- The intrinsic concentration n_i varies with temperature T as

$$n_i^2 = A_0 T^3 e^{-E_g/kT}$$

where E_g is the energy gap at 0 K in electron volt, k is the Boltzmann constant in eV/K and A_0 is a constant independent of T.

Effect of Temperature on Conductivity of Intrinsic Semiconductor

- An intrinsic semiconductor will behave as a perfect insulator at absolute zero.
- With increasing temperature, the density of hole-electron pairs increases and hence the conductivity of an intrinsic semiconductor increases with increase in temperature. In other words, the resistivity (inverse of conductivity) decreases as the temperature increases.
- The semiconductors have negative temperature coefficient of resistance.

Doping

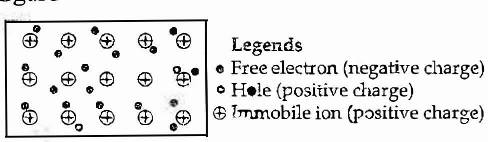
- It is a process of deliberate addition of a desirable impurity to a pure semiconductor in order to increase its conductivity. The impurity atoms added are known as dopants.

EXTRINSIC SEMICONDUCTOR

- A doped semiconductor is known as extrinsic semiconductor. An extrinsic semiconductor is of two types :
  - n-type semiconductor
  - p-type semiconductor

n-type Semiconductor

- When a pure semiconductor of Si or Ge (tetravalent) is doped with a group V pentavalent impurities like arsenic (As), antimony (Sb), phosphorus (P) etc, we obtain an n-type semiconductor. The pentavalent impurity atoms are known as donor atoms.
- It is called n-type semiconductor because the conduction of electricity in such semiconductor is due to motion of electrons *i.e.* negative charges.
- It is called donor type semiconductor, because the doped impurity atom donates one free electron to semiconductor for conduction.
- In n-type semiconductor, electrons are majority carriers and holes are minority carriers.
- The representation of n-type semiconductor is as shown in the figure



- n-type semiconductor is neutral as such.
- In n-type semiconductor

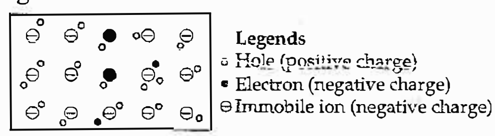
$$n_e \approx N_d >> n_h$$

where N_d is the density of donor atoms.

p-type Semiconductor

- When a pure semiconductor of Si or Ge (tetravalent) is doped with a group III trivalent impurities like aluminium (Al), boron (B), indium (In) etc, we obtain a p-type semiconductor. The trivalent impurity atoms are known as acceptor atoms.
- It is called p-type because the conduction of electricity in such semiconductor is due to motion of holes *i.e.* positive charges.
- It is called acceptor type semiconductor because the doped impurity atom creates a hole in semiconductor which accepts the electron, resulting conduction in p-type semiconductor.
- In p-type semiconductor, holes are majority carriers and electrons are minority carriers.

  The representation of p-type semiconductor is as shown in the figure.



- p-type semiconductor is neutral.
- In p-type semiconductor

$$n_h \approx N_a >> n_e$$

where N_a is the density of acceptor atoms.

Illustration 1

The number densities of electrons and holes in pure Si at 27°C is $2 \times 10^{16}\ \text{m}^{-3}$. When it is doped with indium, the hole density increases to $4 \times 10^{22}\ \text{m}^{-3}$, find the electron density in doped silicon.

Soln.: For extrinsic or doped semiconductor

$$n_e \cdot n_h = n_i^2 \Rightarrow n_e = \frac{n_i^2}{n_h}$$

Here, $n_i = 2 \times 10^{16}\ \text{m}^{-3}$ and $n_h = 4 \times 10^{22}\ \text{m}^{-3}$

$$\Rightarrow \quad n_e = \frac{(2 \times 10^{16}\ \text{m}^{-3})^2}{4 \times 10^{22}\ \text{m}^{-3}} = 10^{10}\ \text{m}^{-3}.$$

Illustration 2

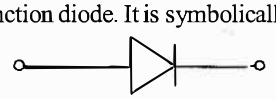
In an n-type silicon, which of the following statement is true:

(a) Electrons are majority carriers and trivalent atoms are the dopants.
(b) Electrons are minority carriers and pentavalent atoms are the dopants.
(c) Holes are minority carriers and pentavalent atoms are the dopants.
(d) Holes are majority carriers and trivalent atoms are the dopants.

Sol. For n-type silicon, statement (c) is true.

p-n junction

- When donor impurities are introduced into one side and acceptors into the other side of a single crystal of an intrinsic semiconductor, a p-n junction is formed. It is also known as junction diode. It is symbolically represented by



- The most important characteristic of a *p-n* junction is its ability to conduct current in one direction only. In the other (reverse) direction, it offers very high resistance.
- The current in the junction diode is given by

  $I = I_0(e^{eV/kT} - 1)$

  where k = Boltzmann constant, I_0 = reverse saturation current.

  In forward biasing, V is positive and low,

  $e^{eV/kT} >> 1$, then forward current,

  $I_f = I_0\,(e^{eV/kT})$

  In reverse biasing, V is negative and high

  $e^{eV/kT} << 1$, then reverse current,

  $I_r = -I_0$

Depletion Region

- In the vicinity of junction, the region containing the uncompensated acceptor and donor ions is known as depletion region. There is a depletion of mobile charges (holes and free electrons) in this region. Since this region has immobile (fixed) ions which are electrically charged, it is also known as the space charge region. The electric field between the acceptor and the donor ions is known as a barrier. The physical distance from one side of the barrier to the other is known as the width of the barrier. The difference of potential from one side of the barrier to the other side is known as the height of the barrier.
- For a silicon *p-n* junction, the barrier potential is about 0.7 V, whereas for a germanium *p-n* junction, it is approximately 0.3 V.
- The width of the depletion layer and magnitude of potential barrier depends upon the nature of the material of semiconductor and the concentration of impurity atoms.

  The thickness of the depletion region is of the order of one tenth of a micrometre.

Forward Biasing of a *p-n* Junction

- When the positive terminal of external battery is connected to *p*-side and negative to *n*-side of *p-n* junction, then the *p-n* junction is said to be forward biased.
- In forward biasing, the width of the depletion region decreases and barrier height reduces.
- The resistance of the *p-n* junction becomes low in forward biasing.

Reverse Biasing of a *p-n* Junction

- When the positive terminal of the external battery is connected to *n*-side and the negative terminal to *p*-side of a *p-n* junction, then the *p-n* junction is said to be reverse biased.

  In reverse biasing, the width of the depletion region increases and barrier height increases.
- The resistance of the *p-n* junction becomes high in reverse biasing.

Breakdown Voltage

- A very small current flows through *p-n* junction, when it is reverse biased. The flow of the current is due to the movement of minority charge carriers. The reverse current is almost independent of the applied voltage. However, if the reverse bias voltage is continuously increased, for a certain reverse voltage, the current through the *p-n* junction will increase abruptly. This reverse bias voltage is thus known as breakdown voltage. There can be two different causes for the break down. One is known as zener breakdown and the other is known as avalanche breakdown.

I-V characteristics of a *p-n* junction.

- The *I-V* characteristics of a *p-n* junction do not obey Ohm's law. The *I-V* characteristics of a *p-n* junction are as shown in the figure.

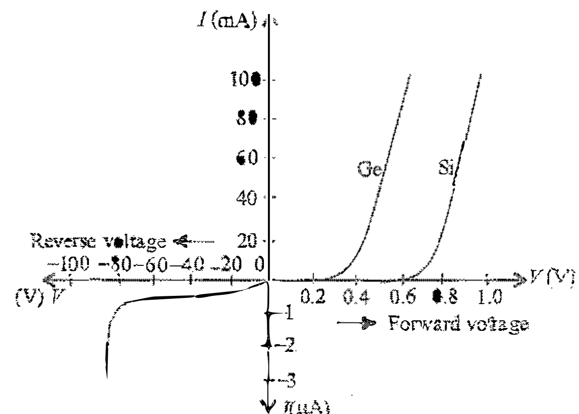


Illustration 3

In a *p-n* junction, the depletion layer of thickness 10^{-6} m has 0.1 V potential across it. Find the electric field.

Soln.: Electric field $= \dfrac{V}{d}$

or $E = \dfrac{0.1}{10^{-6}} = 10^5$ V/m.

Illustration 4

If the forward voltage in a semiconductor diode is changed from 0.5 V to 0.7 V, then the forward current changes by 1.0 mA. Find the forward resistance of diode junction.

Soln.: Forward resistance $= \dfrac{\Delta V}{\Delta I}$

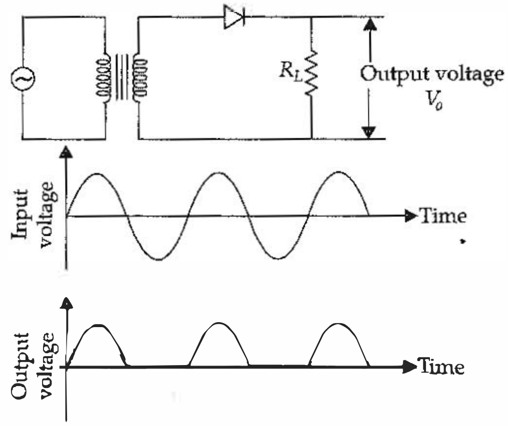
$\therefore \dfrac{\Delta V}{\Delta I} = \dfrac{0.7 - 0.5}{1.0 \times 10^{-3}} = 200\ \Omega.$

DIODE AS A RECTIFIER

- It is a device which converts ac voltage to dc voltage.
- Rectifier is based on the fact that, a forward bias *p-n* junction conducts and a reverse bias *p-n* junction does not conduct.
- Rectifiers are of two types:
  - Half wave rectifier
  - Full wave rectifier

Half Wave Rectifier

- The circuit diagram, input and output voltage waveforms for a half wave rectifier are as shown in the following figure.



- Peak value of current is

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

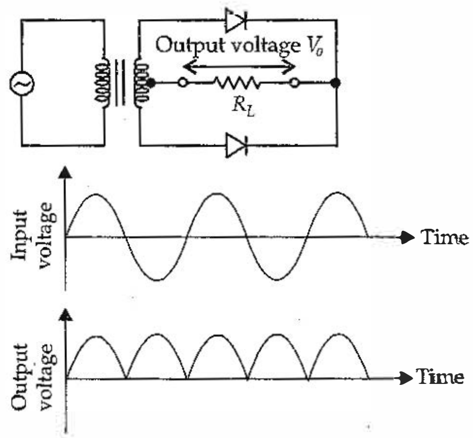
where r_f is the forward diode resistance, R_L is the load resistance and V_m is the peak value of the alternating voltage.

- rms value of current is $I_{rms} = \frac{I_m}{2}$
- dc value of current is $I_{dc} = \frac{I_m}{\pi}$
- Peak inverse voltage is $P.I.V = V_m$
- dc value of voltage is

$$V_{dc} = I_{dc} R_L = \frac{I_m}{\pi} R_L$$

Full Wave Rectifier

- The circuit diagram, input and output waveforms for a full wave rectifier are as shown in the figure.



- Peak value of current is $I_m = \frac{V_m}{r_f + R_L}$
- dc value of current is $I_{dc} = \frac{2I_m}{\pi}$
- rms value of current is $I_{rms} = \frac{I_m}{\sqrt{2}}$
- Peak inverse voltage is $P.I.V = 2V_m$
- dc value of voltage is $V_{dc} = I_{dc} R_L = \frac{2I_m}{\pi} R_L$

- **Ripple frequency**

$\upsilon_r = \upsilon_i = 50$ Hz (half wave rectifier)

$\upsilon_r = 2\upsilon_i = 100$ Hz (full wave rectifier)

- **Ripple factor**

The ripple factor is a measure of purity of the dc output of a rectifier, and is defined as

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

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

For half wave rectifier,

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

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

For full wave rectifier,

$$I_{rms} = \frac{I_m}{\sqrt{2}}, I_{dc} = \frac{2I_m}{\pi}$$

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

$$= 0.482$$

- **Rectification efficiency**
  - The rectification efficiency tells us what percentage of total input ac power is converted into useful dc output power. Thus, rectification efficiency is defined as

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

  - For a half wave rectifier,

dc power delivered to the load is

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$$

Input ac power is

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

Rectification efficiency

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(I_m/\pi)^2 R_L}{(I_m/2)^2 (r_f + R_L)} \times 100\%$$

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

If $r_f << R_L$,

Maximum rectification efficiency, $\eta = 40.6\%$.

  - For a full wave rectifier,

dc power delivered to the load is

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

Input ac power is