1. Ohm's Law & Resistance

1.Definitions:

Conductors: A substance, which has free charge carriers to conduct electricity, is called a conductor.

Examples: (i) Metals: metals have free electrons as charge carriers,

(ii) Electrolytic solutions: they have positive and negative ions as charge carriers.

Insulators: A substance having no or very few free charge carriers, hence unable to conduct electricity, is called a bad conductor or an insulator.

Examples: wood, plastics, glass etc.

Semiconductors: A substance, which is an insulator in ordinary conditions but conduct electricity when a certain potential difference is applied, impurity is mixed or its temperature is increased.

The conductivity of a semiconductor lies between that of a conductor and an insulator.

Examples: Si, Ge, GaAs etc.

Comparison of the electrical properties of a conductor, insulator and semiconductor

	Conductor	Semi-conductor	Insulator
Free Electron Density	$\approx 10^{28}m^3$	$\approx 10^{16}m^{-3}$ (*when doped* $\approx 10^{23}m^{-3}$)	*Practically no free electrons*
Resistivity	$\approx 10^{-8}\Omega m$	$\approx 10^{-3}$ to $10^{+3}\Omega m$	$\approx 10^{10}$ to $10^{16}\Omega m$
Temperature dependence of resistivity	*increases with temperature*	*decreases with temperature*	*Practically no dependence*

2.Electric current:

Flow of electric charge is called '*electric current*'.

Quantitatively (as a physical quantity), the *rate of flow of charge* is the magnitude of electric current denoted as 'i'.

If amount of charge dq flows through a cross section of the flow-path in time dt then current is given as: $i = dq/dt$. Electric current is a *scalar quantity*.

Unit: In SI system current is basic physical quantity and its unit is ampere 'A'.

Dimensions: $[i] = [A]$.

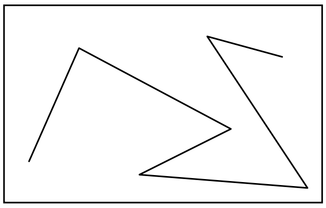
Definition of *ampere* : *one ampere is the electric current corresponding to the flow of 1/(1.602 176 634 × 10^{-19}) elementary charges per second.*

3.Free electron model of metal:

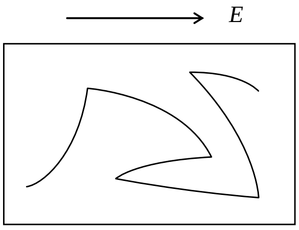
According to *free electron model* of metals,

- A great many electrons in the metal (of the order of 10^{28} per unit volume) are free to move throughout the volume in random directions with a great speed of the order of 10^6 m/s, at normal temperature. This is called **thermal motion**.
- The electrons collide repeatedly with the fixed ions of the metallic crystal and emerge with the same speed as before, that is, the collision is perfectly elastic.
- Average velocity of electrons in any direction is zero.
- When a constant potential difference is maintained across the conductor, electric field appears inside the conductor. The electrons, now, experience a force and start accelerating opposite to the field. But they do not continue accelerating for long. Due to collisions with the positive fixed ions in the conductor, in a very short time after start, they lose their acquired velocity, hence kinetic energy, which is converted in to heat. After collision they start accelerating freshly and the process is repeated. Therefore, at a given point of time, all the electrons in the conductor appear moving with the average of their velocities. This average velocity is called the **drift velocity**.

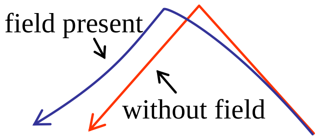
4.Path of randomly moving electrons in metal modified after a potential difference is applied across the conductor:



Path of an electron in absence of field



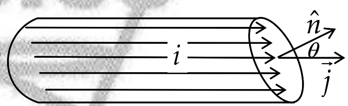
Path of an electron in presence of field



Path of the charge carriers in conduction of current

5. Current density $\vec{j}$:

Current per unit area, perpendicular to the direction of current flow, is called **current density**, denoted as $\vec{j}$. This is a vector quantity having direction along the current flow or parallel to the electric field.
Its SI unit is A/m^2.
If a small current *di* flows across a small cross sectional area *ds* and the normal to the area makes angle θ with direction of current flow, then $j = \dfrac{di}{ds\cos\theta}$. $\Rightarrow di = j ds\cos\theta$ or $\boxed{di = \vec{j}\cdot d\vec{s}}$.



The total current across a given area *S* can be calculated by integrating *di*, i.e., $i = \int_S \vec{j}\cdot d\vec{s}$.

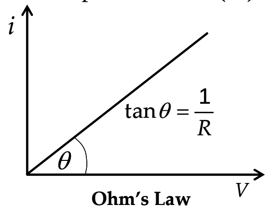
Therefore, 'total *flux of* $\vec{j}$ through a given area is current'.

6. Ohm's law:

"*the current passing through isotropic homogenous conductor is proportional to the potential difference* (*or voltage V*) *across the conductor*".

$$\Rightarrow i \propto V. \quad \text{Or,} \quad i = \frac{V}{R}.$$

Here *R* is a constant for a given conductor at a given temperature, called '*resistance*'.
Unit of resistance: Unit of resistance is volt/ampere or ohm (Ω). **Dimensions:** [ML^{2}T^{-3}A^{-2}].



Ohm's Law

7. The factors on which the resistance of a conductor depend:

Resistance is a property of conductor which is the ratio of the voltage across the resistor and the current through it. Resistance (*R*) of a conductor depends upon:

(i) Length of the conductor (*l*).

(ii) Cross sectional area of the conductor (*A*).

(iii) Nature of the substance which the conductor is made of. (This is characterised by a quantity called resistivity (ρ) and it depends upon temperature.)

$$\text{The relation is } R = \rho\frac{l}{A}.$$

(iv) The resistance depends on the temperature also.

8. Resistivity:

Resistivity (or 'specific resistance') is the resistance of a material with unit cross sectional area and unit length.

Unit: $\Omega m^2/m = \Omega m$. **Dimensions:** $[ML^3T^{-3}A^{-2}]$.

Since, $R = \rho \frac{l}{A}$, therefore, $\rho = \frac{RA}{l}$.

This is a property of the conducting material. If $A = 1$ unit, $l = 1$ unit, then $R = \rho$.

The factors affecting the resistivity are: **(i)** Temperature, **(ii)** State of material (solid, liquid or gas).

9. Temperature variation of Resistivity & Resistors:

Fractional change in resistivity is directly proportional to the rise in temperature.
Supposed at a reference temperature T_0 resistivity is ρ_0 and at a higher temperature T it is ρ.

Therefore, $\frac{\rho - \rho_0}{\rho_0} \propto (T - T_0)$. $\Rightarrow \frac{\rho - \rho_0}{\rho_0} = \alpha(T - T_0)$ or, $\rho = \rho_0 [1+\alpha (T-T_0)]$

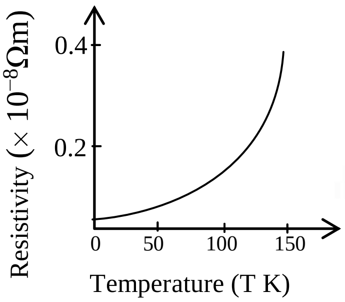
Here α is a constant called *temperature coefficient of resistivity*. This is a property of material.

The temperature dependence of the resistance is obtained by multiplying the relation with $\frac{l}{A}$ both sides, where l is length and A is the cross sectional area of the conductor.

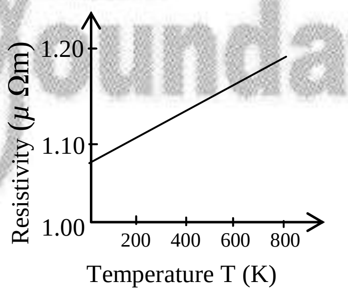
Thus, $R = R_0 [1+\alpha (T-T_0)]$ where R = resistance at a temperature T and R_0 = resistance at the reference temperature T_0.

Value of α is positive for conductors and negative for carbon and semiconductors.

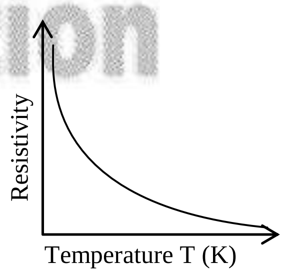
10. Graph of Temperature variation of Resistivity & Resistors:



Copper



Nichrome



Semiconductor

11. Conductance and Conductivity.

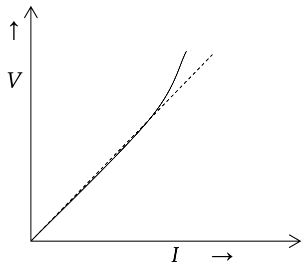
Reciprocal of *resistance* is called '***conductance***' (C). $\Rightarrow C = 1/R$.
Unit: Ω^{-1} or 'mho' or siemens. **Dimensions:** $[M^{-1}L^{-2}T^3A^2]$.

Reciprocal of *resistivity* is called ***conductivity*** (σ) i.e., $\sigma = \frac{1}{\rho}$.

Unit: $(\Omega m)^{-1}$ = mho–m^{-1} = siemens–m^{-1}. **Dimensions:** $[M^{-1}L^{-3}T^3A^2]$

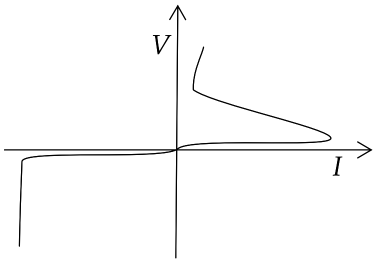
12. Limitations of the Ohm's law:

Ohm's law is not fundamental law of nature but it shows the behaviour of *conductors only in moderate conditions of current and voltage*.
Departure from Ohm's law is observed as:
(i) *V-I* relation is non-linear. Example: good conductors at high temperature

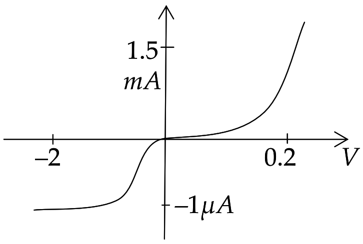


Good conductor at high current

(ii) *V-I* relation depends upon the sign of the voltage. Example: Thyristor, diodes and transistors.

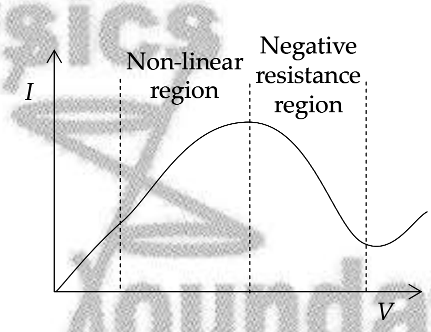


Thyristor



diodes

(iii) *V-I* relation is non-unique, i.e., for a given value of *I*, *V* can have more than one value, and *vice versa*. Example GaAs.



GaAs

13. *Ohmic* and *Non-Ohmic* conductors:

A conductor, which obeys ohm's law, that is, for which the *I–V* curve is a straight line passing through the origin, is called '**ohmic conductor**'.
Examples: Metals (for moderate currents).

A conductor which departs from linear *I–V* relation is called '**non-ohmic conductor**.
***Examples*:** Gases, thermionic diodes, thermistors (sensitive temperature measuring semiconductor device), *p-n* junction diodes, thyristor (four layer alternate *p-n* junction used to control alternating currents, where the change of polarity of the current causes the device to switch off automatically), transistors, tetrode valves (tunnel diodes) etc.
A good conductor at high current behaves like a non - ohmic conductor.

14. Kinds of Resistors:

A material used to provide resistance in an electrical circuit is called **resistor**. It is mainly of two types:
(i) Wire Bound resistors: These resistors are made of the coil of thin wires of certain alloys like, Manganin (86% copper, 12% manganese, and 2% nickel), Constantan (55% copper and 45% nickel), Nichrome (Nickel 80% chromium 20%) etc.
Specialty of wire bound resistors:

(a) Range of the value of these resistors is from an ohm to a few hundreds ohms.
(b)The materials have very low dependence on temperature or relatively insensitive to the temperature.
(c) They are expensive.
(d) They are larger than carbon resistors.

(ii) Carbon resistors: Resistors of higher range are made of carbons.

Specialities of carbon resistors:

(a) They are compact.

(b) They are inexpensive.

A good resistor should have the following properties:

(i) *High resistivity*.

(ii) *Little or no temperature variation of resistivity* (low *temperature coefficient*).

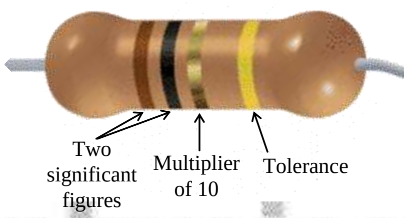
This is why manganin is used as standard resistor.

15. Colour Coding of Carbon Resistors:

Carbon resistors are coded in colour bands to indicate their values. This is because carbon resistors are very small and their values cannot be read if printed in figures.

Scheme of coding: On left side there are three bands of colours, the first two bands give first two significant figures of the resistance and the third band gives power of ten.

On right side there is either silver or golden or no colour. This indicates the tolerance.



Different types of resisters

Colour	Number/Power of 10	
Black	0	
Brown	1	
Red	2	
Orange	3	
Yellow	4	
Green	5	
Blue	6	
Violet	7	
Gray	8	
White	9	
Gold	5	% tolerance
Silver	10	
No colour	20	

Example: