Electrical Resistivity

Resistance is the measure of a material that shows how much current it can oppose. SI unit of resistance is the ohm (Ω).

Resistance of a material can be measured by:

$$\mathbf{R = \rho(L/A)}$$

Where,

L = length of the conductor

A = area of the cross-section of the conductor

ρ = resistivity

From the above equation, resistance (R) is directly proportional to the (L) length of the conductor and (ρ) resistivity. And the resistance (R) is inversely proportional to (A) area of the cross-section of the conductor. So, the resistance of a material is affected by its length, area of cross-section of material, and temperature.

Electrical resistivity (also called specific electrical resistance or volume resistivity) is **a fundamental property of a material that measures how strongly it resists electric current**. A low resistivity indicates a material that readily allows electric current and high resistivity indicates a material that hardly allows electric current.

Definition

The electrical resistivity of a material is defined as the resistance of a conductor of unit length and unit area of cross-section. The electrical resistivity of a material is mathematically expressed as follows

$$\boldsymbol{\rho = (R \times A) / L = \text{ohm} \times \text{metre}^2/\text{metre} = \text{ohm metre } (\Omega m)}$$

Unit : The SI unit of resistivity is **ohm metre** or **Ω*m***.

Classification of conducting material

Based on the resistivity /Conductivity behaviour, the conducting materials are classified into two. They are

1. **Low resistivity or high conductivity conducting materials.**
2. **High resistivity materials or low conductivity conducting materials.**

1. Low Resistivity or High Conductivity Conducting Material

Materials having low resistivity or high conductivity are very useful in manufacturing electrical engineering products. These materials are used as conductors for all kind of windings required in electrical machines, apparatus and devices. These materials are also used as conductor in transmission and distribution of electrical energy. Some examples of materials having low resistivity or high conductivity are listed below.

Examples:

- Copper
- Aluminum
- Silver → Due to their cost, their use is restricted
- Gold

2. High Resistivity or Low Conductivity Conducting Material

Materials having High resistivity or Low conductivity conducting are very useful for electrical engineering products. These materials are used to manufacture the filaments for incandescent lamp, heating elements for electric heaters, space heaters and electric irons etc. Some examples of materials having High resistivity or Low conductivity are listed below.

Examples:

- Tungsten
- Carbon
- Nichrome or Brightray – B
- Nichrome – Vor Brightray – C
- Manganin

The factors influencing electrical resistivity of materials

There are several factors that affect the electrical resistivity/conductivity of a material, and these include temperature, impurities, electromagnetic fields, frequency, and crystal structure.

Factors influencing the electrical resistivity of materials are listed below

1. Temperature.
2. Alloying.
3. Mechanical stressing.
4. Age Hardening.
5. Cold Working.

1. Temperature

The resistivity of materials changes with temperature. Resistivity of most of the metals increases with increase of temperature. The change in the resistivity of material with change in temperature is given by formula given below

$$\rho_{t_2} = \rho_{t_1}[1 + \alpha_1(t_2 - t_1)]$$

Where,

ρ_{t1} is the resistivity of material at temperature of t_1° C and

ρ_{t2} is the resistivity of material at temperature of t_2°C

α_1 is temperature coefficient of resistance of material at temperature of t_1° C.

If the value of α_1 is positive, the resistivity of material is increase.

The resistivity of metals increases with increase of temperature. It means that the metals are having positive temperature coefficient of resistance. Several metals exhibit the zero resistivity at temperature near to absolute zero. This phenomenon is called the **"superconductivity"**. The resistivity of semiconductors and insulators are decreased with increase in temperature. It means that the semiconductors and insulators are having negative temperature coefficient of resistance.

2. Alloying

Alloying is a solid solution of two or more metals. Alloying of metals is used to achieve some mechanical and electrical properties. The atomic structure of a solid solution is irregular as compared to pure metals. Due to which the electrical resistivity of the solid solution increases more rapidly with increase of alloy content. A small content of impurity may increase the resistivity metal considerably. Even the impurity of low resistivity increases the resistivity of base metal considerably.

For example, the impurity of silver (having lowest resistivity among all metals) added in copper increases the resistivity of copper considerably.

3. Mechanical Stressing

Mechanical stressing of the crystal structure of material develops the localized strains in the material crystal structure. These localized stains disturb the movement of free electrons through the material which results in an increase in resistivity of the material. Subsequently, annealing of metal reduces the resistivity of metal. Annealing of metal, relieve the mechanical stressing of material due to which the localized stains got removed from the crystal structure of the metal. Due to this, the electrical resistivity of the metal will decrease. For example, the resistivity of hard drawn copper is more as compared to annealed copper.

4. Age Hardening

Age hardening is a heat treatment process used to increase the yield strength and to develop the ability in alloys to resist the permanent deformation by external forces. Age hardening is also called **"Precipitation Hardening"**. This process increases the strength of alloys by creating solid impurities or precipitate. These created solid impurities or precipitate, disturb the crystal structure of metal which interrupts the flow of free electrons through metal/Due to which the resistivity of metal increases.

5. Cold Working

Cold working is a manufacturing process used to increase the strength of metals. It is also known as **"Work hardening"** or **"Strain hardening"**. It is mainly used to increase the mechanical strength of the metal. Cold working disturbs the crystal structure of metals which interfere with the movement of electrons in metal, due to which the resistivity of metal increases.

High Resistivity Materials

Alloys of nickel, chromium, copper, iron, manganese are extensively used as resistance materials. These alloys have high specific resistance (about 25 times that of pure copper) and a very low-temperature coefficient of resistance (about one-twentieth of that of pure copper).

General properties of high resistivity materials

The high resistivity materials have the following general properties.

- It has high melting point.
- It has high mechanical strength.
- It has high ductility, so that it can be drawn in the form of wire easily.
- It has high corrosion resistance (i.e., free from oxidation).
- It is low cost.
- It has long life (i.e., durable).
- It has high flexibility.

The following materials are used as **high resistance materials.**

1. Constantan
2. Molybdenum disilicide
3. Nichrome

1. CONSTANTAN

In 1887, Edward Weston discovered that metals can have negative temperature coefficients of resistance and invented what he called "Alloy No. 2" and was produced in Germany and renamed "Konstantan". **Constantan** is a copper–nickel based alloy wire that has a high resistivity and is mainly used for thermocouples and electrical resistance heating. It is also known as **Eureka**, **Advance**, and **Ferry**. Its main feature is the constant resistivity (low thermal variation of its resistivity) over a wide range of temperatures.

Composition

Primarily, constantan is composed of Nickel and Copper. It contains 60% of nickel and 40% of copper.

Constantan Wire

Constantan Foil

Characteristics of Constantan

Constantan has a number of special characteristics due to which, it is known as the most versatile alloy that is available. Some of its important characteristics are

- High specific heat resistance
- Negligible temperature Coefficient
- Easily ductile
- Resistant to atmospheric corrosion
- Can be easily soldered and molded

The physical properties of constantan are

Melting point	–	1225 to 1300 °C
Specific Gravity	–	8.9 g/cc
Solubility in Water	–	Insoluble
Appearance	–	A silver-white malleable alloy
Odor	–	Odorless
Electrical resistivity at room temperature	-	0.49 μΩ/m
At 20°C	–	490 μΩ/cm
Density	–	8.89 g/cm^3
Temperature Coefficient	-	±40 ppm/K^{-1}
Specific heat capacity	-	0.39 J/(g·K)
Thermal Conductivity	-	19.5 W/(m.K)
Elastic Modulus	-	162 GPa
Elongation at fracture	–	<45%
Tensile strength	–	455 to 860 MPa
Linear Coefficient of Thermal Expansion	-	14.9×10^{-6} K^{-1}

Uses of Constantan

Constantan is used for the measurement of temperature. It is used for the formation of thermocouples, along with the wires of other metals such as copper, iron, and chromel. It is especially used for resistance purposes since its resistance does not change much with the change in its temperature. It is used for DC current shunts. In the DC current shunts, the precision low-value resistance wire is placed in series with the load in a direct current circuit, which is already carrying a high current.

Applications of Constantan

The application of constantan falls into three important categories:

1. Temperature Measurement

Constantan is used for the formation of thermocouples with the wires of copper, iron, and chromel. It is used to form chrome-constantan thermocouples and good iron constantan thermocouples also.

2. Heavy Duty Industrial Rheostats

Constantan is an ideal alloy for electric motor starter resistances and for heavy-duty industrial rheostats. Since it has high specific heat resistance, and good ductile nature, it satisfies the entire important requirement for this category of specifications. Constantan is transformed into wires of large size or this kind of requirement.

3. Wire Wound Precision Resistors

Constantan is one of the most widely used alloys in wire-wound precision resistors, volume control devices, and temperature-stable potentiometers. It is the main attraction in this field owing to the fact that it has a negligible temperature coefficient and high resistance. Development of a high thermal E.M.F – This is another important property of constantan, that it develops a high thermal E.M.F against other metals. It is therefore used in thermocouple alloys, with other metals like iron and copper.

Effects of Constantan on Health

- Constantan has certain negative impacts on the health of human beings as well as animals. If the animals inhale the copper dust from this alloy, it can lead to the hemolysis of the red blood cells and deposition of hemofuscin in the pancreas and the liver.
- To a normal human being, exposure to nickel can present some health hazards. Since nickel is a confirmed carcinogen, it may cause cancer in people. Another common problem is the hypersensitivity to nickel. It may cause allergy and dermatitis, pulmonary asthma, inflammatory reactions, and conjunctivitis.
- It has other acute effects on the other parts of the body as well. Some of its harmful effects are:
- Eyes – dust powder may cause abrasive irritation to the eyes
- Skin – No chronic health effect
- Ingestion – Nickel has low oral toxicity, copper may cause vomiting and nausea.
- Inhalation – There are certain cases of asthma that have been reported due to the inhalation of nickel and copper dust. There is a high possibility of respiratory sensitization.

Precautions

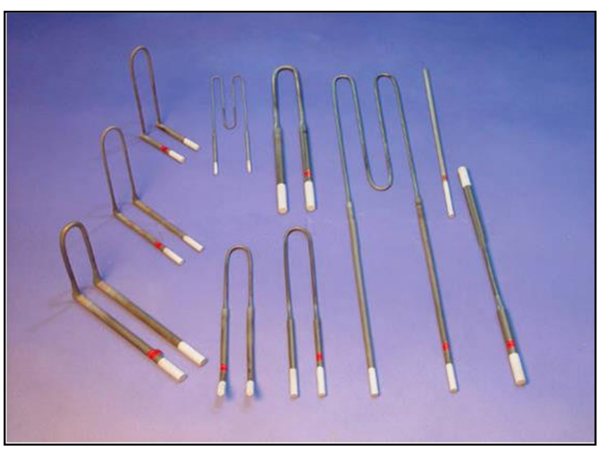
There are certain precautions that need to be taken for the storage of Constantan.

- It should be stored in a cool and dry area, in a tightly sealed container.
- After handling the constantan, hands should be washed thoroughly with soap and water.
- Use gloves to touch constantan wires, and should not come in direct contact.

2. MOLYBDENUM DISILICIDE ($MoSi_2$)

The crystal of **molybdenum disilicide** (MoSi2) has a tetragonal structure. It is an intermediate phase with the highest silicon content in the Mo-Si binary alloy system. It is a Dalton intermetallic compound with a fixed composition. It is gray with metallic luster. It has good electrical and thermal conductivity, excellent mechanical properties and high temperature oxidation resistance.

Molybdenum disilicide and $MoSi_2$-based materials are usually made by Sintering. Plasma spraying can be used for producing its dense monolithic and composite forms; material produced this way may contain a proportion of β-$MoSi_2$ due to its rapid cooling.



Molybdenum disilicide –Heating element

Properties of Molybdenum Disilicide

Compound Formula	-	$MoSi_2$
Molecular Weight	-	152.11
Melting Point	-	1900-2050 °C
Density	-	6.23-6.31 g/cm^3
Crystal Phase / Structure	-	Tetragonal
Electrical Resistivity	-	0.0000270 - 0.0000370 ohm-cm
Specific Heat	-	0.437 J/g-°C (23 °C)
Tensile Strength	-	185 MPa
Thermal Conductivity	-	66.2 W/m-K (23 °C)
Vickers Hardness	-	900-1200

- $MoSi_2$ is a grey metallic-looking material with tetragonal crystal structure (alpha-modification); its beta-modification is hexagonal and unstable.
- It is insoluble in most acids but soluble in nitric acid and hydrofluoric acid.
- While $MoSi_2$ has excellent resistance to oxidation and high Young's modulus at temperatures above 1000 °C, it is brittle in lower temperatures. Also, at above 1200 °C it loses creep (deformation) resistance. These properties limits its use as a structural material, but may be offset by using it together with another material as a composite material.

Crystallographic properties: It belongs to a tetragonal crystal structure with a density of 5.9-6.3g/cm. Pure molybdenum disilicide has no phase change before it reaches the melting point and has good thermal stability. Within the upper limit of its effective temperature range, the rise and fall of temperature will not be destroyed by changes in crystallographic properties.

Thermodynamic properties: It has high thermal conductivity (similar to SiO_2), and small thermal expansion coefficient. These characteristics are necessary conditions for the production of high-temperature heating elements or thermocouple protection tubes, and help to increase the thermal shock resistance of their products.

Electromagnetic properties: It has low resistivity (2×10-5Ω·cm), high electric rate and it is a good conductor. This material is an excellent material for manufacturing heating elements, thermocouple thermo electrodes and temperature protection tubes (when used as thermocouple protection tubes, please pay attention to insulation).

Mechanical properties: The tensile strength and bending strength are not lower than that of general metal materials and some oxide materials (such as Al_2O_3), and the hardness and compressive strength are higher than that of metals. Compared with metal, the biggest disadvantage is poor impact toughness, so it belongs to brittle material like general ceramic products.

Chemical properties: The chemical state is acidic. It is insoluble with most acids and alkalis at room temperature. Except for oxide ceramics, $MoSi_2$ is the most stable of all refractory compounds. Since the solubility of silicon in molybdenum is about 1% (1800°C), it determines the oxidation stability temperature of MoSi2 below 1700°C.

Molybdenum disilicide itself is not resistant to high-temperature oxidation, but at 1300~1600°C, a thin and dense silicon dioxide glassy protective layer is formed on its surface to inhibit continued oxidation.

MoSi2 is not only stable in oxidizing media, but also can be used to high temperatures in reducing, neutral, inert and some strong corrosive atmospheres. For example, in N_2, CO_2, SO_2 and other media.

Uses of molybdenum disilicide:

- It can be used as a heating element and has better performance than silicon carbide.
- Its early application was as a high-temperature and corrosion-resistant coating protection material on the surface of a metal substrate.
- It was first applied to the coating of gas turbine parts, jet engine combustion chambers and missile combustion chambers.
- Nowadays, the main industrial applications of molybdenum disilicide materials are in the production of high-temperature heating elements and thermocouple protection tubes.

- Molybdenum disilicide heating elements can be used for temperatures up to 1800 °C, in electric furnaces used in laboratory and production environment in production of glass, steel, electronics, ceramics, and in heat treatment of materials.
- Molybdenum disilicide is used in microelectronics as a contact material. It is often used as a shunt over polysilicon lines to increase their conductivity and increase signal speed.

3. NICHROME

Nichrome is an alloy mainly composed of nickel and chromium. Its most common form consists of 80% Nickel and 20% Chromium. It is chemically called as NiCr. Other types of nichrome contain varying concentration of the two elements. Iron is also a component of this alloy although it is a very small part in the total concentration. The chemical formula in this case becomes NiFeCr.

Nichrome Coil

Some peculiar properties of nichrome are listed below.

- Nichrome is consistently silvery-gray in colour

- It is corrosion-resistant. Upon heating at high temperature the outer layer forms a covering of chromium oxide which acts as a shield to the inner layers and prevents further corrosion. For this reason unlike other metals and alloys, nichrome is resistant to high heat.

- It has a high melting point of about 1,400 °C (2,550 °F).
- It has an electrical resistivity of around 112 microOhm-cm, which is around 66 times higher resistivity than copper of 1.678 microOhm-cm.
- Nichrome alloys have high mechanical strength and high creep strength.
- It is a bad conductor of electricity and therefore heats up very quickly when supplied with electric current.
- It remains ductile even after repeated uses without losing its nature.
- Unlike other metals used in heat producing devices, nichrome does not have to be drawn into thin wires to increase its resistivity as it is able to do so naturally which maintains its tensile strength and ensures longevity.
- It is non-magnetic at low temperatures which make it suitable to very specific industries.

Applications of Nichrome:

Due to high electrical resistivity, it can be used in heat – generating devices such as iron, toasters, hair dryer, electric ovens etc. some of the applications are listed below.

- It is used in the ignition systems of rockets, electric matches and electronic cigarettes.
- It has a wide range of applications in enterprises that extract metal using equipment like blast furnaces and other systems that require high heat resistance.
- Because of its low cost of manufacture, strength, ductility, resistance to oxidation, stability at high temperatures, and resistance to the flow of electrons, nichrome is widely used in electric heating elements in applications such as hair dryers and heat guns.
- Nichrome is used in the explosives and fireworks industry as a bridge wire in electric ignition systems, such as electric matches and model rocket igniters.
- Nichrome wire is used in hot-wire foam cutters for industry and recreation.
- Nichrome wire is frequently used in ceramics as an interior support system to help some clay sculpture components maintain their shape while the clay is still pliable. Nichrome wire is used for its ability to withstand the high temperatures that occur when clay work is fired in a kiln.

- Nichrome wire can be used as an alternative to platinum wire for flame testing by colouring the non-luminous part of a flame to detect cations such as sodium, potassium, copper, calcium, etc.
- Other applications include motorcycle mufflers, specific areas of microbiology lab equipment, heating elements in plastic extruders used in the RepRap 3D printing community, solar panel deployment mechanisms on the Light Sail-A spacecraft, heaters in c oils of electronic cigarettes and so on.