Electric Current and Drift Velocity

Objectives

After going through this lesson the learners will be able to:

- Visualize movement of electric charges in a metallic conductor wire with and without external potential difference placed across it
- Derive a relation between current and drift velocity
- State Ohm's Law
- Define mobility, resistance and specific resistance
- Draw V-I Characteristics curve (Linear and nonlinear)

Content Outline

- Syllabus
- Module wise distribution of syllabus
- Words you must know
- Introduction
- Meaning of current in Physics
- Flow of charge in metals, and concept of drift velocity.
- Mobility of charge carriers
- Relation between current and drift velocity
- Ohm's Law
- Solved Problems
- Try yourself
- Summary

Unit Syllabus

Chapter-3: Current eElectricity

Electric current, flow of electric charges in a metallic conductor; drift velocity, mobility and their relation with electric current.

Ohm's law; electrical resistance, V-I characteristics (linear and nonlinear), electrical energy and power, electrical resistivity and conductivity.

Carbon resistors; colour code for carbon resistors; series and parallel combinations of resistors; temperature dependence of resistance.

Internal resistance of a cell; potential difference and e.m.f. of a cell, combination of cells in series and in parallel, Kirchhoff's laws and simple applications. Wheatstone bridge, metre-bridge.

Potentiometer– principle and its application to measure potential difference and for comparing emf of two cells; measurement of internal resistance of a cell.

Module Wise Distribution Of Unit Syllabus - 08 Modules

The above unit has been divided into 8 modules for better understanding.

Module 1	• Electric current • Solids liquids and gases • Need for charge carriers, speed of charge carriers in a metallic conductor • Flow of electric charges in a metallic conductor • Drift velocity • Mobility and their relation with electric current • Ohm's law
Module 2	• Electrical resistance • V-I characteristics (linear and nonlinear) • Electrical energy and power • Electrical resistivity and conductivity • Temperature dependence of resistance
Module 3	• Carbon resistors • Colour code for carbon resistors • Metallic Wire resistances • Series and parallel combinations of resistors • Grouping of resistances • Current and potential differences in series and parallel circuits
Module 4	• Internal resistance of a cell • Potential difference and emf of a cell • Combination of cells in series and in parallel • Need for combination of cells
Module 5	• Kirchhoff's laws

	● Simple applications of Kirchhoff's law for calculating current and voltages ● Numerical
Module 6	● Wheatstone bridge ● Balanced Wheatstone bridge condition derivation using Kirchhoff's laws ● Wheatstone bridge and Metre Bridge. ● Application of meter bridge
Module 7	● Potentiometer ● Principle ● Applications to ● Measure potential difference ● Comparing emf of two cells; ● Measurement of internal resistance of a cell. ● Numerical
Module 8	● Numerical ● Electrical energy and power

Module 1

Words You Must Know

- **Conductors:** Substances that can easily allow heat and electrical charges from one point to another are called conductors. Good heat carriers are called heat conductors and good charge carriers are called current conductors.

- **Current (I):** It is the rate of flow of charge carriers through any cross-section of a given conductor.

- **Charge (q):** Physical property of matter that causes it to experience a force when placed in an electromagnetic field. Note charge is just a property, however, particles possessing this property, like, electron, proton, ions are also sometimes termed as charge, this is technically incorrect as charge does not matter, and it is just a property.

- **Potential Difference (V):** It equals the work done in carrying a unit positive charge from one point to another. Also defined as work done per unit positive charge

$$V = \frac{W}{q}$$

- **Electric Field (E):** It is a measure of the strength of electric force per unit charge at a given point. A unidirectional electric field gets established when we put a cell in an electrical circuit. It is the electric field that results in a flow of electric current in the circuit. **Larger the Electric field higher is the rate of flow of charge (current)**.

Introduction

As you know metals are rich in free electrons, which are constantly in motion within the conductor. Why do metals have a large number of free electrons? From where do these free electrons come from? The presence or otherwise of free electrons depends upon the nature of the materials. Metals have a tendency to lose their outer shell electrons easily. Their atoms which contribute to free electrons become ions.

The word 'current' means 'flow' hence electric current means 'flow of charge'.

As a physical quantity electric current is defined as **rate flow of charge through a given cross-section of a conductor**. It is very much similar to flow of liquid or gases, we can also talk of water current, wind current, in the same way as we talk of electric current.

Meaning of Current in Physics

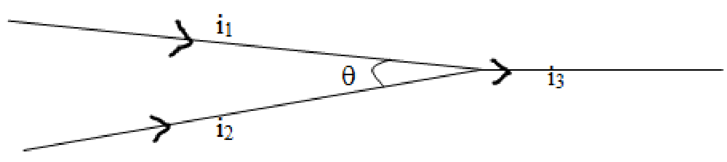
As per its definition, electric current is defined as the amount of charge passing per unit time through a cross-section of conductor.

$$I = \frac{q}{t}$$

Its S.I. unit is ampere and its symbol is A.

- Electric Current flows in a particular direction; from a higher potential point to a lower potential point. However, **it is not a vector quantity**. **We say so because it does not follow the law of vector addition.**

  For example



Here $i_1 + i_2 = i_3$

This result, for current, is true irrespective of the value of 'θ', as shown in the above figure.

Electronic Current: Current is always flow of charge carriers The direction of flow of electrons in conductors is often referred to as the direction of the 'electronic current'.

Conventional Current: At the time of discovery of electric current, it was assumed that the direction of electric current is that of current flow of positive charges. It is this direction of current that is conventionally marked in electric circuits. We now know that positive charges do not flow in conductors because they lie within the nucleus. The direction of 'electronic current' is opposite to that of the 'conventional current'.

Do Solids, Liquids and Gases conduct Electricity?

Any material, in any state (solid liquid or gas) can conduct electricity provided charge carriers are free to move in it.

By charge carrier we mean charged particles within the material. Consider a solid, made up of a large number of atoms. Each atom with a positively charged nucleus (due to protons), surrounded by electrons whose collective charge is equal to the positive charge on the nucleus making the atom neutral.

So what are the 'charge carriers'?

Electrons which are loosely bound to a nucleus may be shared in the atomic arrangement of solids. You can imagine the loosely bound electrons to move like gas molecules. In solid conductor materials these electrons respond to an external electric field and hence are called charge carriers.

Charge carriers in a:-

1. Solid → free electrons
2. Liquid → positive and negative ions
3. Gas → free electrons and positive ions

Electric Potential

In fluids, pressure difference between the two ends of the tube, determines the rate of flow of the fluid. In electricity, it is the potential difference (V) between the two ends of a given conductor that determines the rate of flow of charge (current) through it. We can think of 'potential' as being similar to 'pressure'. Also 'Potential difference' is the cause of current.

Resistance

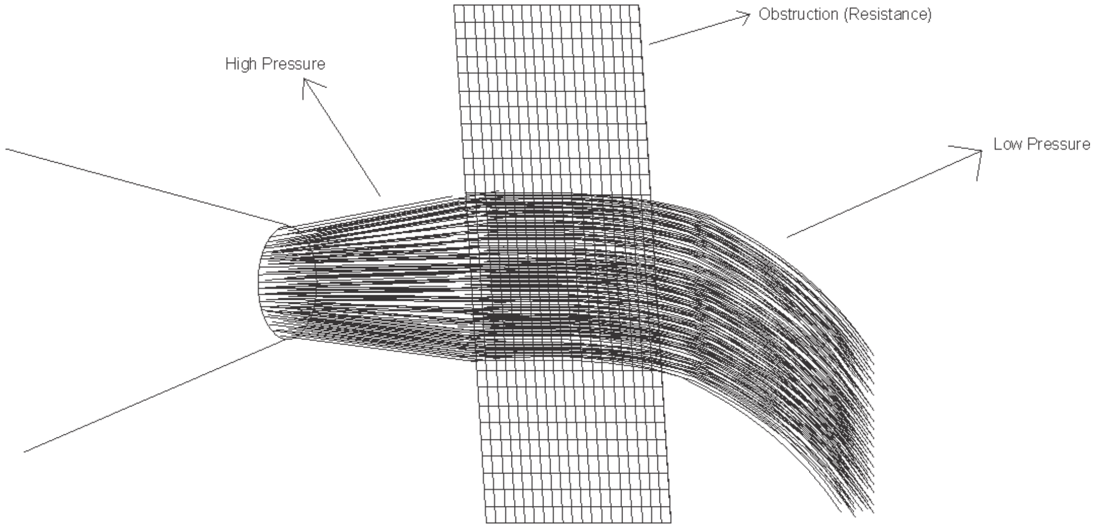
Resistance is basically an indicator of the 'obstruction' in the path of flow of anything. In electricity, it is a 'cause' that is hindering the flow of electric charges (current).

Role of Resistance

It can control the amount of flow of charges (electric current) in an electric circuit.. We can think in terms of a 'drop in potential' when electric current flows through a resistor.

Let us consider an example:

If we put a mesh in front of a gas emanating fire fighter jet, the mesh acts as a 'resistance' because it obstructs or opposes the flow of gas.



Here, on the incoming side, there is a higher pressure (potential) and at the outgoing side of obstruction (resistance), there is a lower pressure (potential). There is a fall of pressure (potential) across the mesh (resistance).

A similar thing happens in case of electric resistance in electricity. Let us consider current I flows through a resistance R as shown in the figure below.in other words we can say that by the use of resistance we can control the magnitude of current .

The current will flow from higher potential to lower.

The potential difference in this case is 200 V-120 V= 80 V

The incoming end has a potential of say, 200 V; the outgoing end may have a potential of, say, 120 V.

- There is a potential drop of 80 V. As per Ohm's law (V=IR), V the potential difference between the two ends of resistance, equals 80V.

V= IR , whereI is current and R is called resistance

- It is for this reason that we always say there is a "**potential drop across resistance**".

Let's think it over!

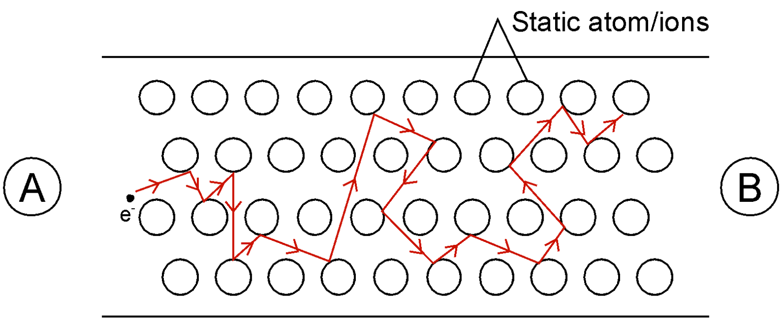
Question:

Why do different metals have different resistance, even for the same dimensions?

Answer:

It is because the detailed structure of atoms in different metals is different. This leads to a difference in the 'number density' of their free electrons. The atomic or molecular arrangement may be different for different metals.

Flow Of Charge In Metals, And Concept of Drift Velocity



The figure illustrates the motion of a free electron within the conductor

The basic knowledge of chemistry tells us that each substance is made up of atoms. The metals have a large number of free electrons (which move like gas particles), which are in constant motion and collide with one another as well as with atoms or ions which fall in their way. They rebound, again collide, and again rebound.

These collisions of electrons with one another, with the atoms and /or ions, are the cause of resistance. We see that due to collisions and rebounding, an electron takes a lot of time in going from end A to end B of the conductor. Hence, its average velocity is very small this is their drift velocity.

Drift Velocity (V_d)

It is the average velocity with which the free electrons move in a conductor, under the influence of a given external electric field.

Case 1: In Absence of External Electric Field

In absence of an external electric field, at room temperature, electrons gain thermal energy and move in all possible directions (randomly). Hence, their average velocity equals zero.

$$\frac{u_1+u_2+u_3+...u_n}{n} = 0$$

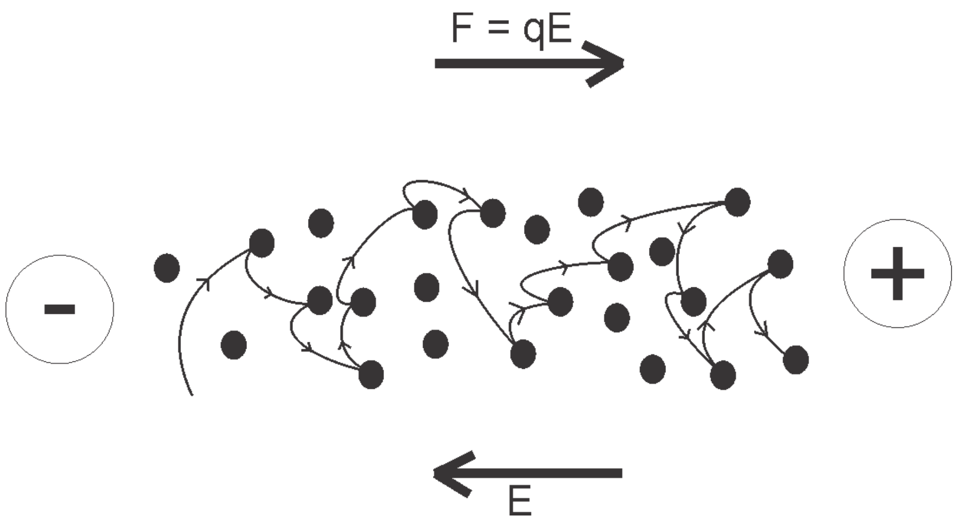
Here, u_1, u_2, u_3,. ..., u_n are the thermal velocities of the 1^{st}, 2^{nd}, 3^{rd}, ...n^{th} electron.

The number (n) of free electrons, per unit volume is called **number density**.

Note that

- **n absence of external electric field path of electron between two successive collisions is straight line as shown in figure illustrating motion of free electron within the conductor**

Case 2: In Presence of External Electric Field



The electrons experience a force directed opposite to the direction of applied external electric field (E).

In presence of external electric field, the electric field exerts a force = (eE) on the electrons and makes them move towards the positive terminal of the battery, with an acceleration, a.

$$a = \frac{eE}{m}$$

m = mass of electron.

Using **v = u + at**, we can write

$v_1 = u_1 + a\tau_1$

$v_2 = u_2 + a\tau_2$

$v_3 = u_3 + a\tau_3$

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Similarly,

$v_n = u_n + a_n$

As per definition of **drift velocity**, it is the average velocity of all the electrons, therefore

$$v_d = \frac{v_1+v_2+v_3+...+v_n}{n}$$

$$v_d = \frac{u_1+a\tau_1+u_2+a\tau_2+......u_n+a\tau_n}{n}$$

$$v_d = \frac{u_1+u_2+....u_n+}{n} + \frac{a(\tau_1+\tau_2....\tau_n)}{n}$$

$$v_d = 0 + a\tau$$

(τ= average time between successive collisions=$\frac{t_1+t_2+t_3+.....+t_n}{n}$)

$v_d = \frac{eE}{m}\tau$

We refer to **τ as average 'relaxation time'**.

It is the average time between the two successive collisions. Over this time the electron gains energy from the field; it loses this energy during collision. In between the collisions, **the velocity of electrons is very high, of the order 10^5 m/s. while the value of drift velocity is of the order of $10^{-4}\ m/s$.**

Think About This:

If drift velocity (v_d) $10^{-4}\ m/s$, then how does a bulb glow, instantly, when switched on?

Answer:

- The number density of free electrons is very high ($\approx 10^{28}/m^3$), a large number of electrons are present at every cross section of the conductor.
- When the switch is turned on, an electric field is established, which exerts a force on electrons. This electric field propagates with the speed of light. Its force therefore acts on all electrons of the conductor; they thus move together resulting in current at every cross-section.

Mobility

Mobility (μ) of a charge carrier, responsible for current flow, is defined as the magnitude of drift velocity of charge carrier per unit applied electric field i.e.

$$\text{Mobility } \mu = \frac{magnitude\ of\ drift\ velocity}{electric\ field}$$

$$\mu = \frac{v_d}{E}$$

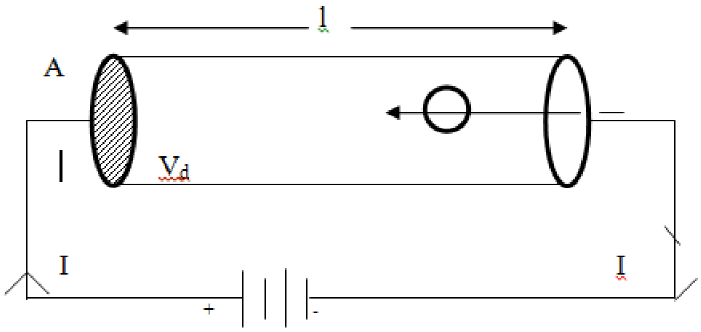
$$\mu = \frac{q\,E\,\tau}{m\,E}$$

$$\mu = \frac{q\,\tau}{m}$$

Therefore the mobility of the charge carrier depends on the specific charge ratio (q/m) and the average relaxation time τ.

The Mass/charge (q/m) ratio of electrons is much larger than that of protons. Therefore, electrons have a considerably higher mobility than that of protons.

Relation Between Current And Drift Velocity (I And V_d)



Consider the current in a conductor of cross-sectional area A.

The volume of a section of the conductor of length L is A L .

If n represents the number of mobile charge carriers per unit volume also called the **charge carrier density**, the number of carriers in the given section of conductor is **N= n A L**.

Therefore, the charge ΔQ in this section is given as

$$\Delta Q = e\,(n\,A\,L)$$

Here e is the charge on each carrier.

The carriers move with a speed v_d under the influence of the external electric field due to the potential difference across the two ends of the conductor.

The time $\Delta t = \frac{L}{v_d}$ in which an electron goes from one cross-section to another all the free electrons in the section of conductor between the two cross-sections will go through the latter cross-section.

Therefore average current through a given cross-section of a conductor is

$$I = \frac{\Delta Q}{\Delta t} = \frac{e\,n\,A\,L}{\frac{L}{v_d}} = n\,A\,e\,v_d$$

Ohm's Law

Ohm's law relates the potential difference current and resistance. It states that the current flowing through a conductor is directly proportional to potential difference across the two ends of the given conductor provided its temperature and other physical conditions remain constant. $I \propto V$ Or $\frac{V}{I} = R$

Where, R is the resistance of the conductor, which is constant for a given conductor, under given conditions.

Deduction of Ohm's Law:

As we have deduced, the drift velocity for electron can be written as

$$v_d = \frac{eE\tau}{m}$$

$$v_d = \frac{eV\tau}{mL} \qquad \text{(as E = V/L)}$$

Also $I = nAev_d$

$$I = nAe\left(\frac{eV\tau}{mL}\right)$$

Therefore $\frac{V}{I} = \frac{mL}{ne^2\tau A} = R$

(R= constant for a given conductor)

Hence V = IR

This is Ohm's Law.

Solved Examples

Example:

A uniform copper wire of length 1 m and cross sectional area 5 x 10^{-7} m^2 carries a current of 1 A. Assuming that there are 8 x 10^{28} free electrons per cm^3 , in copper how long will an electron take to drift from one end of the wire to the other? (Charge on an electron = 1.6 x 10^{-19} C).

Solution: Given L=1m

$A = 5 \times 10^{-7} m^2$

I=1A

$n = 8 \times 10^{28}$ electrons per cm^3 $= 8 \times 10^{34}$ per m^3

$v_d = \frac{1}{t}$

Also

$I = v_d e n A$

$I = \frac{1}{t}(1.6 \times 10^{-19} \times 8 \times 10^{34} \times 5 \times 10^{-7})$

$t = 64 \times 10^{8}s$

$= 6.4 \times 10^{9}s$

Example:

Two wires X, Y have the same resistivity, but their cross–sectional areas are in the ratio 2:3 and lengths are in the ratio 1:2. They are first connected in series and then in parallel to a given d.c. source. Find out the ratio of the drift speeds of the electrons in the two wires for the two cases.

Solution: **In Series**

$I_1 = I_2$

$v_{d1} e n A_1 = v_{d2} e n A_2$

$\frac{v_{d1}}{v_{d2}} = \frac{A_2}{A_1}$

$\frac{v_{d1}}{v_{d2}} = \frac{3}{2}$

In Parallel

$V_1 = V_2$

$I_1R_1 = I_2R_2$

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

$n A_1 ev_{d1} \times \rho\frac{L_1}{A_1} = n A_2 ev_{d2} \times \rho\frac{L_2}{A_2}$

$\frac{v_{d1}}{v_{d2}} = 2$

Example:

A potential difference V is applied to a conductor of length L, diameter D. How are the electric field E, the drift velocity v_d and the resistance R, affected when

i. V is doubled

ii. L is doubled

iii. D is doubled ?

Solution: We know, Electric field, $E = \frac{V}{L}$

Drift velocity, $v_d = \frac{eE}{m}\tau = \frac{eV}{mL}\tau$

Resistance, $R = \rho\frac{L}{A} = \frac{4\rho L}{\pi D^2}$

Hence

(i) When V is doubled, E gets doubled, v_d gets double but R remains unchanged.

(ii) When L is doubled, E becomes half, v_d becomes half but R gets doubled.

(iii) When D is doubled, E remains unchanged, v_d is also unchanged but R becomes one-fourth.

Example:

A conductor of length L is connected to a dc source of emf ε. If this conductor is replaced by another conductor of the same material and same area of cross-section, but of length 3 L, how will the drift velocity change?

Solution: Drift velocity, $v_d = \frac{I}{neA} = \frac{V/R}{neA} = \frac{V/(\frac{\rho L}{A})}{neA}$

Therefore, $v_d = \frac{V}{n\rho eL}$

Hence $v_d \propto \frac{1}{L}$

$\frac{v_d'}{v_d} = \frac{L}{3L}$ or $v_d' = \frac{v_d}{3}$

Try Yourself

- When electrons drift in a metal from a lower to a higher potential, does it mean that all the free electrons, of the metal, are moving in the same direction?
- Two conducting wires x and y of same diameter but different materials are joined in series across a battery. If the number density of electrons in x is twice that in y find the ratio of drift velocity of electrons in the two wires.
- What happens to (i) the drift velocity of an electron and (ii) to the resistance R, if the length of the conductor is doubled (keeping potential difference unchanged)?

- The electron drift speed is estimated to be only a few mm/s for currents in the range of a few amperes? How then is current established, all across the conductor almost at the very instant a circuit is closed?
- The electron drift arises due to the (continuous) force experienced by electrons due to the electric field inside the conductor. Why then do the electrons acquire a steady average drift speed?
- Define drift velocity. Write its relationship, with the relaxation time, in terms of the electric field E, applied to a conductor. A potential difference V is applied to a conductor of length L. How is the drift velocity affected when V is doubled and L is halved?
- Derive an expression for the drift velocity of free electrons in a conductor, in terms of the relaxation time.
- Two metallic wires of the same material have equal lengths but their cross-sectional areas are in the ratio of 1:2. They are connected (i) in series and (ii) in parallel. Compare the drift velocities of electrons, in the two wires in both the cases (i) and (ii).
- Write the mathematical relation between mobility and drift velocity of charge carriers in a conductor. Name the mobile charge carriers responsible for conduction of electric current in (i) an electrolyte (ii) an ionised gas.
- Establish a relation between current and drift velocity.

Summary

- **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.

  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.
- **Drift Velocity (V_d):** It is the average velocity acquired by a free electron, in a conductor under the influence of an external electric field. The magnitude of this velocity is very small, of the order of 10^{-4} m/s hence the name 'Drift Velocity'.
- **Relaxation time (τ):** It is the average time between two successive collisions of the free electrons. During this time the electron gains energy, lost in the collision, from the applied external electric field.

- **Number density (n):** It equals the number of free electrons per unit volume. $n = \frac{N}{V}$
- **Mobility (μ)**: For a charge carrier, responsible for current flow, it is defined as the magnitude of drift velocity of the charge carrier per unit applied electric field.
- **Ohm's law**: It states that the current flowing through a conductor is directly proportional to potential difference across the two ends of the given conductor, provided its temperature and other physical conditions remain constant.

$$I \propto V$$

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

Where, R is the resistance of the conductor, which is constant for a given conductor , under given conditions.

- **Resistance (R):** In simple words, a 'resistance' can be anything which opposes / obstructs the flow of current. The free electrons (in a conductor) constantly collide with its atoms / ions. These collisions are the basic cause of its 'resistance' to 'current flow'. It is measured as potential difference across a conductor per unit current flowing through it. $\frac{V}{I} = R$