# RRB-JE 2024

**Railway Recruitment Board**

Junior Engineer Examination

# Electronics Engineering

## Electronic Components and Materials

Well Illustrated **Theory** *with*
**Solved Examples** and **Practice Questions**

MADE EASY PUBLICATIONS

# Electronic Components & Materials

## Contents

Chapter 1

# Conductors

The conductivity of solids spans a wide range of values to about twenty-three orders of magnitude. No other quantity varies to such an extent. In the present chapter, we will discuss conductive materials which have high conductivity. The main facts relating to conductivities of metals explained are: the range and variation, the temperature dependence, the pressure dependence, the relation of thermal conductivity to electrical conductivity, the conductivity of impure metals or dilute alloys. The properties and applications of high and low conductive materials, and the physics and applications of superconductors have also been discussed.

## 1.1 Electrical Conductivity

As we know that a basic property of a material is its resistivity. Resistivity of a material is related to its resistance as follows:

$$R = \rho \frac{l}{A}$$

where, $R$ = Resistance, $\rho$ = Resistivity, $l$ = Length and $A$ = Area

Resistivity ($\rho$) is expressed in **ohm-m.**

Electrical conductivity ($\sigma$) is the reciprocal of electrical resistivity and is expressed in **ohm$^{-1}$ m$^{-1}$.**

At room temperature a typical insulator has conductivity in the range of $10^{-16}$ ohm$^{-1}$ m$^{-1}$, whereas for a semiconductor the value might be $10^{-2}$ ohm$^{-1}$ m$^{-1}$, and for a metal such as silver, the conductivity will be as high as $10^{8}$ ohm$^{-1}$ m$^{-1}$.

High conductivity of metals is due to the presence of **free or conduction electrons.** These electrons are able to move freely in the lattice and do not belong to any particular atom. These free electrons are given the name of electron gas.

## 1.2 Free Electron Theory of Metals-Ohm's Law

Temperature is the major contributing factor to determine the random velocities of electrons in a particular direction in the absence of electric field. Although the net drift velocity is zero.

On application of electric field, the electrons acquire a systematic velocity, so that, the motion of electrons will have two components:

(i) random motion depending upon temperature,

(ii) directed motion determined by electric field polarity.

Consider a system of free electrons in a conductor which is subjected to an electric field, $E$ volt/m, Fig. 1.1. Let, at any moment average forward acceleration of the electron be $d^2x/dt^2$ in the $x$ direction due to the field with $m$ as the mass of the electron and $-e$ as the charge, we have

$$m\frac{d^2x}{dt^2} = -eE \qquad ...(1.1)$$

where $E$ is the force acting on a unit electron charge.

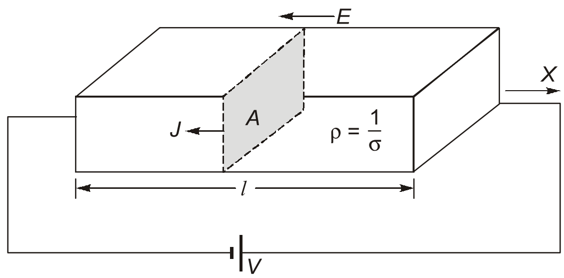



***Fig. 1.1 :** Conductor with electric field E*

Integrating equation (1.1), we have

$$m\frac{dx}{dt} = -eEt + A \qquad (A \text{ is a constant})$$

or
$$\frac{dx}{dt} = -\frac{e}{m}Et + C \qquad ...(1.2)$$

where $C$ is a constant.

$\frac{dx}{dt}$ represents a velocity. Obviously $C$ must have dimensions of velocity, and can only be random velocity of the electrons. So,

or
$$\frac{dx}{dt} = -\frac{eE}{m}t + v_{\text{random}} \qquad ...(1.3)$$

$v_{\text{random}}$ averages to zero, as there is no net transfer of charge in the absence of the field. Taking average effect of (1.3), we have

$$\frac{dx}{dt} = v_x = -\frac{eE\tau}{m} \qquad ...(1.4)$$

where $v_x$ is average drift velocity, and $\tau$ is called the collision time, average interval of successive collisions between the electrons and the lattice (ion cores).

Let $I_x$ be the current carried along the conductor of cross-section $A$, in say $x$ direction by electrons of charge $-e$ and drift velocity $v_x$. With '$n$' as the electrons per unit volume, the charge flowing through the section in time $dt$,

$$dq = -e\,n\,Av_x dt$$

$$\frac{dq}{dt} = I_x = -e\,n\,Av_x$$

and
$$J_x = \frac{I_x}{A} = -env_x \qquad ...(1.5)$$

where $J_x$ is current density. From equation (1.4) and (1.5) we have,

$$J_x = \frac{ne^2\tau}{m}E \qquad ...(1.6)$$

Here,
$$\sigma = \frac{ne^2\tau}{m} \qquad ...(1.7)$$

$\sigma$ is called the conductivity of material and in general;

$$J = \sigma E \quad ...(1.8)$$

This relation is a well known **Ohm's law** in a different form, figure (1.1)

we have,

$$I = J \cdot A = \sigma EA = \sigma\left(\frac{V}{l}\right)A$$

$$I = \frac{V}{R} \quad \text{where } R = \left(\frac{l}{\sigma A}\right)$$

$l$-length of the conductor, $A$-area of cross-section and $V$-voltage applied.

**Mobility ($\mu$)**

Mobility is defined as the magnitude of the average drift velocity per unit field. **Mobility** and **conductivity** thus have the relation

$$\sigma = n e \mu \quad ...(1.9)$$

$\mu$ has the unit **$m^2$ volt$^{-1}$ s$^{-1}$**.

**Example - 1.1** A uniform silver wire has a resistivity of $1.54 \times 10^{-8}$ ohm-m at room temperature, for an electric field along the wire of 1 volt/cm. Compute the average drift velocity of the electrons, assuming there are $5.8 \times 10^{28}$ conduction electrons per $m^3$. Also calculate the mobility and relaxation time of the electrons.

***Solution:***

The number of silver conduction electrons/$m^3$

$$= 5.8 \times 10^{28}$$

$$\therefore \quad n = 5.8 \times 10^{28}$$

$$\sigma = n e \mu$$

Mobility,

$$\mu = \frac{\sigma}{ne} = \frac{1}{\rho ne}$$

$$\Rightarrow \quad \mu = \frac{1}{1.54 \times 10^{-8} \times 5.8 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$\therefore \quad \mu = 6.99 \times 10^{-3} \text{ m}^2 \text{ volt}^{-1} \text{ sec}^{-1}$$

and average drift velocity

$$v_d = \mu E,$$

$$\because \quad E = 1 \text{ V/cm} = 10^2 \text{ V/m}$$

Now,

$$v_d = 6.99 \times 10^{-3} \times 10^2$$

$$v_d = 0.699 \text{ ms}^{-1}$$

**Example - 1.2** The following data is known for copper metal,

Density = 8.92 g/cc
Resistivity = $1.73 \times 10^{-8}$ ohm-m
Atomic weight = 63.5

Calculate the mobility and the average time of collision of the electrons in copper.

***Solution:***

$$\text{Molar volume} = \frac{\text{Atomic Weight}}{\text{density}} = \frac{63.5}{8.92} \times 10^{-6} = 7.12 \times 10^{-6}\ \text{m}^3$$

Valence electrons per unit volume ($N$) is,

$$N = \frac{\text{Avogadro's number}}{\text{Molar volume}} = \frac{6.025 \times 10^{23}}{7.12 \times 10^{-6}} = 8.46 \times 10^{28}\ \text{m}^{-3}$$

$$\text{Mobility } (\mu_e) = \frac{\sigma}{Ne} = \frac{1}{\rho Ne} = \frac{1}{1.73 \times 10^{-8} \times 8.46 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$= 4.27 \times 10^{-3}\quad \text{m}^2\ \text{V}^{-1}\text{sec}^{-1}$$

$$\text{Average time of collision,}\quad \tau = \frac{m\sigma}{Ne^2} = \frac{m}{\rho Ne^2} = \frac{9.1 \times 10^{-31}}{1.73 \times 10^{-8} \times 8.46 \times 10^{28} \times (1.6 \times 10^{-19})^2}$$

$$= 2.42 \times 10^{-14}\ \text{sec}$$

## 1.3 Joule's Law

Joule determined experimentally that the heat developed in a conducting wire of resistance $R$ carrying a current $I$ is $I^2 R$.

This can be put in the form (figure (1.1))

$$I^2 R = \frac{V^2}{R} = \frac{(E\,l)^2}{\rho \frac{l}{A}} = \sigma E^2 \cdot l\,A \qquad \text{...(1.10)}$$

in which $l$ and $A$ are the length of the wire and its cross-section, $E$ is the field in volt-meter$^{-1}$ and $\sigma$ is the conductivity in ohm$^{-1}$ m$^{-1}$. From this, one may infer that volume density of heat developed per second is

$$W = \sigma E^2$$

and with current density

$$J = \sigma E$$

$$W = JE = \sigma E^2 \qquad \text{...(1.11)}$$

If $J$ is in amperes per m$^2$ and $E$ is in volts per m, $W$ is found to be in watts per m$^3$.

## 1.4 Relaxation Time (τ)

When electric field applied across a conducting bar is removed. The drift velocity of electron does not reduce to zero suddenly. Rather it reduces exponentially because of inertia of electron. At any instant ($t > 0$),

$$\boxed{v_d(t) = v_d(0)e^{-t/\tau_r}} \qquad \text{...(1.12)}$$

where '$\tau_r$' is called the relaxation time of the electrons.

Relaxation time is the time required to reduce the drift velocity of electron to 37% of its initial value after the removal of electric field.

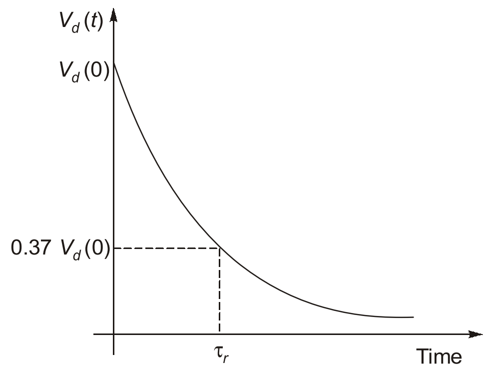



***Fig. 1.2 :** Decay of drift velocity as per equation (1.12)*

## 1.5 Collision Time ($\tau_c$)

It is the average time period between the two successive collisions of an electron for isotropic material, average collision time is always equal to the relaxation time.

## 1.6 Mean Free Path ($\lambda$)

It is the average distance between two successive collisions, mathematically.

$$\boxed{\lambda = v_d \tau_c} \quad \text{...(1.13)}$$

Where, $\tau_c$ is collision time.

## 1.7 Mean Free Path and Velocity at Fermi Level

In this case, $\boxed{\text{mean free path}(\lambda) = v_f \tau_c}$.

At any temperature ($T$), the probability of state corresponding to an energy '$W$' being occupied by an electron is given by,

$$f(W) = \frac{1}{\exp\left[\frac{(W - W_F)}{kT}\right] + 1}$$

Kinetic energy of electron at fermi level is equal to fermi energy ($W_F$).

$$\therefore \quad \boxed{\text{Fermi energy } (W_F) = \frac{1}{2} m v_f^2} \quad \text{...(1.14)}$$

Where, $v_f$ is the drift velocity at fermi level. Which is equal to

$$\boxed{v_f = \sqrt{\frac{2W_F}{m}}} \quad \text{...(1.15)}$$

**Example - 1.3** A conducting wire has a resistivity of $1.5 \times 10^{-8}$ Ωm at 300 K. Its Fermi energy is 5 eV. Its volume of 1 $m^3$ contains $6 \times 10^{28}$ conducting electrons. Calculate the relaxation time of conducting electrons, hence or otherwise obtain the value of drift velocity of electrons. When the conductor is subjected to an electric field of 100 V/m.

Given, mass of electron = $9.107 \times 10^{-31}$ kg

Electron Charge = $1.601 \times 10^{-19}$ Coulomb

***Solution:***

Given data,

$\rho = 1.5 \times 10^{-8}\ \Omega\text{-m}$, $W_F = 5$ eV

$n = 6 \times 10^{28}$, $E = 100$ V/m

$\tau = ?$, $m = 9.107 \times 10^{-31}$ kg

$v = ?$, $e = 1.601 \times 10^{-19}$ Coulomb

(i) ∵ Conductivity,

$$\sigma = \frac{ne^2\tau}{m}$$

∴ Relaxation time,

$$\tau = \frac{m\sigma}{ne^2},\ \left[\sigma = \frac{1}{\rho}\right] = \frac{m}{\rho n e^2}$$

$$= \frac{9.107\times10^{-31}}{1.5\times10^{-8}\times6\times10^{28}\times(1.6\times10^{-19})^2} = 4 \times 10^{-14}\ \text{sec}$$

(ii) Drift velocity

$$v = \frac{e\tau}{m}E = 7.04 \times 10^{-3} \times 10^2 = 0.704\ \text{m/sec}$$

## 1.8 Factors Affecting Electrical Conductivity (or Resistivity) of Conducting Materials

### Temperature

Average collision time of electron in conducting material reduces with increase in temperature. Since the conductivity of the material is directly proportional to average collision time. Therefore conductivity reduces with increasing temperature. Since resistivity is the reciprocal of the conductivity, so resistivity of conducting material increases with increase in temperature. The resistivity of conducting material as a function of temperature is given below:

$$\rho_{T_2} = \rho_{T_1}(1 + \alpha\,\Delta T) \quad \text{...(1.16)}$$

Where, $\Delta T = T_2 - T_1$ = difference of temperature

$\alpha$ = temperature coefficient

Since the electrical conductivity is proportional to $l$, and resistivity ($\rho$) to $l^{-1}$.

Hence,

$$\boxed{\rho_{Total} = \rho_T + \rho_i + \rho_d = \rho_T + \rho_r} \quad \text{...(1.17)}$$

Equation (1.17) is statement of **"Matthiessen's Rule"** and it indicates the various contribution to the resistivity of metals are independently additive.

Also, $\rho_T$ → ideal resistivity varies with temperature.

$\rho_r$ → residual resistivity (depends on impurity).

**NOTE:** The temperature coefficient of conducting material is positive.

### Alloying

The resistivity of alloy has two components called (a) thermal component and (b) residual component. **Thermal component** of conducting material is due to lattice vibration caused by thermal energy. This component reduces with decrease in temperature and becomes zero at absolute zero temperature. The **residual component** of resistivity arise due to impurity of material and lattice imperfection. This component is independent of temperature and will be existing even at absolute zero temperature. Therefore, alloying can induce the resistivity. Alloys generally have a less regular structure than pure metals. Consequently, the electrical conductivity of a solid solution alloy, drops off rapidly with the increase alloy content.

$$\text{Resistivity of alloy } (\rho_{alloy}) = \rho_{puremetal} + s\rho_i \quad ...(1.18)$$

where, $s$ = atomic percentage of added impurity

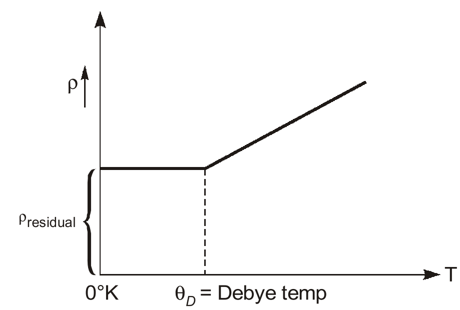
$\rho_i$ = increase in resistivity per atomic%

**Unit of "$\rho_{alloy}$" is μ-ohm-cm.**

⇒ When a copper is added to silver (Ag), the resistivity of alloy is more than resistivity of copper (Cu), and conductivity of alloy is less than conductivity of copper (Cu).

⇒ When a small amount of Ni i.e. 1% is a added to Cu, the resistivity of Cu goes up by 1.3 μ-ohm-cm.

$\rho_{alloy}$ $V_s$ temperature




### Cold Working

The mechanical treatments such as cold working produces localized strain in the material which results in the increase in resistivity of material. **A hard drawn copper wire has lower conductivity than annealed copper.**

### Age Hardening

If material gets hardened with age then its resistivity increases and hence conductivity decreases.

## 1.9 Relation between Temperature Coefficient of Alloys and Pure Metals

⇒ $$\rho_T = \rho_t + \alpha\,\rho_t\,\Delta T$$

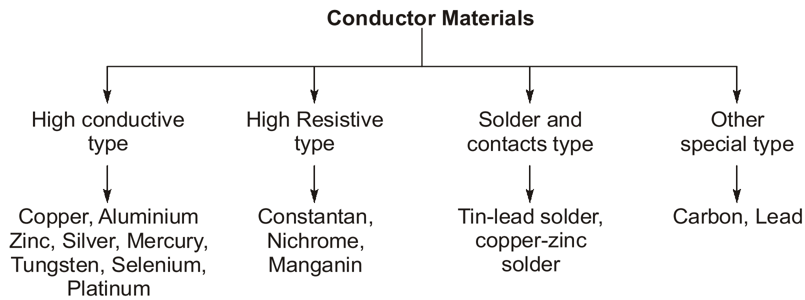
and $$\alpha_{metal} = \frac{1}{\rho_T}\cdot\frac{d\rho_{Thermal}}{dT} \quad ...(1.19)$$

so, $$\alpha_{alloy} = \frac{1}{(\rho_{res.} + \rho_{Thermal})}\times\frac{d\rho_{TH}}{dT}$$

$$= \frac{1}{\left(1+\dfrac{\rho_{res.}}{\rho_{TH}}\right)}\times\frac{1}{\rho_T}\times\frac{d\rho_{TH}}{dT}$$

∴ $$\boxed{\alpha_{alloy} = \frac{\alpha_{metal}}{\left(1+\dfrac{\rho_{res.}}{\rho_{TH}}\right)}} \quad ...(1.20)$$

so, $$\boxed{\alpha_{alloy} < \alpha_{metal}}$$




## 1.10 Application of Conducting Materials

- In transmission lines and cables.
- In DC machines.
- In synchronous generators.
- In transformers.
- In 3-phase induction motors.

## 1.11 Conductors for Electrical Machines

The fundamental requirements to be met by high conductivity materials to be used for electrical machines are:

- highest possible conductivity.
- rollability and drawability.
- good weld ability and solderability.
- least possible temperature coefficient.
- adequate mechanical strength.
- adequate resistance to corrosion.

## 1.12 Thermal Conductivity of Metals-Wiedemann Franz Law

All solids conduct heat. In general, the best heat conductors are the metals. Among the metals the best electrical conductors are also the best heat conductors. In such conductors just like electrical conductivity, the heat conduction is mostly through valence (free) electrons.

When two bodies at different temperatures are brought in contact with each other, heat $Q$ flows from hotter to the colder substance. The change in energy, $\Delta E$, of a system can be expressed by the first law of thermodynamics

$$\Delta E = W + Q \qquad (1.21)$$

where, W is the work done to the system and Q is the heat received by the system from the environment. If W is considered to be zero then

$$\Delta E = Q \qquad ...(1.22)$$

Energy, work and heat have the same unit of Joule ($J$).

Different substances need different amount of heat to raise their temperature by some units i.e. degrees. The **heat capacity** $C$ is the amount of heat $dQ$ which is needed to be transferred to a substance in order to raise its temperature by a certain temperature level, having the unit J/K or J/°C. The heat capacity at constant volume is defined as

$$C_v = \left(\frac{\partial E}{\partial T}\right)_v \qquad ...(1.23)$$

# Student's Assignments

1. According to Wiedemann-Franz law the ratio of thermal conductivity to electrical conductivity of a conductor is
   (a) Independent of temperature
   (b) Directly proportional to temperature
   (c) Inversely proportional to temperature
   (d) inversely proportional to square of temperature

2. Consider the following metals
   1. Zinc    2. Gold
   3. Silver    4. Copper
   The correct sequence of the increasing order of their resistivities is
   (a) 4, 3, 1, 2    (b) 3, 4, 2, 1
   (c) 4, 3, 2, 1    (d) 3, 4, 1, 2

3. If a small amount of Cu is added to a Ni conductor, then the
   (a) resistivity of Ni will increase at all temperatures because Cu is a better conductor than Ni.
   (b) residual resistivity of Ni at low temperature will increase as Cu atoms act as defect centres.
   (c) resistivity of Ni will increase at all temperatures as Cu destroys the periodicity of Ni and acts as defects.
   (d) resistivity of Ni remains unaltered as Cu atoms give the same number of free electrons as Ni atoms.

4. When copper is added to silver in small quantity so as to form an alloy, the resistivity of such an alloy is
   (a) equal to the resistivity of copper
   (b) equal to the resistivity of silver
   (c) greater than the resistivity of copper
   (d) in between the resistivities of silver and copper

5. What is the correct arrangement of the following alloys in decreasing order of resistivity?
   (a) German silver - constantan - monel metal
   (b) German silver - monel metal - constantan
   (c) Constantan - monel metal - German silver
   (d) Constantan - German silver - monel metal

## STUDENT'S ASSIGNMENTS ANSWER KEY

**1.** (b) **2.** (c) **3.** (c) **4.** (c) **5.** (b)

## STUDENT'S ASSIGNMENTS EXPLANATIONS

**1. (b)**

$$\frac{K}{\sigma} = \frac{\pi^2 K^2}{3e^2} \cdot T$$

where, $K \rightarrow$ thermal conductivity
$\sigma \rightarrow$ electrical conductivity

**4. (c)**

When an alloy is formed adding two or more metals, the resistivity of alloy is greater than that of all those metals.

■■■■