SUPERCONDUCTIVITY

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Electrical Resistivity

Materials like metals through which an electric current will pass are known as conductors. Metals contain a large number of "free electrons" which make them good conductors of electricity. In insulators such as glass or plastic, electrons are bound to the nuclei and are not free to move. They are non-conductors of electricity. We measure the resistance, R, of a conductor between two points by applying a potential difference V between these points and measuring the current I flowing through it. The resistance R is then given by the relation, $R = V/I$ and is measured in ohms.

Related to resistance is the resistivity, ρ which is characteristic of a material rather than of a particular specimen. For a cylindrical wire of length l and area of cross-section A, the resistivity is given by the relation $\rho = RA/l$. The unit of resistivity is Ωm or Ωcm. The reciprocal of resistivity is known as the conductivity σ of the material - ie. $\sigma = \frac{1}{\rho}$ and it is measured in $\Omega^{-1}\ m^{-1}$.

Among ordinary metals, silver is the best conductor of electricity followed by copper. Resistivities of some metals and alloys are given in Table 1.

Table 1

Metal	Resistivity at 20°C (in Ω m)
Silver	1.63×10^{-8}
Copper	1.69×10^{-8}
Aluminium	3.21×10^{-8}
Mercury	94.1×10^{-8}
Manganin alloy	44×10^{-8}

The resistivities of non-metallic substances are more than 10^4 Ω m. Intermediate between conductors and insulators comes the important class of materials known as semiconductors. Germanium and silicon are some examples of semiconductors. The resistivity of germanium is 0.65 Ω m and of silicon is 2.3×10^3 Ω m.

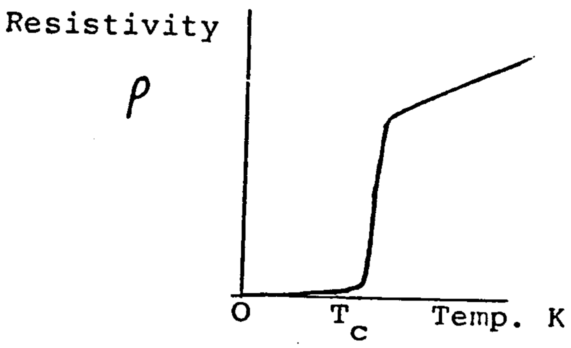
In a metal, the valence electrons are not bound to individual atoms but are free to move about within the solid and are called conduction electrons. In copper, there is one such electron per atom. In a small wire of copper of mass 50 g there are about 10^{23} conduction electrons. In the absence of an electric field, the conduction electrons move in random directions with an average velocity of about 10^8 cm/sec at room temperature. These electrons collide constantly with the atomic cores of the conductor, that is, they interact with the lattice. Collissions between electrons occur only rarely. When an electric field is applied to a metal, the electrons modify their random motion and start to drift in the direction opposite to the direction of the field. The resistivity of the metal arises due to the collisions of conduction electrons among themselves and also with atomic cores in the crystal lattice.

Resistivities of metals vary with temperature, as given by the approximate relation $\rho_t = \rho_o (1 + \alpha t)$ where ρ_t and ρ_o are the resistivities at temperature t °C and 0°C respectively and α is a constant for the material, known as the temperature co-efficient of resistance.

Superconductivity

For many substances, the electrical resistivity becomes zero at very low temperature, close to absolute zero. That is, they lose the property of resistance! This material is then said to be in a superconducting state. The onset of superconductivity occurs at a sharply defined temperature, T_c known as the transition temperature.

This phenomenon was first discovered by Kamerlingh Onnes in the Netherlands in 1911. He observed that when mercury is cooled below 4.2 K, its resistivity becomes essentially zero. Once started, a current in a loop of superconducting material persists even for several months, demonstrating the complete absence of resistance. Above the transition temperature, however, the same current would have ceased in a few seconds.



Placing a superconducting material in a magnetic field lowers its transition temperature. In a sufficiently strong magnetic field, superconductivity vanishes even at absolute zero. Very large currents, in the kilo-ampere range, are possible in superconductors without exessive I^2R losses. This gives the possibility for the development of superstrong magnetic fields for research, magnetically levitated passenger trains and superconducting transmission lines for electrical power distribution. Super-conductors also have the property of repelling magnetic fields. This phenomenon is known as the "Meisner Effect"

BCS Theory

The electrical, magnetic and thermal properties of the superconducting state suggest that the phenomenon must involve some interaction between the conduction electrons, and that it is a co-operative effect involving many electrons, acting together. Phonons or Lattice vibrations also play an important role. The first successful quantum mechanical theory on the origin of superconductivity was proposed by Bardeen, Cooper and Schrieffer (BCS) in 1957. BCS theory related superconducting properties to a specific mechanism of interaction between the electrons. The observation that the superconducting transition temperature T_c varies with the atomic mass M of the elements according to the relation $T_c \propto 1/\sqrt{M}$ (Isotope Effect) has provided the basic clue for the BCS theory. This observation indicates that the vibrational motion of the atomic nuclei in the lattice must play an important role in superconductivity. The BCS theory proposed that superconductivity arises because of an attractive interaction between pairs of electrons by way of lattice vibrations or phonons. In both, the normal and superconducting states, there is, of course, a Coulomb repulsion between pairs of electrons. The essential requirement for superconductivity, according to BCS theory is that the attraction between two electrons, mediated by phonons, should exceed the Coulomb repulsion. The attraction causes the conduction electrons to form bound pairs, known as Cooper pairs. A finite energy 2ϵ is needed to break such a pair and give normal single electrons. This implies that there is an energy gap associated with the superconducting state.

When the material is cooled down to very low temperatures at Tc it transforms from the normal state into the superconducting state. In otherwords, there is a phase change at Tc. In the normal state, when an electric current passes through the material,collisions between electrons and also between electrons and atomic cores, give rise to resistivity, thus dissipating their energy in the form of heat. According to the BCS theory, in the superconducting state, the electron pairs can carry the current avoiding such collisons.

High Temperature Superconductors

Upto 1986, one of the major limitations in practical applications of superconductors was the very low temperatures needed to keep ther materials cool below Tc. The highest known transition temperature was 23K for Nb_3Ge alloy. Therefore, it was necessary to use expensive and rare liquid helium to maintain the material at such low temperatures. This situation, however, changed dramatically in 1986, with the discovery of a new type of superconducting material, La-Ba-CuO with Tc = 35K by Georg Bednorz and Alex Muller, two physicists at the IBM research laboratories in Zurich, Switzerland. A related material, Y-Ba-CuO was later found by Paul C.W. Chu of the University of Houston, U.S.A. This material has a Tc ≃ 100K (or - 173°C). The structure of this new class of high Tc materials was different from the superconducting metals and alloys known earlier. They are brittle like ceramics. But the greatest achievement is that, the Tc^s of around 100 K could easily be obtained with liquid nitrogen (Boiling Point 77K) which is much cheaper and easily accessible in most countries, including Sri Lanka. The new discoveries also have paved the way for searching for materials which become superconducting at ordinary room temperatures.

The mechanism of superconductivity in the new oxide ceramic materials is not yet fully understood. The defects in the crystal structure appear to play a crucial role. Understanding the mechanism of superconductivity in the new materials is vital in order to search for a room temperature superconductor. The brittle nature of the new materials is also a disadvantage because of the difficulty in forming them into flexible wires and ribbons for passing electric currents. However, many physicists, chemists, material scientists and engineers, all over the world are currently working with these exciting materials.

High Tc superconductors have the potential to radically modify most of the electrical and electronic appliances found in the home, making them smaller and more powerful. They could replace petrol and diesel vehicles with electric cars, give us more powerful and superfast computers. Superconducting loops can be used to store vast amounts of electricity for later use. Superconducting magnets can be used in magnetically levitated trains, and electrical power for an entire city could be funneled through a handful of superconducting cases.

If room-temperature superconductivity is achieved, whether in a year or a score of years, its impact will be incalculable.