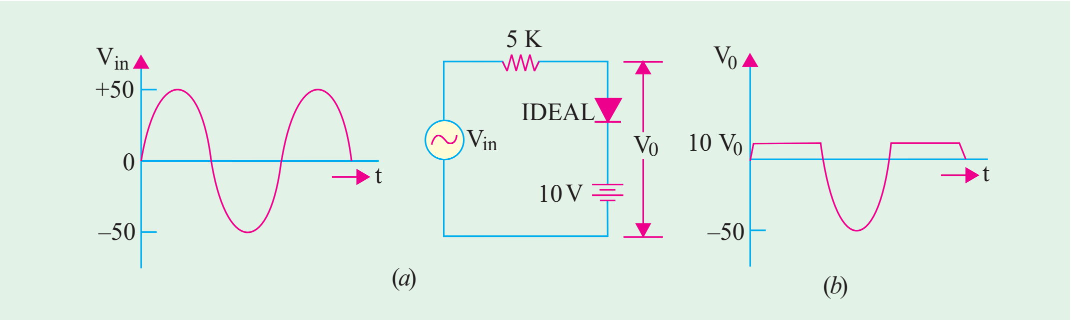


Fig. 52.21

Next, consider the negative input half-cycle. Now, the diode acts like an open switch. Consequently, there is no circuit current and thus no voltage drop across 5 K resistor. Hence, V_0 equals source voltage of peak value 50 V.

It is interesting to note that the above circuit acts as a ***positive*** clipper with a clipping level of 10 V *i.e*. equal to battery voltage. All positive parts of V_{in} above 10 V have been clipped off [Fig. 52.21 (*b*)].

Example 52.14. *Sketch the waveform of the output voltage V_O of the circuit shown in Fig. 52.22 (a)].*

Solution. It is obvious that diode D_1 and its 10 V battery act as positive clipper with positive clipping level at +10 V. Similarly, D_2 and its 10 V battery act as negative clipper with a clipping level at –10 V.

It is clear that output voltage V_0 would be clipped during both the positive and negative half-cycles as shown in Fig. 52.22 (*b*).

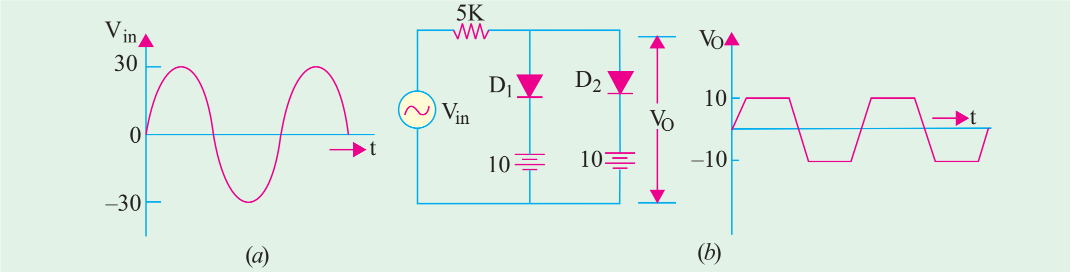


Fig. 52.22

Incidentally, the above example represents one way of obtaining an approximate square waveform from a sine wave. In fact, clipping takes place at +10 V and –10 V regardless of the shape of the input wave *i.e.* whether it is triangular or sawtooth etc.

Example 52.15. *In Fig 52.23 draw input and output waveforms to scale. Consider diode forward resistance of 50 ohms.* **(Nagpur Univ. Winter 2003)**

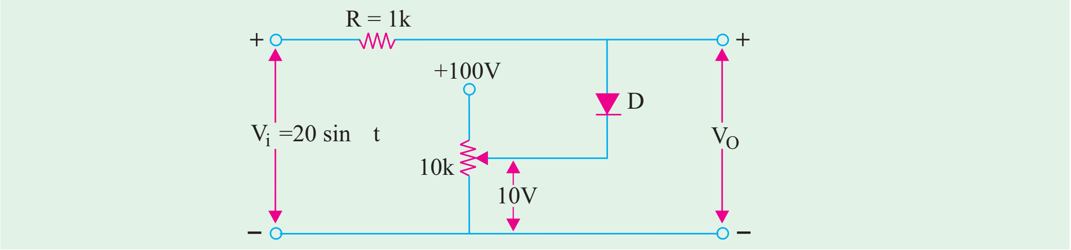


Fig. 52.23

Solution. It is obvious that the diode D and its 10V voltage drop across the 10k variable resistor act as positive clipper. Since the value of R>>R_f (*i.e.* forward resistance of a diode), therefore, the output voltage is clipped at 10V as shown in Fig 52.24.

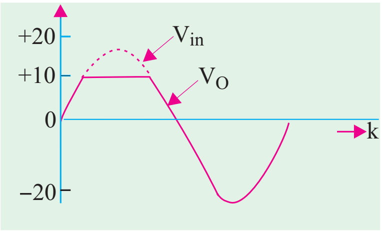


Fig. 52.24

52.13. The Real Diode

A real diode neither conducts in the forward direction with zero resistance nor it offers infinite resistance in the reverse direction.

(*a*) Forward Direction

In this case, we have to take two factors into account. One is that forward current does not start flowing until the voltage applied to the diode exceeds its threshold or knee voltage V_K (0.3 V for Ge and 0.7 V for Si). Hence, a real diode is shown as equivalent to an ideal diode in series with a small ***oppositely-connected*** battery of e.m.f. V_K as shown in Fig. 52.25 (*a*).

The second factor to be considered is the forward dynamic or ac resistance (r_{ac}) offered by the circuit. So far, we considered this resistance to be zero implying that forward characteristic is a straight vertical line [Fig. 52.25 (*a*)]. If we take r_{ac} into account, the forward characteristic becomes as shown in Fig. 52.25 (*b*). Here, the reciprocal of the slope of this characteristic represents r_{ac}.

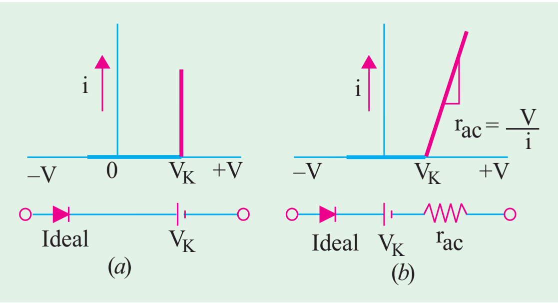


Fig. 52.25

(*i*) Large Signal Operation

Large signal sources are those whose voltage is much greater than the diode knee voltage V_K (nearly equal to barrier potential V_B). Under such conditions, forward current would be large, so that r_j (Art. 52.1) would be negligible.

$$\therefore \qquad r_{ac} = r_j + r_B \cong r_B$$

(*ii*) Small Signal Operation

In this case, the signal voltage is much smaller than V_K (0.3 V for Ge and 0.7 V for Si). Since I_F would be small, r_j would be very large as compared to r_B.

$$\therefore \qquad r_{ac} = r_j + r_B \cong r_j$$

(*b*) Reverse Direction

An actual or real diode does not have infinite resistance in the reverse direction because it will always have some reverse saturation current prior to breakdown. For example, if with a $V_R = 50$ V, I_R is 10 μA, then $R_R = 5 \times 10^6$ Ω = 5 M. Silicon diodes have reverse resistance of many thousands of megohms. Hence, an actual diode in the reverse direction can be thought of as equivalent to a high resistor. This would be true only in the case of signals of low frequencies. For high-frequency signals, we will have to take into account the capacitive effects (Art 52.4).

Example 52.16. *Sketch the waveform for the output voltage V_0 in Fig. 52.26. Take $V_K = 0.3$V for germanium diode which has a forward current of 28 mA at 1 V.*

Solution. $r_B = (1 - 0.3)/28 \text{ mA} = 25\ \Omega\ ;\ r_j = 25/28 = 0.9\ \Omega$ – negligible

$$\therefore \qquad r_{ac} = r_j + r_B \cong r_B = 25\ \Omega.$$

Hence, the equivalent circuit becomes as shown in Fig. 52.27. Whenever V_{in} exceeds 0.3 V in the forward direction, diode is shorted and the circuit offers a total resistance = (25 + 75) = 100 Ω.

The peak voltage = 20 – 0.3 = 19.7 V. Hence, peak value of forward current is = 19.7/100 = 197 mA.

$\therefore$ peak value of output voltage $= 197 \times 10^{-3} \times 75 = 14.77$ V

Hence, the peak value of the half-wave rectified voltage is 14.77 V as shown in Fig. 52.27 (*b*). During the negative half-cycle of the applied voltage, diode acts as an open switch so that $V_0 = 0$. The waveform sketch of V_0 is shown in Fig. 52.27 (*b*).

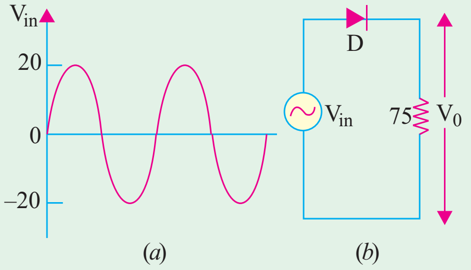


Fig. 52.26

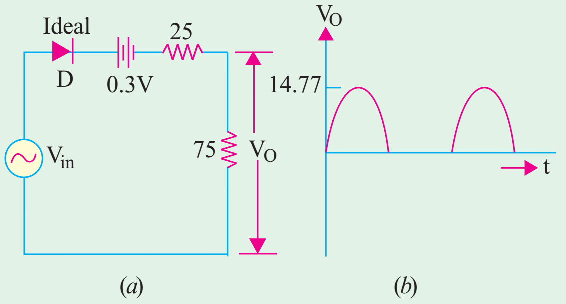


Fig. 52.27

52.14. Diode Circuits with DC and AC Voltage Sources

We will often come across diode and transistor circuits which will contain both dc and ac voltage sources. Such circuits can be easily analysed by using Superposition Theorem (Art 52.15). We will first draw the dc equivalent circuit while neglecting ac-sources and find the required current and voltage values. Next, we will draw the ac equivalent circuit while neglecting the dc sources and again find the voltage and current values. Finally, we will superimpose the two sets of values to get the final result.

While drawing the equivalent circuits, following points must be remembered :

1. Direct current cannot flow 'through' a capacitor. Hence, all capacitors look ***like an open switch to a dc source.***

2. Usually, capacitors used in most circuits are large enough to ***look like a short to an ac source*** particularly one of very high frequency. Similarly, dc batteries would also act as short circuits unless they have very high internal resistances.

Example 52.17. *The silicon diode shown in Fig. 52.28 has a bulk resistance of 1 Ω. The frequency of the 10 mV (peak) signal is so high that the reactance of the coupling, capacitor may be taken as zero. Sketch the approximate waveform of the total voltage 'V' across the diode.*

(Basic Electronics, Punjab Univ.)

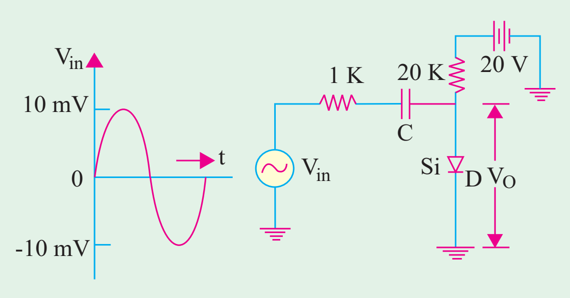


Fig. 52.28

Solution. We will apply Superposition theorem to find *V*. First, voltage drop due to dc source would be found and then it would be added to the drop due to the ac source.

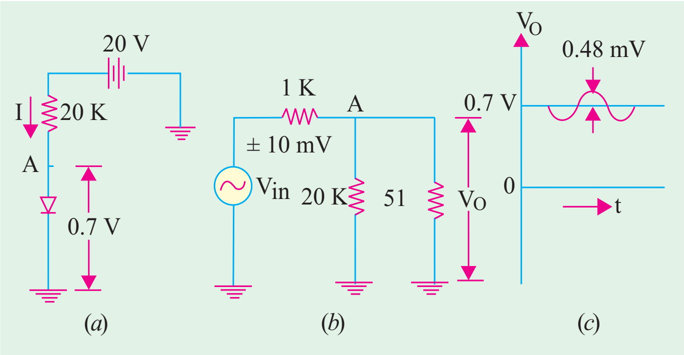
(*i*) DC Equivalent Circuit

It is seen from Fig. 52.26 that the circuit to the left of point *A* is 'open' to the dc source of 20 V because of capacitor *C*. Hence, the equivalent dc circuit is as shown in Fig. 52.29 (*a*). As seen, diode is forward-biased by the battery. Hence, only 0.7 V dc appear across the diode.

The dc current $I = (20 - 0.7)/20\text{ K} \cong 1\text{ mA}$.

(*ii*) AC Equivalent Circuit

Here, the capacitor *C* and the 20-V battery would be treated as shorts thereby giving us the ac equivalent circuit of Fig. 52.29 (*b*).



(*a*) (*b*) (*c*)

Fig. 52.29

Since, it is a silicon diode

$r_j = 50\text{ mV}/1\text{ mV} = 50\ \Omega$

$r_{ac} = r_j + r_B = 50 + 1 = 51\ \Omega$

As shown in Fig. 52.29 (*b*), so far as the signal source is concerned, 20 K resistor and ac resistance of the diode are connected in parallel at point A. Now, 20 K || 51 Ω = 51 Ω. Hence, 1 K and 51 Ω are put in series across the signal source of peak value 10 mV. The peak value of the ac voltage drop over 51 Ω resistance is

$$= 10 \times \frac{51}{51 + 1000} = \mathbf{0.48\ mV}$$

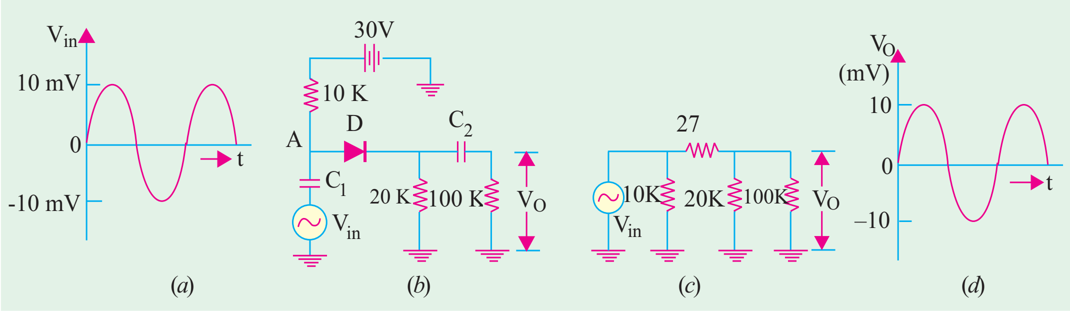
The total drop across the diode is the sum of the ac and dc drops. The combined voltage waveform is shown in Fig. 52.29 (*c*). It consists of a dc voltage of 0.7 V over which rides an ac voltage of peak value ± 0.48 mV.

Example 52.18. *The Ge diode shown in Fig. 52.30 has a bulk resistance of 2 Ω. The two capacitors offer negligible reactance to the a.c. signal. Sketch the waveform of the output voltage.*

Solution. As seen from Fig. 52.30 (*b*), no dc current can pass through 100 K resistor because it is blocked by C_2. Hence, no dc voltage appears across 100-K resistor. The battery current passes through 10 K resistor, through diode, through 20 K resistor and finally to ground.

$$I = (30 - 0.3)/(10 + 20) \times 10^3 = 0.99\text{ mA} \cong 1\text{ mA}$$

$$r_{ac} = r_j + r_B = (25\text{ mV}/1\text{ mA}) + 2 = \mathbf{27\ \Omega}$$



(*a*) (*b*) (*c*) (*d*)

Fig. 52.30

AC equivalent circuit is shown in Fig. 52.30 (*c*) where capacitors and battery have been shorted. As seen, diode resistance of 27 Ω is in series with 20 K || 100 K. It means that only a very small part of ac. Source voltage drops across the diode. Hence, almost all a.c.source voltage appears across 100 K resistor. Obviously, *V* is practically the same as ac source voltage as shown in Fig. 52.30 (*d*).

52.15. Diode Clipper and Clamper Circuits

These are diode waveshaping circuits *i.e.* circuits meant to control the **shape** of the voltage and current waveforms to suit various purposes. Each performs the waveshaping function indicated by its name. The output of the clipping circuit appears as if a portion of the input signal were ***clipped off***. But clamper circuits simply clams (*i.e.* lift up or down) the input signal to a different dc level.

52.16. Clippers

A clipping circuit requires a minimum of two components *i.e.* a diode and a resistor. Often, dc battery is also used to fix the clipping level. The input waveform can be clipped at different levels by simply changing the battery voltage and by interchanging the position of various elements. We will use an ideal diode which acts like a closed switch when forward-biased and as an open switch when reverse-biased.

Such circuit are used in radars and digital computers etc. when it is desired to remove signal voltages above or below a specified voltage level. Another application is in radio receivers for communication circuits where noise pulses that rise well above the signal amplitude are clipped down to the desired level.

Example 52.19. *For the simple parallel clipper of Fig. 52.31, find the shape of the output voltage V_O across the diode if the input sine wave signal is as shown in Fig. 52.31 (a). What will happen when diode and resistor are inter-changed ?*

Solution. When positive half-cycle of the signal voltage is applied to the clipper *i.e.* when *A* is positive with respect to *B*, the diode *D* is reverse-biased. Hence, it acts as an open switch. Consequently, the entire input voltage appears across it.

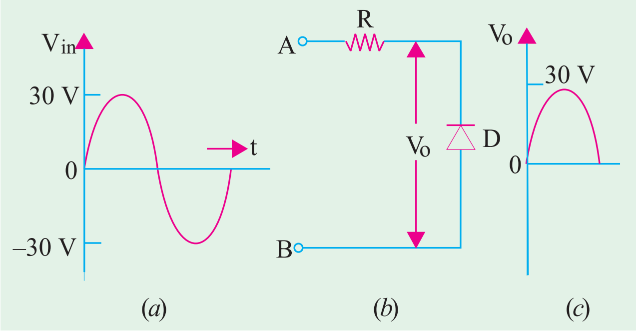


Fig. 52.31

During the negative half-cycle of the signal voltage when circuit terminal *B* becomes positive with respect to *A*, the diode is forward-biased. Hence, it acts like a closed switch (or short) across which no voltage is dropped. Hence, the waveshape of V_0 is as shown in Fig. 52.31 (*c*). It is seen that the negative portion of the signal voltage has been removed. Hence, such a circuit is called a **negative clipper**.

When Diode and Resistor are Interchanged

In this case, the circuit becomes as shown in Fig. 52.32 (*b*). Now, the output voltage V_0 is that which is dropped across *R*. During the positive half-cycle of the signal voltage, *D* acts as an open switch. Hence, all applied voltage drops across *D* and none across *R*. So, there is no output signal voltage.

During the negative input half-cycle, terminal *B* is positive and so it is forward-biases *B* which acts as a short. Hence, there is no voltage drop across *D*. Consequently, all the applied signal voltage drops across *R* and none across *D*. As a result, the negative half-cycle of the input signal is allowed to pass through the clipper circuit. Obviously, now the circuit acts as a **positive** clipper.

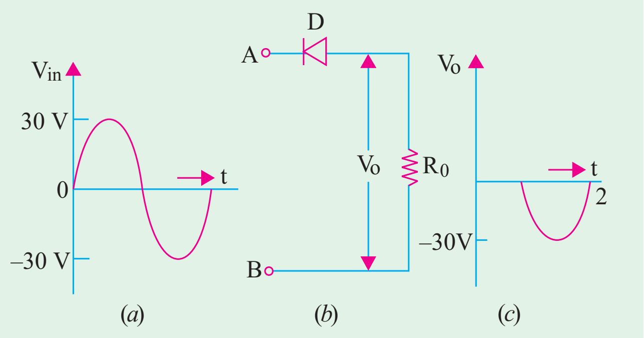


Fig. 52.32

Example 52.20. *What would be the output waveform displayed by the oscilloscope in Fig. 52.33? The silicon diode has a barrier voltage of 0.7 V.*

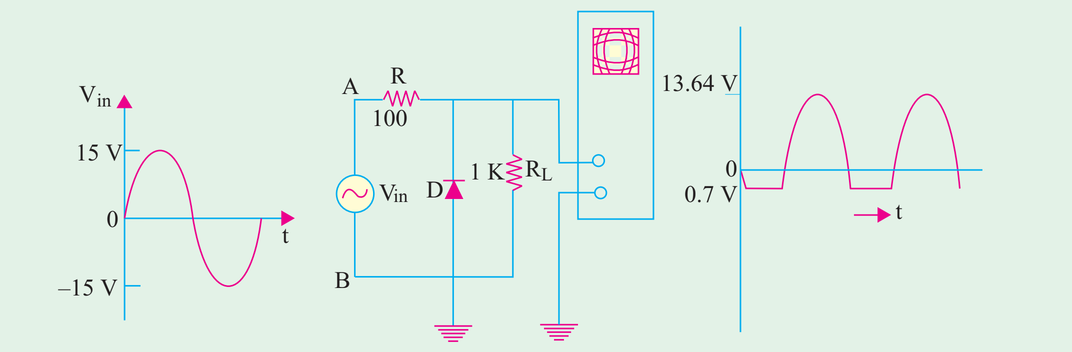


Fig. 52.33

Solution. Consider the negative input half-cycle first *i.e.* when point *B* is positive with respect to point *A*. The diode starts conducting when applied voltage exceeds 0.7 V. Since *D* and R_L are in parallel, voltage across them cannot exceed 0.7 V. Obviously, negative half-cycle beyond 0.7 V gets clipped. Hence, circuit behaves like a negative clipper.

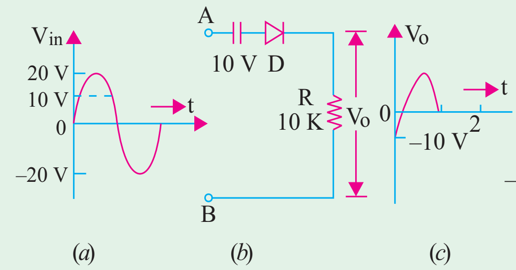
During the positive input half-cycle when point *A* is positive, diode becomes reverse-biased and hence, becomes open-circuited. The applied voltage drops across the resistors *R* and R_L connected in series. The peak value of the output voltage is

$$= 15\left(\frac{R_L}{R+R_L}\right) = 15\times\frac{1}{1.1} = 13.64\text{ V}$$

Hence, the output voltage as displayed by the oscilloscope would be as shown in Fig. 52.33.

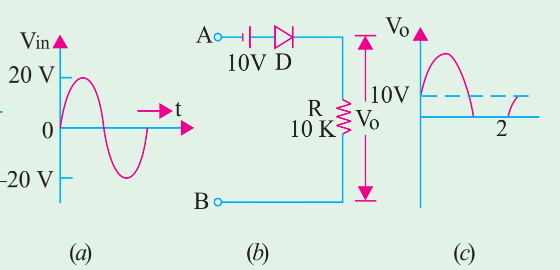
Example. 52.21. *With the sine wave signal input of Fig. 52.34 (a), find the shape of the output signal* V_0 *in the biased series clipper of Fig. 52.34 (b). What would happen if battery connections are reversed ?*

Solution. Let us consider the positive half-cycle of the singal *i.e.* when terminal *A* of the circuit becomes positive with respect to *B*. The diode appears as a short since it is forward-biased.



(*a*) (*b*) (*c*)

Fig. 52.34



(*a*) (*b*) (*c*)

Fig. 52.35

But no current flows till V_{in} exceeds the opposing battery voltage of 10 V. Hence, only upper part of the positive signal voltage passes through the clipper circuit and appears as V_0 across *R*. Its shape is shown in Fig. 52.34 (*c*). The negative half-cycle of the signal voltage is clipped off.

In fact, in this circuit, the entire input is clipped off except positive peak portions.

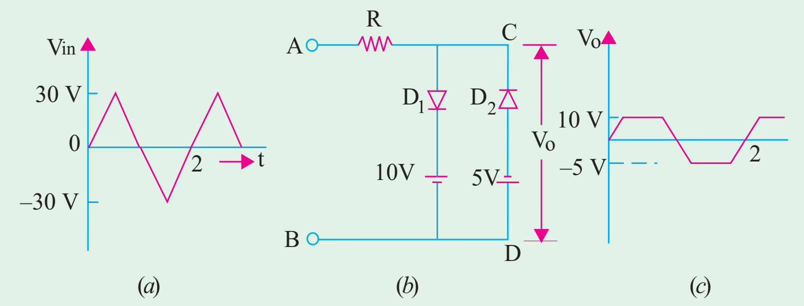
Reversed Battery Connections

The battery connections have been reversed in Fig. 52.35. In this case, during the positive half-cycle of the signal, the voltage across *R* would be the sum of the signal voltage and the battery voltage *i.e.* signal voltage would be lifted up by 10 V as shown in Fig. 52.35 (*c*).

During the negative input half-cycle, the lower peak portions of the signals would be clipped off because of the 10 V battery.

Example. 52.22. *The triangular voltage of Fig. 52.36 (a) is applied to the biased parallel clipper circuit of Fig 52.36 (b). Find the wave-shape of the output voltage.*

Solution. During the positive half-cycle, D_1 would conduct but D_2 will act as an open-circuit. However, value of V_0 cannot exceed 10V because points C and D are electrically connected across the 10 V battery since D_1 is shorted. Hence, signal voltage above 10 V level would be clipped off as shown in Fig. 52.36 (*c*).



(*a*) (*b*) (*c*)

Fig. 52.36

During the negative half-cycle, D_1 is open but D_2 conducts. Again, V_0 cannot exceed 5 V since it is the voltage across points C and D whose value is fixed by the battery connected in that branch. Hence, signal voltage beyond 5 V is clipped off. The wave-shape of V_0 is as shown in Fig. 52.36 (*c*).

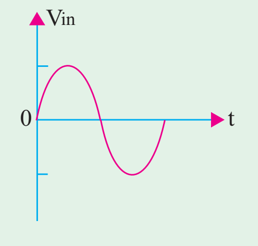


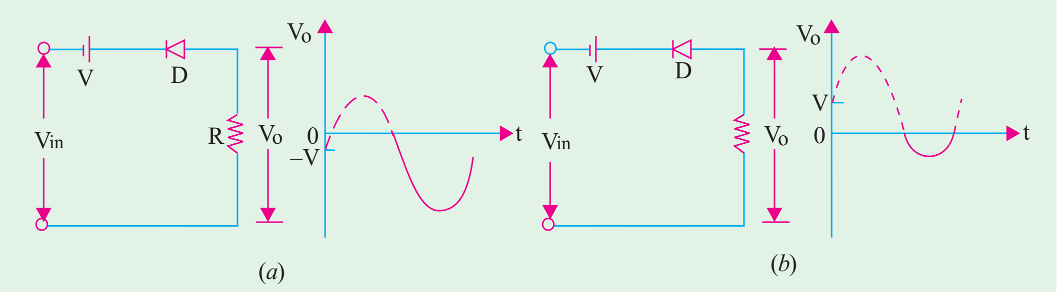
Fig. 52.37

52.17. Some Clipping Circuits

For the following circuits, a sinusoidal input signal as shown in Fig. 52.37 would be assumed.

(*a*) Biased Series Clippers

The output voltage has the waveform as shown in Fig. 52.38.



(*a*) (*b*)

Fig. 52.38

(*b*) Biased Parallel Clippers

The waveforms of the output voltage are as shown in Fig. 52.39.

Clipping has been changed by changing the battery and diode connections.

52.18. Clampers

To put it simply, clamping is the process of introducing a dc level into an ac signal. Clampers are also sometimes known as dc restorers.

By way of illustration, consider the signal shown in Fig. 52.40 (*a*). It is a sine wave with equal positive and negative swings of ± 5 V about 0 V. Hence, its average value over one cycle is zero (it has no dc level).

In Fig. 52.40 (*b*), the signal waveform has been lifted up so as to just touch the horizontal axis. It is now said to have acquired a dc level of 5 V. This output wave-form is said to be ***positively*** clamped at 0 V. Fig. 52.40 (*c*) shows an output waveform which is negatively clamped at 0 V.

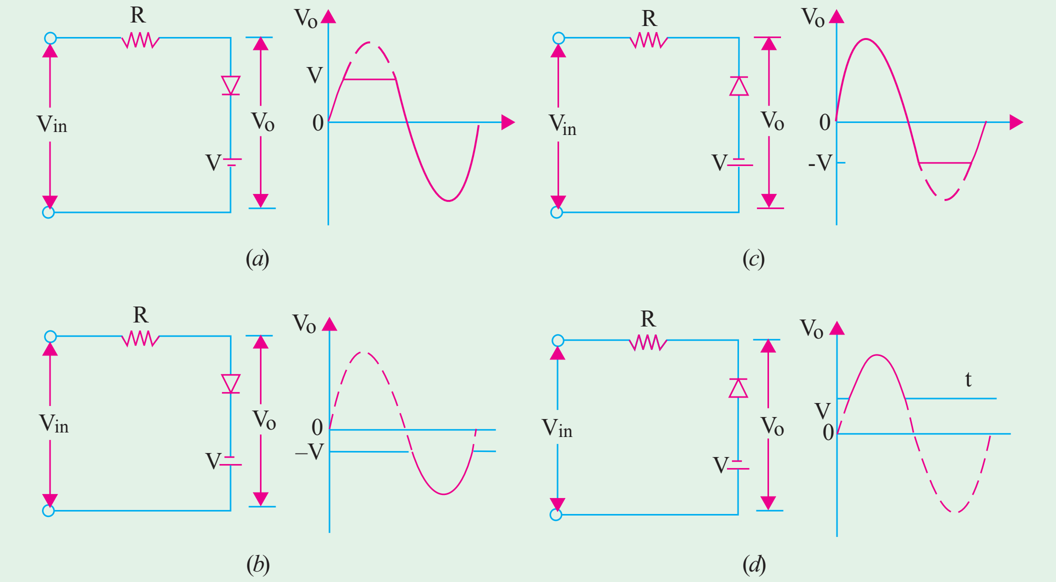


Fig. 52.39

A circuit capable of accepting the input signal shown in Fig. 52.40 (*a*) and delivering the output shown in Fig. 52.40 (*b*) or (*c*) is called a ***clamper***. Such a circuit has a minimum requirement of ***three*** elements.

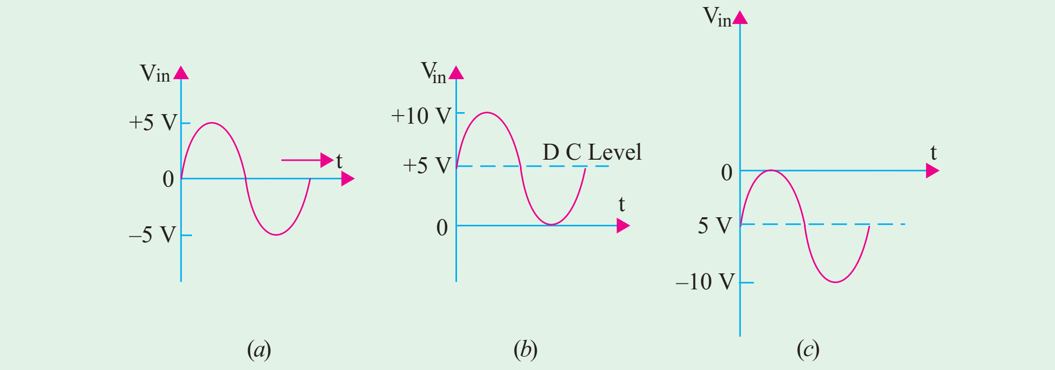


Fig. 52.40

1. a diode **2.** a capacitor and **3.** a resistor.

It will generally need a dc battery also. Following additional points regarding clamper circuits are worth keeping in mind.

1. both *R* and *C* affect the waveform.
2. values of *R* and *C* should produce a time constant ($\lambda = CR$) which is large enough to ensure that capacitor remains almost fully charged during the time-period of the signal. In other words, time constant $\lambda \gg T/2$ where *T* is the time-period of the input signal. For good clamping action, the *RC* time constant should be at least ten times the time-period of the input signal voltage.

3. it is advantageous to first consider the condition under which the diode becomes forward biased.
4. for all clamping circuits, voltage swing of the input and output waveforms is the same.
5. such circuits are often used in TV receivers as dc restorers. The incoming composite video signal is normally processed through capacitively-coupled amplifiers which eliminate the dc component thereby losing the black and white reference levels and the blanking level. These reference levels have to be restored before applying the video signal to the picture tube.

Example 52.23. *The input signal of Fig. 52.41 (a) is applied to the clamper circuit shown in Fig. 52.41 (b). Draw the waveform of the output voltage V_0. How will it change if R is made 100 Ω ?*

(Electronic circuits, Bangalore Univ.)

Solution. As seen, time-period of the input signal is $T = 1/1000$ second = 1 ms

$\therefore \quad 0 \rightarrow t_1 = t_1 \rightarrow t_2 = t_2 \rightarrow t_2 = T/2$ .... = 0.5 ms.

$\lambda = C_R = 1 \times 10^{-6} \times 10 \times 10^3 = 10$ ms

As seen, $\lambda \gg T/2$. Hence, once charged, the capacitor will have hardly any time to discharge by the time signal polarity reverses.

(*a*) Positive Input Half-cycle

When positive half-cycle of the input signal voltage is applied to the clamper circuit, its terminal *A* becomes positive with respect to terminal *B*. Hence, *D* acts like a short as shown in Fig. 52.41 (*c*). A steady positive voltage of 5 V remains applied to *A* for 0.5 ms. At the same time, *R* is also shorted out [Fig. 52.41 (*c*)] because it is in parallel with *D*. Hence, C will rapidly charge to 5 V. Being across a short, $V_0 = 0$ during positive half-cycle as shown in Fig. 52.41 (*d*).

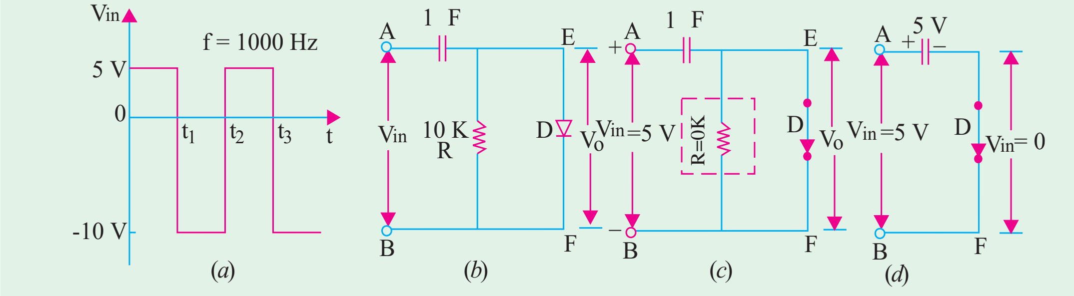


Fig. 52.41

(*b*) Negative Input Half-cycle

In this case, terminal *B* becomes positive and so reverse-biases *D* by 10 V. Hence, *D* acts like an open switch as shown in Fig. 52.42 (*a*). Now, *R* and *C* get connected in series so that their $\lambda = RC$ = 10 ms. As stated earlier, capacitor will take a time of 5λ = 50 ms to get fully discharged. But the input signal will allow it just 0.5 ms during which to discharge. Obviously, *C* would hardly get discharged in this extremely short time interval of 0.5 ms. Hence, it can be assumed to be still fully charged with the original polarity during this negative half-cycle.

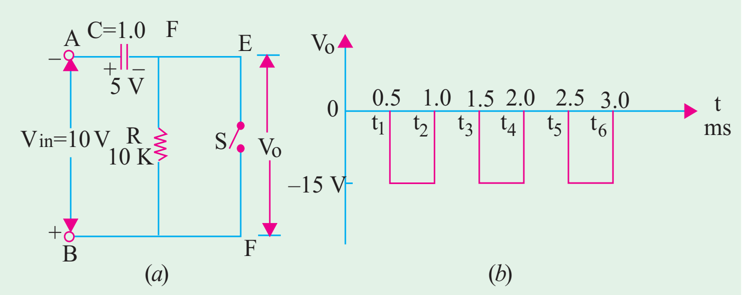


Fig. 52.42

The output voltage V_0 across the 'open' will be

$$= \text{voltage from } E \rightarrow A \rightarrow B \rightarrow F \qquad \text{– Fig. 52.40 } (a)$$

$$= 5 + 10 = 15\text{ V} \qquad \text{– with } E \text{ negative}$$

The waveform of the output voltage is shown in Fig. 52.42 (*b*). It has same frequency as that of the input signal. However, it has been clamped down in the negative region. It is seen that voltage swing of both input and output circuits is the same *i.e.* 15 V. It is never the case in clipping circuits.

When R = 100

Now, $\lambda = 100 \times 1 \times 10^{-6}$ ms = 0.1 ms. Hence, the capacitor which is almost instantaneously charged to +5 V during the positive input half-cycle, will be almost completely discharged during the negative half-cycle because, now, 5 λ (full discharge time) equals the half time-period (0.5 s) of the signal.

Hence, in this case, V_0 would be momentarily equal to – 15 V at the beginning of the negative half-cycle but will fall off to almost 0 V before the signal reverses its polarity (Fig. 52.43). As seen, υ_0 consists of voltage spikes of amplitude – 15 V.

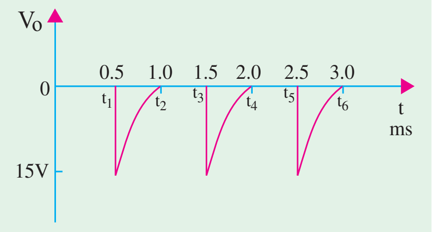


Fig. 52.43

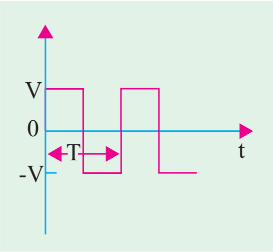
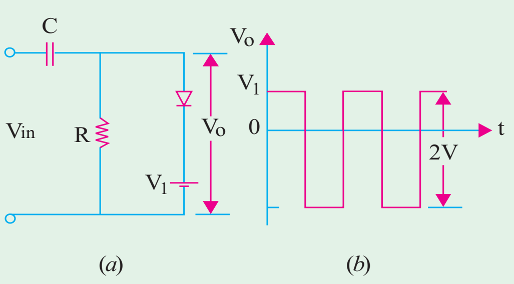


Fig. 52.44

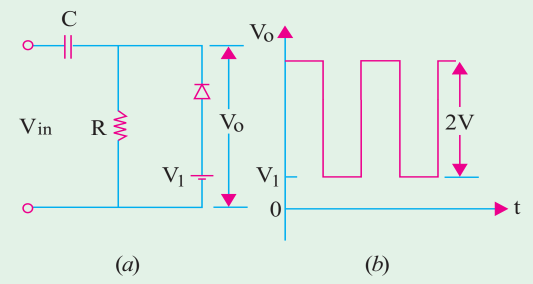
52.19. Summary of Clamping Circuits

In the following clamping circuits, it would be assumed that the amount of the time $5\lambda = 5\,RC$ » $T/2$ where T is the time-period of the input signal. For all circuits, we will take the same input signal shown in Fig. 52.44 with a peak value of V. We will also take note of the change in the output waveform when diode connections are reversed.



(*a*) (*b*)

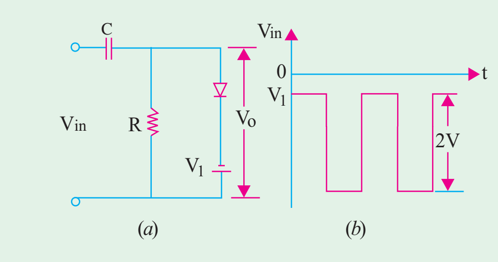
Fig. 52.45



(*a*) (*b*)

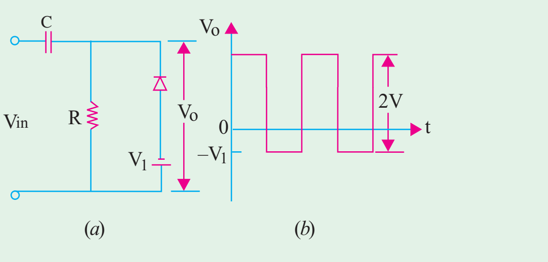
Fig. 52.46

It is seen from Fig. 52.44 and 52.45 that negative clamping has changed to positive clamping when the diode connections are reversed.



(*a*) (*b*)

Fig. 52.47



(*a*) (*b*)

Fig. 52.48

The same thing happens in the case of clamping circuits shown in Fig. 52.47 and 52.48.

Tutorial Problems No. 52.1

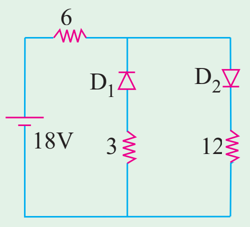


Fig. 52.49

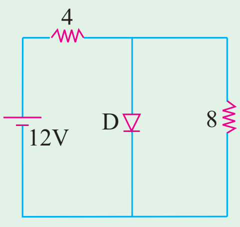


Fig. 52.50

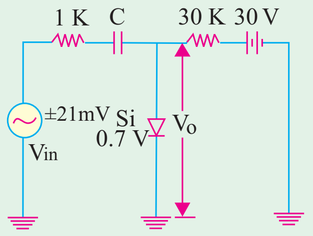


Fig. 52.51

1. Find the current supplied, if any, by the battery in the circuit of Fig. 52.49 which uses two oppositely-connected ideal diodes in parallel. **[1 A]**
2. What is the current supplied by the battery in Fig. 52.50 if *D* is an ideal diode. **[3 A]**
3. In Fig. 52.51, signal voltage has a peak value of ≠ 21 mV and its frequency is so high that reactance of the coupling capacitor can be neglected. If bulk resistance of the silicon diode is neglected, what would be the approximate waveform of the total voltage 'V_0' across the diode. **[0.7 V dc on which rides an ac voltage of peak value = 1 mV]**

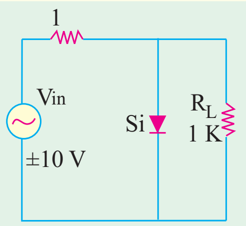


Fig. 52.52

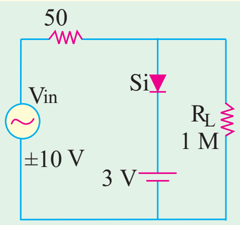


Fig. 52.53

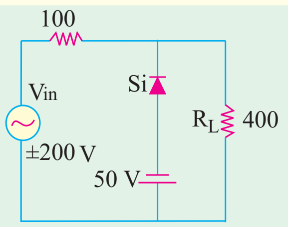


Fig. 52.54

4. Sketch the voltage across R_L in the clipper circuit of Fig. 52.52.
5. Sketch the voltage across R_L in the clipper circuit of Fig. 52.53.
6. What is the waveform of the voltage across R_L in Fig. 52.54 ?
7. What is the approximate dc component in the output of a positive diode clamper with a peak input of 20 V ? **[20 V]**

OBJECTIVE TESTS – 52

1. For a silicon diode, the value of the forward-bias voltage typically
   (*a*) must be greater than 0.3 V
   (*b*) must be greater than 0.7 V
   (*c*) depends on the width of the depletion region
   (*d*) depends on the concentration of majority carriers.
2. When forward biased, a diode
   (*a*) blocks current
   (*b*) conducts current
   (*c*) has a high resistance
   (*d*) drops a large voltage
3. The term bias means
   (*a*) the ratio of majority carriers to minority carriers
   (*b*) the amount of current across the P-N junction
   (*c*) a dc voltage applied across the P-N junction to control its operation
   (*d*) none of the above
4. To forward-bias a P-N junction, diode,
   (*a*) an external voltage is applied that is positive at the anode and negative at the cathode
   (*b*) an external voltage is applied that is negative at the anode and positive at the cathode.

(*c*) an external voltage is applied that is positive at the P-region and negative at the N-region
(*d*) a and c above

5. When a P-N junction is forward-biased
(*a*) the only current is the hole current
(*b*) the only current is the electron current
(*c*) the only currentis produced by majority carriers
(*d*) the current is produced by both holes and electrons.

6. A P-N junction diode's dynamic conductance is directly proportional to
(*a*) the applied voltage
(*b*) the temperature
(*c*) the current
(*d*) the thermal voltage
(**Hint :** Conductance is reciprocal of the resistance)

7. The junction capacitance of a linearly graded junction varies with the applied reverse bias, V_R as
(*a*) V_R^{-1} (*b*) $V_R^{-1/2}$
(*c*) $V_R^{-1/3}$ (*d*) $V_R^{1/2}$
(UPSC Engg. Services 2002)

8. The diffusion capacitance of a forward biased P^+ N (P^+ indicates heavily doped *P*-region) junction diode with a steady current *I* depends on
(*a*) width of the depletion region
(*b*) mean life-time of holes
(*c*) mean life-time of electrons
(*d*) junction-area
(UPSC Engg. Services 2002)

9. The width of depletion layer of a P-N junction
(*a*) decreases with light doping
(*b*) increases with heavy doping
(*c*) is independent of applied voltage
(*d*) is increased under reverse bias.

10. At room temperature of 25°C, the barrier potential for silicon is 0.7 V. Its value at 125°C is .... volt.
(*a*) 0.5 (*b*) 0.3
(*c*) 0.9 (*d*) 0.7.

11. Junction breakdown occurs
(*a*) under high temperature condition
(*b*) with forward bias
(*c*) under reverse bias
(*d*) because of manufacturing defect.

12. Avalanche breakdown is primarily dependent on the phenomenon of
(*a*) collision (*b*) doping
(*c*) ionization (*d*) recombination.

13. Reverse current in a silicon junction nearly doubles for every........... °C rise in temperature.
(*a*) 10 (*b*) 2
(*c*) 6 (*d*) 5.

14. In the forward region of its characteristic, a diode appears as a/an

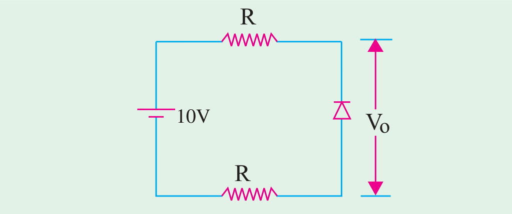


Fig. 52.55

(*a*) OFF switch (*b*) high resistance
(*c*) capacitor (*d*) ON switch.

15. The approximate value of V_O across the diode in Fig. 52.53 is

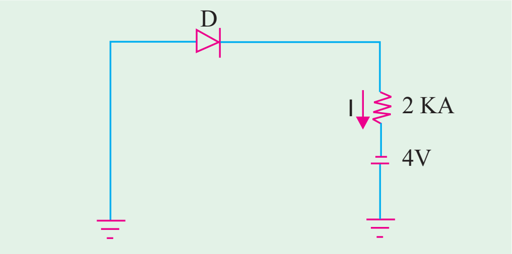


Fig. 52.56

(*a*) zero (*b*) 10 V
(*c*) 5 V
(*d*) dependent onvalue of R.

16. The diode 'D' is ideal in the network shown in Fig. 52.56. The current 'I' will be.
(*a*) Ä 2 n A (*b*) zero
(*c*) 2 m A (*d*) 4 mA

17. The voltages at V_1 and V_2 of the arrangement shown in Fig. 52.57 will be respectively.

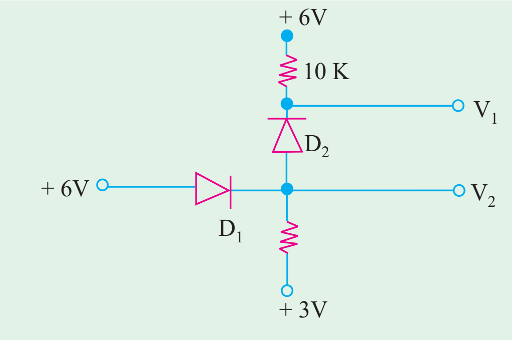


Fig. 52.57

(*a*) 6 V and 5.4 V (*b*) 5.4 V and 6 V
(*c*) 3 V and 5.4 V (*d*) 6 V and 5 V

18. Without a dc source, a clipper acts like a

(*a*) rectifier (*b*) clamper
(*c*) demodulator (*d*) chopper

19. The primary function of a clamper circuit is to

(*a*) suppress variations in signal voltage
(*b*) raise positive half-cycle of the signal
(*c*) lower negative half-cycle of the signal
(*d*) introduce a dc level into an ac signal

20. For an input $V_S = 5 \sin t$ (assuming ideal diode), the circuit shown in Fig. 52.58 will be behave as a

(*a*) clipper, sine wave clipped at –2 V
(*b*) clamper, sine wave clamped at –2 V
(*c*) clamper, sine wave clamped at zero volt
(*d*) clipped, sine wave clipped at 2 V

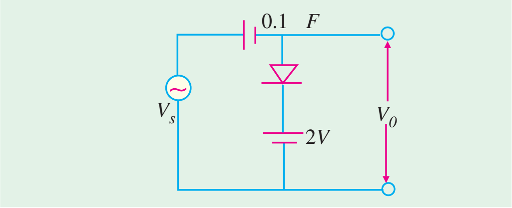


Fig. 52.58

21. A clipping circuit is shown in Fig. 52.59. Its transfer characteristic will be

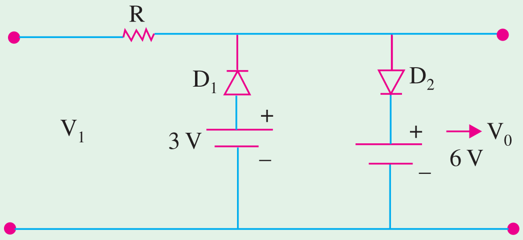
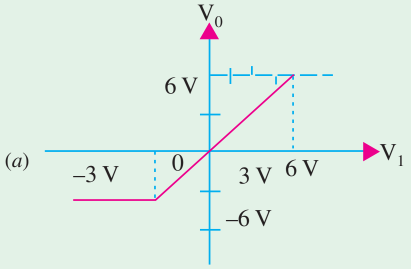
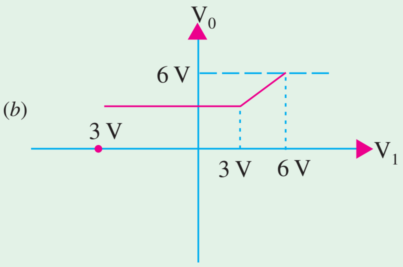
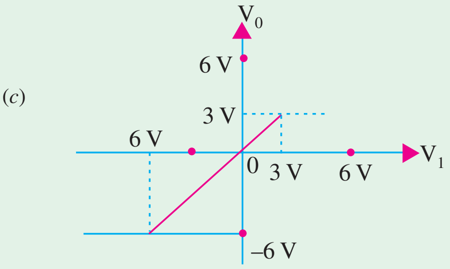
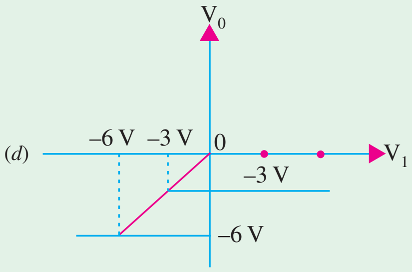


Fig. 52.59









ANSWERS

1. (*b*)	**2.** (*b*)	**3.** (*c*)	**4.** (*d*)	**5.** (*d*)	**6.** (*c*)	**7.** (*c*)
8. (*c*)	**9.** (*d*)	**10.** (*c*)	**11.** (*c*)	**12.** (*a*)	**13.** (*c*)	**14.** (*d*)
15. (*b*)	**16.** (*c*)	**17.** (*a*)	**18.** (*a*)	**19.** (*d*)	**20.** (*b*)	**21.** (*b*)

ROUGH WORK

GO To FIRST