Electrical Conduction and Superconductivity

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The article discusses the origin of electrical conduction and resistance in metals. It also discusses superconductivity in metals and the underlying mechanism. The salient features of high temperature superconductivity are mentioned and difficulties in understanding the mechanism of high temperature superconductivity are briefly discussed.

Introduction

Superconductivity, the awe-inspiring word came into existence when Kamerlingh Onnes (*Box* 1) discovered a new phenomenon in 1911. When he cooled a sample of liquid metal mercury, it lost its electrical resistance at temperatures close to 0 K. Years of careful experimentation at Leiden preceded his success in the liquefactions of helium and the discovery of superconductivity. What then is this superconductivity, one may wonder.

Let us have a look at electrical conduction before attempting to understand superconductivity. All materials offer some resistance to the flow of electric current through them. But they differ widely in the resistivity offered to the flow of current.

Box 1.

Kamerlingh Onnes, Heike (1853-1926) was a Dutch physicist born in Groningen and educated at the University of Groningen. He was Professor of Physics at the University of Leiden from 1882 until his death. He is best known for his work in cryogenics, the study of the production and effects of extremely low temperatures. He succeeded in liquefying helium for the first time in 1908 and studied the effects of extreme cold on a number of gases and metals. He was the first to discover superconductivity and he was awarded the 1913 Nobel Prize for Physics.

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Superconductivity, Meissner effect, Cooper pairs, energy gap, resistivity, energy bands, phonons.

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Perhaps no other parameter in physics assumes such a wide spectrum of values. The electrical resistivity ranges from 10^{-8} ohm-metre in metals to 10^{16} ohm-metre in insulators. We have a host of materials where the resistivity assumes a value inbetween the extreme values in metals and insulators. We call them semiconductors. Suitable materials can be added to the semiconductors and their properties can be altered. This is called doping. This has revolutionized the entire electronics industry towards the second half of the last century.

Energy Band Structure of Metals

Let us have a look at how electrons in metallic solids behave. The electrons that belong to different atoms prefer to move within the solid as if they don't have a definite parentage. A theory of the behavior of electrons in solids may be conceived as follows. We consider an atom with all its orbitals clubbed together with the nucleus except the outermost. An atom devoid of a few electrons belonging to the outermost orbital will form a positively charged ion. Solids consist of an array of such ions together with the electrons, which are shared among all of them. In physics a description involving such short distances should be obtained by using the laws of quantum mechanics.

A quantum description with such an array of ions together with all the electrons they have contributed to the solid is a hard problem to handle. Physicists often tackle this difficulty by making simplifying assumptions. Quite often that is the only way they can attack their problems. Can you guess what assumption they make to overcome this difficulty? They consider all the ions that form a definite array and consider how a single electron added to such a system would behave. This is a problem they can solve. What they have found is interesting. There are states with definite energies, which the electron can have.

The possible energies of such an electron form very closely spaced values forming bands, each band separated by rather wide gaps from the neighboring ones. Physicists have found that several such bands are possible for the electron. But we shouldn't forget that there are a huge number of electrons supplied by various ions. For the sake of simplification let us assume that they don't feel each other (neglecting electron–electron interactions). The electrons can go to any of these levels and stay undisturbed. But the great physicist Pauli has shown that there cannot be two identical particles having half integer value of intrinsic angular momentum (spin) in a state. Electrons are half integer spin particles. Much of what we learn in chemistry can be understood by the judicious application of this principle, known as Pauli's exclusion principle.

In metals, the conduction band and in some cases the valence band energy levels are partially filled. In semiconductors and insulators, the valence band is filled and the conduction band is empty.

Let us come back to the main theme of our discussion – electrical conduction and electrical resistance. The electrons of the solid will be filling up the levels from the bottom up. As a result of this sort of filling, some of the lower bands get completely filled up. These bands are called valence bands. The top band that gets partially filled up or remains unfilled is called the conduction band.

This band structure is different in different classes of solids. This will help us in understanding why insulators are what they are and why metals behave the way they do. In metals, the conduction band and in some cases the valence band energy levels are partially filled. In semiconductors and insulators, the valence band is filled and the conduction band is empty. Here the two bands are separated by an energy gap which is large for insulators and small for semiconductors. The chance of an electron going from a valence band to the conduction band by thermal excitation is very small for insulators, but appreciable for semiconductors. As the temperature increases the probability for this event increases.

The resistance of all materials is temperature dependent. In this temperature dependence also they differ widely. In metals, the resistance increases as their temperature increases. But this is just the opposite in semiconductors. This shows that there is a

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fundamental difference between the electrical conduction in these classes of materials.

Electrical conduction is due to the flow of electrons. In metals this is how we describe the mechanism. But in semiconductors it is far more complicated and we can divide them into two types. In one type of doped materials, a better description would be in terms of a vacancy in an otherwise filled electron cloud. We call this as hole. This class of semiconductors is called P-type semiconductors. In the other type description of an electron is enough. This is called an N-type material. The P stands for positive charge and N stand for negative charge.

Electrical Conduction

Now let us have a look at how electrical conduction happens in solids. The electrons are distributed in energy bands. As a result there must be an electron, which occupies a level close to the unfilled energy levels of the conduction band. When an electric field is applied, this electron can be lifted to this higher energy level. Suppose we apply an electric field parallel to the x-axis. The electron will be going over to a higher energy level in which the particle will be moving parallel to the x-axis. This explains electrical conduction in metals.

But why the conductors offer resistance is still not clear. Here the culprit is the deviations of the ionic lattice (which govern the band structure) from the perfect configuration. The deviations can be due to defects, impurities and thermal vibrations of the lattice. In either case the effect of the deviations can be thought of as the scattering of electrons from one band state into another. The scattering due to impurities is temperature independent whereas that due to vibrations of the ionic lattice is temperature dependent. The amplitude of lattice vibrations is quantized (phonons) and the number of phonons occupying an energy level depends on the temperature.

The result of the scattering is not only a change in the direction of particles but also a transfer of energy from the electrons to the lattice. The result of the scattering is that the electrons that get accelerated by the electric field soon give up the energy to the lattice and thereby go to a lower velocity parallel to the field. Therefore the electron moves with acceleration inbetween collisions with the lattice and by collisions the electron's velocity can be thought of as going to zero. This gives us the picture that the electrons are moving with a drift velocity. The drift velocity is an average velocity. With an increase in the temperature what do we expect for the drift velocity? The temperature should take many electrons to higher energy levels. But these states do not have any preferred spatial orientation. And as a result there is no reduction in resistance with temperature. But as the temperature increases the electrons are suffering greater number of collisions per second and the mean free time between collisions is much reduced. This makes their resistance increase with temperature.

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In semiconductors, the larger resistance is due to the small number of mobile entities in the conduction band. But as the temperature increases the number of electrons that jump over to the conduction band from the valence band increases and as a result the resistance decreases with temperature in these materials.

Superconductivity

Now let us address the question of why the metals that offers electrical resistance lose all their resistance and start behaving in strange ways when cooled below certain temperatures called their transition (critical) temperatures. (*Figure* 1 shows how the resistivity of a superconductor changes with temperature.)

While discussing electrical resistance in metals we came across the role of lattice. But the electron which gets scattered to another state of lower energy at the same time excites a certain mode of lattice vibration (phonon) having a certain momentum and energy. If the temperature is below certain characteristic values then the lattice vibration will be able to give up this energy and momentum to another conduction electron. Thus though one electron loses its energy and momentum, another

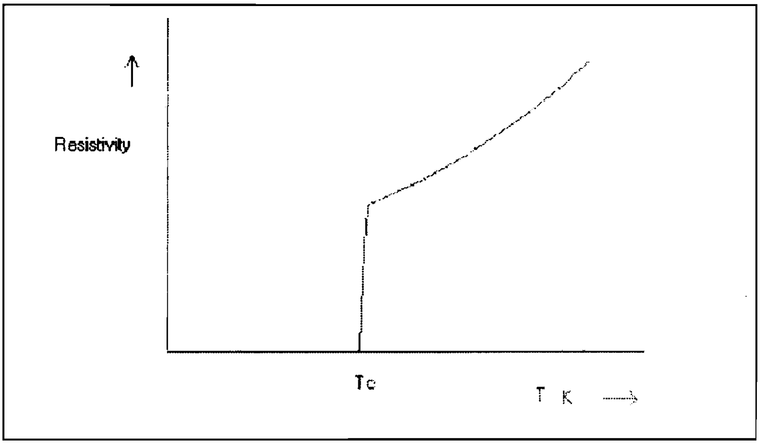


Figure 1. Temperature vs. resistivity.

electron recovers them. By such a virtual process two electrons can form a paired state in which their combined energy is less than that of the electrons with no such attractive interaction between them.

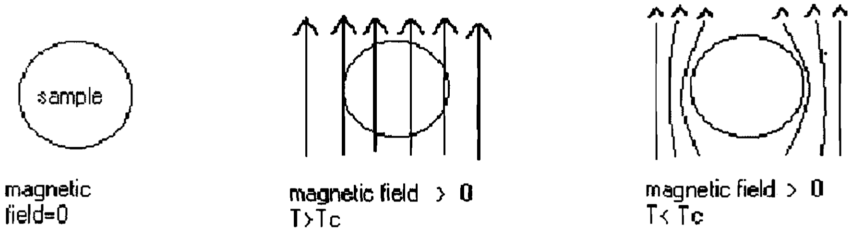
This is a simple-minded picture of what happens in these systems. Physicists conceive electron–electron interaction mediated by the lattice vibrations (phonons) as leading to a paired state called Cooper pair (*Box* 2). Thus if we conceive the system as forming pairs of charge carriers then there is a pair to pair coupling (pair-pair correlation). The distance over which pair correlations prevail is a characteristic length for a superconductor. It is called coherence length.

The paired condition has its rich dividends. We have seen that the scattering by lattice vibrations is one route to dissipate energy. The impurities and imperfections of the lattice are also contributing to scattering. How do the electrons overcome these sorts of events? The pairs and the coupling among pairs are so strong that their excitation energies are separated by a gap. The impurities cannot offer a potential strong enough to effect an excitation across this gap from the ground state.

According to quantum mechanics only those processes that permit a system to go from one quantized energy level to another can occur. Here the conduction electrons in paired states have their energy separated by an energy gap from excited states.

Box 2.

Superconductors also show novel magnetic behavior. If you apply a magnetic field to a metal and cool the metal below its superconducting transition temperature, then the strength of the magnetic field outside the specimen increases as if the magnetic flux lines present within the material previously have been pushed out of the specimen when it makes a transition to the superconducting state. See *Figure* 2. This type of behavior is not new to physics. There are materials, which behave like this. They are called diamagnetic materials. The superconductors also behave as diamagnetic materials in their superconducting state. The pairing theory (Cooper pair) and its sophisticated cousin theory christened BCS is capable of explaining this diamagnetic behavior called Meissner effect in addition to loss of electrical resistance.



Therefore defects and thermally generated lattice vibrations are not strong enough to scatter an electron across the energy gap when the system is below its transition temperature. This shows why the electrons in paired state when pushed to higher energy states of the conduction band by an applied electric field do not loss energy to the lattice by scattering.

What are the factors on which superconductivity depends? Materials superconduct below a certain temperature called the transition temperature. On what does this transition temperature depend? We have seen that the strength of the pair depends on the strength of the electron-phonon interaction. The more this interaction is, the more will be the resistance (or resistivity) of the metal in its normal state. Thus a metal with greater resistivity will make a transition to the superconducting state at a higher temperature than one with smaller resistivity. This is why it is said that a bad metal is a good superconductor.

The transition temperature of all elemental metals is below 20 K. Later it was found that one could synthesize alloys of metals with transition temperature as high as 23 K. The hunt for

Box 3.

J Georg Bednorz, a native of Federal Republic of Germany joined IBM Zurich in 1982 and started collaborating with Alex Muller, the Head of the Department of Physics in 1983. Thus an intense search for high temperature superconductivity in perovskites was started (perovskites were the area of interest of Muller) and this arduous course finally succeeded in the discovery of superconductivity (1986) first at temperatures below 77 K, the boiling point of liquid nitrogen and thereafter well above this temperature in various other materials of ceramic origin. They won the Nobel Prize in Physics the next year itself showing the greatness of their contribution.

superconductivity was extended to other classes of materials. There were suggestions that superconductivity of the kind shown by metals brought in by electron-phonon interaction cannot go beyond the transition temperature 23 K. Physicists explored the possibility of other novel elementary quantized excitations of condensed matter playing a role and effecting the formation of Cooper pairs. But this was largely fruitless.

Though the mechanism remains still inconclusive, towards the end of January 1986 superconductivity was discovered in ceramic materials like lanthanum barium copper oxide at around 30 K. Soon a new era of high temperatures superconductivity was ushered in with transition temperatures well above the boiling point of liquid nitrogen (77K) (*Box* 3). This class of anisotropic materials shows various anomalous normal state properties. It is still not clear how the dissipation of energy and transport of charge in these materials happen. There is a strong view that the band description will not hold in these materials. One has to incorporate the electron–electron interactions right at the beginning and solve the quantum mechanical problem. Condensed matter theoretical physicists call it the breakdown of fermi liquid theory of metals (proposed by Landau) in these systems. It seems that rather strong repulsive interactions among electrons are responsible for this difficulty. But still there is a general consensus that the description should be in terms of pair correlations.

Superconductivity finds applications in a variety of practical situations. Magnetic levitation of trains using magnets made by using superconducting coils has come to be a reality. Superconducting quantum interference devices find applications in resonance imaging techniques used in medical diagnostics. Computer hardware is another area where superconductivity promises many applications.

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Suggested Reading

[1] T V Ramakrishnan and CNR Rao, *Superconductivity Today*, Wiley Eastern Limited, 1992.