To read the value of a carbon resistance, the following sentence is found to be of great help :

B B ROY Great Britain Very Good Wife

The bold-face letters in the above sentence (B, B, R, O, Y, G, B, V, G and W) correspond to the colours Black, Brown, Red, Orange, Yellow, Green, Blue, Violet, Grey and White respectively. These colours of the bands correspond to figures 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 for the first two bands (A and B) and correspond to multipliers $10^0, 10^1, 10^2, 10^3, 10^4, 10^5$, $10^6, 10^7, 10^8$ and 10^9 respectively for the colour of third band (C). If the colour of the fourth band is gold, the tolerance is 5% and in case the colour is silver, the tolerance is 10%. In case, there is no fourth band, then its tolerance is 20%.

The following table gives the colour code for carbon resistance :

Letter as an aid to Memory	Colour	Figure	Multiplier	Colour	Tolerance
B	Black	0	10^0	Gold	5%
B	Brown	1	10^1	Silver	10%
R	Red	2	10^2	No colour	20%
O	Orange	3	10^3		
Y	Yellow	4	10^4		
G	Green	5	10^5		
B	Blue	6	10^6		
V	Violet	7	10^7		
G	Grey	8	10^8		
W	White	9	10^9		

For example, consider a carbon resistance, for which the bands A, B and C are of colours brown, green and orange respectively and the last band D is of silver in colour. The value of the resistance can be found from the table as explained below :

Corresponding to colours of bands A and B, which are brown and green, the figures are 1 and 5. Corresponding to the third band of orange colour, the multiplier is 10^3. Therefore, resistance is of the value $15 \times 10^3\ \Omega$. Since silver colour of the fourth band corresponds to a tolerance of 10%, the value of resistance is $15 \times 10^3\ \Omega \pm 10\%$.

2.06. CARRIERS OF CURRENT

The American physicists Tolman and Stewart in 1917 experimentally confirmed that the electric current in a conductor is carried by electrons. They found that a current carrying circular loop and suspended with the help of a suspension wire possesses angular momentum. The possible explanation for this fact is that in solids, atoms are very close to each other. Therefore, the valence electrons of one atom are very close to the neighbouring atoms. In such a solid, an electron does not keep itself attached to a one particular atom but can jump from one atom to the other. In other words, it can move freely in the entire solid. Therefore, the electrons outside the closed shell are free in this sense and can carry current in the solids. It may be pointed out that it is not true for all solids as it cannot explain why such solids are metals and others are insulators. However, it can be safely assumed that a metal has free electrons inside it.

It has been investigated that inside a metal, the distribution of speed among the free electrons (behaving as an electron-gas) is very different from the distribution of speeds among the molecules of an ideal gas. The maximum speed of the free electrons in a metal is of the order of 10^6 m s^{-1}. The free electrons move randomly inside the metal. They do not have a preferred direction of motion.

2.07. NATURE OF ELECTRICAL RESISTANCE

We know that in a metal, electrons move in all directions and the maximum speed of the electrons is of the order of 10^6 m s^{-1}. So long as an electric field is not applied across the piece of the metal, there cannot be any net motion of the electrons in a particular direction. In other words, in the absence of electric field, the free electrons moving in all directions cannot constitute an electric current.

When an electric field is applied, the electrons get accelerated in a direction opposite to the electric field as electrons are negatively charged particles. Due to this acceleration, the velocity of an electron increases but it happens so only for a short time. It is because of the fact that the electron experiences random forces due to vibrating ions in the metal. Therefore, the electron may get deflected or scattered in a wide range of directions due to the action of random forces. Suppose such a deflection takes place once in a time τ on the average. It is called *average relaxation time*. Therefore, electron is accelerated only for a small time τ. If E is strength of the electric field applied, then

force on the electron due to electric field = eE

Here, e is charge on electron. If m is mass of the electron, then acceleration produced is given by

$$a = \frac{eE}{m}$$

Since electron is accelerated for an average time τ, the additional velocity acquired by the electron

$$v_d = a\tau$$

or

$$v_d = \frac{eE}{m}\tau \qquad \text{...(2.08)}$$

This small velocity imposed on the random motion of electrons in a conductor, on applying electric field to it, is called **drift velocity**.

Thus, *drift velocity may be defined as that velocity with which a free electron in addition to its random motion gets drifted under the influence of an external field through the body of the conductor.*

It is the drift of electrons, which constitutes the electric current.

Consider a conductor of length l and area of cross-section A. Suppose it contains n electrons per unit volume. Imagine any section of the conductor and count all the charges that pass through this section in one second. Obviously, it will be equal to the charge on all those electrons, which are contained in volume A v_d. Therefore, charge crossing per second through any section of the conductor *i.e.* current flowing through the conductor will be

$$I = n\,(A\,v_d)e \qquad ...(2.09)$$

From equations (2.08) and (2.09), we have

$$I = nA\left(\frac{eE}{m}\tau\right)e$$

or

$$I = \frac{nA\,e^2\,E\,\tau}{m}$$

Also, from equation (2.09), we have

$$v_d = \frac{I}{neA}$$

If V is potential difference applied across the two ends of the conductor, then

$$E = \frac{V}{l}$$

$$\therefore \quad I = \frac{nA\,e^2\,V\,\tau}{ml}$$

or

$$\frac{V}{I} = \frac{m}{n\,e^2\,\tau}\cdot\frac{l}{A}$$

But according to Ohm's law, $\frac{V}{I} = R$, the resistance of the conductor. Therefore,

$$R = \frac{m}{n\,e^2\,\tau}\cdot\frac{l}{A}$$

Since, $R = \rho\,\frac{l}{A}$, we have

$$\rho = \frac{m}{n\,e^2\,\tau} \qquad ...(2.10)$$

It follows that resistivity of the material of a conductor depends on the following factors :

(*i*) *It is inversely proportional to the number of free electrons per unit volume* (*n*) *of the conductor. Since the value of n depends upon nature of the material, likewise the resistivity of a conductor depends upon the nature of the material.*

(*ii*) *It is inversely proportional to the average relaxation time* (τ) *of the free electrons in the conductor.* As we shall study in next section, the value of τ decreases with increase in temperature of the conductor. Therefore, *resistivity of conductor depends upon its temperature and it increases with increase in temperature in case of a conductor.*

2.08. TEMPERATURE DEPENDENCE OF RESISTIVITY

The resistivity of a material depends upon two parameters of the material namely *number of electrons per unit volume* and the *average relaxation time*. If the temperature of the material increases, the amplitude of atomic vibrations will also increase and it will lead to greater frequency of collisions of electrons with atoms and ions. Due to this, the value of average relaxation time will decrease and hence the resistivity of the material would increase.

In metals, the resistivity increases linearly with temperature up to about 500° C above the room temperature.

For moderate range of temperature θ^0C, the resistance R of a conductor is given by

$$R = R_0 (1 + \alpha \theta),$$

where R_0 is the resistance of the conductor at 0°C and α is the *temperature coefficient of the resistance* for the material which depends upon the nature of material. From the above expression, we have

$$\alpha = \frac{R - R_0}{R_0 \theta}$$

Thus, the temperature coefficient of a resistance is defined as the change in resistance per unit resistance at 0° C per degree rise of temperature.

For copper, the value of α is 0·004 °C^{-1}. For pure platinum, the temperature coefficient is $\frac{1}{273}$ °C^{-1}, the same as that for a perfect gas. Hence, platinum resistance thermometer gives nearly the same temperature as a perfect gas thermometer.

In the case of alloy, the rate at which the resistance changes with temperature is much less. For example, manganin (an alloy of copper, nickel, iron and manganese) has a resistance, which is thirty to forty times as that of pure copper for the same dimensions but its temperature coefficient is very small *i.e.* 0·00001 °C^{-1}. For this reason, it is an excellent substance to be used for the construction of a standard resistance coil.

In case of insulators, the resistivity increases nearly exponentially with decrease in temperature. The number of electrons in thermodynamic equilibrium at a temperature T is given by

$$n = n_0 e^{-E_g/kT} \quad \text{...(2.11)}$$

where k is Boltzmann's constant, n_0 is of the order of 10^{28} m^{-3} and E_g is called energy gap between conduction and valence bands.

From equations (2.10) and (2.11), we have

$$\rho = \frac{m}{n_0 e^2 \tau} e^{E_g/kT},$$

or

$$\rho = \rho_0 e^{E_g/kT}, \quad \text{...(2.12)}$$

where the factor $\rho_0 = \frac{m}{n_0 e^2 \tau}$ has a weak dependence on temperature.

The value of factor kT is about 0·03 e V at room temperature. The value of E_g can vary from nearly zero (for conductors) to several electron volt (for insulators).

The materials, for which $E_g \leq 1$ eV, resistivity at room temperature will not be very high. Such materials are called semi-conductors.

The materials, for which $E_g > 1$ eV, the resistivity at room temperature will be very high and such substances are called insulators.

From equation (2.12) it follows that $\rho = \infty$, when T = 0 K i.e. insulators are substances whose resistance become infinite at T = 0K. Some semiconductors also show this behaviour.

The resistance of semiconductors such as carbon, silicon and germanium, the resistance generally decreases with increase of temperature and thus they possess negative temperature coefficient.

The resistance of insulators such as India-rubber and mica decreases with rise of temperature and same is the case with the resistance of electrolytes. They have, thus, negative temperature coefficients.

Example 2.10