Chan-Joong Kim

Superconductor Levitation

Concepts and Experiments

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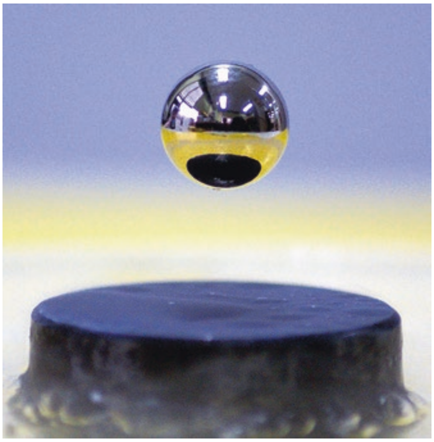
Chan-Joong Kim
Neutron Utilization Research Division
Korea Atomic Energy Research Institute
Daejeon, Korea (Republic of)

Illustrations by Jinwon Kim
Industrial and Management Engineering
Pohang University of Science and Technology
Pohang, Korea (Republic of)

ISBN 978-981-13-6767-0 ISBN 978-981-13-6768-7 (eBook)
https://doi.org/10.1007/978-981-13-6768-7

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore



Preface

Superconductors have two unique properties: the first is zero resistance, and the second is perfect diamagnetism. This perfect diamagnetism was discovered by the German physicist Meissner, and is called “Meissner effect.” Since superconductors repel the magnetic field of a magnet, they levitate above it. Following the discovery of high-temperature (T_c) superconductors in 1986 by Bednorz and Müller, Meissner effect can now be observed in general scientific laboratories.

I have been studying the manufacturing process and properties of high-T_c superconducting materials for over 30 years. Over the course of long-term studies, I planned and conducted many exciting experiments on superconductivity with students. I also collected useful photographs of the Meissner effect and the magnetic flux pinning of superconductors. I have explored the phenomenon of superconductivity through various superconducting experiments, and have included the useful knowledge in this book.

Chapter 1 introduces the history of superconducting phenomena, which formed the topic of a Nobel Prize in Physics. The discoveries of superconducting phenomena, BCS theory, Josephson tunnelling, Type 2 superconductors and the high-T_c superconductors are briefly summarized. It also describes the basic knowledge of superconductivity needed for superconductivity experiments, including zero resistance, persistent current, the Meissner effect, and superconductors of Types 1 and 2.

Chapter 2 introduces the method of synthesis of the high-T_c oxide superconductors used in superconductivity experiments. Descriptions are given of the solid-phase synthesis method in which raw powders are mixed and heated to form a superconducting phase, and the melt growth processes that produce large-grained superconductors with high magnetic levitation forces.

Chapters 3 and 4 present the method of the measurement of the magnetic levitation force and the magnetic field trapped in the superconductors. The magnetization process of superconductors using the mixed state of a Type 2 superconductor is described.

Chapter 5 introduces the Meissner effect experiment, in which a superconductor levitates above a magnet. Chapter 6 presents an easy way to measure the magnetic levitation force of a superconductor using a kitchen or electronic scale.

Chapter 7 introduces various superconducting levitation experiments. These experiments exploit both the perfect diamagnetism and trapped magnetic field in the (superconducting + normal) mixed state of Type 2 superconductors. A description is given of the field-cooling method that traps the magnetic force of the magnet in superconductors and a method for adjusting the position and height of the magnet levitating above a superconductor. Techniques for levitating multiple magnets, toy cars, a fishbowl, and human being above superconductors are also described.

Chapters 8 and 9 introduce superconducting suspension experiments using the flux pinning of superconductors. This phenomenon is known as the suspension effect or the fishing effect. Descriptions are given of the levitation of a superconductor above a single magnet, the simultaneous levitation of a superconductor and a magnet, the suspension of superconductors next to a magnet, a suspension experiment using a glass or measuring cup and a method for manufacturing a suspension experiment kit.

Chapter 10 explains how to make superconducting magnetic levitation (Maglev) trains. A description is given of the method of the elliptical magnetic rail, used for the demonstration of the Maglev train. A description is also given of how to construct the Maglev train with superconductors, how to cool the superconductors to keep the train moving on the rails, and how to adjust the levitation height of the train.

Finally, Chap. 11 summarizes the applications of superconductors, including a flywheel energy storage device with high energy storage efficiency, magnetic separation using bulk superconductors, frictionless bearings, current leads and superconductors for magnetic shielding, superconducting wires, and superconducting propulsion ships.

I am very pleased to have published a book on superconducting demonstration methods. This book is based on research conducted at the superconductivity laboratory of the Korea Atomic Energy Research Institute (KAERI). This book contains more than 400 original photos taken in the laboratory. I believe this is the first book to systematically summarize superconducting magnetic levitation and suspension experiments. I aimed to make it easy for the public to follow the superconductivity experiments, and I hope this book will provide useful information about superconductivity experiments to high school students, college students, science teachers and professors.

I would like to thank the students and collaborators who have conducted superconductivity research in the KAERI laboratory with me. I would also like to express my gratitude to my beloved wife Sunyoung, my daughter Sunkyoung and my son Sunho, who encouraged my research activities in daily life. Finally, I would like to share the proceeds of this book with missionaries working for God's kingdom.

Daejeon, Korea (Republic of) Chan-Joong Kim
February, 2019

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About the Author

Chan-Joong Kim is a Principal Research Scientist of the Korea Atomic Energy Research Institute. He was born in 1958. In 1990, he received a Ph.D. from the Korea Advanced Institute of Science and Technology on the topic of high-temperature oxide superconductors. In 1992, he worked as a postdoctoral fellow at the University of Notre Dame, USA, and as a visiting professor at the Shibaura Institute of Technology, Japan in 2010. He has published over 200 papers in the International Science Journal and published five books on science. The author has been teaching superconductivity to youth for over 20 years under the title of "Science Ambassadors." In 2017–2018, he served as a president of the Korea Society of Superconductivity.

Chapter 1
History of Superconductivity

1.1 Nobel Prizes in Superconductivity Research

The beginning of superconductivity [Heike Kamerlingh Onnes, Netherlands experimental physicist, 1853–1926]

The phenomenon of superconductivity, in which electricity flows without resistance, was first discovered by Kamerlingh Onnes of the University of Leiden. Onnes challenged the liquefaction of helium (He) gas and succeeded in liquefying He on July 10, 1908. As a result of the He liquefaction, he was recorded as the first scientist to achieve the lowest temperature (4.2 K,−269.1 °C) [1]. After that, his research team measured the electrical conductivity of pure metals at low temperatures. On 8 April 1911, He found that at 4.2 K, the resistance in a solid mercury wire immersed in liquid He (LHe) suddenly disappeared [2]. Onnes was awarded the Nobel Prize for Physics in 1913 for the achievements of reaching the lowest temperature through the liquefaction of He and the research work on the electrical properties of metals at low temperatures.

BCS theory [John Bardeen, 1908–1991], [Leon N Cooper, born in 1930], [John Robert Schrieffer, born in 1931]

Bardeen, Cooper, and Schrieffer of the University of Illinois, USA, won the Nobel Prize for Physics in 1972 for establishing the superconducting theory. Based on Cooper's electron pair model, they created an electron-phonon interaction model that explains the superconducting phenomenon [3]. This theory is called the BCS theory after the first letters of the names of proposers Bardeen (B), Cooper (C) and Schrieffer (S). Professor Bardeen is the only physicist to have received the Nobel Prize for Physics twice.

Josephson effect [Brian David Josephson, British physicist, born in 1940]

Paired superconducting electrons pass through a thin insulating layer. This phenomenon can be observed through a superconductor-insulation-superconductor

C.-J. Kim, *Superconductor Levitation*,
https://doi.org/10.1007/978-981-13-6768-7_1

junction called "Josephson junction." Josephson, a 22-year-old genius, published a paper in 1962 titled "Possible new effect in superconductive tunnelling" [4]. In it, he theoretically explained the tunnelling phenomenon of paired superconducting electrons in a solid. Josephson was awarded the Nobel Prize for Physics in 1973 along with Leo Esaki, the founder of the tunnelling phenomenon of Germanium (Ge) p-n junction diode, and Ivar Giaever.

High-temperature (T_c) superconductor [Karl Alexander Müller, Swiss physicist, born 1927], [Johannes Georg Bednorz, German physicist, born in 1950]

In 1986, Bednorz and Müller at the IBM Institute at Zürich found the superconducting phenomena that involved finding zero resistance in oxides of lanthanum-barium-copper-oxygen (La-Ba-Cu-O) [5]. After that, many oxide superconductors with a superconducting transition temperature (T_c) higher than liquid nitrogen (LN_2) temperature were discovered [6–8]. The discovery of superconductivity in the oxide materials with high T_c implied a modification of the BCS superconducting theory and the potential for creation of new industries with the material. Bednorz and Müller won the Nobel Prize for Physics in 1987, just 1 year after the publication of the article that followed the discovery of the high-T_c oxide superconductor.

Type 2 superconductor [Alexei A. Abrikosov, Russian theoretical physicist, born in 1928]

Single-element metal superconductors have only two states: a superconducting state and normal state. The metal superconductors are called Type 1 superconductors. When the temperature of the superconductor exceeds the T_c or the external magnetic field exceeds the critical magnetic limit, the superconducting state changes to a normal state. On the other hand, the alloy superconductors have two critical magnetic limits. The alloy superconductors are called Type 2 superconductors. The Russian physicist Abrikosov found that the magnetic field penetrating the superconductor had a complex sequence [9]. He explained how the Type 2 superconductors could accommodate both superconductivity and magnetism. His research became a breakthrough in the exploration of superconducting materials required in the industry. He received the Nobel Prize for Physics in 2003.

1.2 Zero Resistance

After the successful liquefaction of the He gas, Onnes studied the electrical resistance of the metal at low temperature. His research team chose mercury (Hg) as the research subject since mercury is a liquid at room temperature and as it was easy to make pure Hg without impurities. The purpose of this study was to minimize the influence of impurities on the resistance of Hg. His research team lowered the temperature while measuring the electric resistance of Hg. Surprisingly, the resistance of Hg disappeared at a specific temperature and he discovered the zero resistance superconducting phenomenon [2]. He named the phenomenon "superconductivity."

The research team then confirm the superconductivity in other metals such as lead (Pb) and tin (Sn) [10].

1.3 Persistent Current

Onnes expected the zero resistance of superconductors to change the energy industry innovatively. As the resistance of superconductors is zero, superconductors have no energy loss. Electricity may infinitely flow in the circuit made of the superconductor. It is also possible to manufacture a superconducting magnet that generates a large magnetic field. When the infinite power transmission and large magnetic field are put into practical use, the superconductivity phenomenon brings innovation to the energy industry.

Onnes experimented to confirm the zero-electric loss of the superconductor. His research team made a superconducting closed circuit using Pb wires [11, 12]. The circuit was cooled using LHe, and a magnetic field was applied to the circuit from the outside. This experiment was conducted in 1914. When an external magnetic field is applied to the conductor, a current is induced in the conductor according to Faraday's law [13]. A compass (a magnetic indicator) was placed outside the circuit to measure the magnetic field induced by the supercurrent. When they applied the magnetic field to the superconducting closed circuit, the compass moved due to the induced magnetic field. Furthermore, they found that the current induced in the superconducting closed circuit did not disappear in 24 h. This was comparable to the induced current of a normal conductor that disappeared shortly afterwards. He was delighted to find the persistent current of the superconductor.

1.4 Influence of Magnetic Field

Onnes thought that devices without energy loss can be made from the result of the persistent current experiment. The energy efficiency of electric motors, cables, generators, and magnets can be significantly improved using superconductors. Furthermore, due to the large current capacity of the superconductor, the electric devices can be downsized.

He predicted that the superconducting coil could generate a large magnetic field of 10 Tesla (T, 1 T = 100,000 Gauss (G)). However, he was unable to produce a large magnetic field from the persistent current experiment. When the current exceeded a critical value, resistance was generated in the superconducting wires. The metal superconductors could not withstand the small magnetic fields of several hundred G. To use the superconductor for practical applications, the superconductor should withstand a large magnetic field of several T. Unfortunately, the superconductivity of the metal superconductors discovered in earlier studies was destroyed in the small magnetic field 600 G [14]. Later, it was understood that the magnetic field interferes with the flow of the superconducting current.

He spent much time trying to understand the influence of magnetic field on superconductivity up to the First World War. His primary research objective was to make a powerful superconducting magnet of several T. However, he could not realize this dream during his lifetime. It took a few more decades for this dream to become true. Forty years after the discovery of superconductivity, his dream was partially realized by other researchers with the discovery of Type 2 superconductors that shows high current capacities in high magnetic fields [15].

1.5 Meissner Effect: Perfect Diamagnetism

Twenty years after the discovery of zero resistance by Onnes, in 1933, the German physicist Meissner (F.W. Meissner, 1882–1974) and his student Ochsenfeld discovered another superconducting phenomenon, perfect diamagnetism [16]. This phenomenon, in which the superconductor expels the magnetic field, is called "the Meissner effect."

In 1933, Meissner and Ochsenfeld tried to measure the magnetic field distribution in a superconducting state for high purity Sn and Pb single crystals. They filled the cooling vessel with LHe and placed a Pb plate on it. Then, they put a light ferrite magnet on top of the Pb plate. The ferrite magnet levitated above the Pb plate without touching the base of the dish.

When the Pb plate is placed in LHe, the temperature of Pb decreases and the Pb plate becomes superconducting. Since the Pb plate in the superconducting state repels the magnetic force of the ferrite magnet, the ferrite magnet levitates above the Pb plate. When the Pb plate is in the normal conducting state, the ferrite magnet falls to the Pb plate. Perfect diamagnetism is not a phenomenon caused by zero resistance but another feature of superconductivity.

It was difficult to conduct the Meissner effect experiments in science laboratories as the T_c of the superconductors discovered until then was quite low. Only a few research institutes equipped with an He liquefier were able to carry out the Meissner effect experiment. However, after the discovery of the La-Ba-Cu-O superconductor by Bednorz and Müller in 1986 [5], many oxide superconductors with a T_c higher than liquid nitrogen (LN_2) temperature (77 K) were discovered [6–8]. Now, we can easily observe the Meissner effect in science laboratories using LN_2.

1.6 Type 1 Superconductors

Superconductors are classified into Type 1 superconductors and Type 2 superconductors depending on how they react to external magnetic field (H). Figure 1.1 shows magnetic flux lines at (a) superconducting state and (b) normal state of Type 1 superconductor.

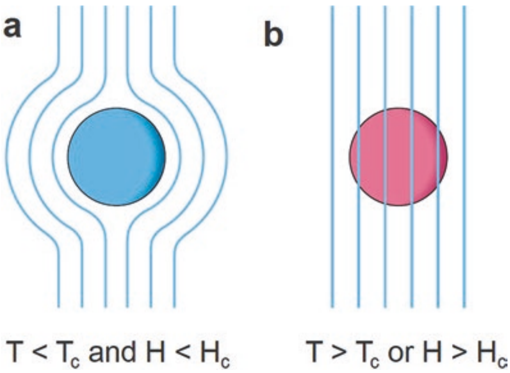

Fig. 1.1 Magnetic flux lines of Type 1 superconductors: (**a**) Superconducting state, (**b**) Normal state

In Type 1 superconductors, the superconducting state is suddenly destroyed when the external magnetic field exceeds the critical value (H_c) or the temperature (T) of the superconductor is higher than T_c. If $T < T_c$ and $H < H_c$, the magnetic field is pushed out of the superconductor (Fig. 1.1a), and if $T > T_c$ or $H > H_c$, the magnetic field passes through the superconductor (Fig.1.1b).

1.7 Type 2 Superconductors

The scientist who reported the most outstanding results in the superconducting theory after Onnes was Soviet physicist Lev Davidovich Landau (1908–1968). He proposed an idea to explain the relationship between superconductivity and magnetic field along with the former Soviet theoretical physicist Vitaly Ginzburg (1916–2009). They then developed the Ginzburg-Landau (GL) theory to explain the fundamental properties of superconductors in 1950 [17]. The approach was based on the general theory of the second order phase transition proposed by Landau in 1937.

The H_c of most Type 1 superconductors was not high. Because of the low H value, it is difficult to use Type 1 superconductors in practical applications. A new material that showed superconductivity in high magnetic fields was reported by Shubnikov of the Kharkov University of Ukraine in 1935 [18]. The material fabricated by Shubnikov was lead-indium (Pb-In) alloy crystals. Shubnikov pointed out that there were two magnetic field limits in the alloy superconductor. His work contained new exciting results on the magnetic properties of superconductors, but no one paid attention to his paper. In 1952, a decade after the publication of his paper, Russian physicist Abrikosov had an interest in Shubnikov's work, which showed the presence of two magnetic limits in the alloy superconductor. In the papers published so far, superconducting phenomena have been described as the two states of a superconducting state and a normal state. However, according to the results of Shubnikov, the superconducting-magnetic field relationship in alloy superconductors was not so simple. The Pb-In alloys showed two magnetic field limits. The alloy type superconductor is called "Type 2 superconductor."

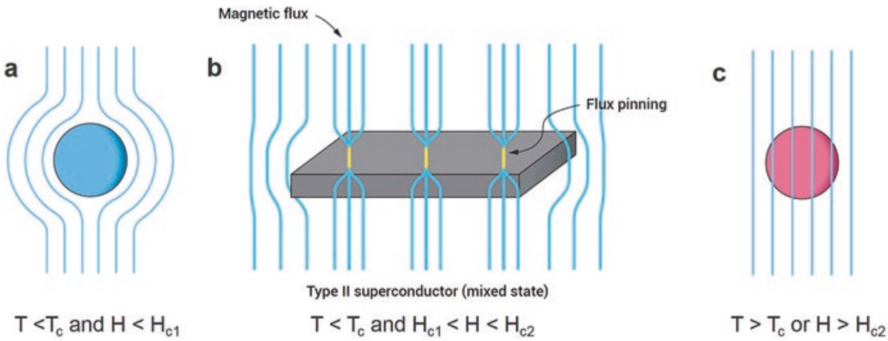

Fig. 1.2 Magnetic flux lines of Type 2 superconductor: (**a**) Superconducting state, (**b**) Mixed state, (**c**) Normal state

Figure 1.2 shows the magnetic flux lines of Type 2 superconductor. Type 2 superconductor has two critical magnetic fields: H_{c1} and H_{c2}. When $H < H_{c1}$, the magnetic field cannot enter the superconductor (a superconducting state, see Fig. 1.2a). When $H_{c1} < H < H_{c2}$, the magnetic field penetrates the superconductor, and the superconducting state is locally destroyed around a vortex. Therefore, the superconducting state and the normal state coexist (a mixed state). The vortex is often captured by defects present in the superconducting matrix (see Fig.1.2b). This phenomenon is called "Magnetic flux pinning." When $H > H_{c2}$, the superconducting state is destroyed entirely (a normal state, Fig.1.2c).

In 1957, a paper titled "On the magnetic properties of superconductors of the second group" was published in the Soviet Physics JETP [9]. This paper explained the motion of flux lines in alloy superconductors. After that, many Type 2 superconducting materials were discovered [19–22], and the experimental works that followed went on to prove the theory.

In 1961, the AT & T Bell Laboratories in the United States reported incredible results for the Type 2 superconductor as a result of the studies on the properties of the metal compound superconductors undertaken by the reseachers over a long period of time. One of the research objects was Nb_3Sn whose superconducting temperature is 18 K [21]. They measured the current properties of Nb_3Sn as a function of temperature and an external magnetic field. Surprisingly, the Nb_3Sn showed current densities exceeding 100,000 A/cm^2 in high magnetic fields as large as 88 kG (8,8 T) [15]. Later on, the existence of Type 2 superconductors was confirmed in many alloy type superconductors. The alloy superconductors showed the superconducting phenomenon even in high magnetic fields of several tens T. Nb_3Sn is currently used as superconducting wires to generate high magnetic fields [22].

Abrikosov received the Nobel Prize for Physics in 2003, 45 years after his paper was published. Shubnikov, who discovered the Type 2 superconductor experimentally, was victimized by the war and unfortunately did not enjoy the honor of being a discoverer.

Single element substances such as Hg, Pb and Sn are Type 1 superconductors and the alloy and oxide superconductors are Type 2 superconductors. Superconducting devices such as motors, generators, magnets, and medical MRI operate in magnetic field environments. Type 2 superconductors with high current characteristics at high magnetic fields can be used for these applications. Alloy compounds such as NbTi, Nb_3Sn, MgB_2, high-T_c oxide superconductors ($REBa_2Cu_3O_{7-y}$ (REBCO, RE: rare-earth elements), and $Bi_2Sr_2Ca_1Cu_2O_8$ (BSCCO)) belong to Type 2 superconductors.

1.8 BCS Theory

After Onnes discovered superconductivity, much research has been done to reveal the mechanism of superconductivity. Superconductivity could not be explained theoretically until 1950. In the early 1950s, Prof. John Bardeen, postdoctoral researcher Leon Cooper and John Robert Schrieffer, graduate student, studied superconducting theory at the University of Illinois, USA. Bardeen was interested in electron transfer in a superconducting state without resistance. He thought that the interaction between electrons and atomic lattice vibrations (phonons) would be essential in superconductivity.

Herbert Fröhlich (1905–1991), a theoretical physicist, published a paper describing the state in which electrons can attract each other [23]. He thought that superconductivity was a result of the interaction between electrons and phonon oscillations. He strongly suggested that most of the superconductors found so far have very high resistance at room temperature and that there is a close relationship between phonon oscillation and superconductivity. His suggestion was as follows:

Before examining the interaction between phonon oscillation and electrons, we assume that an attractive force acts between electrons, and one electron attracts positively charged ions, a (+) charge region forms. Electrons with the same sign of electric charge cannot directly attract each other, but if positively charged ions surround electrons, electrons may move together to the positively charged region, which can be said to be the attractive force acting between the two electrons. It is an unusual thought, but this assumption may theoretically serve as a clue to explain superconductivity.

In the 1950's, the resistance was found to be changed when isotopes are added to the superconductor [24, 25]. Isotopes are variants of specific chemical elements with different numbers of neutrons. Bardeen was interested in the results of isotopic studies. The isotopes are the same element, and only have a different mass. The fact that the isotope influences superconductivity implies that the mass of the element affects the movement of the electron. Bardeen thought that knowledge of particle physics is necessary to clarify superconductivity and invited Cooper to the University of Illinois.

An attractive force must exist between electrons to explain superconductivity. Classical Coulomb's law does not allow the attraction of electrons because electrons repel each other [26]. It is assumed that two electrons having different spins move in the opposite direction at the same speed. Due to the interaction between electrons and the ion matrix positively charged, the attractive force between electrons may become larger than the repulsive force.

Cooper suggested that if the electrons with the same charge attracted each other, the electrons would move in pairs without resistance. The pair of electrons that he proposed to explain zero-resistance superconductivity is called a "Cooper pair."

A mathematical interpretation has been added to Cooper's electron-pair model to complete the electron-phonon interaction model that describes superconductivity. This theory is called the BCS theory, named after its proposers Bardeen, Cooper and Schrieffer. The BCS theory presented in Physical Review [3] was accepted as a theory that can fully explain the superconductivity phenomena. Bardeen, Cooper and Schrieffer received the Nobel Prize for Physics in 1972 for their theoretical explanations of superconducting phenomena.

1.9 High-T_c Superconductors

Onnes discovered the superconducting phenomenon in 1911 [2]. By 1986 after more than 70 years, the T_c increased by only 19 °C. The BCS theory, which explained the superconducting phenomenon, said that T_c is not so high. Since the discovery of niobium gallium (Nb_3Ge, T_c = 23.3 K [19]) in 1973, which is a metal alloy type superconductor, there has been no progress in the research on the synthesis of new superconducting materials. The T_c of all superconductors found so far was lower than 30 K which is the T_c limit proposed by the BCS theory.

Karl Alexander Müller (born in 1927, a Swiss physicist) and Johannes Georg Bednorz (born in 1950, a German physicist) of Solid State Physics Laboratory at IBM Zurich synthesised a new superconducting material in the spring of 1986. That was the beginning of high-T_c superconductors.

Bednorz and Müller synthesised oxide superconducting materials. Barium oxide (BaO), copper oxide (CuO), and lanthanum oxide (La_2O_3) were used as raw materials for forming a new oxide with a perovskite structure. They synthesised many La-based compounds with various chemical compositions and heat treatment conditions using the powder reaction method. They prepared samples in different ratios of barium/lanthanum (Ba/La). T_c has increased rapidly in specific Ba/La ratio. They found a resistance drop of about 35 K on the temperature-resistance curve of the oxide compound. The T_c of the material was higher than the previously reported superconductors. They submitted a paper on the discovery of new superconducting materials to Z. Physic B [5].

Bednorz and Müller synthesised the La-based compounds by mixing and heating the raw powders. They would have compacted the synthesised powders into a form similar to the pellet shown in Fig. 1.3 and then heat-treated them under various conditions.

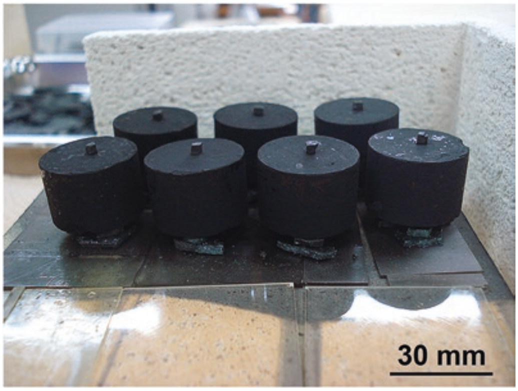

Fig. 1.3 Powder compacts for heat treatment

The oxide materials synthesised by Bednorz and Müller are rocky and brittle, and have low electrical conductivity at room temperature. Discovering new substances requires enthusiasm as well as effort. They attempted to synthesise about 300 oxides over 3 years. As a result of these efforts, they successfully synthesised the La-based oxides with a T_c of 35 K. The discovery of the new high-T_c superconducting oxide has greatly influenced the world scientific community during the late 1980s.

The results of Bednorz and Müller's work are important in physics. The BCS theory, which was published in 1959, and won the Nobel Prize for Physics in 1972, has been recognized as a theory that fully explains superconductivity. Scientists believed that the BCS theory solved all the secrets of superconductivity. The limit of T_c defined by BCS theory was between 30 and 40 K. This means that no material in the universe exhibits superconducting phenomena above 30–40 K.

Bednorz and Müller synthesised the La-Ba-Cu-O oxide superconductors. The T_c of the new high-T_c superconductor was about 35 K. This temperature is close to the T_c limit of the BCS theory. After that, many superconductors with a T_c exceeding the BCS limit were found in oxide materials [6–8]. For example, T_c of $YBa_2Cu_3O_{7-y}$ (YBCO or Y123) superconductor in which the La site of La-Ba-Cu-O oxide replaced by Y is 93 K [6]. Scientists thought that there was a new secret behind superconductivity that they did not realize, or that the BCS theory might have been modified. After the discovery of the new superconductor, many studies began to discover new materials with a higher T_c. Bednorz and Müller received the Nobel Prize for Physics in 1987, only a year after publishing the paper.

1.10 High-T_c and Low-T_c

Superconductors are substances that exhibit superconducting phenomena. In the early study, "superconductivity" meant that the resistance at a certain temperature was zero. However, German physicist Meissner discovered that the superconductors have a perfect diamagnetic phenomenon that expels the magnetic field. It has been shown that perfect diamagnetism is another feature of superconductivity that is different from zero resistance. Therefore, when you say, "This material is a superconductor," the material must have zero resistance at a certain temperature and at the same time be completely diamagnetic.

The oxide superconductors found after La-Ba-Cu-O are called "high-T_c superconductors." YBCO has a T_c of 93 K (−180 °C) and 14 K higher than the LN_2 temperature (77 K, −196 °C). However, this temperature is still quite low. Why do people call this oxide superconductor a high-T_c superconductor? The reason for this: The term "high-T_c" superconductor means that there is a superconductor with a low T_c. Actually, other substances called a low-T_c superconductor exist. The T_c of the low-T_c superconductors was less than 30 K. For example, the T_c of V_3Ga and Nb_3Sn, the low-T_c superconductors, is 16.5 K [20] and 18 K [21] respectively. Compared to the low-T_c superconductors, the T_c of oxide superconductors is relatively high. This is the first reason behind naming oxide superconductors as high-T_c superconductors.

BCS theory, which is based on the interaction between atomic oscillation and electrons, clearly illustrates the superconductivity of low-T_c superconductors. According to the BCS theory, the T_c of a superconductor should be lower than 30–40 K. After the La-Ba-Cu-O oxide superconductor, many other high-T_c superconductors were found. The T_c of the oxide superconductors exceeded 100 K. For example, The T_c of Bi-Sr-Ca-Cu-O [27], Tl-Ba-Ca-Cu-O [8], and Hg-Ba-Ca-Cu-O [28] are 110 K, 120 K, and 133 K, respectively. It suggests that the BCS theory needs to be modified to explain the high T_c of the oxide superconductors. This is another reason why oxide superconductors are called "high-T_c" superconductors.

Figure 1.4 shows the Meissner effect of the high-T_c oxide superconductor. The YBCO oxide superconductor is levitating above a ring-shaped Nd-B-Fe magnet. The oxide superconductor was cooled using LN_2. The perfect diamagnetism of the superconductor that expels the magnetic force causes the superconductor to levitate above the ring-shaped magnets. The discovery of high-T_c superconductors whose T_c is higher than the LN_2 temperature enabled the Meissner effect experiments in general science laboratories.

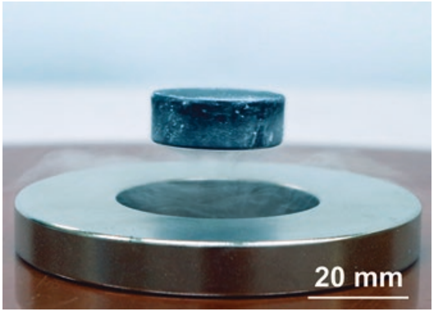

Fig. 1.4 Meissner effect of a high-T_c oxide superconductor

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Chapter 2
Synthesis of High-T_c Oxide Superconductors

2.1 Introduction

Perfect diamagnetism and zero resistance are unique phenomena of superconductivity. Because of perfect diamagnetism, superconductors push against the magnetic field of magnets. Therefore, a high-T_c oxide superconductor cooled using LN_2 levitates above a magnet. People may think that superconducting materials are not easy to synthesize because the superconducting phenomenon is a special physical phenomenon occurring in particular materials. However, synthesising superconductors is not difficult. People can manufacture superconductors in scientific laboratories. Synthesising an oxide superconductor consists of weighing raw material powder, powder mixing, calcination to synthesise a superconducting phase, forming, and sintering for increasing density, etc. For the calcination and sintering processes, a heat treatment furnace that can heat up to 1000 °C is needed. The manufacturing method for $YBa_2Cu_3O_{7-y}$ (Y123) superconductors used for superconducting magnetic levitation experiments and measuring the magnetic levitation forces of superconductors are described in this chapter.

2.2 Solid State Reaction Process

2.2.1 Materials Needed for Synthesis

1. Raw material powder: It is recommended to use powder with a purity of 99.9% or more of yttrium oxide (Y_2O_3), barium carbonate ($BaCO_3$), barium oxide (BaO) and copper oxide (CuO) (see Fig. 2.1). The higher the raw material purity, the better the superconductor quality.
2. Digital balance: A scale is necessary to measure the weight of raw powder, powder mixture and calcined cakes. A laboratory electronic scale is needed for

C.-J. Kim, *Superconductor Levitation*,
https://doi.org/10.1007/978-981-13-6768-7_2