Electrical Conductivity in Materials

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INTRODUCTION

Different materials vary considerably in their electrical properties. In this article we shall examine the behaviour of materials under the influence of electric fields.

Nearly all materials fall into two major categories: conductors through which electric currents can flow easily and insulators through which currents have great difficulty in flowing. Metals, some liquids, and plasmas (gases whose molecules are charged) are electrical conductors. Nonmetallic solids (e.g., polymers) and certain liquids and gases whose molecules are electrically neutral are insulators. Semiconductors are intermediate in their ability to conduct current. In many materials the electrical resistivity becomes zero at very low temperatures close to absolute zero and the material becomes superconducting.

ELECTRICAL CONDUCTIVITY

A flow of electric charge from one place to another is called an electric current. An electric current in metals is due to a movement of electrons, whereas in other materials positive or negative ions may be involved. The ions are responsible for conduction of electricity through electrolytes. The magnitude of an electric current (I) is the amount of charge passing a given point per second. Just as the rate of flow of water between two points depends upon the difference of height between them, the rate of flow of electric current between two points depends upon the difference of potential between them.

The current (I) that flows in a conductor is proportional to the potential difference (V) between its ends (Ohm's Law).

$$I = \frac{1}{R} V. \qquad (1)$$

The constant of proportionality is written as 1/R and R is called the resistance of the conductor. The resistance of a conductor depends upon:

- the material it is composed of,
- its length (L), and
- the cross-sectional area (A).

Therefore, the resistance (R) of the conductor is represented by the equation

$$R = \rho \frac{L}{A}.$$

The constant of proportionality (ρ) is called the resistivity of the material and is measured in Ω m. It is important to note that the resistivity is the material property and not the total resistance. The reciprocal of resistivity is known as the conductivity (σ) of the material (i.e., $\sigma = 1/\rho$) and is measured in $\Omega^{-1}m^{-1}$.

Table 1 gives a list of resistivities of several materials at 20°C.

Material	**Resistivity (Ωm)**
Aluminium	2.69×10^{-8}
Copper	1.62×10^{-8}
Gold	2.30×10^{-8}
Germanium	4.6×10^{-1}
Iron	20×10^{-8} - 6×10^{-8}
Mercury	94×10^{-8}
Silver	1.60×10^{-8}
Sulfur	1×10^{17} - 1×10^{16}
Silicon	230×10^{1} - 64×10^{1}

You may notice that there is a substantial variation in resistivity of materials. For example, sulfur (insulator) has a resistivity of almost 10^{25} greater than that of silver. Germanium and silicon are semiconductors and have intermediate resistivity values between insulators and conductors.

CONDUCTORS

The electrical properties of solids are mainly determined by the properties of electrons in them. In a metal the valency electrons are relatively free to move through the metallic lattice which makes metals good conductors of electricity. When a potential difference is applied across a conductor, an electric field is set up in the conductor which creates an electric force on the electrons and hence a current. Actually, the electrons do not simply move in straight lines along the conductor. Instead, they undergo repeated collisions with the metal ions, which results in a complicated zig-zag motion. The energy transferred from the colliding electrons to the metal ions causes an increase in the temperature of the conductor (Joule heating). However, despite the collisions, the electrons move slowly along the conductor (in direction opposite to the electric field) with an average velocity called the drift velocity. The electric field does work on the electrons that exceed the average loss due to collisions, which results in a net current. However, any factor which impedes the movement of electrons will reduce conductivity. The increase in temperature introduces greater thermal agitation as ions vibrate about their mean position. This reduces the mean free path of electrons and their mobility, resulting in a decrease in conductivity with increasing temperature.

Although the free electron theory is a convenient way of explaining many properties of metals, it is an oversimplification of the true situation for many other cases. In a single atom the electrons occupy a number of discrete energy levels and their energy levels become closer together the further they are from the nucleus. When atoms are brought as close together as those in a crystal, they interact with one another to such an extent that their outer electron shells constitute a single system of electrons common to the entire array of atoms. However, Pauli's Exclusion Principle prohibits more than two electrons (one with each spin) in any energy level of the system. Therefore, the electrons are compelled to seek slightly different energy levels. As a result of these shifts in the energy levels, an energy band exists in a crystal in place of each sharply defined energy level of its component atoms (see Figure 1). Within even a small crystal containing many millions of atoms, the energy levels will be replaced by densely filled bands. For example, a sodium atom has only one valency electron so that only half of the energy states in the 3S (or valency) band are filled. For this reason, the energy required to raise a valency electron to an empty state is negligible.

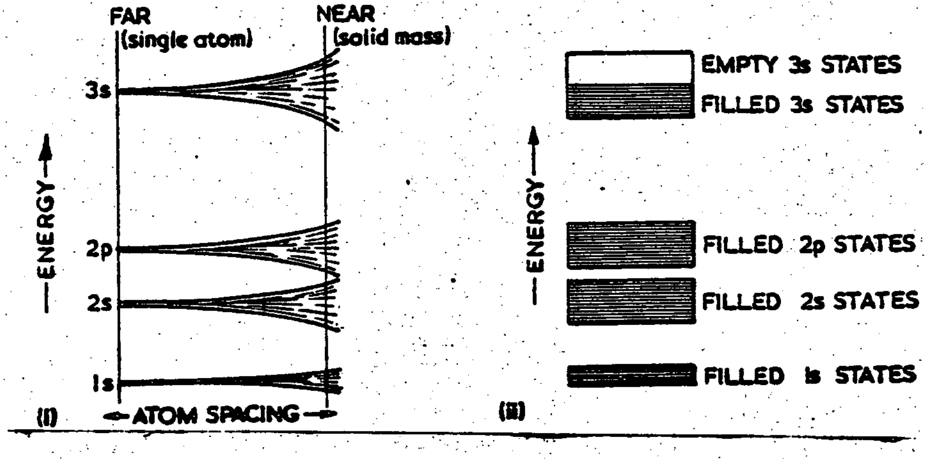

Figure 1. Energy states of electrons in sodium.

This enables the valency to move freely within the crystal and so to conduct electricity. In case of magnesium, the 3S band is filled, but since it actually overlaps with the 3p band (Figure 2), magnesium conducts electricity very easily. However, in some materials, the adjacent energy bands do not overlap in this way and energy is then required to move electrons across this 'energy gap.' In diamond, this energy gap is great (about 8.5 x 10^{-19} J at 20°C) and, therefore, diamond has very high electrical resistivity.

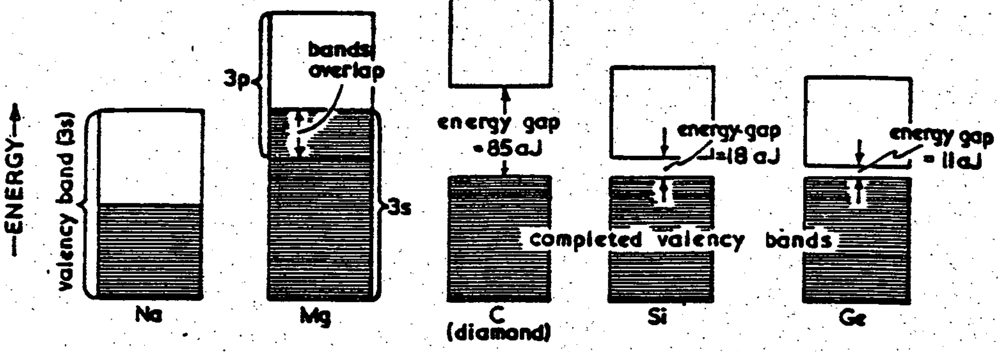

Figure 2. Energy bands in different materials.

INSULATORS

Nonconducting materials or insulators are those in which bonding is either covalent or ionic. Valency bands in insulators are completely filled and there is a wide energy gap between the valency band and the next possible energy band. Under such circumstances, a large input of energy would be required for an electron to cross the gap. A very small number of electrons may acquire such energy, if the material is subjected to a high potential difference and these insulators possess very low but measurable conductivities. At high temperatures, individual electrons will possess greater energies and so the chances of these electrons escaping are more. Conductivity will therefore increase. Insulating materials may break down under the pressure of an electrical potential difference that is high enough to raise the energies of large numbers of electrons to the point where they can cross the energy gap and become free. Such a potential difference is termed the 'breakdown voltage.'

SEMICONDUCTORS

A few decades ago, a three-valve radio set was housed in a large cabinet which occupied a considerable space in a household. Its bulk was due to the size of the thermionic valves and the volume of surrounding air space required to cool the large valves. A radio receiver of equivalent performance can now be housed in a matchbox. This was made possible by the development of transistors in the late 1940s. The complex electronics industry, which has developed since then, is dependent upon these semiconductors.

The other elements of Group IV of the periodic table have similar valence electron structure and crystalline structure like that of diamond. This structure is with four covalent bonds per atom. In silicon and germanium, however, the energy gap between the 'valency band' and the 'conduction band' is relatively small compared with that in diamond and, therefore, it is easier to free an electron into the conduction band (for silicon it is 1.8×10^{-19}J and for germanium it is 1.1×10^{-19}J at 20°C). The transfer of this electron leaves a vacancy, such that one atom in the lattice (Figure 3) possesses only three valency bands instead of four. This deficiency is referred to as an 'electron hole.'

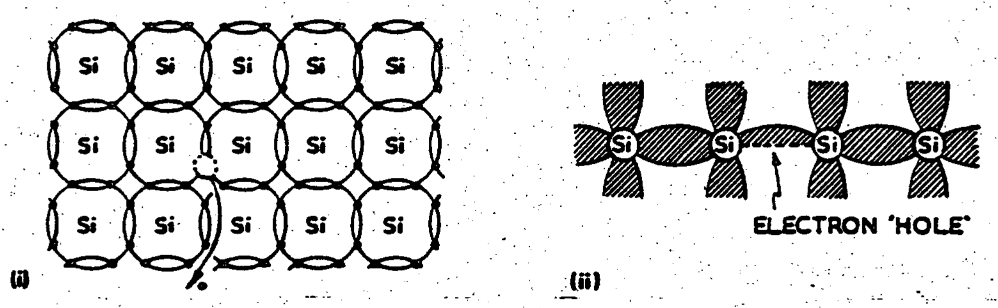

Figure 3.

Another valency electron is able to jump into this hole and so cause the movement of the hole to proceed in the opposite direction to that in which the electrons are moving. This can be regarded as equivalent to the motion of a positive charge (Figure 4). Materials in which conduction occurs in this manner are called 'intrinsic' semiconductors. The conduction is due to the combined flow of freed valency electrons and of holes in the opposite direction. Valency electrons can be freed through the energy gap and into the conduction band by supplying thermal energy. For this reason raising the temperature of an intrinsic semiconductor increases its conductivity. In normal conductors the opposite effect is obtained by increasing the temperature.

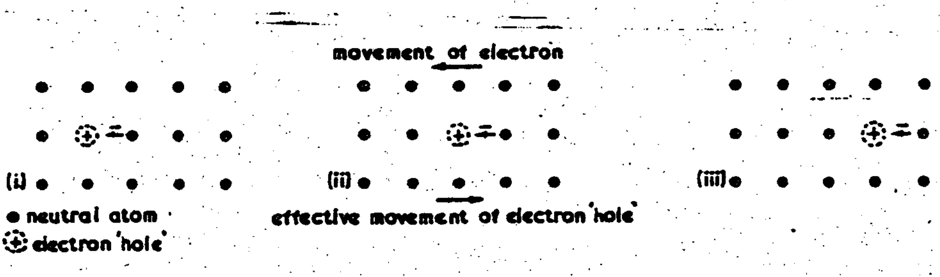

Figure 4.

The conductivity of semiconductors is markedly affected by slight amounts of impurity. These are called 'extrinsic' semiconductors. The trace elements concerned are generally those of Group III or Group V, that is those whose atoms contain either one less or one more valency electron than the Group IV atom concerned. If an atom of the Group V element such as phosphorus (or arsenic) is added to silicon, it will fit into the crystal structure of silicon because its atomic radius is of the right order. But because silicon has a valency of four and phosphorus has a valency of five an extra electron will be available. Only a very little energy will be required to free this electron from the phosphorus atom and, at room temperature, the thermal energy present in the lattice is sufficient to do this. An extrinsic semiconductor of this type which utilises the movement of freed electrons is called an 'n-type' and the element (in this case phosphorus) which provides the electron is referred to as a 'donor.'

If, on the other hand, an impurity atom of a Group III element such as boron (or aluminium) is added to the silicon lattice, it will provide only three-valency electrons for the four bands involved. This deficiency of one electron will be equivalent to the presence of a positive hole. This form of semiconductor is referred to as a 'p-type' and the impurity element involved is called an 'acceptor.' By controlling the small amounts of impurity atoms present in either silicon or germanium crystals, semiconductors with specific properties in either n- or p-types can be produced. A semiconductor in which a section of p-type material shares a common interface with a piece of n-type material is known as a 'p-n' junction. It is upon the properties of this p-n interface that the diodes and transistors of modern radio and other electronic equipment depend.

SUPERCONDUCTORS

For many substances the electrical resistivity become zero at very low temperatures close to absolute zero. In other words, these materials lose the property of resistance. Such material is then said to be in a superconducting state. The onset of superconductivity for a particular material occurs at a sharply defined temperature which is called the transition temperature or T_c (Figure 5). This phenomenon was first discovered by Kamerlingh Onnes in the Netherlands in 1911. He observed that when mercury is cooled below 4.2K, its resistivity essentially becomes 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.

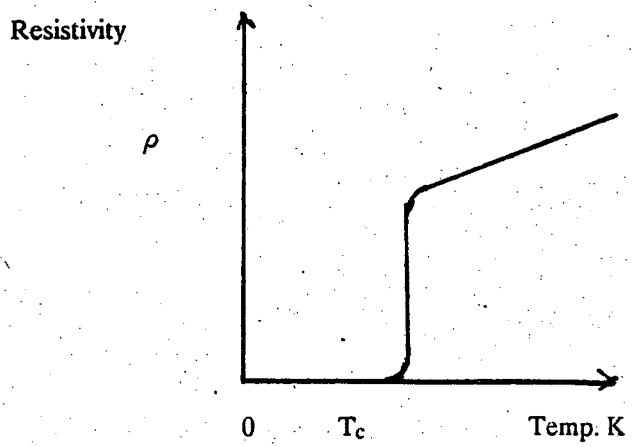

Figure 5

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 excessive 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. Superconductors also have the property of repelling magnetic fields. This phenomenon is known as the 'Meisner Effect.'

Untill 1986, one of the major limitations in practical applications of superconductors was the very low temperatures needed to keep their materials cool below T_c. The highest known transition temperature was 23K for Nb_3Ge alloy. Therefore, it was necessary to use liquid-helium, which is rare and expensive, 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 a T_c of 35K, by George 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, USA. This material has a T_c of 100K (or -173°C). Later, in 1988 and 1989, scientists discovered two more high-temperature superconducting materials, Bi-Sr-Ca-Cu-O with a T_c of 110K and Ta-Ca-Ba-CuO with a T_c of 125K. The structure of this new class of high-T_c materials was different from the superconducting materials and alloys known earlier. But the greatest achievement is that a T_c3 of around 100K could easily be obtained with liquid nitrogen (boiling point 77K) which is much cheaper than liquid-helium and easily accessible in most countries, including Sri Lanka. The new discoveries have also paved the way for searching for materials that become superconducting at ordinary room temperature.