SUPERCONDUCTING MATERIALS AND DEVICES

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Summary

Superconductivity is a special property of some materials. If some non-magnetic metals such as niobium, alloys such as niobium aluminum or ceramics such as yttrium barium copper oxide are cooled to a sufficiently low temperature, the electrical resistivity drops away to a value close to zero. This phenomenon was first discovered in 1911 in Leiden by Kamerlingh Onnes three years after the liquefaction of helium, a gas at room temperature that can becomes a liquid at -268.8 ^{o}C (4.2 K). Other properties of

superconductivity are the exclusion of magnetic flux called the Meissner effect and the quantization of magnetic flux.

Small structures of superconductors isolated by a thin insulator are called Josephson junctions. These structures can be placed into a superconducting device, which is very sensitive to magnetic fields. These devices are called SQUIDs.

In 1987, there was great excitement with the discovery of a new class of superconducting materials called High Temperature Superconductors (HTS), which become superconducting at the relatively high cryogenic temperature of –200^{o}C.

This chapter describes superconductivity, the materials and some devices that can be formed and notes some of the applications for their use making them interesting materials.

1. Introduction

A short study of the list of Nobel prizes in physics will indicate that superconductivity has had 4 awards over 76 years. These awards are listed in Table 1.

Nobel Prize Winner	Year	Topic	Comments
Heike Kamerlingh Onnes	1913	Mercury becomes a superconductor when cooled by liquid helium	This was the discovery of superconductivity marking a new era in physics.
John Bardeen, Leon N. Cooper and J. Robert Schrieffer	1972	Explanation of the physics of superconductivity. The central feature of their theory, called the BCS theory, is the Cooper pair.	High temperature superconductivity in materials appears to be a special case of the BSC theory and is not completely understood.
Brian D. Josephson	1973	Dc Josephson effect	Inventor of the Josephson junction which is the basis of a large number of superconducting devices.
J. Georg Bednorz and K. Alexander Muller	1987	High temperature superconductivity	Developed the basis for the successful search for superconductors with T_c higher than 77 K.

Table 1: A list of the Nobel Prizes in Physics in the area of Superconductivity

This high level of interest by the physics community is due to their most unusual behavior requiring exciting research in physics, materials science and chemistry making them a very special class of materials. Furthermore, their application ranges over many different uses from detection of the minute magnetic fields that come from the brain to the basis of magnetically levitated trains and low loss power distribution.

This chapter will give a brief history of superconductivity, explain simply the physics of the phenomenon, describe the materials and then look briefly at their application in electronic devices. Although the main focus will be on the more recently discovered "high" temperature superconductors, some information on low temperature superconductors will also be given.

1.1. Some History

The new 20^{th} century saw not only major industrial changes but also many significant discoveries in physics. One center for physics research was in Leiden University, Holland where Kamerlingh Onnes was a scientist working on the liquefaction of gases. In 1908, Onnes succeeded in liquefying helium, a gas that becomes a liquid at –268.8^{o}C (or in the absolute temperature scale 4.2 K). Three years later in 1911, Onnes measured the resistance of mercury as it was cooled to these very low temperatures by submersion in liquid helium. He found that the resistance dropped to a value close to zero at a temperature of about 4.2 K. Onnes realized that he had witnessed a new state of the material, which he called the superconducting state. The temperature at which the material makes the transition from the normal state to the superconducting state is called the transition temperature or T_c. The actual critical temperature of a material is dependant on the purity of the material, the crystal orientation and whether it is a single crystal or polycrystalline sample.

Element	T_c, ^{o}K
Al	1.2
Cd	0.5
Ga	1.1
In	3.4
La(α)	4.8
La(β)	4.9
Pb	7.2
Hg(α)	4.2
Hg(β)	4.0
Mo	0.9
Nb	9.3
Os	0.7
Rh	0.5
Ta	4.5
Tc	8.2
Tl	2.4
Th	1.4
Sn	3.7

Ti	0.4
W	0.01
U(α)	0.6
U(β)	1.8
V	5.3
Zn	0.9
Zr	0.8

Compound	T_c, ^oK
$Nb_3Al_{0.8}Ge_{0.2}$	20.1
Nb_3Sn	18.1
Nb_3Al	17.5
Nb_3Au	11.5
Nb_3N	16.0
M0N	12.0
V_3Ga	16.5
Nb_3Ge	23.2

HTS Compound	T_c, ^oK
$La_{1.85}Ba_{0.15}CuO_4$	40
$YBa_2Cu_3O_{7-x}$	98
$HgBa_2CuO_{4+x}$	94
Bi-Sr-Cu-O	up to 115
Tl-Ba-Ca-Cu-O	up to 125
$YCaBa_4Cu_5(NO_3)_{0.3}(CO)_{0.7}O_{11}$	82

Table 2: A list of pure single crystal superconducting materials and their transition temperatures in the absolute temperature scale

Onnes found similar transitions in lead and tin. Among the elements, niobium was found to have the highest T_c of about 9.3 K. Many non-magnetic metals and alloys were found to be superconducting. These are listed with their T_c values in Table 2. Before 1986, the highest T_c of about 23.2 K was achieved in Nb_3Ge.

In 1986, there was great excitement in the world of physics when Bednorz and Muller of IBM Zurich announced cautiously that they had found a new class of superconducting materials. These materials were superconducting at what is thought in cryogenics to be a high temperature of 40 K. These materials were very interesting as they were not metals but rather ceramics of the copper oxide or cuprate family. Although liquid helium was still required to cool these materials, it excited an explosion of research to find a ceramic superconductor that has a critical temperature higher than the boiling point of liquid nitrogen. This was seen as a Holy Grail because helium is an expensive and difficult cryogenic liquid to handle and makes the application of superconductivity complex and costly. Liquid nitrogen, on the other hand, is cheap and relatively easy to handle. It can be contained in vacuum flasks and has a boil off rate 60 times less than helium. If these relatively high temperature superconductors could be found, the application of superconductivity would move from being limited to a laboratory curiosity to specialist applications such as superconducting magnets or magnetic field sensors. This creates the potential for the exploitation of a wide range of applications opening the way to new multi-billion dollar industries.

Success in finding a superconductor with a transition temperature above 77 K, the boiling point of nitrogen, was achieved by Paul Chu at the University of Houston and Wu at the University of Alabama. They found that $YBa_2Cu_3O_{7-x}$ (YBCO) was a ceramic that has a transition temperature of about 92 K. Since then there have been many other HTS materials that are superconducting. Only recently a new class of materials has been discovered to have superconducting properties. The material is MgB_2 with a transition temperature of 39 K, discovered by J. Akimitsu at Aoyama Gakuin University in Japan. Although it has a critical temperature below 77 K, it may lead to a new generation of materials, which are easier to handle and fabricate than the cuprates.

2. Superconducting Properties

The physics of superconductivity is complex and there are many excellent texts that give clear overviews. In this section, I wish to provide a sufficient understanding of superconductivity to give the reader a true appreciation of how special and exciting these materials are.

Superconductors have three main properties: zero resistance, exclusion of magnetic flux and quantum coherence. Each of these properties will be considered here.

2.1. Zero Resistance and Exclusion of Magnetic Flux

2.1.1. Background

Zero resistance is useful for applications such as high-field electromagnets because the power dissipation is minimal. If a superconductor has a current going through it, as there is no resistance, the current should persist indefinitely. In reality, a superconductor has a resistivity of about 10^{-24} Ωcm (c.f. Cu 1.7 x 10^{-6} Ωcm). This means that a current would persist in a superconductor for about 10^5 years. These resistive losses that cause the minute resistance are important mechanisms, which require understanding to enable the application of superconductivity.

Soon after its discovery, it was found that superconductivity was destroyed not only by heating a sample but also by the application of magnetic fields. In 1960's, a second type of superconductor called Type II was discovered during the study of the behavior of superconductors in magnetic fields.

To understand the properties of real superconducting materials, it is useful to start with the behavior of an ideal superconductor as understood by various theoretical approaches.

2.1.2. The Basic Quantities of T_c, H_c and I_c

An important magnetic characteristic of a bulk superconductor is its thermodynamic critical field, H_c. In normal materials, magnetic fields penetrate with only a small attenuation. In 1933, Meissner and Ochsenfeld found that when a superconductor is cooled below T_c in a weak magnetic field, $H<H_c$, the magnetic field within the superconductor is expelled. This expulsion of magnetic fields is called diamagnetism and is a fundamental property of superconductors. The effect is called the Meissner effect. This property can be easily realized in HTS materials where a bulk sample of superconductor is cooled in a dish with liquid nitrogen and a magnet is positioned above the superconductor. Because screening supercurrents flow in a thin surface layer of the sample, exactly canceling out the external field from the magnet, the magnetic field inside the superconductor is zero. However the magnet sees a magnetic field from the superconductor, which is equal in strength and has a like-pole causing the magnet to be repelled from the superconductor. This causes magnetic levitation as shown in Fig. 1.

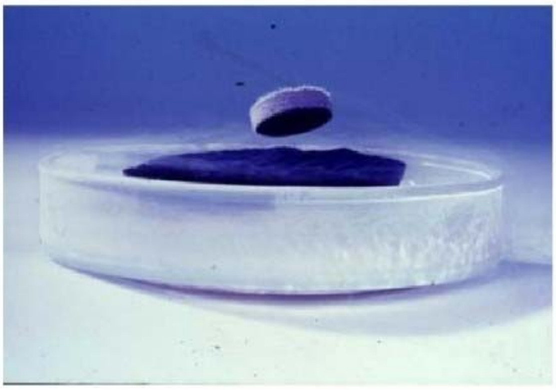

Figure 1: A photograph showing the levitation of an iron neodymium boride magnet over a bulk sample of high temperature superconducting material known as YBCO. The superconductor is cooled to 77 K by liquid nitrogen. This is an example of the Meissner effect

However at some field $H>H_c$, the superconducting state is unstable and a transition to the normal state with a finite resistance occurs. An empirical relation describing the dependence of H_c on temperature is given by:

$$H_c(T) = H_c(0)[1-(T/T_c)^2] \qquad (1)$$

with $H_c(0)$ being the value for elements typically less than 10^3 Oe. (See Table 3 for a listing of magnetic units.) The critical field vanishes as T gets close to T_c. This is schematically shown in Fig 2.

<u>Magnetic Flux Density (also known as Magnetic Induction)</u>
Symbol: B
Vector Quantity
Units:
1 gauss = 10^{-4} tesla (weber/m^2)

Magnetic Flux
Symbol: Φ

Scalar Quantity Units: weber= 10^8 maxwell **Magnetic Field Strength (also known as Magnetic Intensity)** Symbol: H Vector Quantity Units: amperes metre^{-1}=1.257x 10^{-2} oersted (1 oersted=$10^3/4\pi$ Am^{-1})

Table 3: Magnetic Units

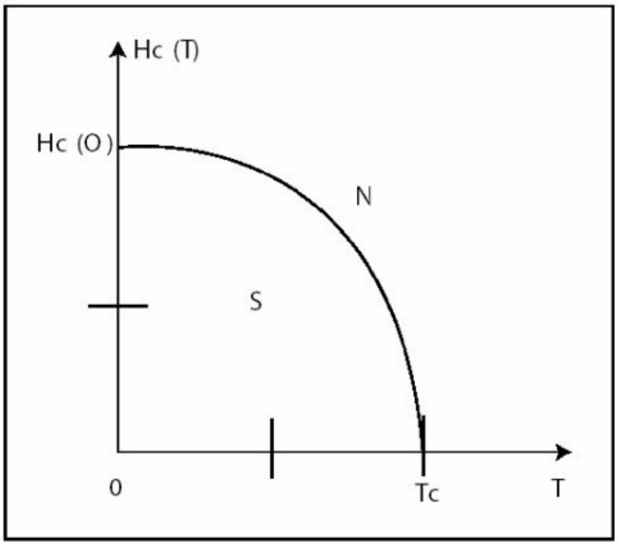

Figure 2: A graph showing the relationship of the critical magnetic field and temperature. "S" corresponds to the superconducting state and "N" corresponds to the normal state of the material

Another important characteristic of a superconductor is the maximum transport current which can flow without dissipation. This is called the critical current, I_c. Its value is very sample dependent and can be affected by the sample shape and material quality. There is a criterion that says a superconductor looses its zero resistance when, at any point on the surface, the total magnetic field strength, due to the transport current and applied magnetic field, exceeds the critical field strength H_c. This quantity, I_c, is called the critical current. I_c depends on the external magnetic field experienced by the superconductor and has typical values of the order of 10^6-10^8 A cm^{-2} depending on the sample temperature.

In reality, I_c is much smaller than the ideal value due to penetration of magnetic flux into a superconductor at fields lower than H_c. According to Abrikosov (1952) superconductors are classified into two kinds: Type I which has I_c described above and Type II where the complete flux expulsion at $H<H_c$ does not occur. (see Table 3).

2.1.3. Type I and Type II Superconductors.

In Type I superconductors, the magnetic field $H<H_c$ is completely screened due to the Meissner effect and zero resistance is preserved in fields up to H_c. Most Type I superconductors are pure elements such as aluminum, mercury and tin.

Type II superconductors are characterized by incomplete flux expulsion, even in small magnetic fields. Magnetic fields penetrate Type II superconductors in the form of superconducting vortices or discrete bundles. Each vortex carries a magnetic flux equal to the superconducting flux quantum, Φ_0. Φ_0 is a fundamental constant given by:

$$\Phi_0 = hc/2e \approx 2.07 \times 10^{-15} \text{ Wb}, \qquad (2)$$

where h is Plank's constant (6.6262 x 10^{-34} Js), e is the charge on an electron (1.60219 x 10^{-19} C) and c is the speed of light (2.997 x 10^{8} ms^{-1}).

Most practical superconductors are Type II superconductors. They can only be practical, however, if the magnetic vortices interact with the crystal lattice and are trapped to prevent them from moving when currents are passing through the superconductor. This notion of flux pinning is very important for most applications of superconductivity. A schematic diagram of the captured flux is shown in Fig. 3.

2.1.4. Microscopic Theory of Superconductivity

An explanation of why materials become superconducting came in1957, when John Bardeen, Leon N. Cooper and J. Robert Schrieffer published their Nobel Prize winning article reporting their theoretical work describing what is now called the BCS theory. (BCS comes from the authors' initials).

The Theory centers on the concept of the Cooper pair, which is two electrons of opposite spin and momentum which are bound together so that their total spin momentum is zero. The attractive force causing the pairing is from subtle interactions between the electrons and the positively charged ion cores in the superconducting material. These ion cores are pulled toward an electron as it moves through the lattice of the solid, creating a region of enhanced positive charge. This region attracts another electron from nearby. A common analogy used to describe this effect is two baseballs on a waterbed. If the indentations caused by the two baseballs overlap, the baseballs become attracted to each other. The two electrons are then weakly bound together with energy typically of one millielectron volt.

Normal electrons move with resistance because in ordinary conductors, impurities, defects and lattice vibrations (called phonons) deflect the moving single electrons. Such scattering of electrons gives the material resistance.

The energy binding the electrons together in a Cooper pair, though low, is high enough to prevent the pair from being separated by the scattering. Hence, the paired electrons or Cooper pairs move without resistance through the material. Very low temperature is essential because it reduces the lattice vibrations. At higher temperatures, the thermal energy is sufficient to break up or depair the Cooper pairs.

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Biographical Sketch

Catherine Foley received her BSc (Hons), DipEd. and PhD degrees from Macquarie University, Sydney Australia in 1980 and 1985. From 1985 to the present time, she has been a research scientist with the CSIRO Telecommunications and Industrial Physics starting as a Research Fellow in Magnetics Research to a Senior Principal Research Scientist and Leader of the Applied Quantum Systems Group. She has developed High Temperature Superconducting systems for mineral exploration, detection of metal for quality assurance in manufacturing and systems for security monitoring. This multiple million-dollar project assisted with the discovery and delineation of a number of mines and her team has commercialized several systems. Her group was the first team to successfully fly superconducting systems. Dr. Foley has a world-class reputation in her field being a Fellow of the Institute of Physics in the UK.

Dr. Foley is well known for her interests in quantum systems and superconductor physics, science education, women in science, science in the media and nuclear disarmament.