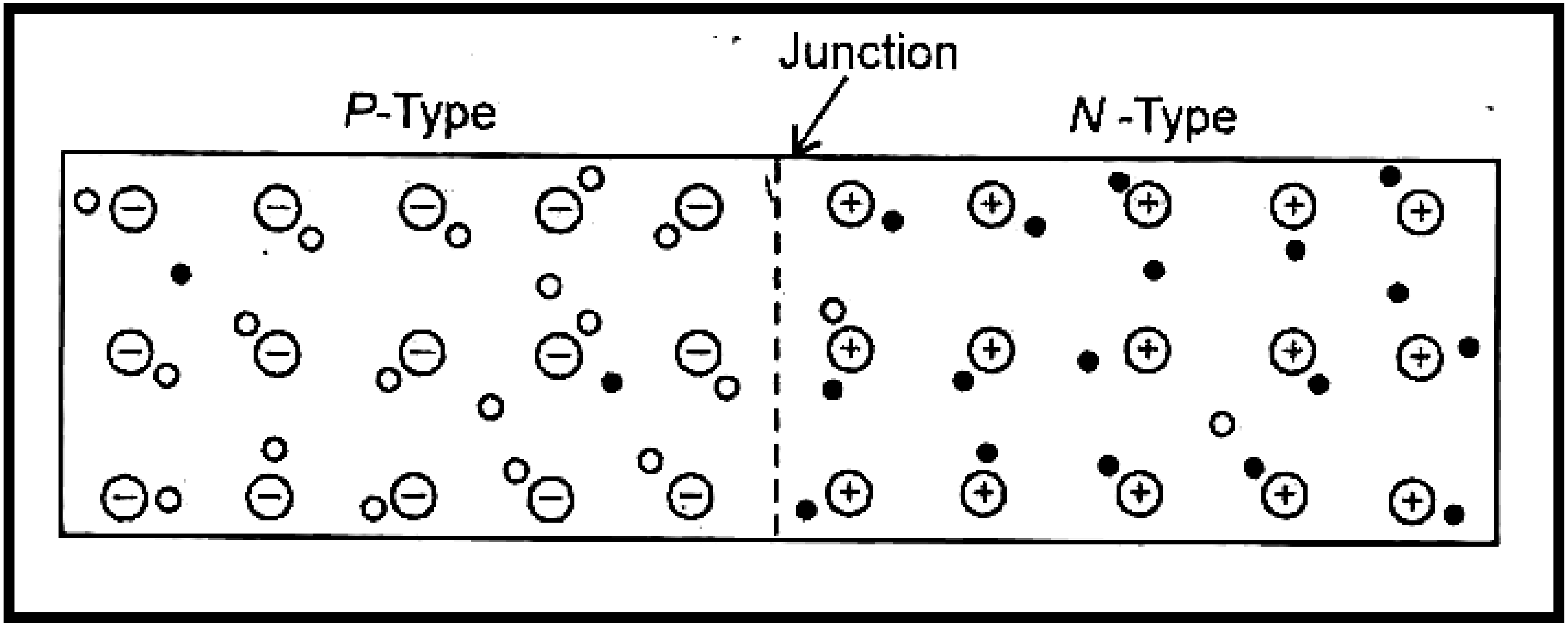
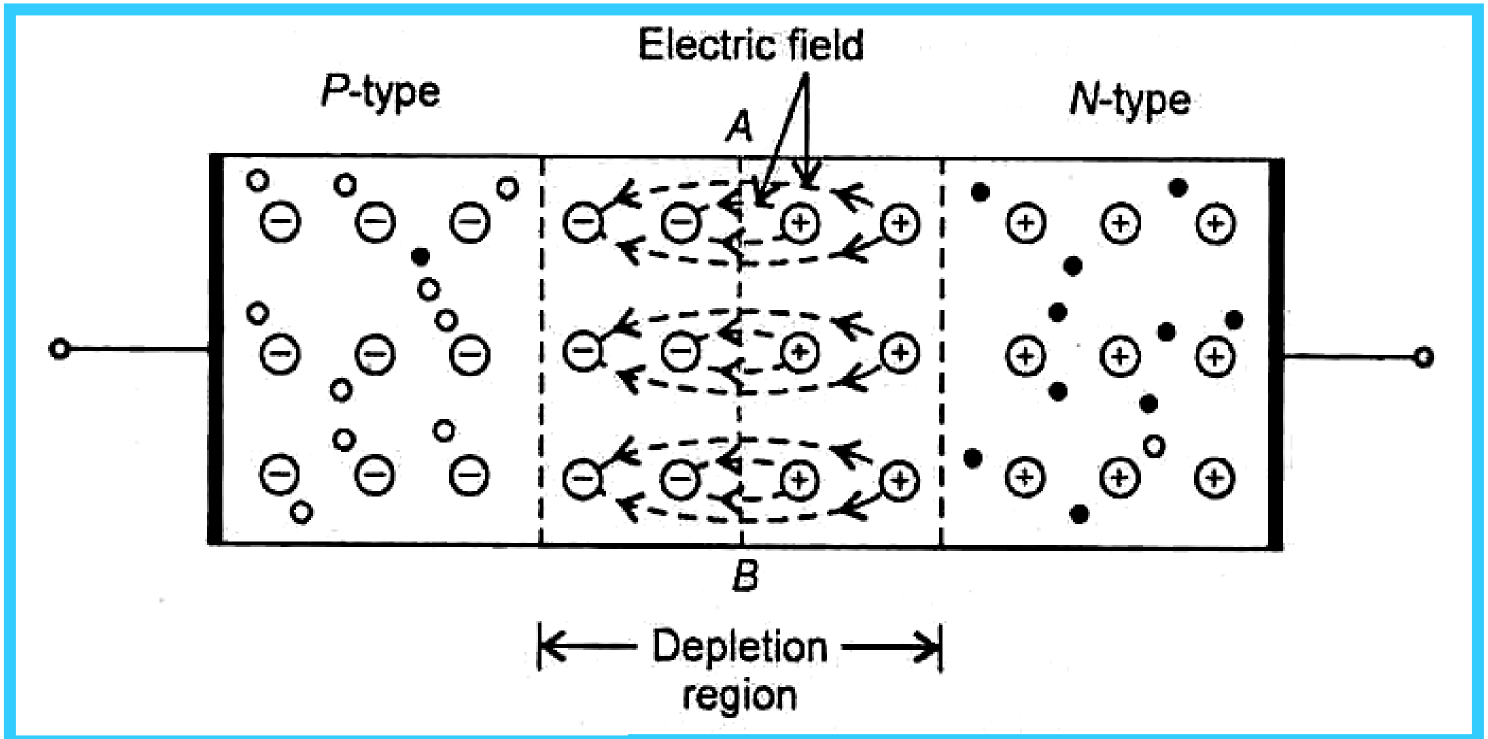
PN-junction Diode

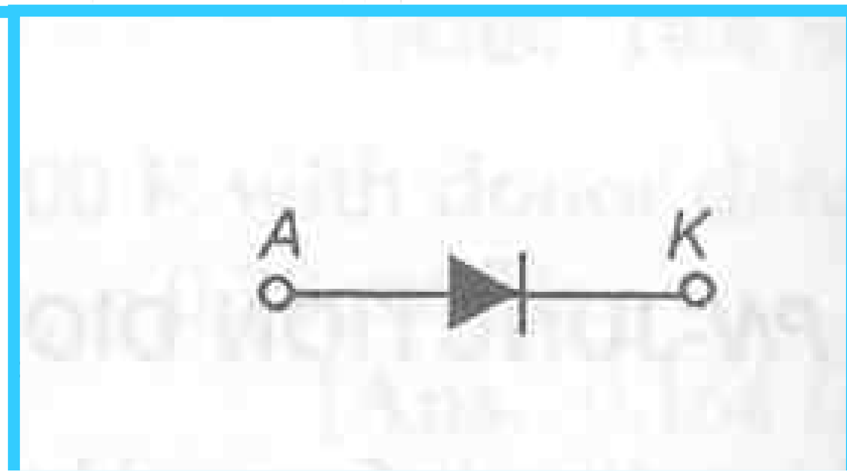
- *PN*-junction is formed by growing a single crystal of Si or Ge, which is half *P*-type and half *N*-type.



Formation of Depletion Region



Symbol



- Because of diffusion of electrons from *N*-type into *P*-type, and of hole from *P*-type into *N*-type, depletion region or space-charge region is formed.
- This region has extremely high resistance and the potential due to Electric field is called barrier potential or contact potential or diffusion potential.

$$V_0 = 0.7 \text{ V for Si}$$

$$V_0 = 0.3 \text{ V for Ge}$$

❖ The barrier discourages the diffusion of majority carriers across the junction.

❖ But the same barrier helps the minority carriers to drift across the junction.

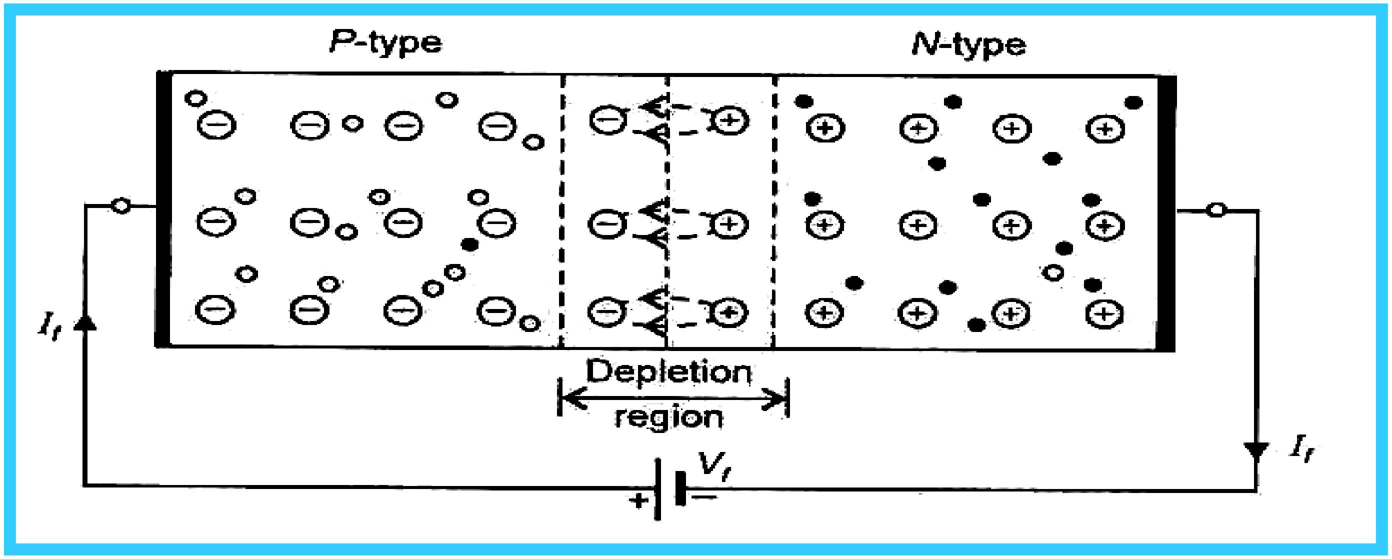
❖ The minority carriers are constantly generated due to thermal energy.

❖ Does it mean that there should be constant current due to the minority carriers crossing the junction ?

❖ No. How can there be current without any external connection ?

- Ans.: The net current across the junction has to be zero. The majority carrier having high energy still diffuse across the junction. The two currents counterbalance each other.

PN-Junction with Forward Bias

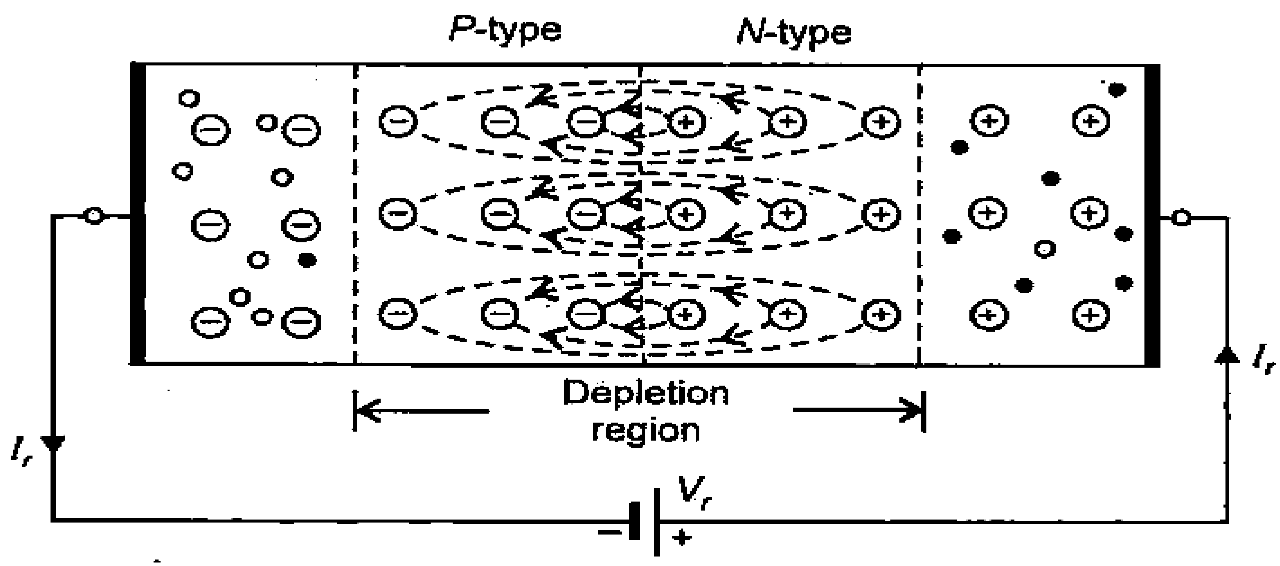


- Applied voltage opposes the contact potential.
- Net barrier potential V_B is reduced.
- Diffusion current increases.
- Drift current slightly decreases.
- The forward biasing current is

$$I_f = I_{dif} - I_{dr}$$

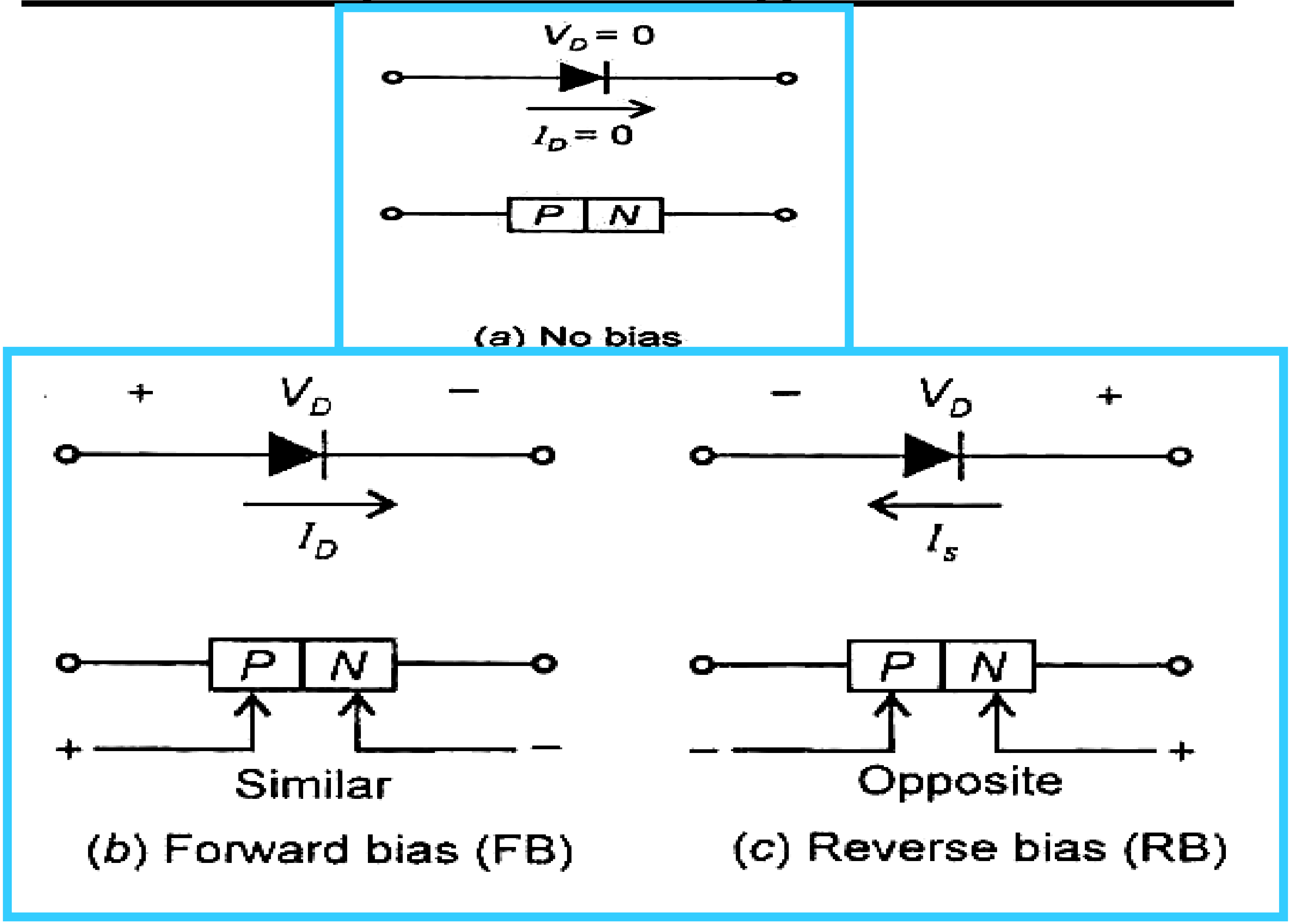
PN-Junction with Reverse Bias

$$I_r = I_{dr} - I_{dif} \approx I_{dr}$$



- Barrier potential V_B increases.
- I_{dif} due to majority carriers reduces to almost zero.
- I_{dr} slightly increases.
- The net current I_r remains constant till breakdown, hence called saturation current I_s .

Summary of Biasing Conditions

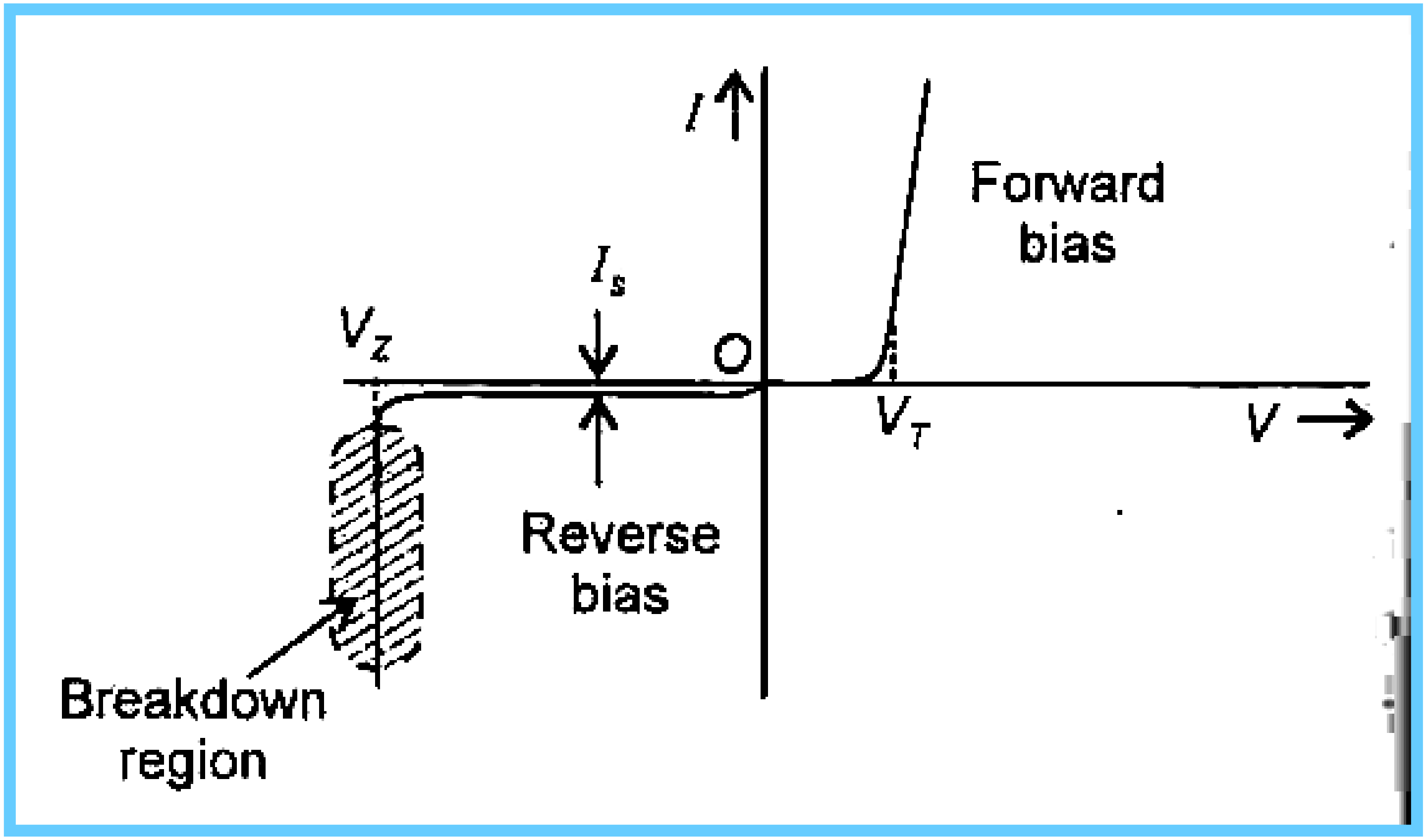


(a) No bias

(b) Forward bias (FB)

(c) Reverse bias (RB)

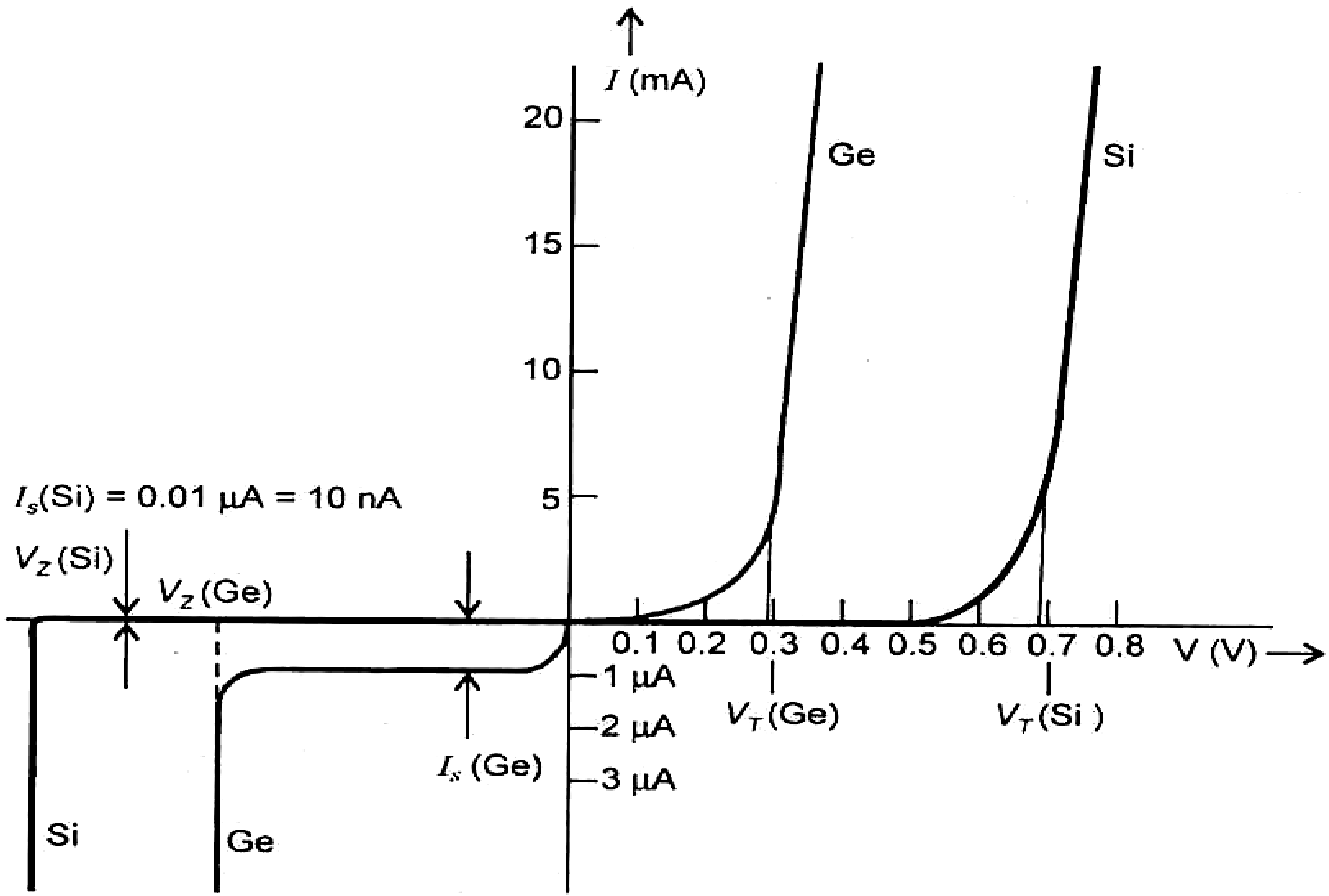
V-I Characteristics of Diode



- V_T is cut-in, knee, offset, turn-on, or threshold voltage.
- I_s is reverse saturation current.

$$V_T \approx 0.7\ \text{V} \qquad \text{(for Si diodes)}$$
$$V_T \approx 0.3\ \text{V} \qquad \text{(for Ge diodes)}$$

Si Diode vs Ge Diode



Reverse Breakdown

- At some high reverse voltage, called breakdown voltage (V_Z), the current abruptly increases. Two phenomena :

1. Zener Breakdown:

The field across depletion region becomes so high (about 10^7 V/m) that large number of covalent bonds break.Hence large current starts flowing.

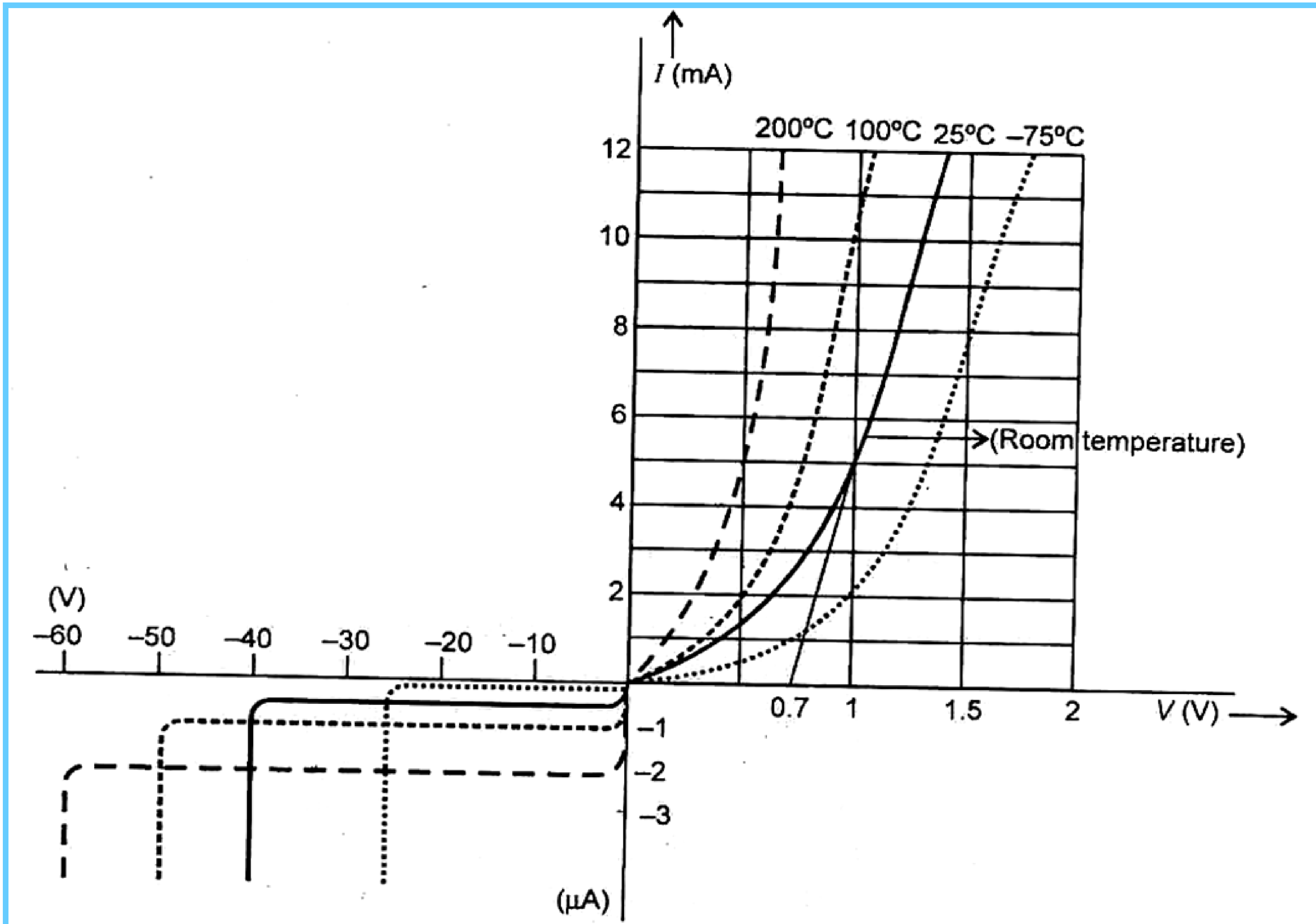
2. **Avalanche Breakdown:**

- Increased field causes large increase in the velocities of minority carriers.These carriers cause impact ionization.
- Cumulative multiplication of charge carriers occur.

- *Zener is predominant for V_Z less than 4 V.*
- *Avalanche is predominant for V_Z greater than 6 V.*

Temperature Effects

- I_s almost doubles for every 10 °C rise in temperature.
- V_Z increases with temperature.
- The width of the depletion layer decrease and hence barrier potential decreases with rise in temperature.
- As a result, V_T decreases by 2 mV for each celsius degree rise in temperature.



I (mA)
200°C 100°C 25°C −75°C
12
10
8
6
4
2
→(Room temperature)
(V)
−60
−50
−40
−30
−20
−10
0.7
1
1.5
2
V (V)
−1
−2
−3
(µA)

Example 3.1 The threshold voltage of a silicon diode is 0.7 V at 25 °C. What will be the value of threshold voltage if the junction temperature rises to 100 °C.

Solution : The barrier potential decreases by 2 mV per Celsius degree rise in temperature. Therefore if the temperature rises to 100 °C from 25 °C, the decrease in barrier potential

$$= (100 - 25) \times 2 \text{ mV} = 150 \text{ mV} = 0.15 \text{ V}$$

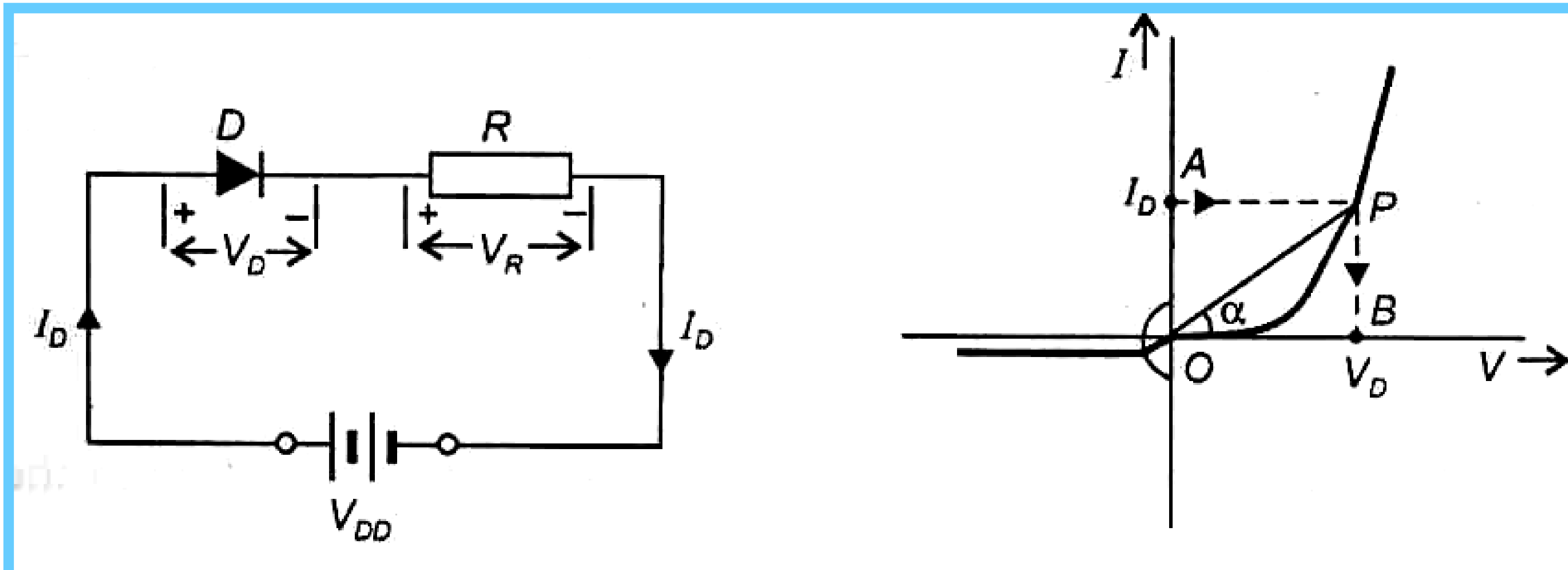
Thus, the threshold voltage at 100 °C is

$$V_T = 0.7 \text{ V} - 0.15 \text{ V} = \mathbf{0.55\ V}$$

DIODE RESISTANCE

- Two kinds :
  1. Static or DC Resistance (High Value): It is the resistance offered by the diode to a dc current.
  2. Dynamic or AC Resistance (Low Value): It is the resistance offered by the diode to ac (varying) current.

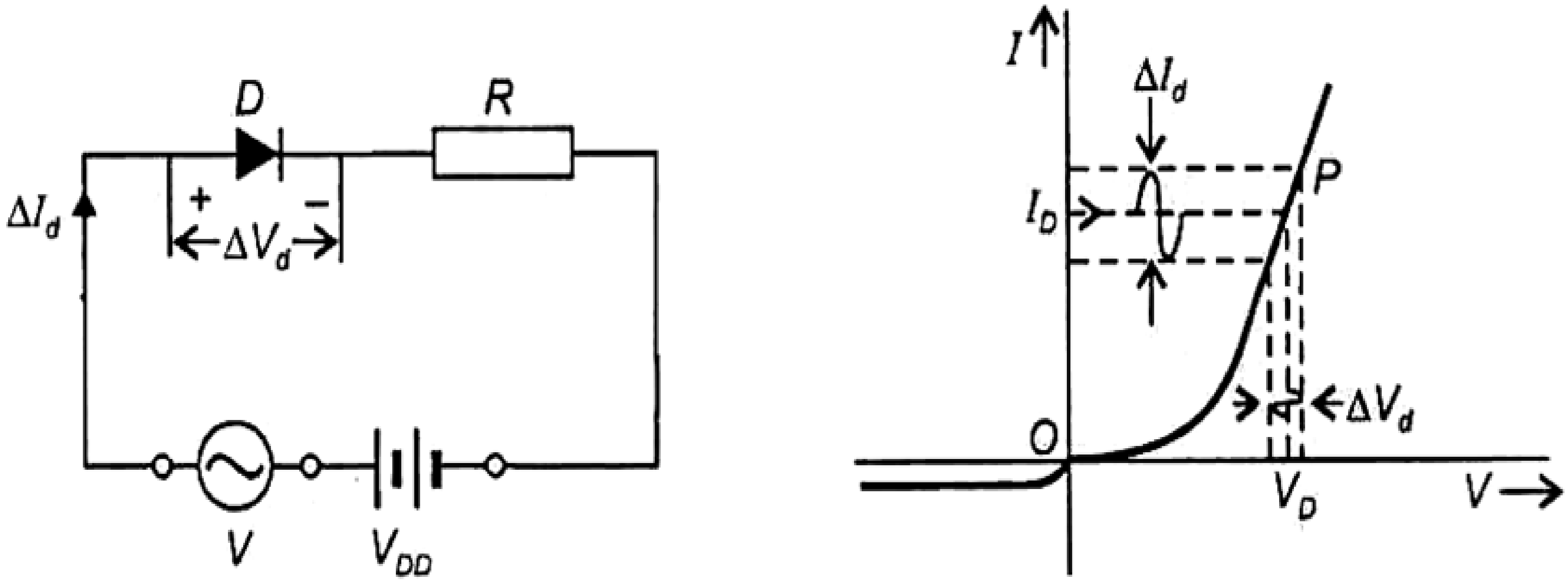
Static or DC Resistance



$$R_F = \frac{V_D}{I_D}$$

$$R_F = \frac{V_D}{I_D} = \frac{OB}{OA} = \frac{OB}{BP} = \cot \alpha$$

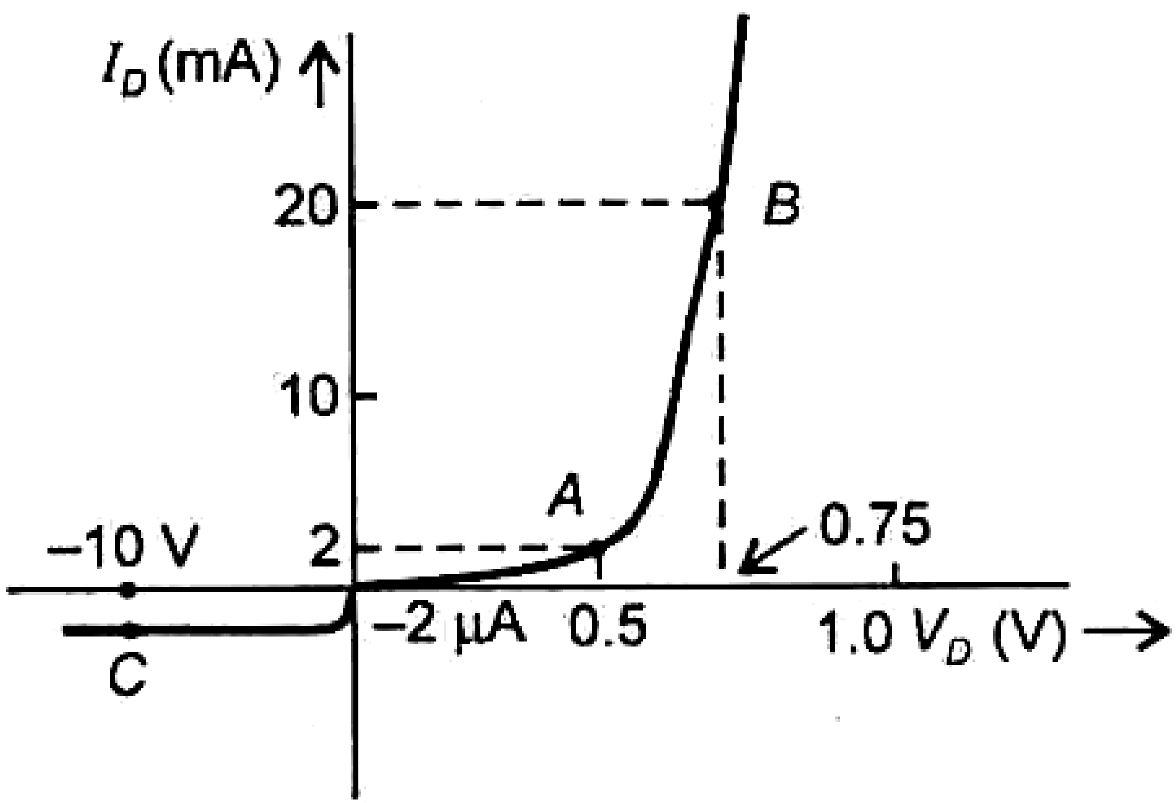
Dynamic or AC Resistance



$$r_f = \frac{\Delta V_d}{\Delta I_d}$$

$$r_f = \frac{\Delta V_d}{\Delta I_d} = \frac{MN}{NL} = \cot\beta$$

Example 3.2 Determine the dc resistance of a silicon diode, whose *V-I* characteristics is given in Fig. 3.12, at *a* I_D = 2 mA, (b) I_D = 20 mA, and (c) V_D = –10 V.



Solution :

(a) At $I_D = 2$ mA, $V_D = 0.5$ V (from the given curve).

$$\therefore \quad R_F = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

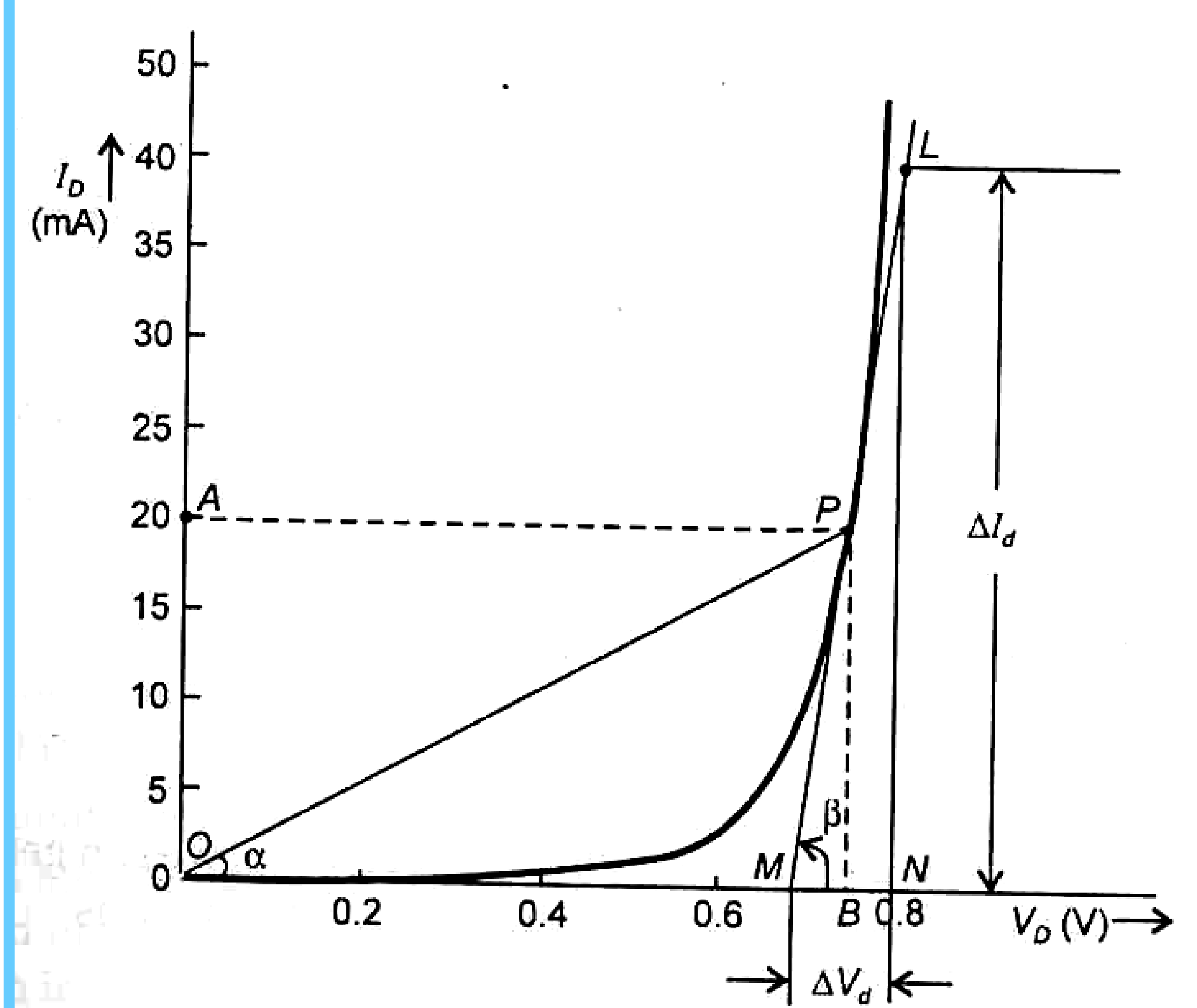
(b) At $I_D = 20$ mA, $V_D = 0.75$ V (from the given curve).

$$\therefore \quad R_F = \frac{V_D}{I_D} = \frac{0.75\text{ V}}{20\text{ m A}} = \mathbf{37.5\ \Omega}$$

(c) At $V_D = -10$ V, $I_D = -2$ μA (from the given curve in the reverse-bias region).

$$\therefore \quad R_R = \frac{V_D}{I_D} = \frac{-10\text{ V}}{-2\ \mu\text{A}} = \mathbf{5\ M\Omega}$$

Example 3.3 The *V-I* characteristics of a silicon diode in forward bias is given in Fig. 3.14 Calculate the dc and ac resistances of the diode when the diode current is 20 mA.



Solution : Point A on the vertical axis denotes diode current of 20 mA. Corresponding operating point is P. Point B gives the diode dc voltage. Therefore, the dc resistance of the diode,

$$R_F = \cot\alpha = \frac{OB}{PB} = \frac{0.75\ \text{V}}{20\ \text{mA}} = \mathbf{37.5\ \Omega}$$

$$r_f = \cot\beta = \frac{MN}{NL} = \frac{(0.8 - 0.68)\ \text{V}}{(40 - 0)\ \text{mA}} = \frac{0.12\ \text{V}}{40\ \text{mA}} = \mathbf{3\ \Omega}$$

Diode Equation

$$I_D = I_s\,(e^{V_D/V_T} - 1)$$

$$V_T = \frac{kT}{e}$$

k = Boltzmann constant = 1.38×10^{-23} J/K

T = absolute temperature (in K)

e = charge on an electron = 1.6×10^{-19} C

Dynamic (ac) Resistance of a Diode:

$$r_f = \frac{V_T}{I_D} \simeq \frac{25\,(\text{mV})}{I_D\,(\text{mA})}$$

Example 3.4 Estimate the value of ac resistance that would be offered by a semiconductor diode at (a) $I_D = 10$ mA, (b) $I_D = 20$ mA.

Solution :

(a) At $I_D = 10$ mA,

$$r_f = \frac{25\,(\text{mV})}{I_D\,(\text{mA})} = \frac{25\text{ mV}}{10\text{ mA}} = \mathbf{2.5\ \Omega}$$

(b) At $I_D = 20$ mA,

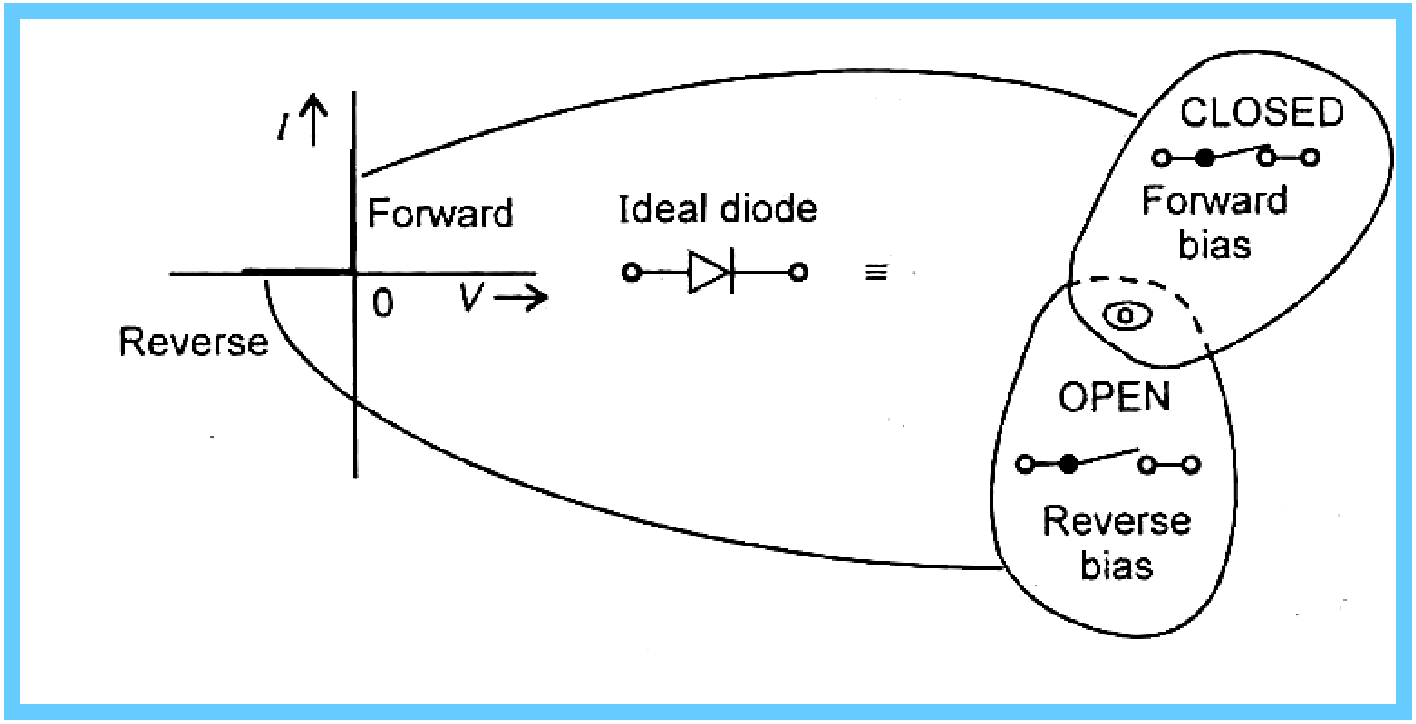
$$r_f = \frac{25\,(\text{mV})}{I_D\,(\text{mA})} = \frac{25\text{ mV}}{20\text{ mA}} = \mathbf{1.25\ \Omega}$$

Ideal Diode

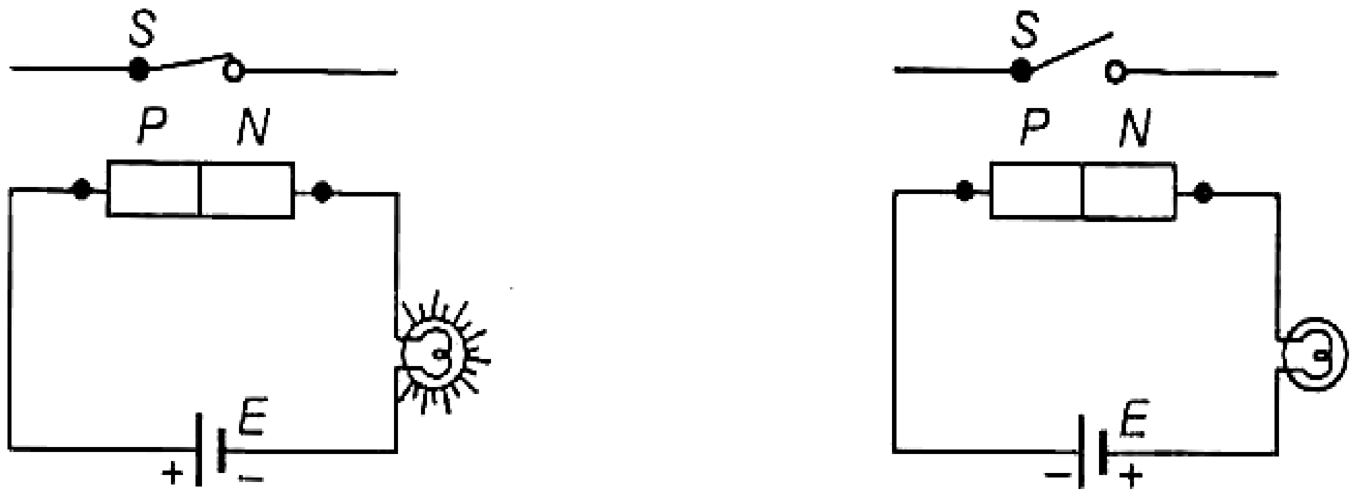
- Ideally, a diode should have

$$R_F = 0 \quad \text{and} \quad R_R = \infty$$

- *V-I* characteristics of an ideal diode:



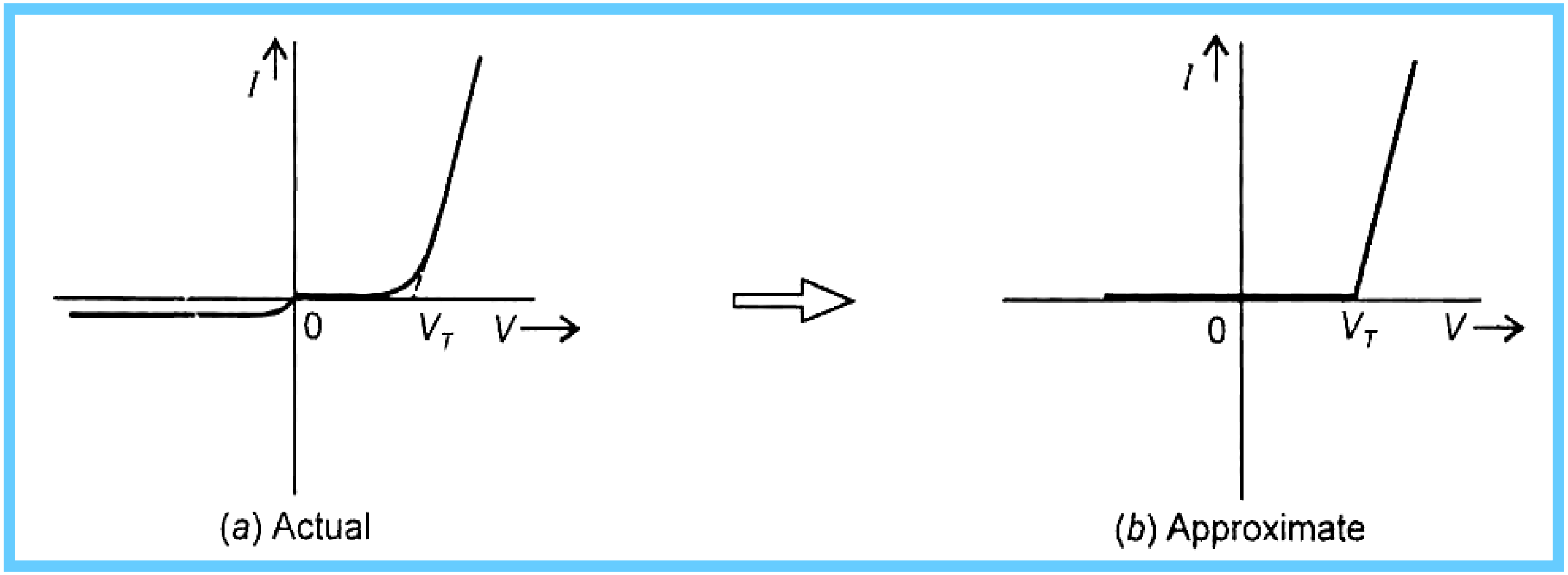
Unidirectional Property of Diode

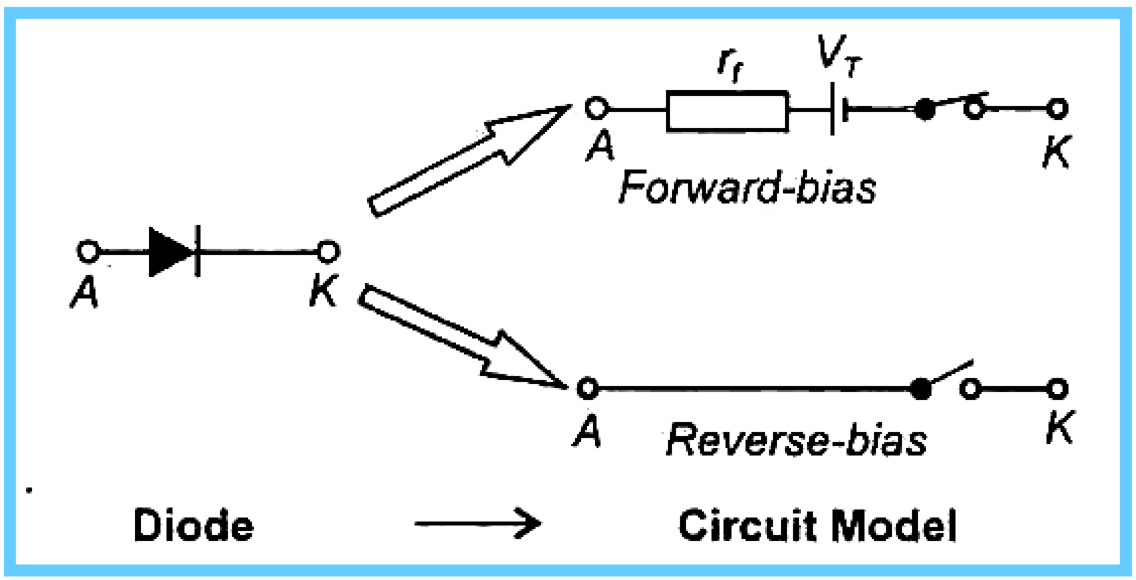


(a) Forward-bias (FB)
(Closed swicth)

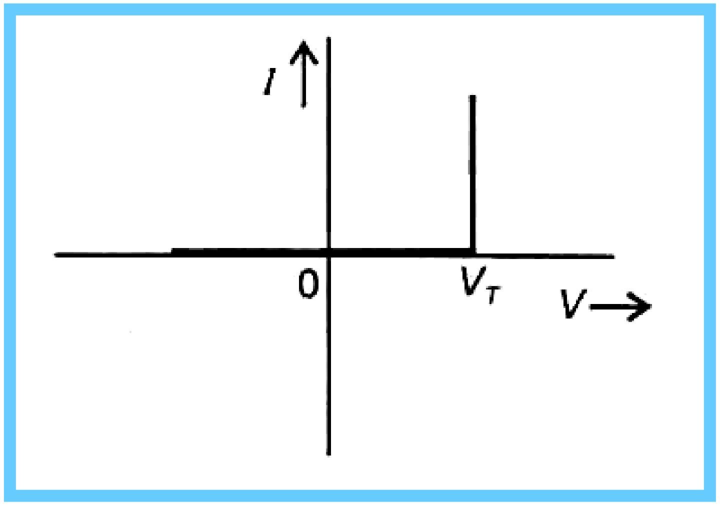
(b) Reverse-bias (RB)
(Open switch)

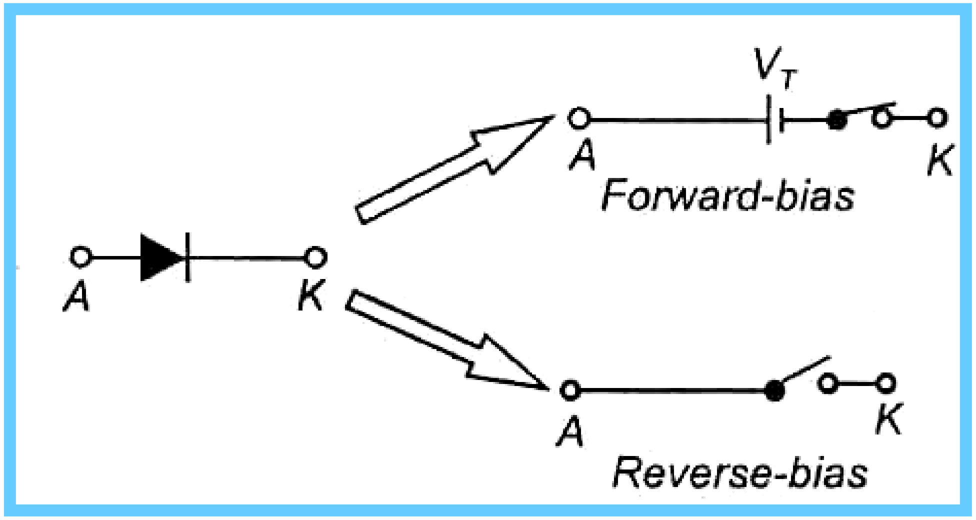
Circuit Model of a Diode



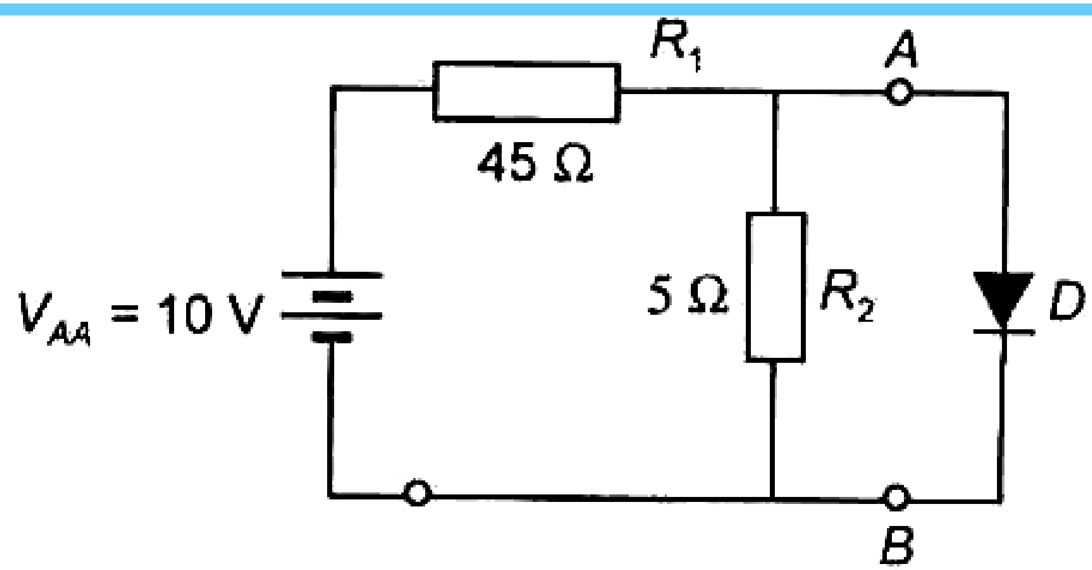


Simplified Circuit Model





Example 3.5 For the circuit shown in Fig. 3.19, find the current through the diode *D* assuming the diode to be (a) ideal, (b) real with piecewise linear circuit model having threshold voltage V_T = 0.3 V, and average resistance r_f = 25 Ω.



Solution :

(a) *Assuming diode D to be ideal* : Ignoring diode D, the voltage across R_2 is given as (by applying potential divider concept)

$$V_{AB} = V_{AA}\frac{R_2}{R_1 + R_2} = 10 \times \frac{5}{45+5} = 1.0\ \text{V}$$

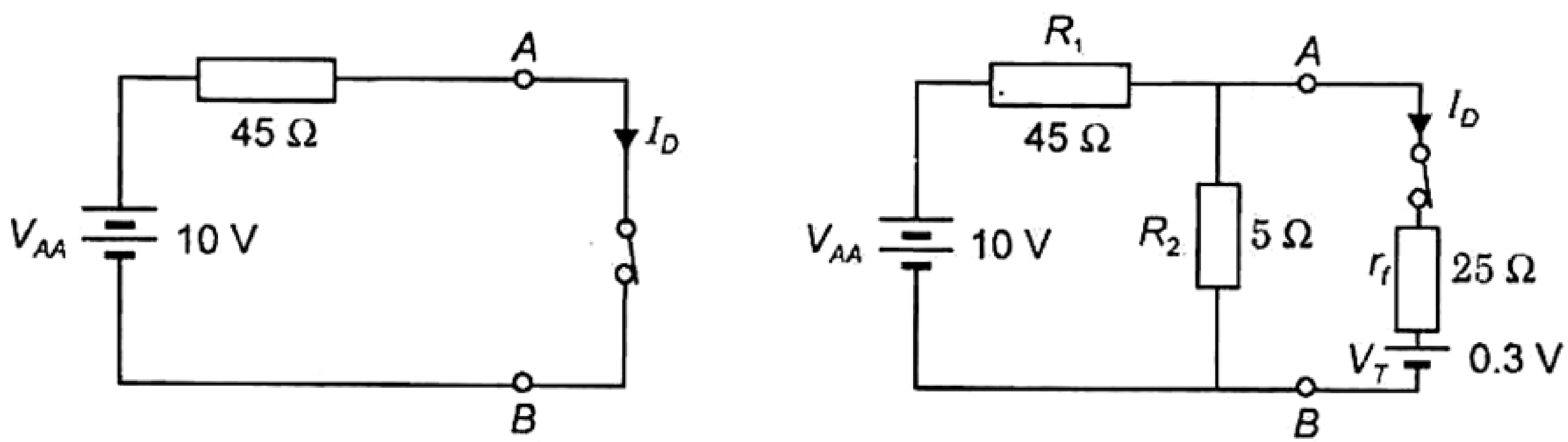
$$I_D = \frac{V_{AA}}{R_1} = \frac{10}{45} = \mathbf{222\ mA}$$

V_{TH} = open circuit voltage across AB

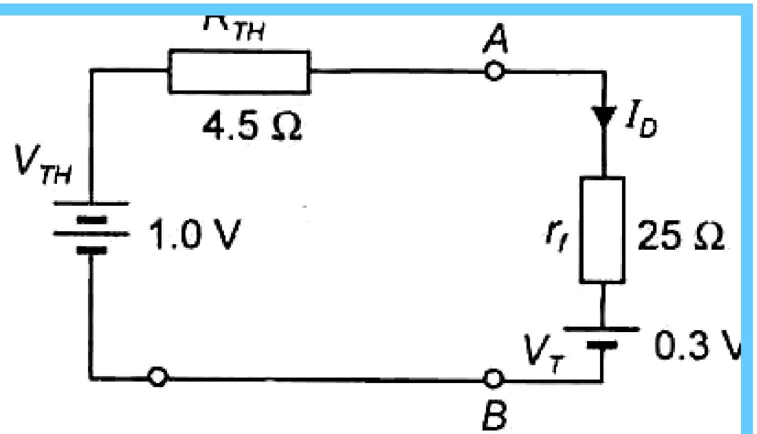
$$= V_{AA} \times \frac{R_2}{R_1 + R_2} = 10 \times \frac{5}{45+5} = 1.0\ \text{V}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{45 \times 5}{45+5} = 4.5\ \Omega$$

$$I_D = \frac{V_{TH} - V_T}{R_{TH} + r_f} = \frac{1.0 - 0.3}{4.5 + 25} = \frac{0.7}{29.5} = \mathbf{23.7\ mA}$$



(a) (b)



(c)

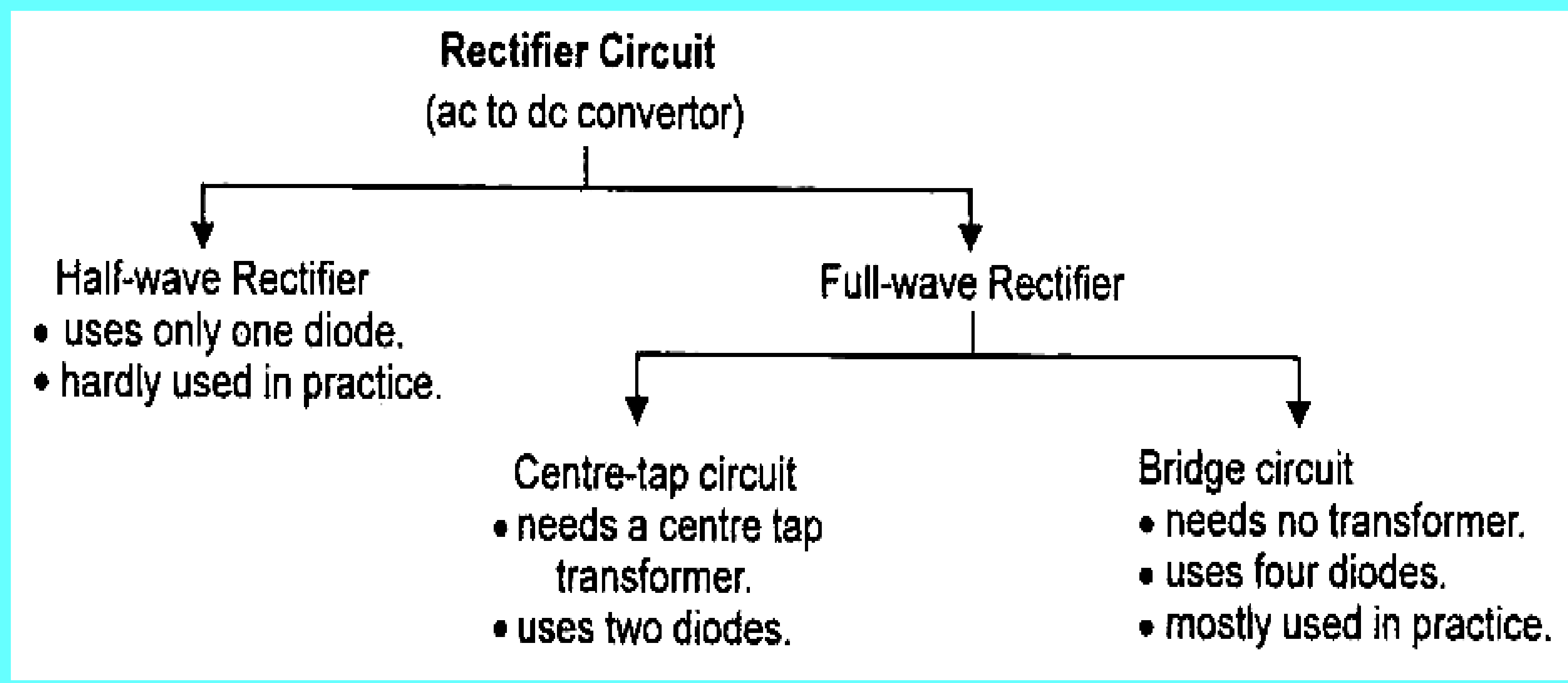
Junction Capacitances

- Two kinds :

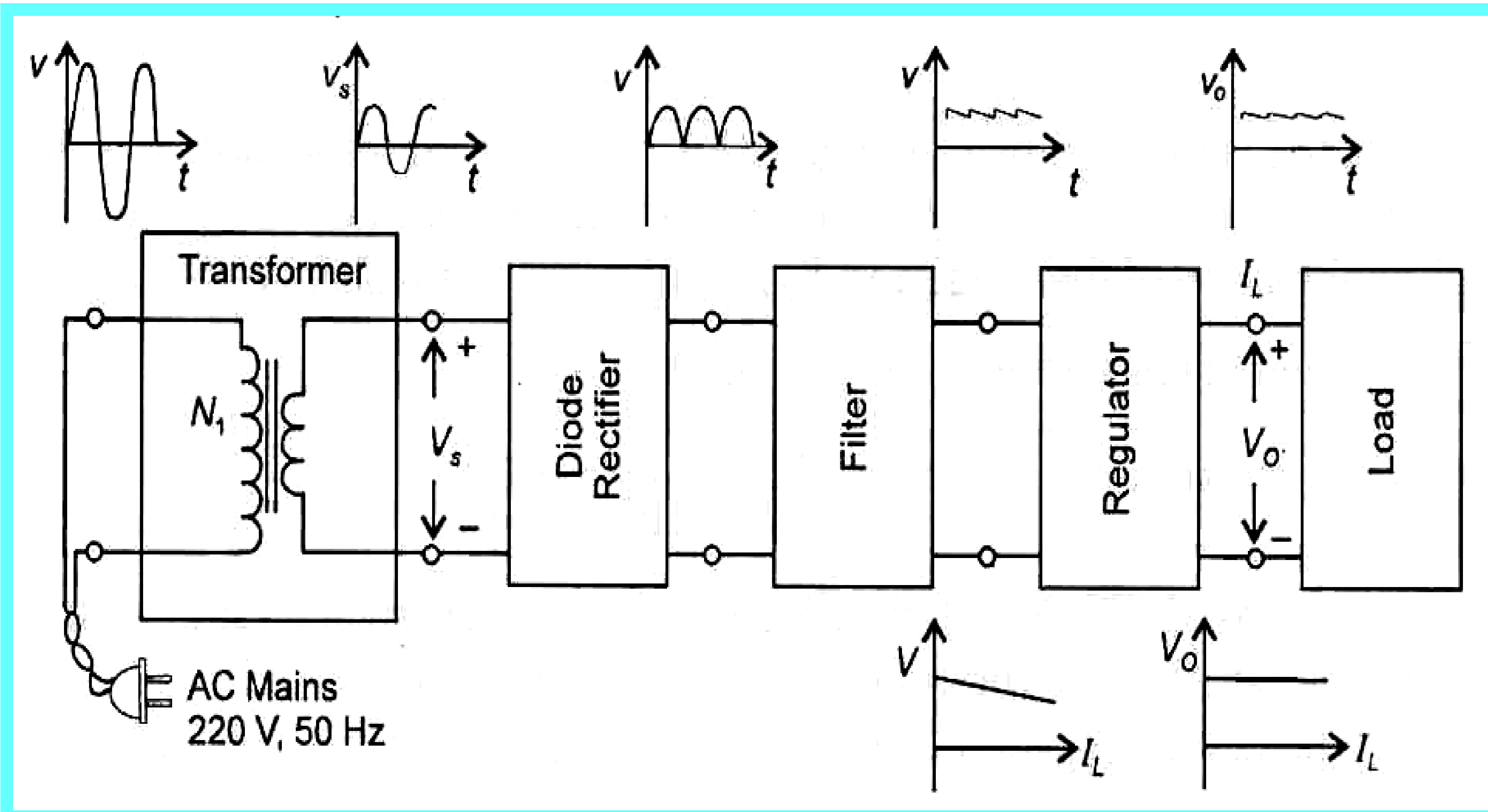
1. Transition or Depletion Capacitance, C_T :
   This is predominant in reverse bias. It decreases with applied voltage.

2. Storage or Diffusion Capacitance, C_D :
   This is predominant in forward bias. Of the order of several hundred pF.

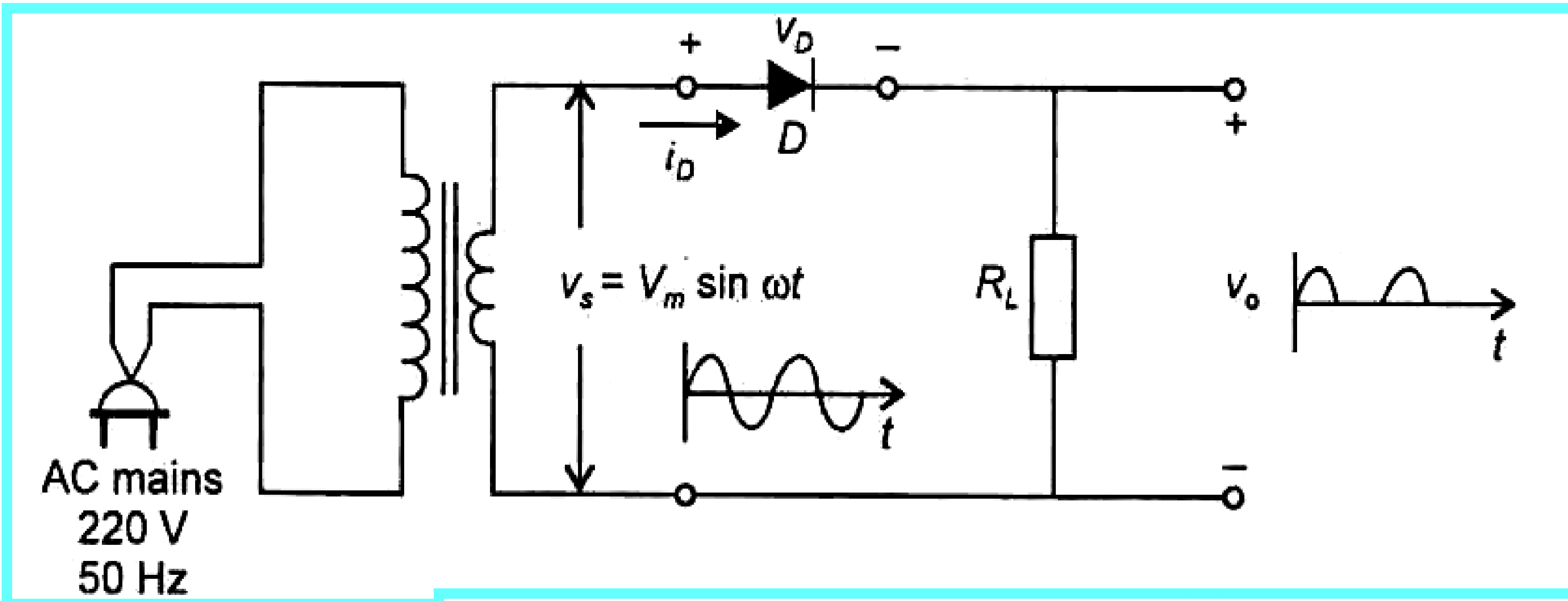
Diodes in Rectifier Circuits

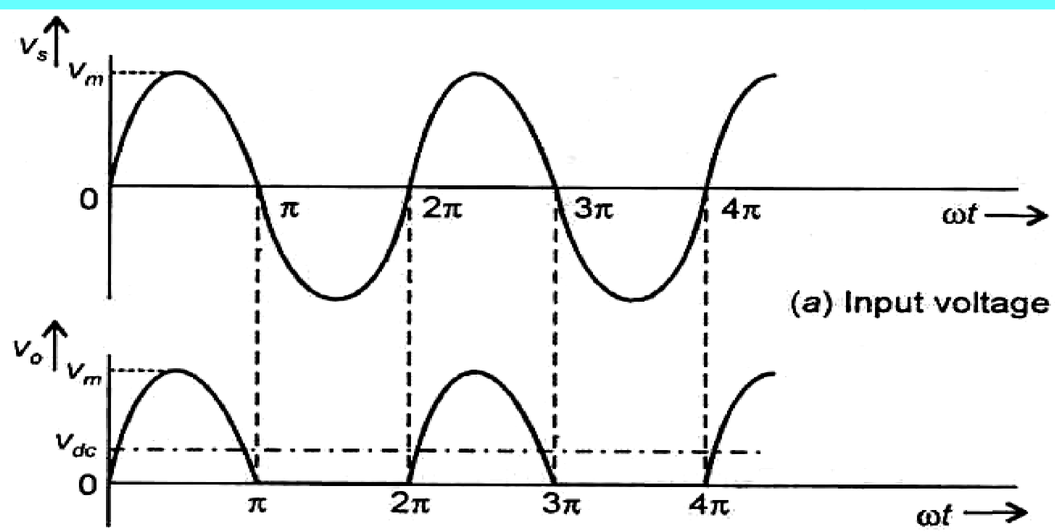


Block Diagram of DC Power Supply



Half-wave Rectifier





(*a*) Input voltage waveform

(*b*) Output voltage waveform

Performance of Half-wave Rectifier

$$i_L = \begin{cases} I_m \sin \omega t & \text{for } 0 \le \omega t \le \pi \\ 0 & \text{for } \pi \le \omega t \le 2\pi \end{cases}$$

$$I_m = \frac{V_m - V_T}{R_L + r_f}$$

$$I_{dc} = \frac{\text{Area}}{\text{Base}} = \frac{\int_0^{2\pi} i_L \, d(\omega t)}{2\pi} = \frac{1}{2\pi} \int_0^{2\pi} i_L \, d(\omega t)$$

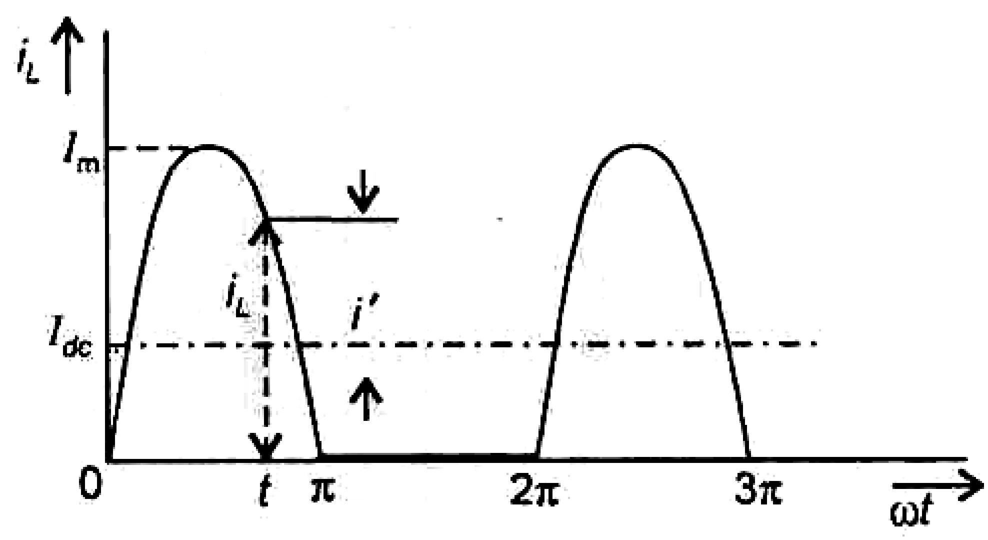
$$= \frac{1}{2\pi} \int_0^{\pi} I_m \sin \omega t \, d(\omega t) + \frac{1}{2\pi} \int_{\pi}^{2\pi} 0 \, d(\omega t)$$

$$= \frac{I_m}{2\pi} \left[-\cos \omega t \right]_0^{\pi} + 0 = \frac{I_m}{\pi}$$

Total RMS Value :

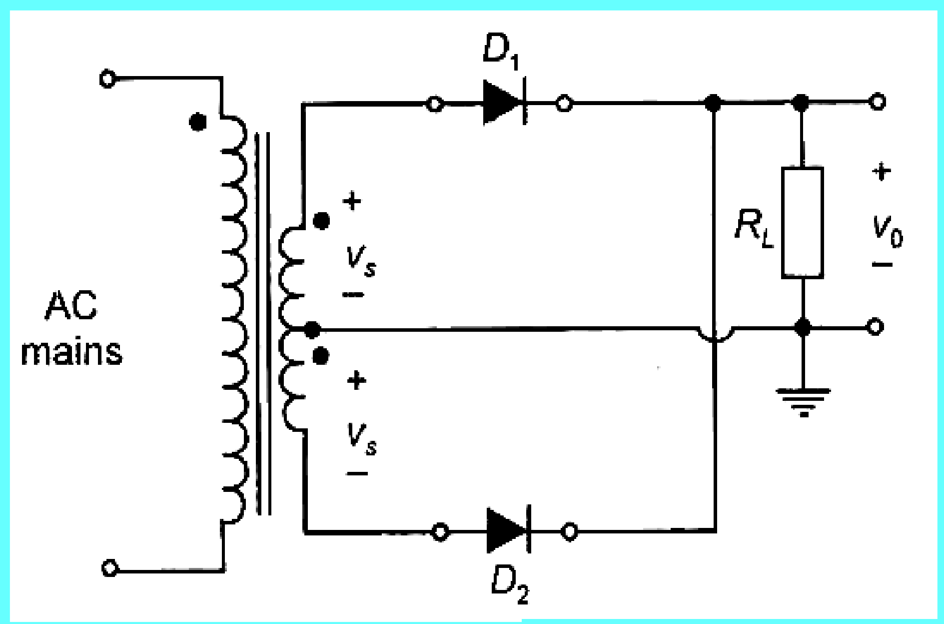
$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 \, d(\omega t)} = \sqrt{\frac{1}{2\pi}\left[\int_0^{2\pi} I_m^2 \sin^2 \omega t \, d(\omega t) + \int_\pi^{2\pi} 0 \, d(\omega t)\right]}$$

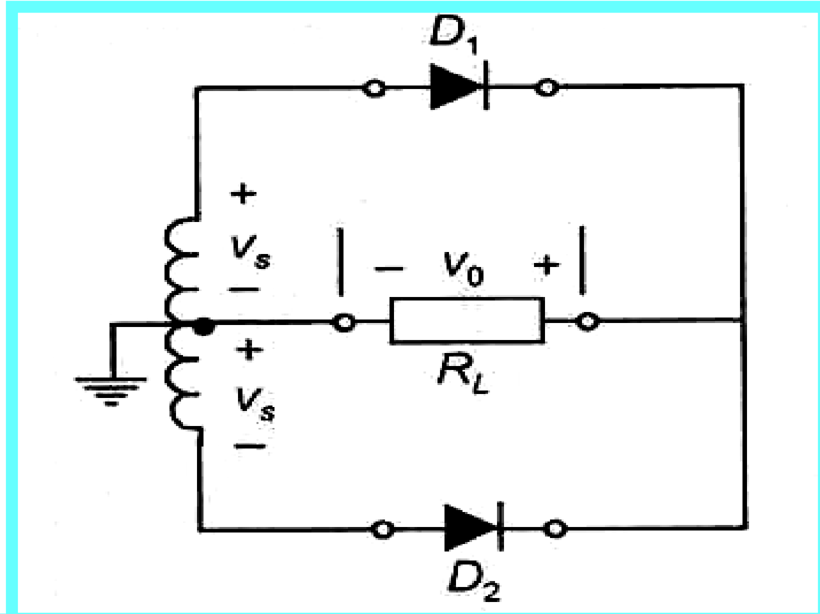
$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{(1-\cos 2\omega t)}{2} \, d(\omega t)} = \frac{I_m}{2}$$

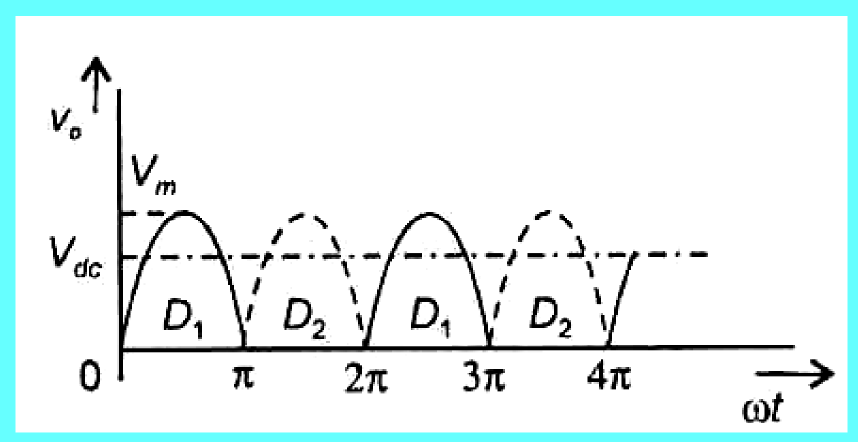


$$i' = i_L - I_{dc}$$

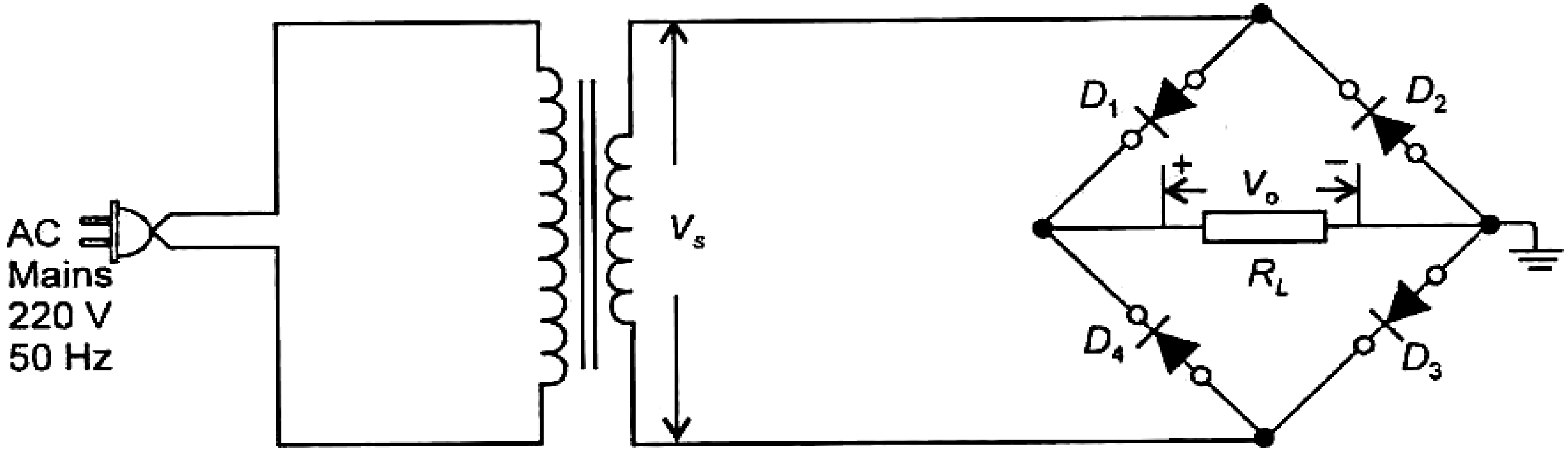
Full-wave Rectifier (Centre-tap)

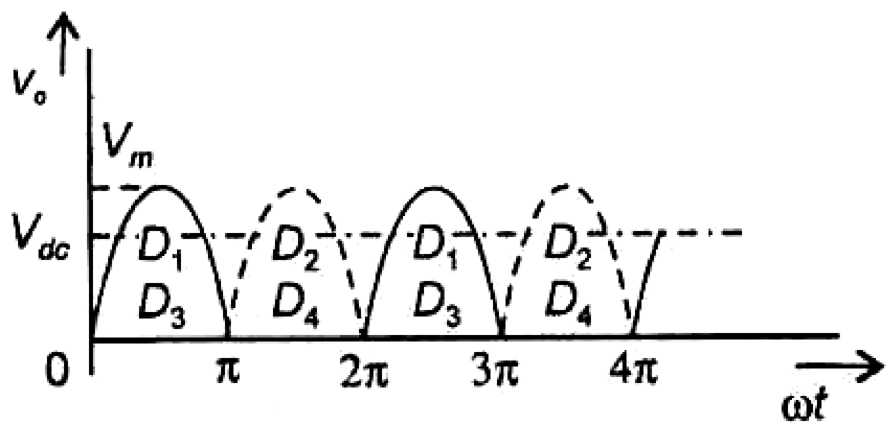




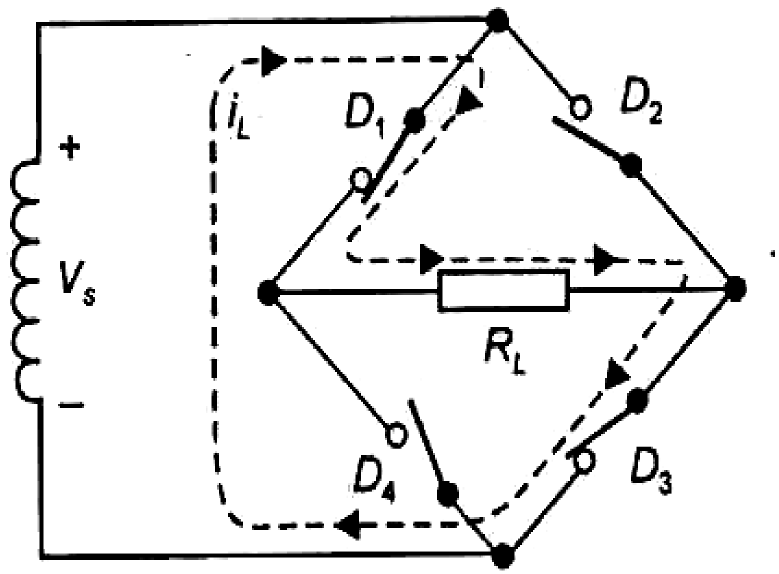


Full-wave Rectifier (Bridge)

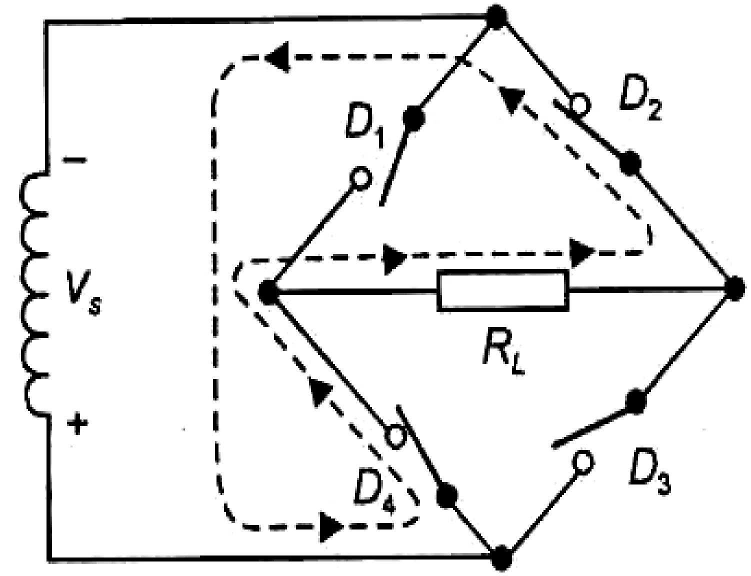




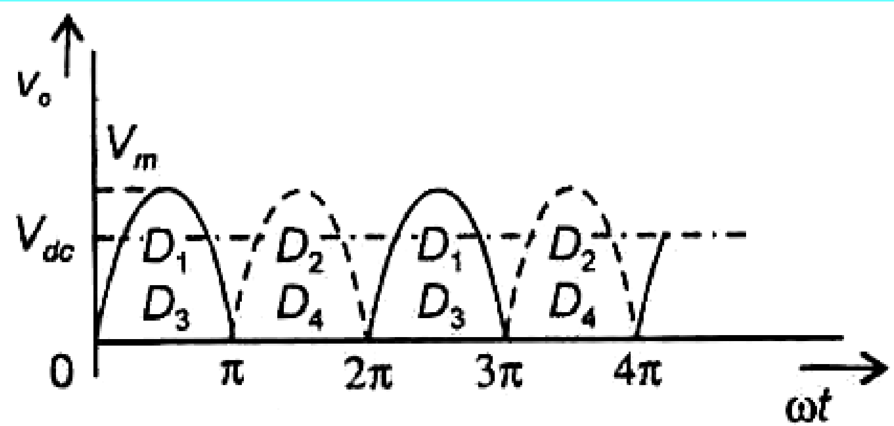
(c) Output voltage waveform



(a) During positive half-cycles

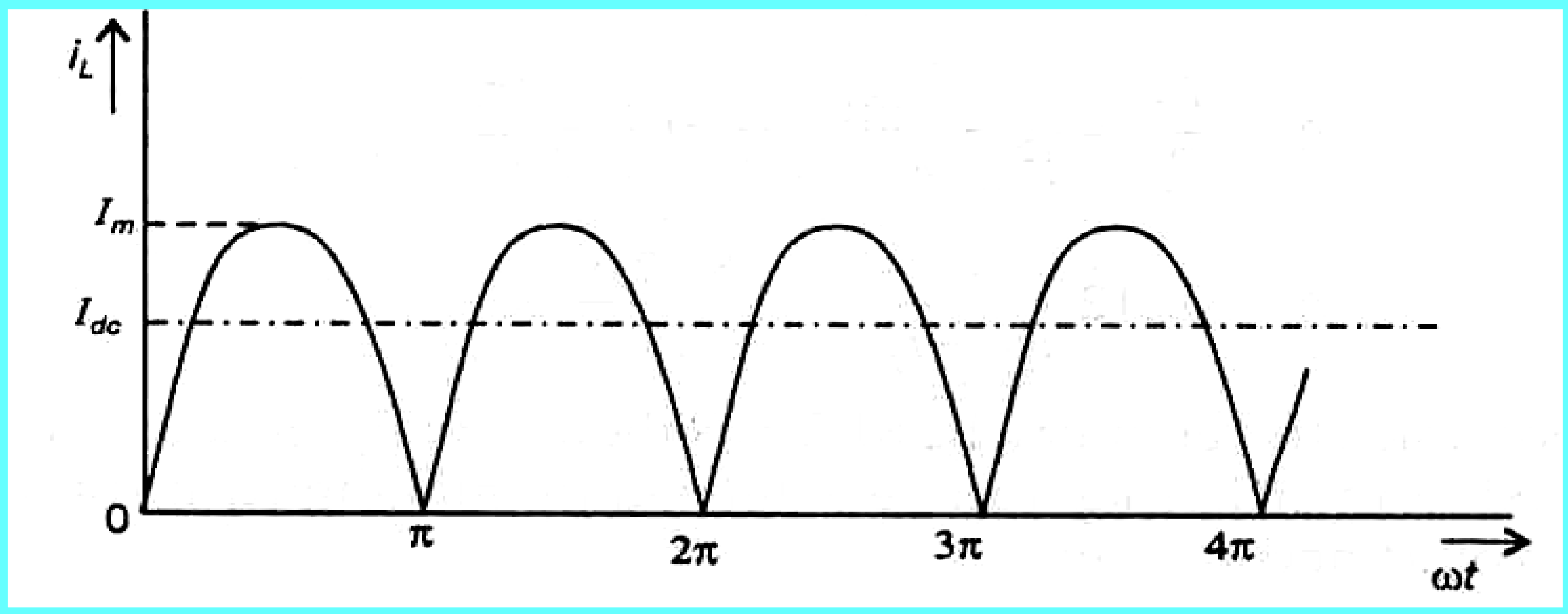


(b) During negative half-cycles



(c) Output voltage waveform

Performance of Full-wave Rectifier



How much is its period in terms of ωt ?

Its period is π, and not 2π.

$$i_L = I_m \sin \omega t \qquad 0 \le \omega t \le \pi$$

$$I_m = \frac{V_m - V_T}{R_L + r_f} \qquad \text{for centre-tap rectifier}$$

$$I_m = \frac{V_m - 2V_T}{R_L + 2r_f} \qquad \text{for bridge rectifier}$$

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i_L \, d(\omega t) = \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t \, d(\omega t) = \frac{I_m}{\pi}\left[-\cos \omega t\right]_0^{\pi}$$

$$I_{dc} = \frac{2I_m}{\pi}$$

Total RMS Value :

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} i_L^2 \, d(\omega t)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \; d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi} \frac{(1-\cos 2\omega t)}{2} d(\omega t)} = \sqrt{\frac{I_m^2}{\pi}\left|\frac{\omega t}{2} - \frac{\sin 2\omega t}{4}\right|_0^{\pi}}$$

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

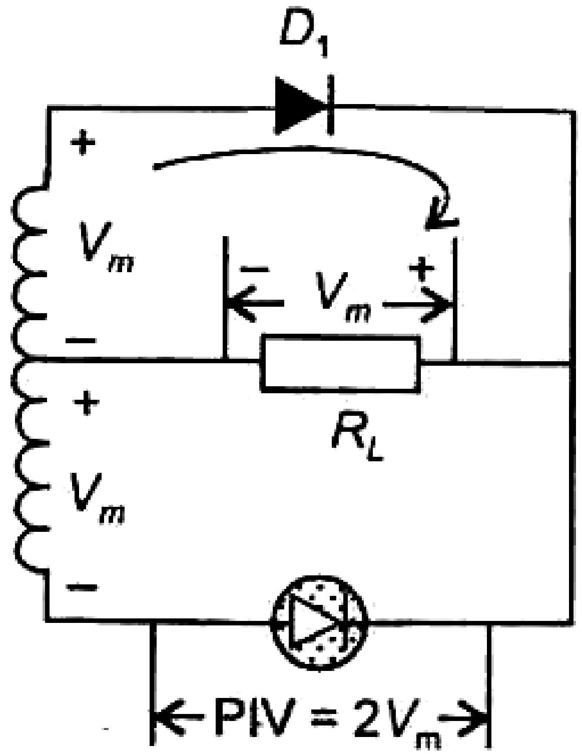
Diode Ratings

1. Current Handling Capacity.

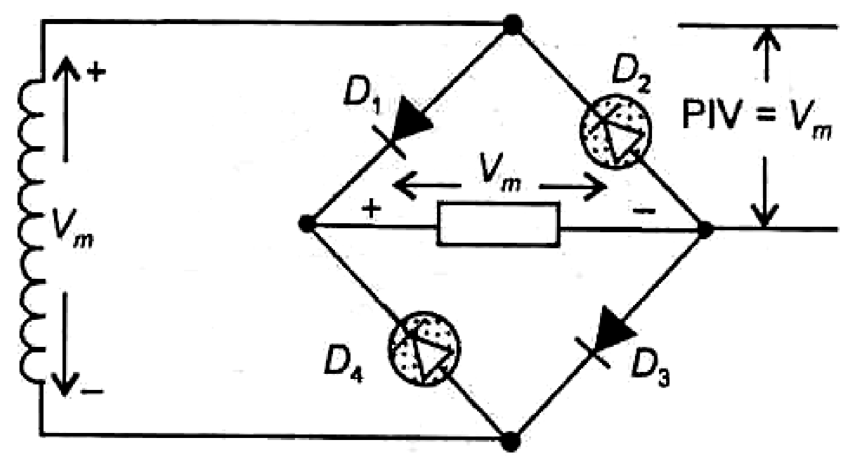
2. Peak Inverse Voltage (*PIV*): It is the largest reverse voltage that is expected to appear across the diode. Usually, diodes are selected which have V_Z at least 50 % greater than *PIV*.

PIV Ratings

- For half-wave rectifier : V_m



(*a*) Centre-tap rectifier



(*b*) Bridge rectifier

Figures of Merit of a Rectifier

1. Ripple Factor (*r*):

$$r = \frac{\text{rms value of the ac components of wave}}{\text{average or dc value}}$$

2. Rectification Efficiency (η):

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

1. Ripple Factor (r) :

$$r = \frac{I'_{rms}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

Now, for Half-wave Rectifier:

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

Rectification Efficiency for Half-Wave rectifier:

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{I_{dc}^2 \ R_L}{I_{rms}^2 \ (R_L + r_f)} = \left(\frac{I_{dc}}{I_{rms}}\right)^2 \frac{R_L}{R_L + r_f}$$

$$= \left(\frac{I_m/\pi}{I_m/2}\right)^2 \frac{R_L}{R_L + r_f} = 0.406 \frac{R_L}{R_L + r_f}$$

$$= \frac{40.6}{1 + r_f/R_L} \%$$

Ripple Factor Full-wave Rectifier:

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

$$r = 0.482$$

Rectification Efficiency for Full-Wave rectifier: :

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{I_{dc}^2 R_L}{I_{rms}^2 (R_L + r_f)} = \left(\frac{2I_m/\pi}{I_m/\sqrt{2}}\right)^2 \frac{R_L}{R_L + r_f}$$

$$\eta = 0.812 \frac{R_L}{R_L + r_f} = \frac{81.2}{1 + r_f/R_L}\%$$

Example 3.8 In a half-wave rectifier, the turns ratio of the transformer is $N_1/N_2 = 31:2$. The primary of the transformer is connected to power mains, 220 V, 50 Hz. The average dynamic forward resistance of the diode used is 20 Ω and the load resistance is 1 kΩ. If the threshold voltage of the diode is 0.66 V, determine (a) the dc current through the load, (b) the rectification efficiency, and (c) the peak inverse voltage.

Solution : Given $N_1/N_2 = 31/2$; $r_f = 20\ \Omega$; $R_L = 1000\ \Omega$; $V_T = 0.66$ V.

(a) The maximum (peak value) of the primary voltage is

$$V_p = \sqrt{2}\, V_{rms} = \sqrt{2} \times 220 = 311 \text{ V}$$

Therefore, the peak value of the secondary voltage is

$$V_m = \frac{N_2}{N_1} V_p = \frac{2}{31} \times 311 = 20.06 \text{ V}$$

$$\therefore \quad I_m = \frac{V_m - V_T}{R_L + r_f} = \frac{20.06 - 0.66}{1000 + 20} = \frac{19.4}{1020} = 0.019 \text{ A}$$

$$\therefore \quad I_{dc} = \frac{I_m}{\pi} = \frac{0.019}{3.141} = 0.006 = 6 \text{ mA}$$

(b) The rectification efficiency is given as

$$\eta = \frac{40.6}{1 + \frac{r_f}{R_L}}\% = \frac{40.6}{1 + 20/1000}\% = \mathbf{39.8\ \%}$$

(c) PIV = V_m = **20.06 V**

Example 3.9 A bridge rectifier uses a transformer with turns ratio $N_1 : N_2 = 12 : 1$. Its primary is connected to 220 V (rms). Assuming the diodes to be ideal, find the dc voltage across the load. What is the PIV of each diode ? If the same dc voltage is obtained by using a centre-tap rectifier, what would be the PIV ?

Solution : Given : $N_1/N_2 = 12/1$, $V_1 = 220$ V(rms).

The peak value of the primary voltage is

$$V_{p1} = \sqrt{2}\ V_1 = \sqrt{2} \times 220 = 311 \text{ V}$$

Therefore, the peak value of the secondary voltage is

$$V_m = V_{p2} = \frac{N_2}{N_1} \times V_{p1} = \frac{1}{12} \times 311 = 25.9 \text{ V}$$

$$\therefore \qquad V_{dc} = \frac{2V_m}{\pi} = \frac{2 \times 25.9}{3.141} = \mathbf{16.5\ V}$$

The PIV (for bridge rectifier) is

$$\text{PIV} = V_m = \mathbf{25.9\ V}$$

The PIV (for centre-tap rectifier) is

$$\text{PIV} = 2V_m = 2 \times 25.9 = \mathbf{51.8\ V}$$

Example 3.10 A centre-tap full-wave rectifier supplies a dc current of 100 mA to a load of $R_L = 25\ \Omega$. The resistance of each half of the secondary is $R_S = 5\ \Omega$. The two diodes are identical and each has $r_f = 2\ \Omega$. Assume that the diodes have zero threshold voltage and offer infinite resistance when reverse-biased. Determine

(a) the dc power supplied to the load,

(b) the power conversion efficiency, and

(c) the PIV rating of the diode used.

Solution : Given : $I_{dc} = 100$ mA $= 0.1$ A; $R_L = 25\ \Omega$; $R_S = 5\ \Omega$; $r_f = 2\ \Omega$.

(a) The dc power supplied to the load is

$$P_{dc} = I_{dc}^2\ R_L = (0.1)^2 \times 25 = \mathbf{0.25\ W}$$

(b) The power conversion efficiency or rectification efficiency is given as

$$\eta = \frac{81.2\ R_L}{(R_L + r_f + R_S)}\% = \frac{81.2 \times 25}{(25 + 2 + 5)}\% = \mathbf{63.44}\ \%$$

(c) For a full-wave rectifier, $I_{dc} = 2I_m/\pi$.

$$\therefore \qquad I_m = \frac{\pi I_{dc}}{2} = \frac{3.141 \times 0.1}{2} = 0.157 \text{ A}$$

For this much I_m, the required V_m is

$$V_m = I_m (R_L + r_f + R_S) = 0.157 (25 + 2 + 5) = 5.024 \text{ V}$$

The peak voltage across the load,

$$V_{Lm} = V_m - I_m(R_S + r_f) = 5.024 - 0.157 \times (5 + 2) = 3.925 \text{ V}$$

$$\textbf{PIV} = V_m + V_{Lm} = \mathbf{5.024 + 3.925 = 8.949 \text{ V}}$$

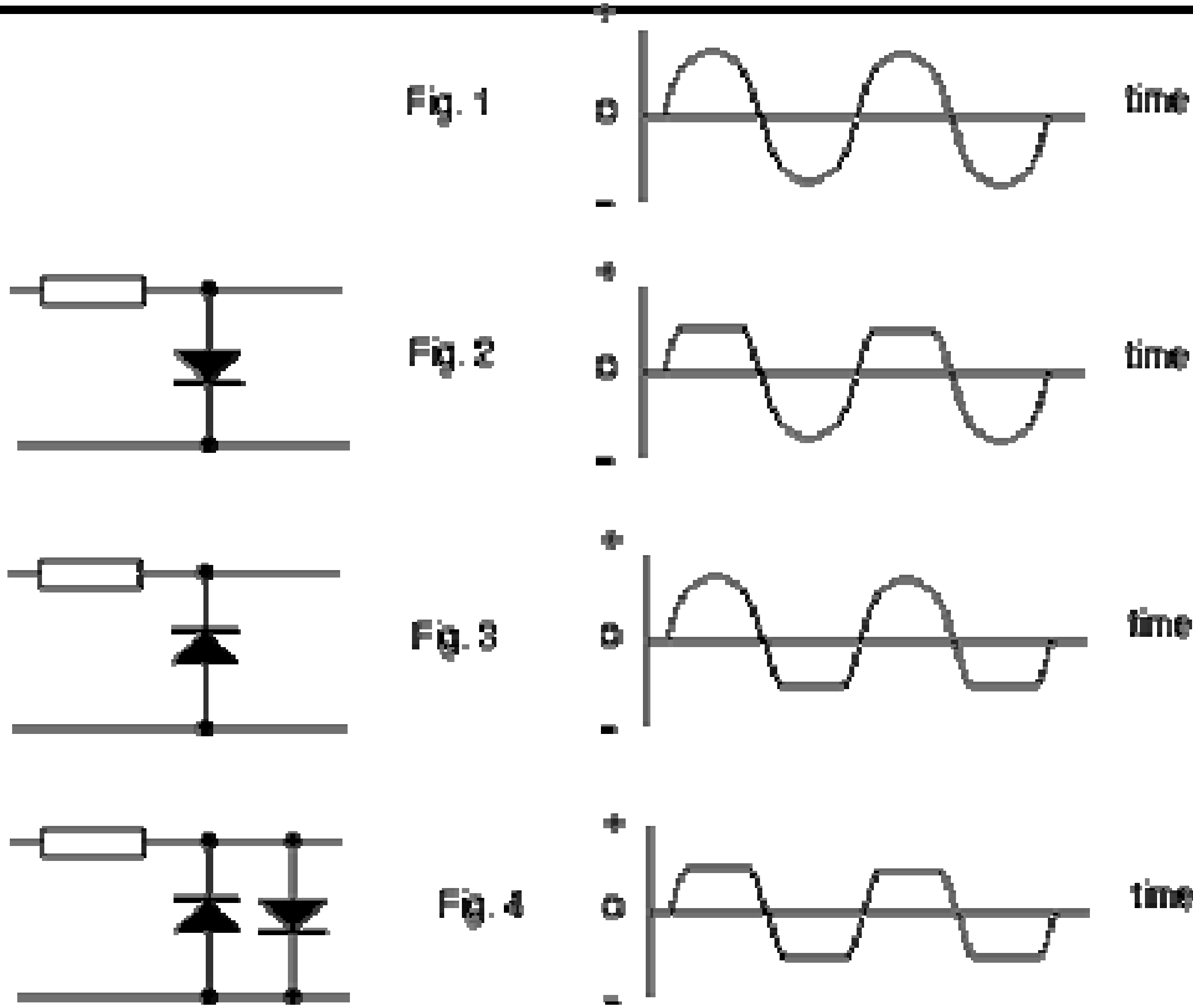
Clippers and Clampers

- Diodes can be used in wave shaping circuits.
- Either:
  - Limit or "clip" signal portions.

    Clippers
  - Shift the dc voltage level of a signal.

    Clampers

SIMPLE POSITIVE & NEGATIVE CLIPPERS



Biased Positive Clipper

The circuit shown in **fig. 3**, clips the input signal above a reference voltage (V_R).

In this clipper circuit,

If $v_i < V_R$, diode is reversed biased and does not conduct. Therefore, $v_o = v_i$

and, if $v_i > V_R$, diode is forward biased and thus, $v_o = V_R$.

The transfer characteristic of the clippers is shown in **fig. 4**.

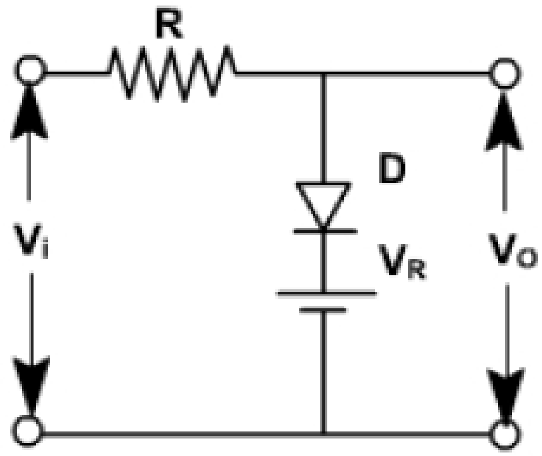
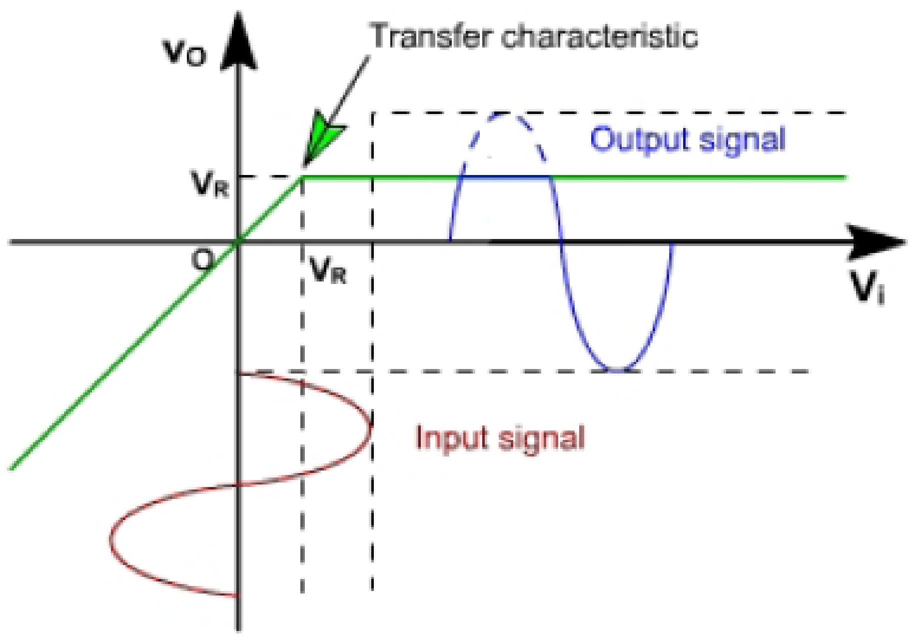


Fig. 3



Biased Negative Clipper

The clipper circuit shown in fig. 5 clips the input signal below reference voltage V_R.

In this clipper circuit,

If $v_i > V_R$, diode is reverse biased. $v_o = v_i$

and, If $v_i < V_R$, diode is forward biased. $v_o = V_R$

The transfer characteristic of the circuit is shown in fig. 6.

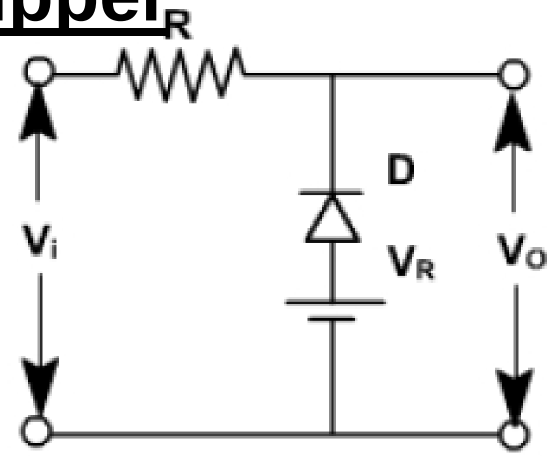
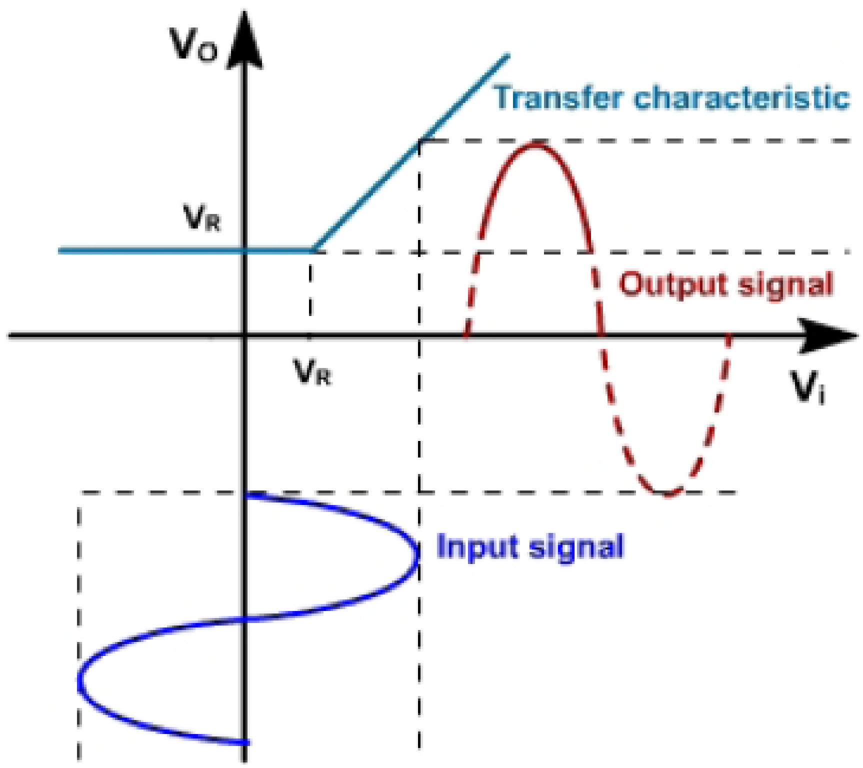


Fig. 5



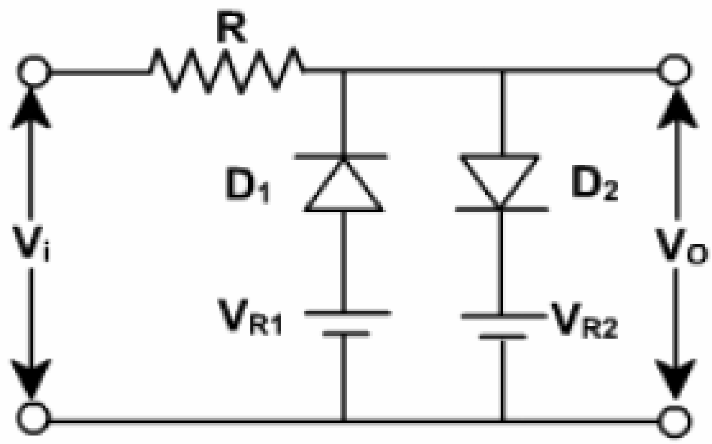
To clip the input signal between two independent levels ($V_{R1} < V_{R2}$), the clipper circuit is shown in fig. 7.

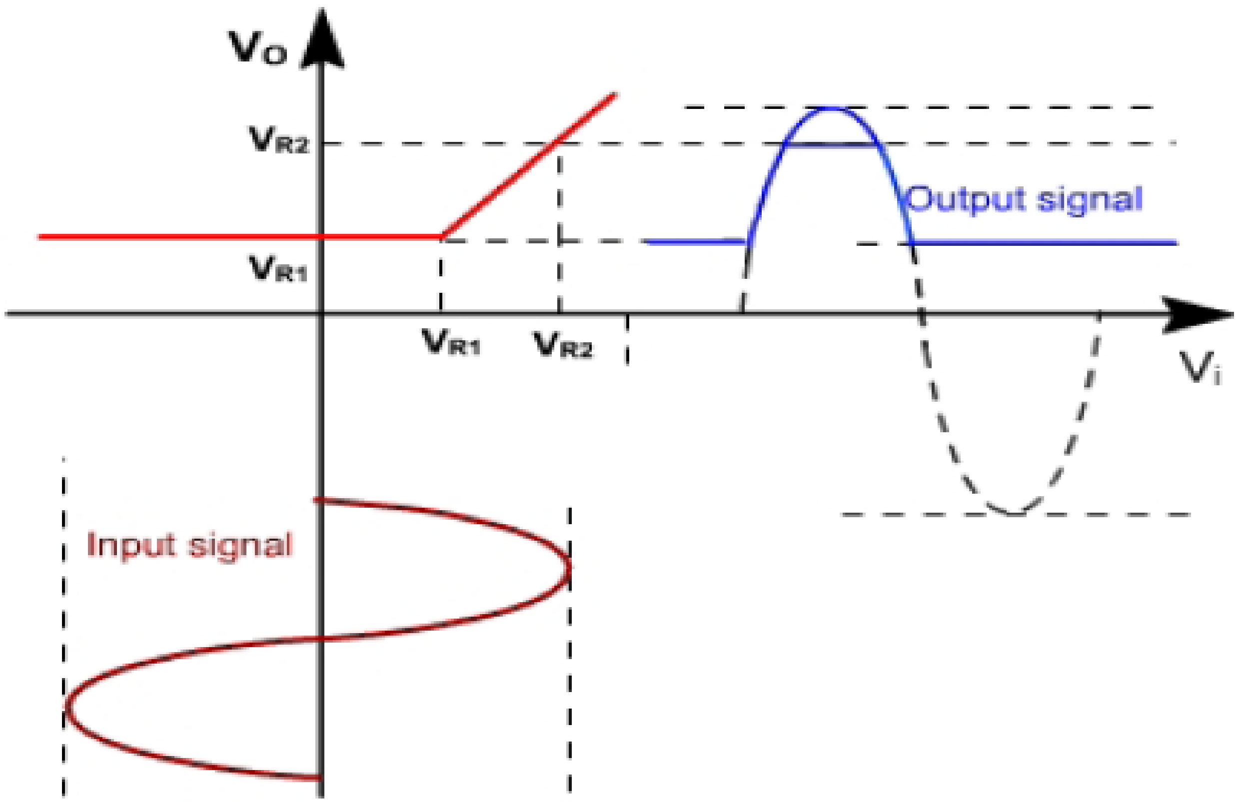
The diodes D_1 & D_2 are assumed ideal diodes.

For this clipper circuit, when $v_i \le V_{R1}$, $v_o = V_{R1}$

and, $v_i \ge V_{R2}$, $v_o = V_{R2}$

and, $V_{R1} < v_i < V_{R2}$ $v_o = v_i$

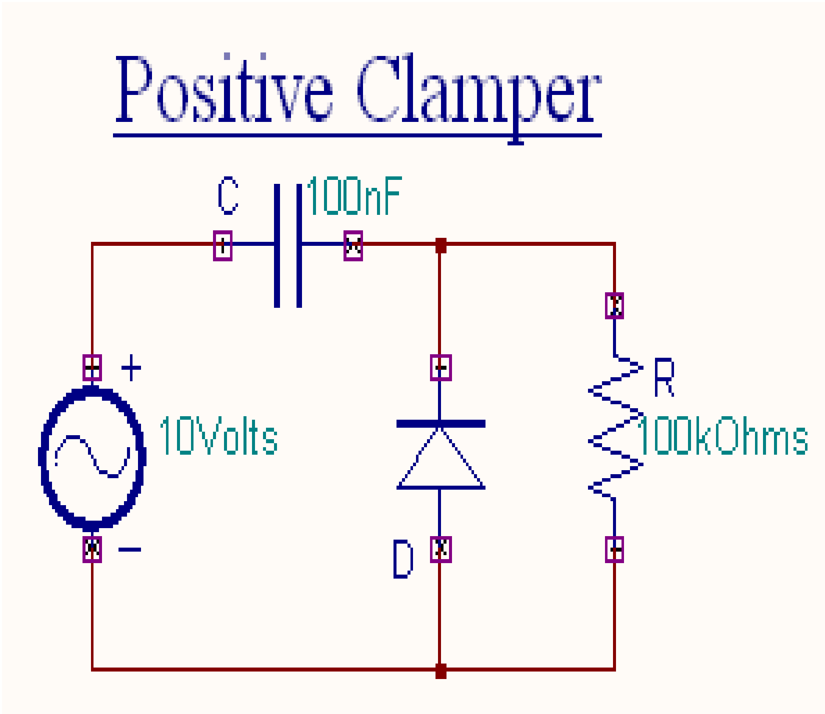




Positive Clamper

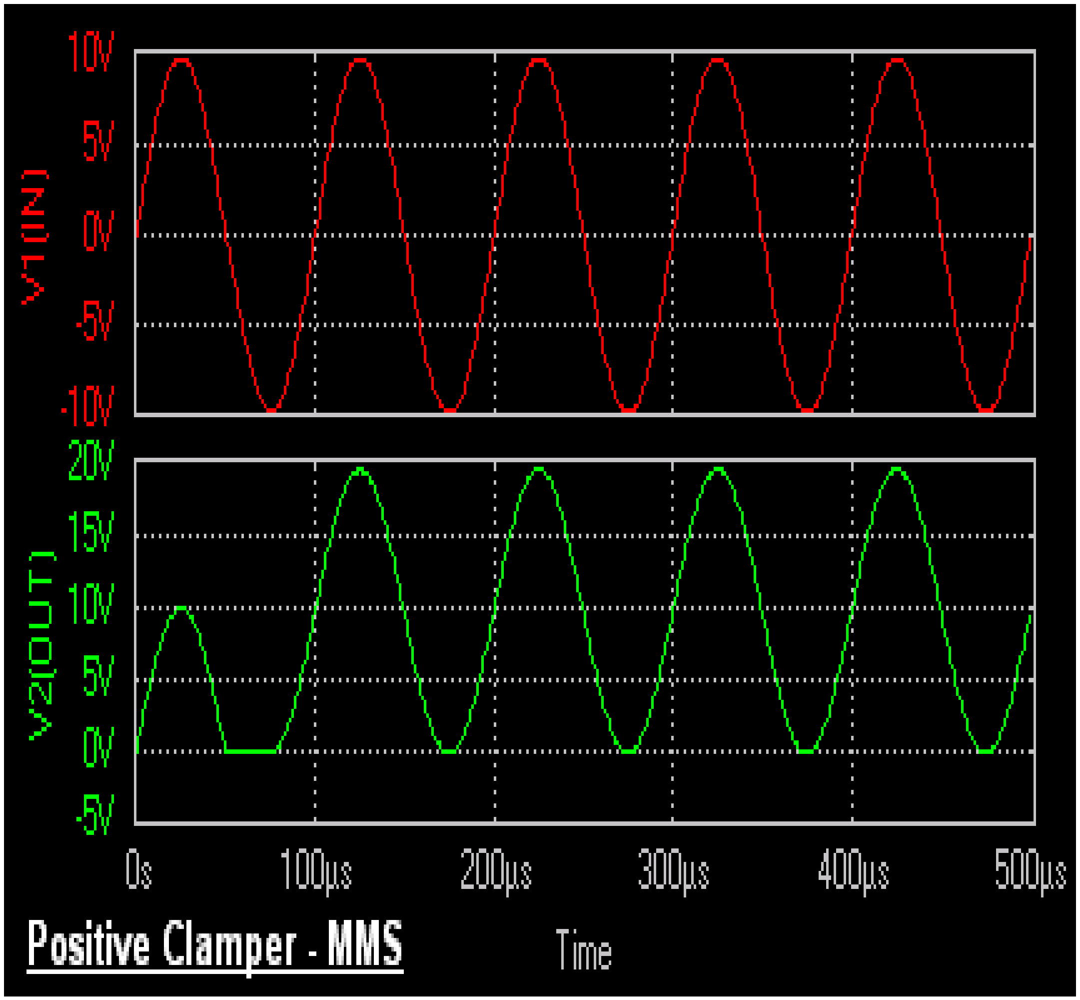
During the negative half cycle of the input signal, the diode conducts and acts like a short circuit. The output voltage $V_o \Rightarrow 0$ volts . The capacitor is charged to the peak value of input voltage V_m. and it behaves like a battery.

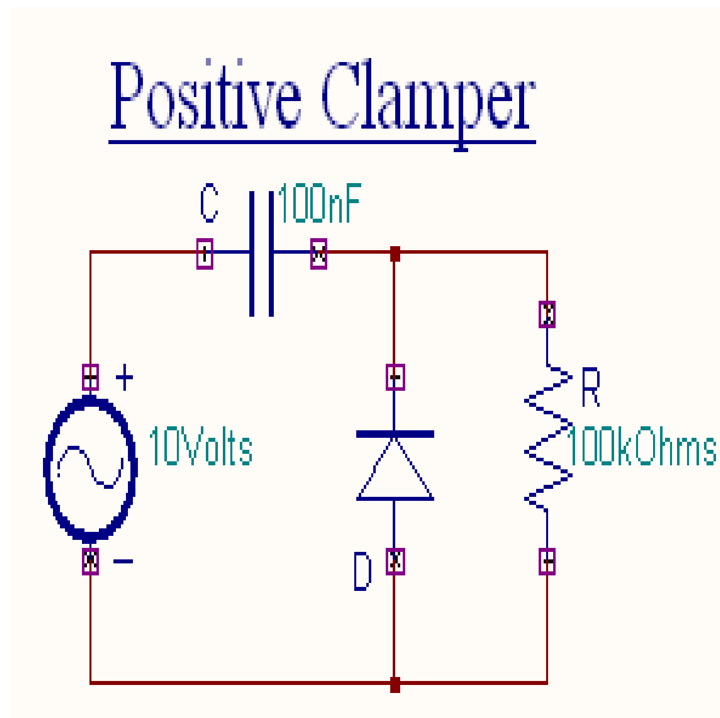
During the positive half of the input signal, the diode does not conduct and acts as an open circuit. Hence the output voltage $V_o \Rightarrow V_m + V_m$ This gives a positively clamped voltage.



$$V_o \Rightarrow V_m + V_m = 2\ V_m$$

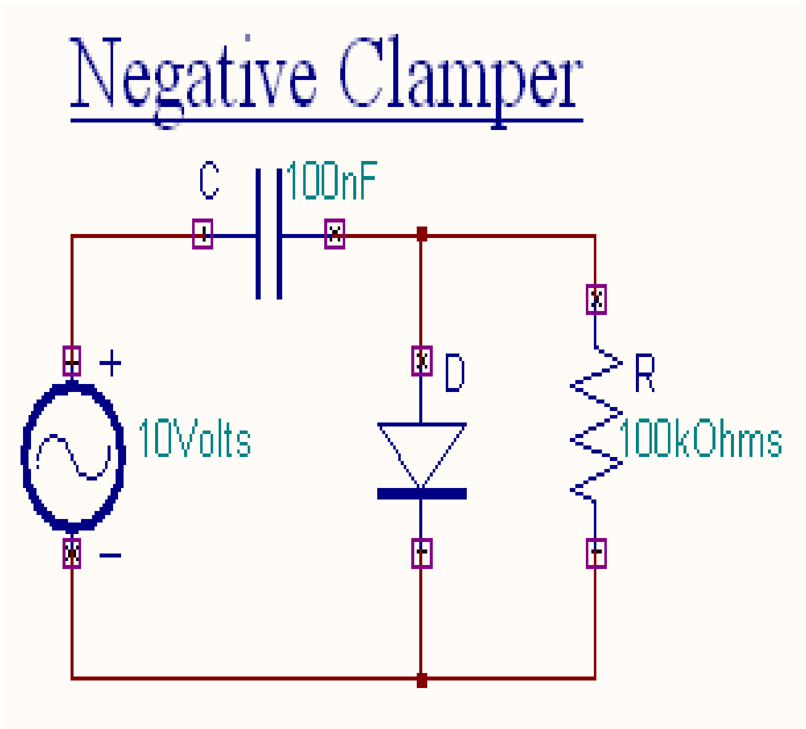
Positive Clamper





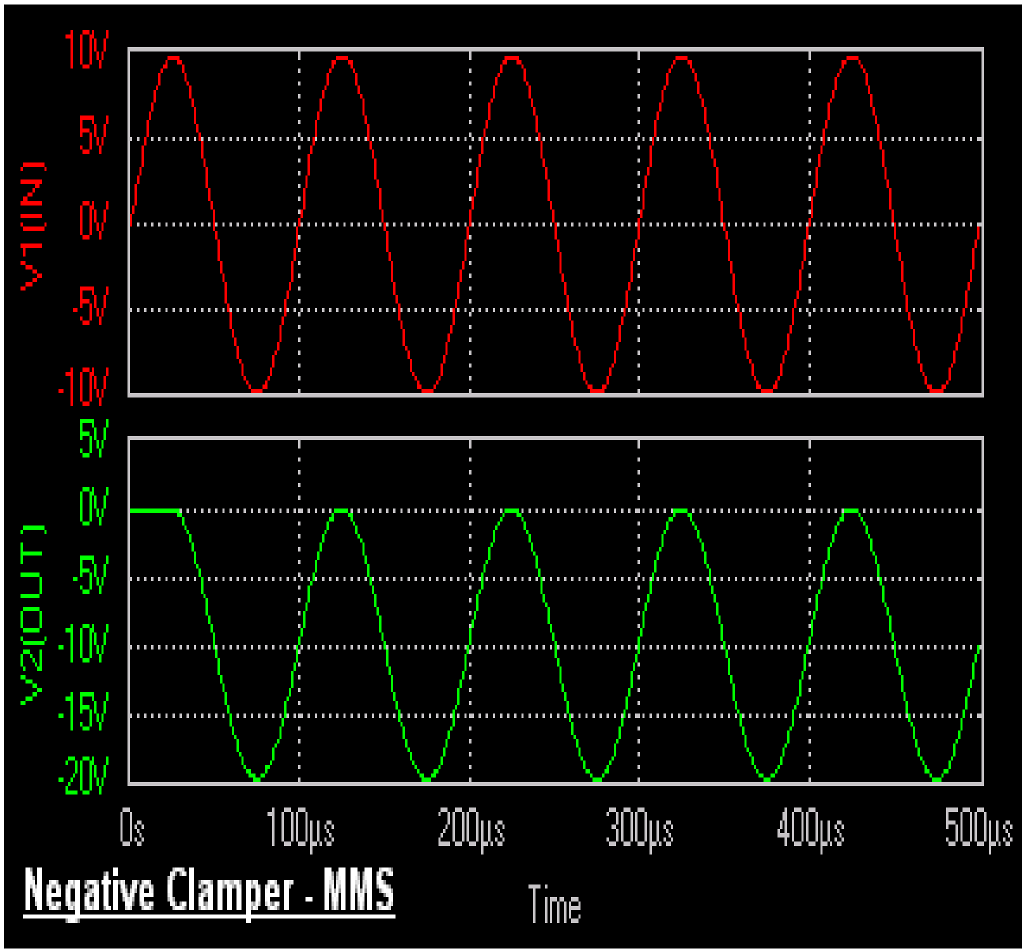
Negative Clamper

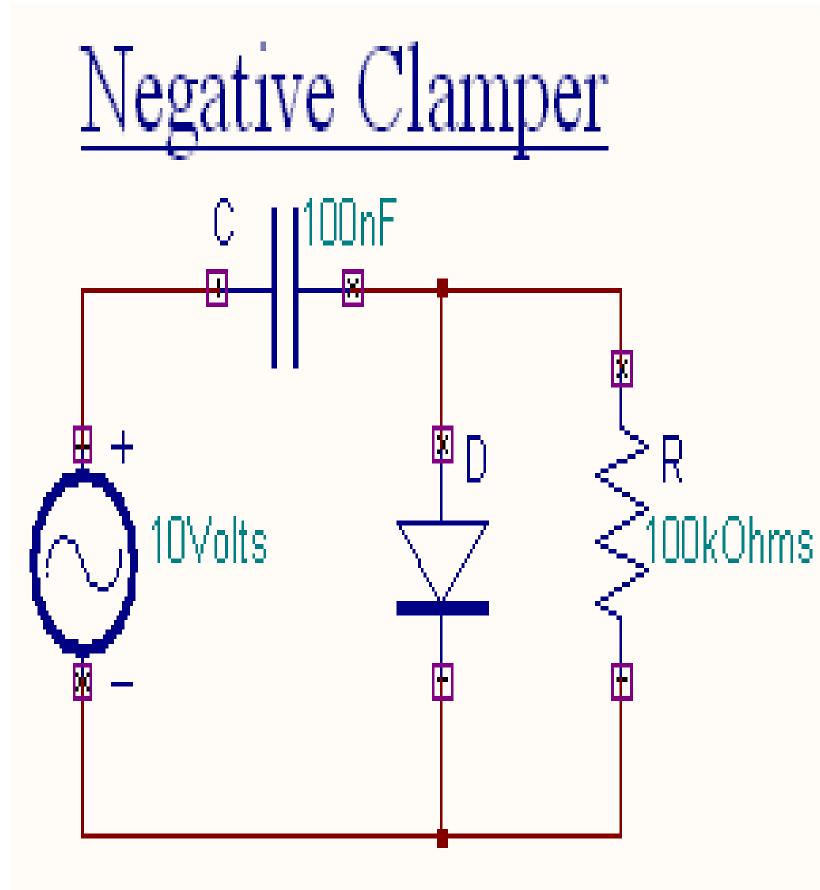
During the positive half cycle the diode conducts and acts like a short circuit. The capacitor charges to peak value of input voltage V_m. During this interval the output *Vo* which is taken across the short circuit will be zero During the negative half cycle, the diode is open. The output voltage can be found by applying KVL.



$$-V_m - V_m - V_o = 0 \qquad V_o = -2V_m$$

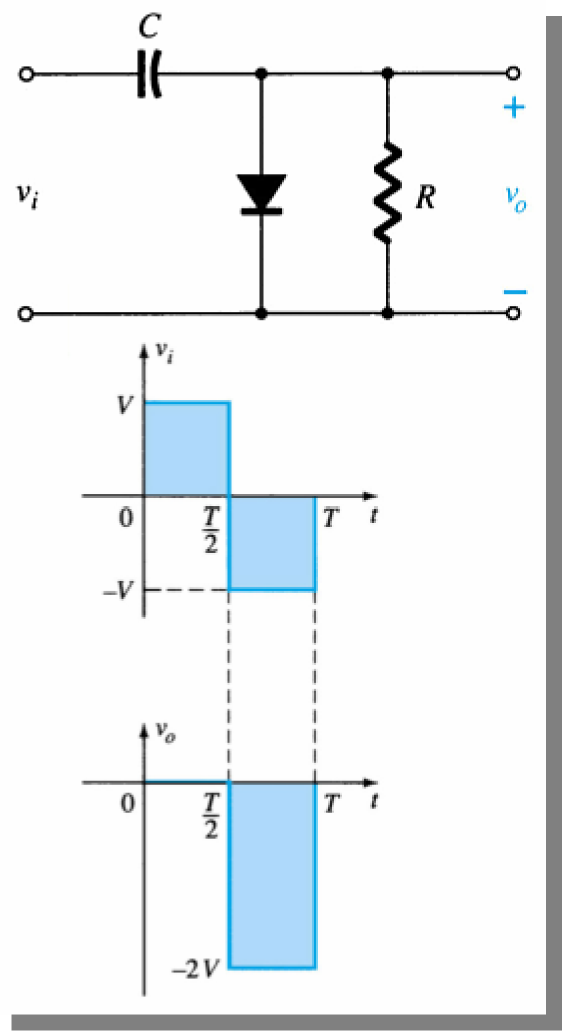
Negative Clamper





Negative Clampers

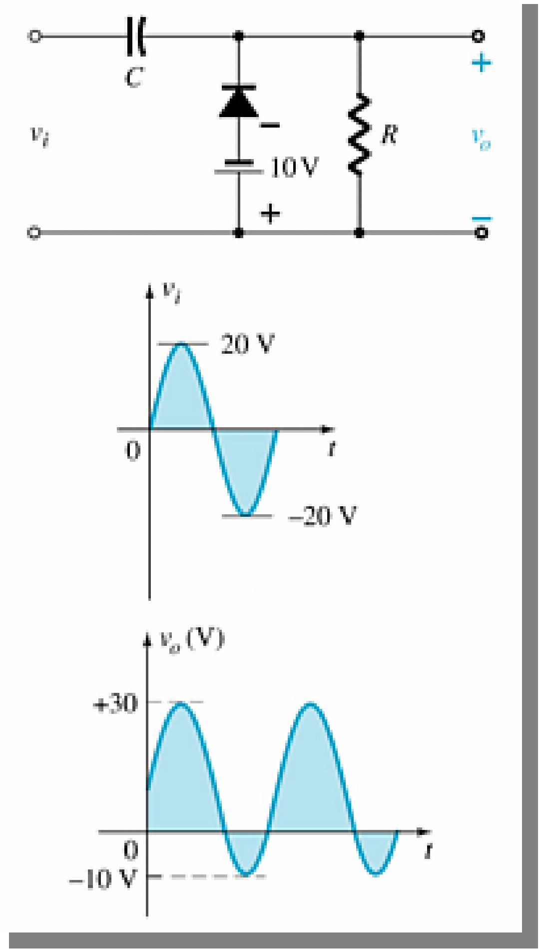
A diode and capacitor can be combined to “clamp” an AC signal to a specific DC level.



Biased Clamper Circuits

The input signal can be any type of waveform such as sine, square, and triangle waves.

The DC source lets you adjust the DC camping level.



Positively biased clamper

During the negative half cycle of the input signal the diode is forward biased and acts like a short circuit. The capacitor charges to V_i+V_s. Applying the KVL to the input side

$$-V_i + V_c - V_s = 0 \qquad V_c = V_s + V_i$$

During the positive half cycle of the input signal, the diode is reverse biased and it acts as an open circuit. Hence V_s has no effect on V_o. Applying KVL around the outside loop.

$$V_i + V_c - V_o = 0$$ ction Dio $$\therefore \quad V_o = V_i + V_c$$

Summary of Clamper Circuits