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Rainer Wesche

High-Temperature Superconductors

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Preface

More than 110 years ago, the history of superconductivity started with the discovery of the phenomenon by Heike Kamerlingh Onnes in 1911 at the University of Leiden. The discovery by J. G. Bednorz and K. A. Müller that the superconducting state can exist in complex oxides at temperatures above 30 K stimulated research in the field of superconductivity and opened up high-temperature superconductivity as a new field of research. Within a few years, a large number of cuprate superconductors with transition temperatures well above 77 K, the boiling point of liquid nitrogen, was discovered. The possibility of cooling superconducting magnets and cables with liquid nitrogen re-stimulated the interest in applications of superconductivity in the electric power sector. The cuprate high-T_c superconductors provide not only critical temperatures above 77 K but also extremely high upper critical fields above 100 T. The interest in the use of high-T_c superconductors for the generation of extremely high magnetic fields not accessible with Nb_3Sn increased in the last decade and is today one driver in the development of high-T_c superconductor wires and tapes. The development of a generally accepted, consistent theory of high-temperature superconductivity is still a subject of research.

A big surprise in the field was the discovery in 2001 that MgB_2, a simple binary compound known since the nineteen-fifties, is superconducting at a temperature as high as 39 K. In 2008, Hosono et al. discovered high-T_c superconductivity in iron-pnictide superconductors with a maximum known critical temperature of 58 K. The iron-based superconductors (iron-pnictides, iron-chalcogenides) have to be considered as a second class of chemically complex high-temperature superconductors. A further interesting phenomenon is the discovery of superconductivity at the $SrTiO_3$/FeSe interface. In a monolayer of FeSe, the transition temperature can exceed 65 K.

The study of the superconductivity of elements under high pressure led to the discovery of critical temperatures up to 29 K (Ca at 216 GPa). Drozdov et al. reported transition temperatures above 200 K in sulfur and lanthanum hydrides under extremely high pressures above 150 GPa. In both hydrides, a pronounced isotope effect was observed suggesting that the electron-phonon interaction is of importance as in conventional metallic superconductors.

The present book illustrates the status of the field in mid-2023 and focuses on cuprate and iron-based high-T_c superconductors. The special case of MgB_2 is also described in more detail. Besides the main physical properties of these superconductors, the status of the manufacture and the performance of superconducting wires and tapes is described. Because of their importance for superconductor electronics and measurement techniques, the deposition and the properties of superconductor films are also briefly considered.

Finally, an outlook on future research and development and potential applications of high-temperature superconductivity is provided.

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Bad Zurzach, Switzerland Rainer Wesche

About This Book

The book should be suitable for use in graduate-level courses on superconductivity. It focuses on the status of research and development in the field of high-temperature superconductivity reached in mid-2023.

In Chap. 1, the main characteristics of the superconducting state and economic aspects for applications of superconductivity are introduced. Chapter 2 provides a brief overview of the milestones in the history of superconductivity including the discovery of new superconducting materials (cuprate superconductors, superconducting iron-pnictides and iron-chalcogenides, MgB_2). Steps towards superconducting magnets are briefly mentioned. As a basis for the description of the properties of high-T_c superconductors, Chap. 3 describes the superconducting state in conventional metallic superconductors and highlights the fact that superconductivity is a macroscopic quantum phenomenon. Some of the main results of the BCS theory are briefly presented.

Chapter 4 provides an overview of various classes of superconducting materials including metals, alloys, intermetallic compounds, molecular superconductors (organic superconductors, fullerides), magnesium diboride, cuprate and iron-based high-T_c superconductors. The layered crystal structures of MgB_2, cuprate and iron-based high-T_c superconductors are described. The phase diagrams of cuprate high-T_c superconductors indicate that a superconducting state evolves from an antiferromagnetic Mott insulator by means of doping. The relations between the critical temperature and the doping level are discussed. Outstanding features of cuprate superconductors are the occurrence of a pseudogap well above the critical temperature and the d-wave symmetry of the superconducting energy gap. In iron-pnictides, a superconducting state evolves from a metal with magnetic ordering by means of doping. Recent results on the superconductivity of elements and hydrides under extremely high pressure are presented.

Chapter 5 is devoted to selected physical properties of high-T_c superconductors including the special case of MgB_2. Starting from the characteristic length scales, the weak link problem (blocking of the supercurrents by high-angle grain boundaries) in high-T_c superconductors is discussed. The critical fields are presented, and the occurrence of an irreversibility field well below the upper critical field is highlighted. Data of the normal state resistivity, the thermal conductivity and the specific heat are provided.

In Chap. 6, the deposition and the properties of superconductor films are described. The relations between film thickness and critical temperature are considered. The dependence of the critical temperature on epitaxial strain is discussed. The properties of multilayers and the occurrence of interfacial superconductivity are further aspects of importance.

Chapter 7 describes the manufacture of superconducting wires and tapes. First generation high-T_c and MgB_2 wires and tapes are industrially manufactured by the powder-in-tube (PIT) method. The PIT method has also been used for the manufacture of developmental iron-based superconductor wires and tapes. Because of the need for a biaxial texture, $REBa_2Cu_3O_{7-x}$ coated conductors are manufactured by means of the deposition of a superconductor film on long, flexible metallic substrates with suitable buffer layers.

In Chap. 8, the performance of developmental and industrially manufactured high-T_c and MgB_2 superconductor wires and tapes is presented. The effect of strain and stress on the superconducting properties of various superconducting wires and tapes is discussed.

Chapter 9 provides an outlook on possible future research and development in the field of high-T_c superconductivity. Potential further progress in the manufacture of superconducting wires and tapes is briefly discussed. Many applications require currents much higher than the critical current of single wires and tapes, and hence superconducting cables are required. Possible designs of cables made of superconducting tapes with a high aspect ratio are introduced. Finally, possible applications of high-T_c superconductors are mentioned.

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About the Author

Rainer Wesche studied Physics at the University of Constance, Germany. After completing his diploma in 1984, he was assistant during 1985–1989 (Ph.D. in 1988). From 1989 to 1993, he was a research scientist at the Paul Scherrer Institute in Switzerland, where he led an experimental study of high-current applications of high-T_c superconductors funded by the Swiss National Science Foundation. Since 1994, he has been a senior scientist at the Swiss Federal Institute of Technology Lausanne. His research is in the field of applied superconductivity.

Abbreviations

A	Alkali Atoms (Li or Na)
AAS	Atomic Absorption Spectroscopy
ABAD	Alternating Beam Assisted Deposition
AE	Alkaline Earth
AMR	Angular Magneto-Resistivity
ARPES	Angle-Resolved Photoemission Spectroscopy
Ba-122	$Ba(Fe_{1-x}Co_x)_2As_2$
Ba-122	$Ba_{1-x}K_xFe_2As_2$
Ba-122	$BaFe_2(As_{1-x}P_x)_2$
(Ba, K)-122	$Ba_{1-x}K_xFe_2As_2$
(Ba, Na)-122	$Ba_{1-x}Na_xFe_2As_2$
$B_{c1} = \mu_0 H_{c1}$	Lower Critical Field
$B_{c2} = \mu_0 H_{c2}$	Upper Critical Field
BCS theory	Bardeen-Cooper-Schrieffer Theory
Bi-22(n-1)n	$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$
Bi-2201	$Bi_2Sr_2CuO_{6+x}$
Bi-2212	$Bi_2Sr_2CaCu_2O_{8+x}$
Bi-2223	$Bi_2Sr_2Ca_2Cu_3O_{10+x}$
Bi-2223	$(Bi_{1-x}Pb_x)_2Sr_2Ca_2Cu_3O_{10+x}$
(Bi, Pb)-2223	$(Bi_{1-x}Pb_x)_2Sr_2Ca_2Cu_3O_{10+x}$
BSCCO	Bi-Sr-Ca-Cu-O (Bi-2223)
(Ca, K)-1144	$CaKFe_4As_4$
Ce-1111	$CeFeAsO_{1-x}F_x$ or $CeFeAsO_{1-x}H_x$
Ch	Chalcogenide (S, Se, Te)
CORC cables	Conductor On Round Core cables
d_i	Inner Diameter
d_o	Outer Diameter
Dy-123	$DyBa_2Cu_3O_{7-x}$

EIES	Electron Impact Emission Spectroscopy
ESE	Extrapolative Scaling Expression
Eu-123	$EuBa_2Cu_3O_{7-x}$
EuBaCuO	Eu-123
FC	Field-Cooled
Fe(Se, Te)	$FeSe_{1-x}Te_x$
Gd-1111	$GdFeAsO_{1-x}F_x$ or $GdFeAsO_{1-x}H_x$
GdBaCuO	$GdBa_2Cu_3O_{7-x}$
(Hg, Cu)-1201	$(Hg, Cu)Ba_2CuO_{4+x}$
Hg-12(n-1)n	$HgBa_2Ca_{n-1}Cu_nO_{2n+2}$
Hg-1201	$HgBa_2CuO_{4+x}$
Hg-1212	$HgBa_2CaCu_2O_{6+x}$
Hg-1223	$HgBa_2Ca_2Cu_3O_{8+x}$
HIP	Hot Isostatic Pressing
HP	Hot-Pressed
HPCVD	Hybrid Physical-Chemical Vapor Deposition
HTS	Cuprate High-T_c Superconductor
IBAD	Ion-Beam-Assisted Deposition
IBS	Iron-Based Superconductors
I_c	Critical Current
I_{c0}	Critical Current at Zero Strain
IMD	Internal Magnesium Diffusion
ISD	Inclined Substrate Deposition
ITER	International Thermonuclear Experimental Reactor
J_c	Critical Current Density
J_e	Engineering Critical Current Density
La-1111	$LaFeAsO_{1-x}F_x$ or $LaFeAsO_{1-x}H_x$
La-214	$(La_{1-x}M_x)_2CuO_4$, M = Sr or Ba
La-Ba-Cu-O	$La_{2-x}Ba_xCuO_4$
LAO	$LaAlO_3$
Ln	Lanthanide
MBE	Molecular Beam Epitaxy
MOCVD	Metal Organic Chemical Vapor Deposition
MOD	Metal Organic Decomposition
Nd-1111	$NdFeAsO_{1-x}F_x$ or $NdFeAsO_{1-x}H_x$
N-I-N contact	Normal Conductor-Insulator-Normal Conductor Contact
NMR	Nuclear Magnetic Resonance
PLD	Pulsed Laser Deposition
PIT method	Powder-In-Tube Method
Pr-123	$PrBa_2Cu_3O_{7-x}$
RABiTS	Rolling Assisted Biaxially Textured Substrate

RE	Rare Earth Element
RE-123	$REBa_2Cu_3O_{7-x}$
RE-Ba-Cu-O	$REBa_2Cu_3O_{7-x}$
RRR	Residual Resistivity Ratio
S-I-S contact	Superconductor-Insulator-Superconductor Contact
Sm-1111	$SmFeAsO_{1-x}F_x$ or $SmFeAsO_{1-x}H_x$
Sm-123	$SmBa_2Cu_3O_{7-x}$
Sr-122	$Sr(Fe_{1-x}Co_x)_2As_2$ or $(Sr_{1-x}K_x)Fe_2As_2$
SS	Stainless Steel
STAR REBaCuO wires	Symmetric Tape Round REBaCuO Wires
STO	$SrTiO_3$
STS	Scanning Tunneling Spectroscopy
T_c	Critical Temperature
TFA	TriFluoroAcetic Acid
Tl-12(n-1)n	$TlM_2Ca_{n-1}Cu_nO_{2n+3}$, M = Sr or Ba
Tl-1212	$TlBa_2CaCu_2O_7$
Tl-22(n-1)n	$Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4}$
Tl-2212	$Tl_2Ba_2CaCu_2O_{8+x}$
Tl-2223	$Tl_2Ba_2Ca_2Cu_3O_{10+x}$
WP	Winding Pack
Y-123	$YBa_2Cu_3O_{7-x}$
Y-124	$YBa_2Cu_4O_8$
(Y, Pr)-123	$Y_{0.5}Pr_{0.5}Ba_2Cu_3O_{7-x}$
ZFC	Zero-Field-Cooled

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Introduction

1

Abstract

The two outstanding features of the superconducting state are current transport without resistance and perfect diamagnetism. The sudden drop to zero resistance occurs at the critical temperature, which is a characteristic property of the superconductor in question. The discovery of high-temperature superconductivity in 1986 shifted the known critical temperatures from 23.2 K in metallic superconductors to values well above 30 K in copper-oxide (cuprate) high-temperature superconductors. A remarkably high critical temperature of 39 K has also been found in MgB_2. Transition temperatures well above 77 K, providing the possibility of significantly reduced cooling cost, re-established the interest in applications of superconductivity in the power sector.

1.1 The Main Characteristics of the Superconducting State

The two outstanding characteristics of the superconducting state are current transport with zero resistance and perfect diamagnetism. At the transition temperature, typically denoted as the critical temperature (T_c), the resistance suddenly drops several orders of magnitude to an unmeasurably small value. The phenomenon of zero resistance was first observed in mercury, tin, lead, and thallium [1]. The critical temperature is a characteristic property of the superconductor in question. In addition to the loss of electrical resistivity, a magnetic flux is excluded from the interior of a superconductor below T_c. The transition temperature can be determined by measurements of the resistance or the magnetization of the superconductor as a function of temperature.

In principle, it is not possible to prove experimentally that the resistance in the superconducting state is in fact zero. The detection of the decay of the magnetic field caused by a current induced in a superconducting loop is the most accurate way to determine

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an upper limit of the resistance. Upper resistivity limits between 3.6×10^{-23} and 2×10^{-18} Ω cm have been reported for lead [2] and $YBa_2Cu_3O_7$ [3, 4]. These values are orders of magnitude smaller than the resistivity of 10^{-10} Ω cm achievable in very pure and annealed metals, and hence it is justified to assume zero resistance below T_c for all practical applications.

In Fig. 1.1, the transitions to the superconducting state in a low- and a high-temperature superconductor are compared. The magnetically measured critical temperature of lead [5], a low-temperature superconductor with a midpoint T_c of 7.193 K, is presented in Fig. 1.1a. The transition to the superconducting state occurs within a temperature interval of less than 5 mK. The resistively measured transition temperature of a sintered $La_{1.85}Sr_{0.15}CuO_4$ high-temperature superconductor is shown in Fig. 1.1b. The measured T_c is 36.3 K with a transition width of more than 2 K [6].

Due to the broadened transition, the critical temperature of high-T_c superconductors depends slightly on the criterion used to define T_c. In Fig. 1.2, different definitions of the critical temperature are illustrated for a Ag/Bi-2212 wire with the $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) filaments embedded in a silver matrix. The onset of the transition starts at a temperature of 92.1 K and the end of the transition is reached at 89.3 K, while the midpoint of the transition is at a temperature of 90.3 K. Because of the difficulty to exactly determine the onset and the end of the transition, it is more convenient to use the difference of the values $T_c(90\%)$ and $T_c(10\%)$ to define the transition width $\Delta T_c \cong 90.9\ \text{K} - 89.7\ \text{K} = 1.2\ \text{K}$.

In Fig. 1.3, the magnetic behavior of a superconductor is compared with that of a perfect conductor. The magnetic behavior for zero-field-cooling is presented in Fig. 1.3a, where the temperature of the superconductor is lowered below T_c in the absence of an applied magnetic field. The application of an external magnetic field at a temperature below T_c induces screening currents in the surface layer of the superconducting sphere, which generate a magnetic flux opposite to that of the applied magnetic field leading to zero flux density everywhere inside the superconductor. Because of the superposition of the magnetic flux of the applied magnetic field and that generated by the screening currents in the surface layer of the superconductor the magnetic flux outside of the sphere is enhanced. The removal of the applied magnetic field induces screening currents in the opposite direction leading to an unmagnetized superconductor. A perfect conductor would show a similar behavior. In Fig. 1.3b, the magnetic behavior of a field-cooled superconductor is illustrated. The magnetic field is applied at a temperature above T_c and the magnetic flux enters the interior of the superconductor in the normal state. The temperature of the superconductor is lowered below T_c in the presence of the applied magnetic field. At the transition to the superconducting state the magnetic flux is expelled from the interior of the superconductor. This remarkable behavior cannot be explained by perfect conductivity. The different behavior of a field-cooled perfect conductor is shown in Fig. 1.3c. Because of the fact, that the magnetic field has been applied in the resistive state the magnetic flux enters the interior of the perfect conductor. The lowering of temperature