12 Electric Current

12.1 Current and Charge

To make an electric current pass round a circuit.

- The circuit must be **complete**.
- There must be a **source of potential difference**.

The electric current is the **rate of flow of charge**.

Electric current is due to the passage of **charged particles**, they are referred to as **charge carriers**.

- In **metals**, the charge carriers are **conduction electrons**.
  - They move about inside the metal.
  - Repeatedly colliding with each other and the fixed positive ions in the metal.
- In a **salt solution**, the charge is carried by **ions**, which are charged atoms or molecules.

Test for Conduction

The meter shows a non-zero reading whenever any conducting material is connected into the circuit.

1. The battery forces the charge carrier **through the conducting material**.
2. Causes them to **pass through the battery** and the meter.
3. Electrons enter the battery at its positive terminal and leave at the negative terminal.

Conventional current flows from positive to negative.

- The unit of current is the **ampere** - defined in terms of the magnetic force between two parallel wires when they carry the same current.
- The unit of charge is the **coulomb** - equal to the **charge flow** in one second when the current is one ampere.

For current I, charge flow ΔQ in time Δt is given by

$$\Delta Q = I\Delta t$$

Charge Carriers

- In an **insulator**, each electrons is attached to an atom and cannot move away from the atom.

  When a voltage is applied across an insulator, no current passes through the insulator, because no electrons can move through the insulator.
- In a **metallic conductor**, some electrons are **delocalised** - they are the **charge carriers in the metal**.

  When a voltage is applied across the metal, these conduction electrons are attracted towards the positive terminal of the metal.

- In a **semiconductor**, the number of charge carriers increases with an increase in temperature.

  The resistance of a semiconductor therefore decreases as its temperature is raised.

  - Conduction is due to electrons that **break free from the atoms** of the semiconductor.

A pure semiconducting material is referred to as an **intrinsic semiconductor**.

12.2 Potential Difference and Power

1. Each electron moves around the circuit and **takes a fixed amount of energy from the battery** as it passes through it.
2. Each electron passing through a circuit component **does work** to pass through the component and therefore transfers some of its energy.

Potential difference is defined as the energy transfer per unit charge.

The unit of potential difference is the **volt**, equal to one joule per coulomb.

$$V = \frac{\Delta E}{\Delta Q}$$

The **emf of a source** of electricity is defined as the electric energy produced per unit charge passing through the source.

$$\text{Electrical energy produced} = Q\varepsilon$$

The unit of emf is also the volt.

Energy Transfer in Devices

- Any device with **resistance**, the work done of the device is transferred as thermal energy.

  Charge carriers repeatedly collide with atoms in the device the transfer energy to them, so atoms vibrate more and the resistor becomes hotter.

- In an **electric motor** turning at a **constant speed**, the work done on the motor is equal to the energy transferred to the load and surroundings by the motor.

  The electrons need to be **forced through the wires** against the opposing force on the electrons due to the motor's magnetic field.

- In a **loudspeaker**, work done on the loudspeaker is transferred as **sound energy**.

  Electrons need to be **forced through the wires** of the coil against the force on them due to the loudspeaker magnet.

Electrical Power

Consider a component with pd V across its terminals and a current I passing through it.

$$\begin{aligned}\Delta Q &= I\Delta t\\ \Delta E &= \Delta QV\\ &= IV\Delta t\end{aligned}$$

So

$$\text{Electrical power } P = \frac{IV\Delta t}{\Delta t} = IV$$

12.3 Resistance

- The resistance of a component is a measure of the **difficulty of making current pass through** the component.
- Resistance is caused by the **repeated collisions** between the charge carriers in the material with each other and with the fixed positive ions in the materials.

The resistance of any component is defined as

$$\frac{\text{pd across the component}}{\text{current through it}}$$

For a component which passes current I when the pd across it is V

$$R = \frac{V}{I}$$

The unit of resistance is the **ohm** (Ω) equal to 1 volt per ampere.

Resistance Measurements

- The **ammeter** is used to measure the current through the resistor.
  - In series with the resistor so the same current passes through both the resistor and the ammeter.
- The **voltmeter** is used to measure the pd across the resistor.
  - Parallel with the resistor so they both have the same pd.
- A **variable resistor** is used to adjust the current and pd as necessary.

1. The variable resistor is **adjusted in steps**, at each step the current and pd are recorded from the ammeter and the voltmeter.
2. The measurements can be plotted on a graph of **pd against current**.

The graph is a **straight line through the origin**.

- Resistance is the same regardless of the current.
- Resistance is equal to the **gradient of the graph**.

Ohm's law states that the pd across a metallic conductor is proportional to the current through it, provided the physical conditions do not change.

Resistivity

For any conductor of length L and uniform cross-sectional area A

$$R \propto L$$
$$R \propto \frac{1}{A}$$

Hence $R = \dfrac{\rho L}{A}$ where ρ is a constant for the material known as its resistivity.

Rearranging for resistivity

$$\rho = \frac{RA}{L}$$

The unit of resistivity is the **ohm meter** (Ωm).

Resistivity Measurements

1. **Measure the diameter** d of the wire using a micrometer at several points along the wire.
2. **Calculate the cross-sectional area** A using the mean value for d.
3. **Measure the resistance** R for different lengths L of the wire.
4. **Plot a graph** of R against L.

The resistivity of the wire is given by graph gradient $\times A$

Superconductivity

A **superconductor** is a material that has **zero resistivity** at and below a **critical temperature** that depends on the material. This property of the material is called **superconductivity**.

The wire has zero resistance below the critical temperature of the material. When a current passes through it, there is **no pd across it** because its resistance is zero, so the current has **no heating effect**.

A **high-temperature superconductor** is any material with a critical temperature above the **boiling point of nitrogen**.

Superconductors are used to

- Make **high-power electromagnets** that generate very strong magnetic fields.
  - MRI scanners.
  - Particle accelerators.
  - Lightweight electric motors.
- **Power cables** that transfer electrical energy without energy dissipation.

12.4 Components and Their Characteristics

Each type of component has its own symbol which is used to **represent the component in a circuit diagram**.

- A **cell** is a source of electrical energy.
- A **battery** is a combination of cells.
- A **diode** allows current in one direction only.
- A **light-emitting diode** emits light when it conducts.
  - The direction in which it conducts is referred to as its **forward direction**.
  - The opposite direction is referred to as its **reverse direction**.
  - Diodes are used in the **protection of DC circuits** in case the voltage supply is connected the wrong way round.
- A **resistor** is a component designed to have a certain resistance.
- The resistance of a **thermistor** decreases with increasing temperature.
- The resistance of a **light-dependent resistor** decreases with increasing light intensity.

I/V Characteristics of Components

- A **potential divider** varies the pd from zero.
- A **variable resistor** varies the current to a minimum.

A potential divider allows the current through the component and the pd across it to be **reduced to zero**, this is not possible with a variable resistor.

Measurements can be plotted as a graph of **current against pd**.

- A **resistor** at constant temperature gives a **straight line through origin -** the resistance of a resistor does not change when the current changes.
- A **filament bulb** gives a curve with **decreasing gradient** because its resistance increases as it becomes hotter.
- A **thermistor** at constant temperature gives a straight line. The **higher the temperature, the greater the gradient** of the line.
- A **diode** conducts easily in its forward direction above a pd of about 0.6V, and hardly at all below 0.6V or in the opposite direction.

Temperature Coefficients

- A metal have a **positive temperature coefficient** because its resistance increases with increase of temperature.
  - The positive ions **vibrate more** when its temperature is increased.
  - The conduction electrons therefore **cannot pass through as easily**.

- An intrinsic semiconductor has a **negative temperature coefficient** because the number of charge carriers increases when the temperature is increased.

Because its **percentage change of resistance per kelvin change of temperature** is much greater than for a metal, thermistors are often used as the temperature-sensitive component in a temperature sensor.