

Unit 2: Current Electricity

Current Electricity is the study of electric charges in motion. While electrostatics deals with stationary charges, current electricity focuses on the steady flow of charges, such as those found in domestic appliances or chemical cells.

1. Electric Current and Flow of Charges

Electric current is defined as the amount of charge passing through a given area per unit time.

If a net charge ΔQ flows across a cross-section in

time Δt , the current I at time t is:
$$I = \lim_{\Delta t \rightarrow 0} \frac{\Delta Q}{\Delta t}$$

- **Direction of Flow:** In metallic conductors, current is carried by **negatively charged electrons**. By convention, the direction of current is taken to be the direction of flow of positive charges, which is opposite to the actual flow of electrons.
- **Steady Current:** If the flow of charge does not change with time, $I = q/t$.
- **SI Unit:** The unit of current is the **ampere (A)**. One ampere is one coulomb of charge flowing per second.

2. Drift Velocity and Mobility

A. Drift Velocity (v_d)

In the absence of an electric field, free electrons in a metal move randomly due to thermal motion, resulting in zero net current. When an electric field E is applied, electrons experience an acceleration $a = -eE/m$. However, frequent collisions with positive ions in the metal cause the electrons to acquire a small, steady average speed called **drift velocity** (v_d).

The mathematical expression for drift velocity is:

$$v_d = \frac{eE\tau}{m} \text{ where:}$$

- e is the charge of an electron.
- τ is the **relaxation time** (the average time interval between successive collisions).
- m is the mass of the electron.

B. Relation between Current and Drift Velocity

The current I flowing through a conductor of cross-sectional area A with electron number density n is given by: $I = neAv_d$ The **current density** (j), which is current per unit area, is:

$$j = \frac{I}{A} = nev_d$$

C. Mobility (μ)

Mobility is defined as the magnitude of drift velocity per unit electric field: $\mu = \frac{|v_d|}{E}$ Using the

expression for v_d : $\mu = \frac{e\tau}{m}$ Mobility is always positive and its SI unit is $m^2V^{-1}s^{-1}$.

3. Ohm's Law and V-I Characteristics

Ohm's Law states that for a conductor, the current I is directly proportional to the potential difference V across its ends, provided physical conditions like temperature remain constant. $V = IR$ where R is the **resistance** of the conductor, measured in **ohms (Ω)**.

A. Linear and Non-linear V-I Characteristics

- **Ohmic Conductors:** Materials that obey Ohm's law exhibit a **linear** V-I relationship (a straight line passing through the origin).
- **Non-Ohmic Devices:** In many materials and devices, V is not proportional to I . Examples include:
 - **Diodes:** The relation between V and I depends on the sign of V .

- **Gallium Arsenide (GaAs):** The relation is non-unique; more than one voltage can produce the same current.



4. Resistivity and Conductivity

The resistance R of a conductor depends on its length l and area A : $R = \rho \frac{l}{A}$ where ρ is the **electrical resistivity** of the material.

- **Resistivity (ρ):** A property of the material itself, independent of dimensions. Its unit is Ωm .
- **Conductivity (σ):** The inverse of resistivity:

$$\sigma = \frac{1}{\rho}$$
- **Microscopic form of Ohm's Law:** Current density can be expressed as: $j = \sigma E$

From the drift velocity model, resistivity is related to microscopic parameters by: $\rho = \frac{m}{ne^2\tau}$

5. Temperature Dependence of Resistance

Resistivity varies with temperature. Over a limited range, the resistivity ρ_T at temperature T is: $\rho_T = \rho_0[1 + \alpha(T - T_0)]$ where α is the **temperature coefficient of resistivity**.

- **Metals:** As temperature increases, collisions become more frequent, τ decreases, and **resistivity increases**.
- **Semiconductors and Insulators:** As temperature increases, the number density of charge carriers n increases significantly, which more than compensates for the decrease in τ . Thus, **resistivity decreases** with temperature.
- **Alloys (e.g., Nichrome, Manganin):** Exhibit a very weak dependence of resistivity on temperature, making them ideal for standard resistors.

6. Electrical Energy and Power

When a current I flows through a resistor R across a potential difference V , the chemical energy of the source is converted into heat.

- **Electrical Power (P):** The rate of energy dissipation.
$$P = VI = I^2R = \frac{V^2}{R}$$
- **Power Transmission:** To minimize "Ohmic loss" in transmission cables, power is transmitted at **high voltages** and low currents, because power wasted in cables is $P_c \propto 1/V^2$.

7. Cells, EMF, and Internal Resistance

A. Electromotive Force (EMF) and Potential Difference

- **EMF (\mathcal{E}):** The potential difference between the electrodes of a cell in an **open circuit**

(when no current is drawn). It is the work done per unit charge by the source.

- **Internal Resistance (r):** The resistance offered by the electrolyte inside the cell to the flow of current.
- **Terminal Voltage (V):** When a current I flows, the potential difference between the terminals is: $V = \varepsilon - Ir$

B. Maximum Current

The maximum current that can be drawn from a cell is $I_{max} = \varepsilon/r$ (when external resistance $R = 0$).

8. Combination of Cells

A. Series Combination

For n cells connected such that the current leaves each from the positive electrode:

- **Equivalent EMF:** $\varepsilon_{eq} = \varepsilon_1 + \varepsilon_2 + \dots + \varepsilon_n$.
- **Equivalent Internal Resistance:**
 $r_{eq} = r_1 + r_2 + \dots + r_n$.

B. Parallel Combination

For cells connected in parallel between two points:

- **Equivalent Internal Resistance:**
 $\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \dots + \frac{1}{r_n}$.
- **Equivalent EMF:**
 $\frac{\varepsilon_{eq}}{r_{eq}} = \frac{\varepsilon_1}{r_1} + \frac{\varepsilon_2}{r_2} + \dots + \frac{\varepsilon_n}{r_n}$.

9. Kirchhoff's Rules

Complex circuits are analyzed using two fundamental rules:

1. **Junction Rule (First Rule):** At any junction, the sum of currents entering equals the sum of currents leaving. It is

based on the **conservation of charge**.

$$\sum I_{in} = \sum I_{out}$$

2. **Loop Rule (Second Rule):** The algebraic sum of changes in potential around any closed loop is zero. It is based on the **conservation of energy**. $\sum \Delta V = 0$



10. Wheatstone Bridge

The **Wheatstone Bridge** is an arrangement of four resistors R_1, R_2, R_3, R_4 used to measure an unknown resistance.

- **Balanced Condition:** The bridge is balanced when the current through the galvanometer I_g is zero. This occurs when:
 $\frac{R_1}{R_2} = \frac{R_3}{R_4}$
- **Application:** By knowing three resistances, the fourth can be calculated as $R_4 = (R_2/R_1)R_3$. The **Meter Bridge** is a practical application of this principle.