Chapter 2

Electronic Fundamentals

Topics Covered:

Voltage • Current • Resistance • Resistor
Drift Velocity • Mobility of Electrons
Sources of Electricity • Flow of Current
Factors Affecting Resistance • Resistivity
Classification of Materials • Conductance

1. Voltage (V)

Definition

Voltage is the expression of potential difference between two points within an electric field.

Symbol: V
SI Unit: Volt (V)
Also known as: Electromotive Force (EMF) or Potential Difference (PD)

Formula:

$$V = W / Q$$

Where: W = Work done (Joules) | Q = Charge (Coulombs)

Fig. 1 — Voltage Concept (Two Points in Electric Field)

```
High Potential (A)                         Low Potential (B)
     •────────────────────────────────────────•
  (+V, high)     ◄── Potential Difference ──►    (-V, low)
                 ← Electric Field Direction →

Electric field points from higher potential to lower potential
Voltage (V) = energy required to move unit charge between pts
```

▲Figure

2. Electric Current (I)

Definition

An electric current is the rate of flow of electric charge. These charges can be electrons, ions, and plasma (ionized gases).

Symbol: I
SI Unit: Ampere (A)

Formula:

$$I = q / t$$

Where: q = Charge (Coulombs) | t = Time (Seconds)

If a small cross-section of wire could be isolated and the quantity of charge (q) passing through this cross-section in a certain amount of time (t) is measured, then the current is given by the formula above.

Fig. 2 — Conductor Showing Current Flow

```
←────────── length (l) ────────────→

╔═══════════════════════════════════════════════╗
║  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  ║ → Current (I)
║  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  ║
╚═══════════════════════════════════════════════╝
   ↑
 Area (A)    Electrons flow: negative → positive terminal
             Conventional Current: positive → negative terminal
```

▲Figure

3. Resistance (R)

Definition

Resistance is the property of a resistor that gives the measurement of difficulty to pass electric current through it.

Symbol: R
SI Unit: Ohm (Ω)
Alternative Definition: Ratio of voltage provided to the current flowing through it

Ohm's Law Formula:

$$R = V / I$$

Where: V = Voltage (Volts) | I = Current (Amperes)

4. Resistor

Definition

A resistor is a substance/component that reduces or limits the current passing through it.

Fig. 3 — Resistor Symbol in Circuit

```
┤||├    Standard Resistor Symbol

──┤HHHH├──    Zigzag Symbol (American)
```

```
────[  R  ]────    Box Symbol (European/International)

Circuit representation:

(+)────[Battery]────[Switch]────[Resistor R]───(-)
```

▲Figure

Uses / Advantages of Resistor

- ➤Limits the current and voltage in the circuit
- ➤Used as a safety component in the electronic circuit (e.g. Fuse)
- ➤Used as a current divider and voltage divider in the circuit
- ➤Used in power supply to deliver constant and desirable power

5. Demonstration of Movement of Electrons in Conductors

Random Motion (Without Applied Voltage)

- Every material is made up of atoms which consist of electrons
- These electrons move around the nucleus of their respective atom
- This produces random movement of electrons within the conductor
- This random movement is meant to produce current, but due to their random direction, the average velocity of electrons within conductor is ZERO

Fig. 4 — Random Motion of Electrons (No Applied Voltage)

```
┌──────────────────────────────────────────────────────────┐
│  e⁻↗  e⁻↙   e⁻→  e⁻↖   e⁻↘  e⁻←   e⁻↑  e⁻↓          │
│  e⁻←  e⁻↑   e⁻↙  e⁻→   e⁻↗  e⁻↘   e⁻↖  e⁻→          │
│  e⁻↓  e⁻→   e⁻↗  e⁻↙   e⁻←  e⁻↑   e⁻→  e⁻↘          │
│  e⁻↑  e⁻↘   e⁻←  e⁻↗   e⁻↓  e⁻→   e⁻↙  e⁻↖          │
└──────────────────────────────────────────────────────────┘

Average velocity = 0  (No net current flow)
```

▲Figure

Drift Motion (With Applied Voltage)

- When potential difference is applied across two ends of the conductor, electrons present in material are oriented in same direction
- Electrons gain a certain amount of velocity in one direction
- This velocity that causes the electrons to move in a certain direction is known as DRIFT VELOCITY
- Every current produced in a conductor is due to drift current
- Drift current is produced due to the drift velocity of electrons from lower potential to higher potential

Fig. 5 — Drift Velocity of Electrons (With Applied Voltage)

```
⊖ ───────────────────────────────────────────────────── ⊕
(-)                     CONDUCTOR                       (+)
┌──────────────────────────────────────────────────────────┐
│  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  │
│  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  │
│  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  e⁻→  │
└──────────────────────────────────────────────────────────┘
←──────────── Electron Flow ──────────────
───────────── Current Flow (I) ──────────→

[Battery: ⊖ |==| ⊕]
   (-) terminal         (+) terminal
```

▲Figure

6. Drift Velocity Derivation

Step 1 — Force on Electron due to Electric Field

When the potential difference is applied across the conductor, the electrons within a conductor experience force due to electric field:

Force on Electron (Eq. i):

$$F = eE$$

Where: e = charge of electron | E = electric field (V/m)

Step 2 — Force for Acceleration

This force enforces the electrons to accelerate across the conductor:

Newton's Second Law (Eq. ii):

$$F' = ma$$

Where: m = mass of electron | a = acceleration

Step 3 — Equating Forces (Eq. i = Eq. ii)

Derivation Steps:

From Eq (i) and Eq (ii): $F = F'$

$\Longrightarrow eE = ma$

$\Longrightarrow a = eE / m$ ... Eq (iii) [acceleration of electron]

Velocity gained by electron is given by kinematics:

$V = u + at$ ... Eq (iv)

Since average movement before potential is zero, $u = 0$:

$V = at$

Substituting value of 'a' from Eq (iii):

$V = (eE/m) \times t$

Drift Velocity Formula:

$$v = (eE / m) \times t$$

v = Drift velocity | e = electron charge | E = electric field | m = mass | t = time

7. Mobility of Electrons (μe)

The term eE/m is called the Mobility of Electrons (μe). It represents how easily electrons can move through a conductor under an electric field.

Symbol: μe (mu-e)
Unit: m^2 / V·sec (meters squared per Volt per second)

Mobility Formula:

$$\mu e = eE / m$$

Unit: m^2/V·sec

Note: The drift velocity of electrons is very small (in the range of 0.1 mm/s). With this velocity it will take almost 17 minutes for one electron to pass through 1 m of conducting wire. However, the electric wave travels at the speed of light, so current flows instantly in a circuit.

Current Due to Drift Velocity

The current across the cross-section of wire due to drift velocity is given by:

Drift Current Formula:

$$I = n \cdot e \cdot v \cdot A$$

Where: I = current | n = number of electrons | e = electron charge | v = drift velocity | A = cross-sectional area

8. Sources of Electricity

8.1 Hydro Power (Hydroelectric)

➤Hydropower is the electricity produced from generators driven by turbines that convert potential energy into kinetic energy

➤It is the most commonly used source of electricity in Nepal

➤In generation of hydro electric power, water is stored at higher elevation

➤The stored water is then led downwards with the help of large pipes or tunnel called Penstocks to the lower elevation

➤The difference in elevation is called Head

➤The falling water from penstocks hits the turbine which allows turbine to rotate

➤The turbine is then connected to generators which converts mechanical energy into electrical energy

➤Transformers are then used to convert the generated voltage into suitable higher voltage for transmission

➤The structure that has turbines, generators and into which penstocks are filled is called Powerhouse

➤The electricity generated in generator is given by Faraday's Law of Electro-Magnetic Induction

Fig. 6 — Hydroelectric Power Generation System

```
[Reservoir at High Elevation]
         │
         │  ← Penstock (large pipe)
         │
         ▼
┌──────────────────────────────────────────┐
│         P O W E R H O U S E              │
│   ┌──────────┐   ┌───────────────────┐   │
│   │ Turbine  │──▶│     Generator     │   │──────▶ Electricity
│   │    □     │   │ (Stator + Rotor)  │   │
│   └──────────┘   └───────────────────┘   │
│          │                │              │
└──────────┼────────────────┼──────────────┘
           │                │
         Water             EMF
         exits
                   ┌─────────────┐
                   │ Transformer │──────▶ High Voltage Transmission
                   └─────────────┘

EMF Formula:  emf = BdvSinθ  (or  emf = BlvSinθ)
B = Magnetic field (Stator)   l = length of conductor
v = velocity of conductor     θ = angle between conductor & B-field
```

▲Figure

8.2 Nuclear Energy

➤Nuclear energy is the energy present in the nucleus of an atom

➤The forces due to nuclear energy are called Strong Forces, while gravitational forces are considered weak in comparison

➤Nuclear energy is used to generate electricity by two processes:

- (i) Nuclear Fusion
- (ii) Nuclear Fission

(i) Nuclear Fusion

- It is the nuclear reaction through which two or more small/light nuclei collide with each other to form a heavier nucleus
- Fusion occurs in the sun where atoms of hydrogen (isotopes: Deuterium and Tritium) combine together in high pressure and high temperature to produce an isotope of helium and a neutron
- d_2O = heavy water | H_2O = water

Nuclear Fusion Reaction:

$${}_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 + 18\text{ MeV}$$

(Deuterium) + (Tritium) → (Helium) + (Neutron) + Energy

MeV = Mega Electron Volt

Mass cannot be destroyed nor created but it can pass from one body to another

(ii) Nuclear Fission

- It is a nuclear reaction in which nucleus of a large atom is bombarded with low energy neutrons with splits
- The nucleus splits into small nuclei — during this process large amount of energy is released
- Nuclear fission reactions are used in nuclear power reactors since it is easy to control and produce large amount of energy
- When Uranium (235) is bombarded with slow moving neutrons, the heavy nucleus of uranium splits and produces Krypton (89) and Barium (144) along with free neutrons and energy

Nuclear Fission Reaction:

$${}_{92}U^{235} + {}_0n^1 \longrightarrow {}_{36}Kr^{89} + {}_{56}Ba^{144} + 3\,{}_0n^1 + 200\text{ MeV}$$

Uranium-235 + Neutron → Krypton-89 + Barium-144 + 3 Neutrons + Energy

Note: Fission releases MORE energy compared to Fusion (per gram of fuel)

8.3 Solar Energy

- ➤Solar technology converts light energy into electrical energy either through photovoltaic panels or through mass concentration of solar radiation
- ➤This energy can be used to generate electricity and charge large batteries
- ➤Photovoltaic panels consist of solar cells or photovoltaic cells
- ➤In such cells, small electric voltage is generated when light strikes those cells — this is called Photovoltaic Effect
- ➤Photovoltaic cell consists of two types of semi-conductors placed between metallic plates. These metallic plates are connected to batteries or load
- ➤Negatively charged semi-conductors are called n-type semi-conductor
- ➤Positively charged semi-conductors are called p-type semi-conductor
- ➤When light strikes the junction between metal and semi-conductor (p-type and n-type), electronic voltage is generated between two metallic plates due to emission of electrons and creation of holes — this is called Photo-Electric Effect
- ➤Anti-reflective coating, transparent adhesive are used in solar panels in order to receive maximum light
- ➤The power generated by a single solar cell is only 2 Watts
- ➤Solar panels are faced towards South in order to generate electricity in large amount
- ➤Solar panels should be cleaned regularly to get maximum efficiency

Fig. 7 — Photovoltaic (Solar) Cell

```
□  (Solar Radiation / Light)
       |  |  |  |  |  |
       ▼  ▼  ▼  ▼  ▼  ▼
╔════════════════════════════════════╗   ←── Anti-reflective coating
║  ░░░░░░░░░░░░░░░░░░░░░░░░░░░░░   ║  ← Metallic plate (top)
╠════════════════════════════════════╣
║  ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖ ⊖  ║  ← n-type semiconductor
╠════════════════════════════════════╣   ← p-n Junction
║  ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕ ⊕  ║  ← p-type semiconductor
╠════════════════════════════════════╣
║  ░░░░░░░░░░░░░░░░░░░░░░░░░░░░░   ║  ← Metallic plate (bottom)
╚════════════════════════════════════╝
       |                        |
       └───────[Load/Battery]───┘
                (Electricity)

Photo-Electric Effect: Light → Electrons emitted → Voltage generated
```

▲Figure

8.4 Wind Energy

- ➤Uses aerodynamic force to form the rotor blades to rotate wind turbine which converts wind energy to electrical energy
- ➤The rotor is connected to generator through series of gearbox and brakes which helps to generate consistent turbine rotation even in different speed of wind
- ➤The generator then with the help of rotor converts mechanical energy into electrical energy

Fig. 8 — Wind Energy System

```
      □  Wind →→→→→→→→→→→→→→→→→
                            /
                  ┌────────┤  ← Blade (Rotor)
                  │  Hub   ├──────── Rotor Shaft
                  └────────┤
                            \                        ┌──────────┐
                             │    Gearbox   │   ────────▶ │ Generator│
                        ─────┴──────────────┘          └──────────┘
                        │    Tower                           │
                        │                                    │
                        ▼                             [Electricity]
                   [Ground]

  Wind KE → Rotor (Mechanical) → Gearbox → Generator → Electricity
```

▲Figure

8.5 Thermal Energy

➤Thermal energy is the process of converting heat energy into electrical energy

➤A temperature difference between two dissimilar electrical conductors or semi-conductors produces voltage difference between the two substances

➤This is also known as the Seebeck Effect

> **Note:** Seebeck Effect: When two dissimilar metals are joined and their junctions are maintained at different temperatures, an EMF is generated causing current to flow in the circuit. This is the basis of thermoelectric generators.

9. Flow of Current

Flow of electric current in an electronic circuit is of two types:

- (i) Conventional Flow of Current
- (ii) Modern Flow of Current

Electronic Circuit (Definition)

An electronic circuit is a closed path which has potential difference generated and has electronic load (Bulb, Fan, etc.) and Switch.

Fig. 9 — Basic Electronic Circuit

```
    ┌──────── Switch (ON/OFF) ──────────────────────┐
    │                                               │
    │                                               │
[Battery]                ──── I →────          [Load: Bulb/R]
(+) ─ (-)      Current flows ───────►
    │                                               │
    │                                               │
    └───────────────────────────────────────────────┘

 Closed Path: Battery → Switch → Load → back to Battery
```

▲Figure

9.1 Conventional Flow of Current

- The assumption that positive charges flow from positive terminal to negative terminal is called Conventional Current
- Conventional current is the standard that is followed all over the world
- Electronic circuits produce results that are independent of current direction — that is why this flow of current is still in use

Fig. 10 — Conventional Flow of Current

```
 (+) ─────────────────────── I ──────────────────────── (-)
  │                          →                            │
  │                                                       │
[Bat]  │ ◄──── Positive charges flow this way │    [Load R]
 (+)   │       from + to - terminal           │         │
  │    └──────────────────────────────────────┘         │
  └─────────────────────────────────────────────────────┘

 Direction: Positive terminal → External circuit → Negative term.
 Note: The mobility of proton is LESS than electron
       Positrode = substances that have mass as positrodes
```

▲Figure

9.2 Modern Flow of Current (Electron Flow)

- ➤The electron actually flows from negative potential to positive potential through circuit
- ➤Such type of flow of current is called Modern Flow of Current
- ➤This is the actual physical flow of electrons

Fig. 11 — Modern Flow of Current (Electron Flow)

```
  (−) ────────────────── e⁻ ────────────────────────────  (+)
   │                     ←                                  │
   │    ┌────────────────────────────────────────────┐     │
 [Bat]  │  Electrons actually flow this direction    │  [Load R]
  (−)   │  from − terminal to + terminal             │     │
   │    └────────────────────────────────────────────┘     │
   └────────────────────────────────────────────────────────┘

 Direction: Negative terminal → External circuit → Positive term.
 This is the ACTUAL movement of electrons (modern/scientific view)
```

▲Figure

10. Factors Affecting the Value of Resistance (R)

Factor 1: Length of Conductor (l)

- Resistance of a conductor is directly proportional to the length of wire
- Longer the wire → Greater is the resistance
- Shorter the wire → Lesser is the resistance

Proportionality:

$$R \propto l \quad \text{... Eq (i)}$$

Factor 2: Thickness / Cross-Sectional Area (A)

- Resistance of conductor is inversely proportional to the thickness of conductor or cross-sectional area (A) of conductor
- Thicker wire (larger A) → Lesser resistance
- Thinner wire (smaller A) → Greater resistance

Proportionality:

$$R \propto 1/A \quad \text{... Eq (ii)}$$

Factor 3: Material Used

- Resistance of conductor depends upon the type of substance used
- Metals have low resistance in comparison to non-metals and metalloids
- Different materials have different resistivity values

Factor 4: Temperature

- Resistance of a conductor depends on the temperature of materials used
- Resistance of a majority of conductors INCREASES with increase in temperature
- This is called Positive Temperature Coefficient

Combining Equations (i) and (ii) — Resistivity Formula

Combining both proportionalities: $R \propto l$ and $R \propto 1/A$

We get: $R \propto l/A$

Resistivity Formula:

$$R = \rho l / A$$

ρ (rho) = Resistivity of the material | Unit of ρ = Ω·m (Ohm-meter)

Resistivity (ρ):

- Resistivity is the property of material that determines the resistance
- It is the resistance offered by a conductor of unit length and unit cross-sectional area
- Unit of resistivity (ρ) = $\Omega \cdot m$ (Ohm-meter)
- Symbol: ρ (rho)
- Resistivity depends only on the type of material, not on shape or size

11. Worked Examples — Numerical Problems

✦Example 1: Calculate the resistance of copper wire

Given:

Length (l) = 5 m
Cross-sectional area (A) = 0.01 m^2
Resistivity of copper (ρcu) = 1.72×10^{-8} Ω·m
Resistance (R) = ?

Solution:

```
Using:  R = ρl / A

R = (1.72 × 10⁻⁸ × 5) / 0.01
  = (1.72 × 10⁻⁸ × 5) / 10⁻²
  = 1.72 × 10⁻⁸⁺² × 5
  = 1.72 × 10⁻⁶ × 5
  = 8.6 × 10⁻⁶ Ω
```

∴ **Resistance of given copper wire = 8.6×10^{-6} Ω**

✦Example 2: Calculate the resistance of silver wire

Given:

Length (l) = 8 m
Cross-sectional area (A) = 0.01 mm^2 = 0.01 / (1000×1000) m^2 = 10^{-8} m^2
Resistivity of silver (ρAg) = 1.59×10^{-8} Ω·m
Resistance (R) = ?

Solution:

```
Converting area:  A = 0.01 mm² = 0.01 / (10³ × 10³) = 0.01/10⁶ = 10⁻⁸ m²

Using:  R = ρl / A

R = (1.59 × 10⁻⁸ × 8) / 10⁻⁸
  = 12.72 × 10⁻⁸ / 10⁻⁸
  = 12.72 Ω
```

∴ **Resistance of silver wire = 12.72 Ω**

✦Example 3: Calculate the resistance of iron wire

Given:

Length (l) = 1.5 km = 1500 m
Cross-sectional area (A) = 0.01 cm^2 = 0.01/(100×100) = 10^{-6} m^2
Resistivity of iron (ρFe) = 10^{-7} Ω·m
Resistance (R) = ?

Solution:

```
Converting: l = 1.5 × 1000 = 1500 m
            A = 0.01/(10² × 10²) = 0.01/10⁴ = 10⁻⁶ m²

Using:  R = ρl / A

R = (10⁻⁷ × 1500) / 10⁻⁶
  = 1500 × 10⁻⁷⁺⁶
  = 1500 × 10⁻¹
  = 1500 × 0.1
  = 150 Ω
```

∴ **Resistance of iron wire = 150 Ω**

✦Example 4: Find the length of copper wire

Given:

Cross-sectional area (A) = 10^{-3} cm² = $10^{-3}/(10^2 \times 10^2) = 10^{-7}$ m²
Resistance (R) = 15 Ω
Resistivity (ρcu) = 1.72×10^{-8} Ω·m
Length (l) = ?

Solution:

Converting: $A = 10^{-3} / (100 \times 100) = 10^{-3}/10^4 = 10^{-7}$ m²

Using: $R = \rho l / A \implies l = RA / \rho$

$$
\begin{aligned}
l &= (15 \times 10^{-7}) / (1.72 \times 10^{-8}) \\
&= (15 \times 10^{-7}) / (1.72 \times 10^{-8}) \\
&= (15/1.72) \times 10^{-7+8} \\
&= 8.720 \times 10^{1} \\
&= 87.20 \text{ m}
\end{aligned}
$$

∴ **Length of copper wire = 87.20 m**

✦Example 5: Find the resistance of silver wire with given radius

Given:

Length (l) = 0.5 m
Radius (r) = 0.7 mm = 0.7/1000 = 7×10^{-4} m
Resistivity (ρAg) = 1.59×10^{-8} Ω·m
Resistance (R) = ?

Solution:

First find cross-sectional area (circular wire):

$$
\begin{aligned}
A = \pi r^2 &= (22/7) \times (7 \times 10^{-4})^2 \\
&= (22/7) \times 49 \times 10^{-8} \\
&= 22 \times 7 \times 10^{-8} \\
&= 154 \times 10^{-8} \text{ m}^2
\end{aligned}
$$

Using: $R = \rho l / A$

$$
\begin{aligned}
R &= (1.59 \times 10^{-8} \times 0.5) / (154 \times 10^{-8}) \\
&= (1.59 \times 0.5) / 154 \\
&= 0.795 / 154 \\
&= 5.162 \times 10^{-3}\ \Omega
\end{aligned}
$$

∴ **Resistance of silver wire = 5.162×10^{-3} Ω**

✦Example 6: Change in resistance — copper wire elongated to twice its length, area decreased by 3/4

Given:

Case I: length = l_1, Area = A_1, Resistance = R_1

Case II: length = $l_2 = 2l_1$, Area = $A_2 = (3/4)A_1$, Resistance = R_2

Solution:

$$\text{Case I:} \quad R_1 = \rho l_1 / A_1$$

$$\begin{aligned}\text{Case II:} \quad R_2 &= \rho l_2 / A_2 \\ &= \rho(2l_1) / ((3/4)A_1) \\ &= 2\rho l_1 \times (4/3A_1) \\ &= (8/3) \times (\rho l_1/A_1) \\ &= (8/3) \times R_1\end{aligned}$$

∴ Resistance of copper wire changes by 8/3 times

✦Example 7: Change in resistance — wire cut at its half point

Given:

Case I: length = l_1, Area = A_1, Resistance = R_1

Case II: length = $l_2 = l_1/2$, Area = $A_2 = A_1$ (same), Resistance = R_2

Solution:

$$\text{Case I:} \quad R_1 = \rho l_1 / A_1$$

$$\begin{aligned}\text{Case II:} \quad R_2 &= \rho l_2 / A_2 \\ &= \rho(l_1/2) / A_1 \\ &= (1/2) \times (\rho l_1/A_1) \\ &= (1/2) \times R_1\end{aligned}$$

∴ Resistance of wire changes by 1/2 (halved)

✦Example 8: Wire elongated to 3× length, diameter decreased by 2 times

Given:

Case I: Resistance = R_1, length = l_1, diameter = d_1, Area $A_1 = \pi(d_1/2)^2$

Case II: Resistance = R_2, length = $l_2 = 3l_1$, diameter = $d_2 = d_1/2$

Solution:

$$\begin{aligned}\text{Case I:} \quad A_1 &= \pi(d_1/2)^2 \\ R_1 &= \rho l_1 / A_1 \quad \ldots \text{(i)}\end{aligned}$$

$$\text{Case II:} \quad A_2 = \pi(d_2/2)^2 = \pi(d_1/2\times2)^2 = \pi(d_1/4)^2 = (1/4)\pi(d_1/2)^2 = A_1/4$$

$$\begin{aligned}R_2 &= \rho l_2 / A_2 \\ &= \rho(3l_1) / (A_1/4) \\ &= 3\rho l_1 \times (4/A_1) \\ &= 12 \times (\rho l_1/A_1) \\ &= 12 \times R_1\end{aligned}$$

$\therefore R_2 = 12\, R_1$ (resistance changes by 12 times)

∴ The change in resistance is by 12 times

✦Example 9: Length quadrupled, diameter decreased by 3 times (original R = 5Ω)

Given:

Case I: length = l_1, Resistance = $R_1 = 5\Omega$, diameter = d_1, Area $A_1 = \pi(d_1/2)^2$

Case II: length = $l_2 = 4l_1$, diameter = $d_2 = d_1/3$

Solution:

Case II: $A_2 = \pi(d_2/2)^2 = \pi(d_1/3 \div 2)^2 = \pi(d_1/6)^2 = (1/9)\pi(d_1/2)^2 = A_1/9$

$$\begin{aligned} R_2 &= \rho l_2 / A_2 \\ &= \rho(4l_1) / (A_1/9) \\ &= 4\rho l_1 \times (9/A_1) \\ &= 36 \times (\rho l_1/A_1) \\ &= 36 \times R_1 \\ &= 36 \times 5 \\ &= 180\ \Omega \end{aligned}$$

Change in resistance = 36 times

∴ New resistance of wire = 180 Ω | Change = 36 times

12. Classification of Materials on the Basis of Resistance

Materials are classified into three categories based on their resistance:

- 1. Insulator
- 2. Conductor
- 3. Semi-conductor

12.1 Insulator

- Those substances which do NOT allow the electric current to flow through them easily are called Insulators
- Examples: Plastic, Wood, Rubber, Glass, etc.
- Resistance of the substance is very high as electrons present in the valence band require very high energy to get into conduction band
- Valence band and conduction band have MAXIMUM (largest) gap (electric gap)

Fig. 12 — Energy Band Diagram of Insulator

```
┌───────────────────────────────────────┐
│        Conduction Band   (empty)      │   ← electrons cannot
└───────────────────────────────────────┘     easily reach here
             ↕  ↕  ↕
    LARGE FORBIDDEN ENERGY GAP
             (> 5 eV)
             ↕  ↕  ↕
┌───────────────────────────────────────┐
│         Valence Band   (filled)       │   ← electrons here
└───────────────────────────────────────┘
Outermost shell
Electrons need very HIGH energy to jump the gap → NO conductance
```

▲Figure

12.2 Conductor

- Those substances which allow the electric current to flow through them very easily due to presence of large number of free electrons are called Conductors
- Examples: Copper, Iron, Silver, Gold, Aluminium, etc.
- It offers very low resistance because the free electrons in valence band can easily pass into conduction band
- The valence band and conduction band are OVERLAPPED in conductors
- Valence and conduction band have less electric gap or are overlapped

Fig. 13 — Energy Band Diagram of Conductor

```
┌───────────────────────────────────────┐
│         Conduction Band               │ ←── overlap ───────┐
│   (partially filled/overlapped)       │                    │
├───────────────────────────────────────┤ (OVERLAP)          │
```

```
│          Valence Band            │ ←─────────────────┘
│   (partially filled/overlapped)  │
└──────────────────────────────────┘

NO energy gap (or zero gap) → electrons move FREELY
Free electrons in valence band easily pass to conduction band
```

▲Figure

12.3 Semi-Conductor

- ➤Those substances which have conductivity BETWEEN insulator and conductor are called Semi-Conductors
- ➤Examples: Metalloids — Silicon (Si), Carbon (C), Germanium (Ge), etc.
- ➤At room temperature, they have electrical conductivity lower than that of conductor and higher than that of insulator
- ➤The main property of semi-conductor is that its electrical conductivity can be increased by adding impurities like Aluminium, Boron, etc. — this process is called DOPING
- ➤It has minimum/small electric gap between valence band and conduction band

Fig. 14 — Energy Band Diagram of Semi-Conductor

```
┌──────────────────────────────────┐
│        Conduction Band           │
└──────────────────────────────────┘
          ↕ Small Gap (~1 eV)
┌──────────────────────────────────┐
│          Valence Band            │
└──────────────────────────────────┘
Small forbidden gap → electrons can jump with moderate energy

DOPING Example (Silicon + Aluminium):
Si─Si─Si─Si─Si
Si─Si─Si─Si─Si    →  Add Al (Aluminium) impurity
Si─Si─[Al]─Si─Si  →  Al creates hole (+) → works like conductor
(Insulator → Conductor after Doping)
```

▲Figure

13. Difference Between Resistance and Resistivity

Resistance (R)	Resistivity (ρ)
It is the measurement of difficulty of passing electric current through a material	It is the property of material that determines the resistance of substances having unit length and unit area
Its unit is Ohm (Ω)	Its unit is Ohm-meter (Ω·m)
Depends on length, cross-sectional area, material and temperature	Depends only on the type of material (intrinsic property)
$R = V / I$ or $R = \rho l/A$	$\rho = RA/l$
Changes with dimensions (shape/size) of conductor	Does NOT change with dimensions — only changes with material type

14. Conductance

Definition

Conductance is the measurement of easiness of passing electric current through the material. It is the reciprocal of Resistance.

Symbol: G
SI Unit: Siemen (S) / Mho (℧)

Conductance Formula:

$$G = 1 / R$$

Unit: Siemen (S) or Mho (℧) | $G = I/V$

15. Quick Revision — Key Formulas at a Glance

Topic	Symbol	Formula	Unit
Voltage	**V**	$V = W/Q$	Volt (V)
Current	**I**	$I = q/t$	Ampere (A)
Resistance	**R**	$R = V/I$	Ohm (Ω)
Resistivity	**ρ (rho)**	$R = \rho l/A$	Ohm-meter (Ω·m)
Drift Velocity	**v**	$v = (eE/m) \times t$	m/s
Mobility	**μe**	$\mu e = eE/m$	m^2/V·sec
Drift Current	**I**	$I = n \cdot e \cdot v \cdot A$	Ampere (A)
Conductance	**G**	$G = 1/R$	Siemen (S)
EMF (Generator)	**E**	$E = BlvSin\theta$	Volt (V)

— End of Chapter 2: Electronic Fundamentals —