Current Electricity

- Current through a given area of a conductor is the net charge passing per unit time through the area.
- To maintain a steady current, we must have a closed circuit in which an external agency moves electric charge from lower to higher potential energy. The work done per unit charge by the source in taking the charge from lower to higher potential energy (i.e., from one terminal of the source to the other) is called the electromotive force, or emf, of the source. Note that the emf is not a force; it is the voltage difference between the two terminals of a source in open circuit.
- Ohm's law: The electric current I flowing through a substance is proportional to the voltage V across its ends, i.e.,

  $V \propto I$ or $V = RI$,

  where R is called the resistance of the substance. The unit of resistance is ohm: $1\Omega = 1\ V\ A^{-1}$.
- The resistance R of a conductor depends on its length l and constant cross-sectional area A through the relation,

  $R = \rho l/A$

  where ρ, called resistivity is a property of the material and depends on temperature and pressure.

- Electrical resistivity of substances varies over a very wide range. Metals have low resistivity, in the range of 10 –8 Ω m to 10^{-6} Ω m. Insulators like glass and rubber have 10^{22} to 10^{24} times greater resistivity. Semiconductors like Si and Ge lie roughly in the middle range of resistivity on a logarithmic scale.
- In most substances, the carriers of current are electrons; in some cases, for example, ionic crystals and electrolytic liquids, positive and negative ions carry the electric current.
- Current density j gives the amount of charge flowing per second perunit area normal to the flow,

  $j = nq\, v_d$

  where n is the number density (number per unit volume) of chargecarriers each of charge q, and vd is the drift velocity of the chargecarriers. For electrons q = – e. If j is normal to a cross-sectional areaA and is constant over the area, the magnitude of the current I throughthe area is $n_e$vd A.
- Using E = V/l, I = nevd A, and Ohm’s law, one obtains

$eE/m = \rho n_e^2 v_d/m$

The proportionality between the force eE on the electrons in a metal due to the external field E and the drift velocity v_d (not acceleration) can be understood, if we assume that the electrons suffer collisions with ions in the metal, which deflect them randomly. If such collisions occur on an average at a time interval τ,

$v_d = a\tau = eE\tau/m$

wherea is the acceleration of the electron. This gives

$\rho = m/(n_e^2\tau)$

- In the temperature range in which resistivity increases linearly with temperature, the temperature coefficient of resistivity α is defined as the fractional increase in resistivity per unit increase in temperature.
- Ohm's law is obeyed by many substances, but it is not a fundamental law of nature. It fails if

  (a) V depends on Inon-linearly.

  (b) the relation between V and I depends on the sign of V for the same absolute value of V.

  (c) The relation between V and I is non-unique.

An example of (a) is when ρ increases with I (even if temperature is kept fixed). A rectifier combines features (a) and (b). GaAs shows the feature (c).

- When a source of emf ε is connected to an external resistance R, the voltage V_{ext} across R is given by

  V_{ext} = IR = εR/(r+R)

  wherer is the internal resistance of the source.

- Total resistance R of n resistors connected in series is given by

  R = R1 + R2 +..... + Rn

  Total resistance R of n resistors connected in parallel is given by

  (1/R) = (1/R1)+(1/R2)...(1/Rn)

- Kirchhoff's Rules –

  (a) Junction Rule: At any junction of circuit elements, the sum of currents entering the junction must equal the sum of currents leaving it.

  (b) Loop Rule: The algebraic sum of changes in potential around any closed loop must be zero.

- The Wheatstone bridge is an arrangement of four resistances – R1, R2, R3, R4 as shown in the text. The null-point condition is given by

  R1/R2 = R3/R4

  using which the value of one resistance can be determined, knowing the other three resistances.
- The potentiometer is a device to compare potential differences. Since the method involves a condition of no current flow, the device can be used to measure potential difference; internal resistance of a cell and compare emf's of two sources.

Sample Examples

- The resistance of the platinum wire of a platinumresistance thermometer at the ice point is 5 Ω and at steam point is5.23 Ω. When the thermometer is inserted in a hot bath, the resistanceof the platinum wire is 5.795 Ω. Calculate the temperature of thebath.

  Solution

  R_0 = 5 Ω, R_{100} = 5.23 Ω and R_t = 5.795 Ω

  $T = (R_t – R_0)/(R_{100} – R_0)$

  = (5.795 – 5)/(5.23 – 5) *100

  = (0.795/0.23)*100

  =345.65 °C

- (a) Estimate the average drift speed of conduction electrons in a copper wire of cross-sectional area 1.0×10^{-7} m2 carrying a current of 1.5 A. Assume that each copper atom contributes roughly one conduction electron. The density of copper is 9.0×10^{3} kg/m^{3}, and its atomic mass is 63.5 u. (b) Compare the drift speed obtained above with, (i) thermal speeds of copper atoms at ordinary temperatures, (ii) speed of propagation of electric field along the conductor which causes the drift motion.

  Solution

  (a) The direction of drift velocity of conduction electrons is opposite to the electric field direction, i.e., electrons drif t in the direction of increasing potential. The drift speed vdis given by Eq. (3.18)

  vd = (I/neA)

  Now, e = 1.6×10^{-19} C, A = 1.0×10^{-7}m^{2}, I = 1.5 A. The density of conduction electrons, n is equal to the number of atoms per cubic metre (assuming one conduction electron per Cu atom as is reasonable from its valence electron count of one). A cubic metre of copper has a mass of 9.0×10^{3} kg. Since 6.0×10^{23} copper atoms have a mass of 63.5 g,

$N = (6.0 \times 10^{23} * 9.0 \times 10^{6})/63.5 = 8.5 \times 10^{28}\ m^{-3}$

Which gives vd = = 1.1 mm s^{-1}

(b) (i) At a temperature T, the thermal speed* of a copper atom of mass M is obtained from [<(1/2) Mv^2> = (3/2) kBT] and is thus typically of the order of √ kBTM , where kB is the Boltzmann constant. For copper at 300 K, this is about 2×10^2 m/s. This figure indicates the random vibrational speeds of copper atoms in a conductor. Note that the drift speed of electrons is much smaller, about 10^{-5} times the typical thermal speed at ordinary temperatures.

(ii) An electric field travelling along the conductor has a speed of an electromagnetic wave, namely equal to 3.0×10^8 m s^{-1}