

14/5, 76.

Volume 3

LOW TEMPERATURE PHYSICS - LT 13



Superconductivity

Edited by

K. D. Timmerhaus, W. J. O'Sullivan, and E. F. Hammel

LOW TEMPERATURE PHYSICS-LT 13

Edited by

K. D. Timmerhaus

University of Colorado
Boulder, Colorado and
National Science Foundation
Washington, D.C.

W. J. O'Sullivan

University of Colorado
Boulder, Colorado

and

E. F. Hammel

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico

Volume 3: Superconductivity

PLENUM PRESS • NEW YORK-LONDON

Library of Congress Cataloging in Publication Data

International Conference on Low Temperature Physics, 13th, University of Colorado, 1972
Low Temperature physics—LT 13; [proceedings]

Includes bibliographical references.

CONTENTS: v. 1. Quantum fluids.—v. 2. Quantum crystals and magnetism.—v. 3. Superconductivity.—v. 4. Electronic properties, instrumentation, and measurement.

1. Low Temperatures—Congresses. 2. Free electron theory of metals—Congresses. 3. Energy-band theory of solids—Congresses. I. Timmerhaus, Klaus D., ed. II. O'Sullivan, William John, ed. III. Hammel, E. F., 1918- ed. IV. Title.

QC278.1512 1972 536'.56 73-81092
ISBN 0-306-35123-4(v. 3)

The proceedings of the XIIIth International Conference on Low Temperature Physics, University of Colorado, Boulder, Colorado, August 21-25, 1972, will be published in four volumes, of which this is volume three.

©1974 Plenum Press, New York
A Division of Plenum Publishing Corporation
227 West 17th Street, New York, N.Y. 10011

United Kingdom edition published by Plenum Press, London
A Division of Plenum Publishing Company, Ltd.
4a Lower John Street, London W1R 3PD, England

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, microfilming, recording, or otherwise, without written permission from the Publisher

Printed in the United States of America

Contents*

Superconductivity

1. Plenary Topics

A Survey of Superconducting Materials. <i>J. K. Hulm and R. D. Blaugher</i>	3
Fluctuations in Superconductors. <i>M. Tinkham</i>	14
Superconductivity at High Pressures. <i>J. L. Olsen</i>	27

2. Type II Superconductors

2.1. Structures

Structure of a Vortex in a Dirty Superconductor. <i>R. J. Watts-Tobin and G. M. Waterworth</i>	37
Observation of Landau-Type Branching in the Intermediate State. <i>J. F. Allen and R. A. Lerski</i>	42
Attractive Interaction between Vortices in Type II Superconductors at Arbitrary Temperatures. <i>M. C. Leung and A. E. Jacobs</i>	46
Calculation of the Vortex Structure at All Temperatures. <i>L. Kramer and W. Pesch</i>	49
Magnetic Field Distribution in Type II Superconductors by Neutron Diffraction. <i>J. Schelten, H. Ullmaier, G. Lippmann, and W. Schmatz</i>	54
Neutron Diffraction Test of Type II Theories in Relation to Temperature. <i>R. Kahn and P. Thorel</i>	64
Nuclear Spin-Spin Relaxation in Superconducting Mixed-State Vanadium. <i>A. Z. Genack and A. G. Redfield</i>	69

2.2. Properties

On the Nature of Flux Transport Noise. <i>C. Heiden</i>	75
Flux Kinetics Associated with Flux Jumps in Type II Superconductors. <i>R. B. Harrison, M. R. Wertheimer, and L. S. Wright</i>	79
Impurity Effect on the Anisotropy of the Upper Critical Field of Nb-Ta Alloys. <i>N. Ohta, M. Yamamoto, and T. Ohtsuka</i>	82
Vortex Transport Interference Transitions. <i>A. T. Fiory</i>	86
An Alternating Current Investigation of Pinning Sites. <i>J. Lowell</i>	90
Effects of Surface Superconductivity in Low κ Al-Ag Alloys. <i>A. Nemoz and J. C. Solecki</i>	95

* Tables of contents for Volumes 1, 2, and 4 and an index to contributors appear at the back of this volume.

A Model for Flux Pinning in Superconductors. <i>John R. Clem</i>	102
Flux Flow of Pure and Dirty Superconductors. <i>Y. Muto, S. Shinzawa, N. Kobayashi, and K. Noto</i>	107
The Specific Heat of Very Pure Niobium in the Meissner and Mixed States. <i>C. E. Gough</i>	112
Temperature Dependence of Ultrasonic Attenuation in the Mixed State of Pure Niobium. <i>Frank Carsey and Moises Levy</i>	116
Mixed-State Ultrasonic Attenuation in Clean Niobium. <i>M. K. Purvis, R. A. Johnson, and A. R. Hoffman</i>	120
The Attenuation of Sound, $ql > 1$, in Niobium at Low Flux Densities. <i>R. E. Jump and C. E. Gough</i>	125
Thermal Conduction in the Mixed State of Superconducting Niobium at Low Temperatures. <i>C. M. Muirhead and W. F. Vinen</i>	130
Entropy of a Type II Superconductor in the Mixed State Close to T_c . <i>R. Ehrat and L. Rinderer</i>	134
Flux Pinning in Type II Superconductors. <i>D. de Klerk, P. H. Kes, and C. A. M. van der Klein</i>	138
Magnetic Moment in Superconductors Excited by Heat Flow. <i>N. V. Zavaritskii</i>	143
Transition to the Mixed State in Lead Films at 4.2°K. <i>G. J. Dolan and J. Silcox</i>	147
Observation of Tilted Vortices by Microwave Absorption. <i>P. Monceau, D. Saint-James, and G. Waysand</i>	152
Microwave Absorption in Dirty Type II Superconducting Films Around Their Critical Thickness. <i>Y. Brunet, P. Monceau, E. Guyon, W. Holzer, and G. Waysand</i>	156
Experimental Evidence for the Thompson Term in the Microwave Conductivity of Type II Superconductors. <i>Y. Brunet, P. Monceau, and G. Waysand</i> ..	160
Dynamic Structure of Vortices in Superconductors: Three-Dimensional Features. <i>Richard S. Thompson and Chia-Ren Hu</i>	163
Higher-Order Corrections Due to the Order Parameter to the Flux Flow Conductivity of Dirty Type II Superconductors. <i>Hajime Takayama and Kazumi Maki</i>	168
The Nascent Vortex State of Type II Superconductors. <i>Barry L. Walton and Bruce Rosenblum</i>	172
Hall Effect in Type II Superconductors. <i>H. Ebisawa</i>	177

2.3. Dynamics

Current-Induced Intermediate State in Superconducting Strips of Lead and Indium. <i>R. P. Huebner, R. T. Kampwirth, and D. E. Gallus</i>	183
Dissipation in a Superconducting Indium Wire. <i>L. K. Sisemore, K. J. Carroll, and P. T. Sikora</i>	187
Flux Motion in Lead-Indium Wires with Longitudinal Magnetic Fields. <i>J. E. Nicholson, P. T. Sikora, and K. J. Carroll</i>	192
Faraday Induction and Flux Flow Voltages in Type II Superconductors: Effect of Magnetic Field and Temperature. <i>S. M. Khanna and M. A. R. LeBlanc</i> ..	197

Investigations of Resonances in the RF Absorption of Superconducting Niobium. <i>P. Kneisel, O. Stoltz, and J. Halbritter</i>	202
Dynamics of the Destruction of Type I Superconductivity by a Current. <i>H. D. Wiederick, D. C. Baird, and B. K. Mukherjee</i>	207
Influence of Thermal Effects on the Kinetics of the Destruction of Superconductivity by a Current. <i>E. Posada, D. Robin, and L. Rinderer</i>	212
Fast Neutron Damage in Superconducting Vanadium. <i>S. T. Sekula and R. H. Kernohan</i>	217
The Effect of an Axial Moment on Normal-Phase Propagation in Type II Superconductors Carrying a Current. <i>J. F. Bussière and M. A. R. LeBlanc</i>	221
Response of Magnetically Irreversible Type II Cylinders to Currents and Fields Applied in a Parallel Axial Geometry. <i>D. G. Walmsley and W. E. Timms</i> ..	227
Limited Flux Jumps in Hard Superconductors. <i>L. Boyer, G. Fournet, A. Mailfert, and J. L. Noel</i>	232
Boundary Current and Modulated Flux Motion in Superconducting Thin Pb Films. <i>Y. W. Kim, A. M. de Graaf, J. T. Chen, and E. J. Friedman</i>	238
Effect of Helical Flow on I_c in Cylinders of Type II Superconductors in Axial Magnetic Fields. <i>R. Gauthier, M. A. R. LeBlanc, and B. C. Belanger</i>	241
Achievement of Nearly Force-Free Flow of Induced Currents in Ribbons of Nb_3Sn . <i>A. Lachaine and M. A. R. LeBlanc</i>	247
Effect of DC and AC Currents on the Surface Sheath Conductivity of Niobium Single Crystals. <i>R. C. Callarotti</i>	252

3. Josephson Effect and Tunneling

3.1. Josephson Effect

Thermodynamic Properties of Josephson Junction with a Normal Metal Barrier. <i>C. Ishii</i>	259
Linewidth of Relaxation Oscillations of a Shunted Superconducting Point Contact. <i>R. D. Sandell, M. Puma, and B. S. Deaver, Jr.</i>	264
Evidence for the Existence of the Josephson Quasiparticle-Pair Interference Current. <i>N. F. Pedersen, T. F. Finnegan, and D. N. Langenberg</i>	268
Microwave Emission from Coupled Josephson Junctions. <i>T. F. Finnegan and S. Wahlsten</i>	272
Application of the Shunted Junction Model to Point-Contact Josephson Junctions. <i>Y. Taur, P. L. Richards, and F. Auracher</i>	276
Characteristics of Josephson Point Contacts at the Center of a Spherical Cavity. <i>A. S. DeReggi and R. S. Stokes</i>	281
Temperature Dependence of the Riedel Singularity. <i>S. A. Buckner and D. N. Langenberg</i>	285
Fine Structure in the Anomalous DC Current Singularities of a Josephson Tunnel Junction. <i>J. T. Chen and D. N. Langenberg</i>	289
Temperature Dependence of the Critical Current of a Double Josephson Junction. <i>M. R. Halse and K. M. Salleh</i>	293

3.2. Tunneling

Tunneling Measurement of Magnetic Scattering. <i>N. V. Zavaritskii and V. N. Grigor'ev</i>	297
Josephson Weak Links: Two Models. <i>P. K. Hansma and G. I. Rochlin</i>	301
Anomalous Tunneling Characteristics. <i>M. H. Frommer, M. L. A. MacVicar, and R. M. Rose</i>	306
Tunneling and Josephson Experiments in Normal-Superconductor Sandwiches. <i>A. Gilabert, J. P. Romagnan, and E. Guyon</i>	312
Bulk Tunneling Measurements of the Superconducting Energy Gaps of Gallium, Indium, and Aluminum. <i>W. D. Gregory, L. S. Straus, R. F. Averill, J. C. Keister, and C. Chapman</i>	316
Two-Particle Tunneling in Superconducting PbIn Oxide Pb Junctions. <i>A. M. Toxen, S. Basavaiah, and J. L. Levine</i>	324
Theory and Measurements on Lead-Tellurium-Lead Supercurrent Junctions. <i>J. Seto and T. Van Duzer</i>	328
Tunneling from Pb into Al and Sn in Proximity. <i>R. Olafsson and S. B. Woods</i> ..	334
Magnetic Field Dependence of the Proximity Effect in the Sn/Pb System. <i>J. R. Hook</i>	337
The Superconducting Tunnel Junction as a Voltage-Tunable Source of Monochromatic Phonon Pulses. <i>H. Kinder</i>	341
Tunneling Measurements of Electron Spin Effects in Superconductors. <i>R. Meservey</i>	345
High-Field Behavior of the Density of States of Superconductors with Magnetic Impurities. <i>R. Bruno and Brian B. Schwartz</i>	354

4. Superconductivity Materials

4.1. Elements and Compounds

NMR Anomalies and Superconductivity in Transition Metals: Vanadium. <i>B. N. Ganguly</i>	361
Nuclear Magnetic Resonance and Relaxation in $V_3Ga_{1-x}Sn_x$. <i>F. Y. Fradin and D. Zamir</i>	366
Ultrasonic Evidence against Multiple Energy Gaps in Superconducting Niobium. <i>D. P. Almond, M. J. Lea, and E. R. Dobbs</i>	367
Superconducting Specific Heat of Nb-Ta Alloys. <i>T. Satoh, A. Sawada, and M. Yamamoto</i>	372
Superconductivity of Protactinium. <i>R. D. Fowler, L. B. Asprey, J. D. G. Lindsay, and R. W. White</i>	377
The Superconductive Transition in Cadmium. <i>J. F. Schooley</i>	382
Contributions at the La and Sn-In Sites to Superconductivity and Magnetism in $LaSn_xIn_{3-x}$ Alloys. <i>L. B. Welsh, A. M. Toxen, and R. J. Gambino</i>	387
Variation of the Electron-Phonon Interaction Strength in Superconducting $LaIn_{3-x}Sn_x$. <i>M. H. van Maaren and E. E. Havinga</i>	392

Superconducting Properties of $\text{LaSn}_x\text{In}_{3-x}$. <i>P. K. Roy, J. L. Levine, and A. M. Toxen</i>	395
Superconducting Transition Temperatures and Annealing Effect of Single-Crystalline NbN_x Films. <i>G. Oya, Y. Onodera, and Y. Muto</i>	399
Calorimetric Studies of Superconductive Proximity Effects in a Two-Phase Ti-Fe (7.5 at. %) Alloy. <i>J. C. Ho and E. W. Collings</i>	403
Heat Capacity of Rubidium Tungsten Bronze, <i>W. E. Kienzle, A. J. Bevolo, G. C. Danielsen, P. W. Li, H. R. Shanks, and P. H. Sidles</i>	408
Specific Heat, Optical, and Transport Properties of Hexagonal Tungsten Bronzes. <i>C. N. King, J. A. Benda, R. L. Greene, and T. H. Geballe</i>	411
High-Transition-Temperature Ternary Superconductors. <i>B. T. Matthias</i>	416
Layered Compounds, Intercalation, and Magnetic Susceptibility Measurements. <i>F. J. Di Salvo</i>	417
Fluctuation Effects on the Magnetic Properties of Superconducting Layered Compounds. <i>D. E. Prober, M. R. Beasley, and R. E. Schwall</i>	428
Studies of the Properties of the System $\text{TaS}_{2-x}\text{Se}_x$. <i>J. F. Revelli, Jr., W. A. Phillips, and R. E. Schwall</i>	433
Nuclear Magnetic Resonance in Layered Diselenides. <i>B. G. Silbernagel and F. R. Gamble</i>	438
Microwave Properties of Superconducting Intercalated 2H-TaS_2 . <i>S. Wolf, C. Y. Huang, F. Rachford, and P. C. W. Chu</i>	442
The Influence of the Limits of Phase Stability and Atomic Order on Superconductivity of Binary and Ternary A15-Type Compounds. <i>J. Muller, R. Flukiger, A. Junod, F. Heiniger, and C. Suz</i>	446
The Importance of the Transition Metal Volume in A15 Superconductors. <i>F. J. Cadieu and J. S. Weaver</i>	457
T_c Studies of Nb-Ga Binary and Ternary Compounds. <i>D. W. Deis and J. K. Hulm</i>	461
Synthesis of Low-Temperature Stable Superconducting A15 Compounds in the Niobium System. <i>R. H. Hammond and Subhas Hazra</i>	465
Studies of Superconducting $\text{Nb}_3\text{A}_x\text{B}_{1-x}$ Alloys. <i>G. R. Johnson and D. H. Douglass</i>	468
Low-Temperature Heat Capacity of Nb_3Sn . <i>R. Viswanathan, H. L. Luo, and L. J. Vieland</i>	472
Superconductivity in the Alloy System $\text{V}_3\text{Ga}_x\text{Si}_{1-x}$. <i>B. C. Deaton and D. E. Gordon</i>	475
Superconducting Properties of A15 Phase V-Ir Alloys. <i>J. E. Cox, J. Bostock, and R. M. Waterstrat</i>	480
Superconducting Properties of Some Vanadium-Rich Titanium-Vanadium Alloy Thin Films. <i>Hermann J. Spitzer</i>	485
Superconductivity of Lutetium at Very High Pressure: Implications with Respect to the Superconductivity of Lanthanum. <i>J. Wittig, C. Probst, and W. Wiedemann</i>	490

Superconductivity of Hafnium and the Dependence of T_c on Pressure. <i>C. Probst and J. Wittig</i>	495
Superconducting Properties of Iridium. <i>R. J. Soulen, Jr. and D. U. Gubser</i>	498
The Effect of Stress on the Magnetic Superconducting Transitions of Tin Whiskers. <i>B. D. Rothberg, F. R. N. Nabarro, and D. S. McLachlan</i>	503
The Strain Dependence of T_c in Sn and In Alloy Whiskers. <i>J. W. Cook, Jr., W. T. Davis, J. H. Chandler, and M. J. Skove</i>	507
The Effect of Size and Surface on the Specific Heat of Small Metal Particles. <i>V. Novotny, P. P. M. Meincke, and J. H. P. Watson</i>	510
Pressure-Induced Superconductivity in Cesium. <i>G. M. Stocks, G. D. Gaspari, and B. L. Gyorffy</i>	515
The Influence of Dissolved Hydrogen on the Superconducting Properties of Molybdenum. <i>B. D. Bhardwaj and H. E. Rorschach</i>	517
Low-Temperature Neutron Irradiation Effects in Superconducting Technetium and Niobium. <i>B. S. Brown, T. H. Blewitt, T. Scott, N. Tepley, and G. Kostorz</i>	523
The Superconductivity of Elastically Strained Tin Whiskers Near $T_c(\epsilon)$: A Second-Order Phase Transition with Two Degrees of Freedom. <i>B. D. Rothberg, F. R. N. Nabarro, M. J. Stephen, and D. S. McLachlan</i>	528

4.2. Gases, Films, and Granular Materials

Experimental Evidence for an Atomic-like Parameter Characterizing the Systematics of Superconductivity in the Transition Metals. <i>R. H. Hammond and M. M. Collver</i>	532
Modification of Surface Mode Frequencies and Superconductivity T_c by Adsorbed Layers. <i>D. G. Naugle, J. W. Baker, and R. E. Allen</i>	537
Effect of Surface Charge on the Superconductivity of Vanadium Films. <i>W. Felsch</i>	543
Carrier Concentration and the Superconductivity of Beryllium Films. <i>Kazuo Yoshihiro and Rolfe E. Glover, III</i>	547
The Upper Critical Field and the Density of States in Amorphous Superconductors. <i>G. Bergmann</i>	552
Superconductivity and Metastability in Alloys of the Mo-Re System. <i>J. R. Gavaler, M. A. Janocko, and C. K. Jones</i>	558
Superconducting Properties of Crystalline Films of Aluminum on Silicon. <i>Myron Strongin, O. F. Kammerer, H. H. Farrell, and J. E. Crow</i>	563
Granular Refractory Superconductors. <i>J. H. P. Watson</i>	568
Structural and Superconducting Properties of Granular Aluminum Films. <i>G. Deutscher, H. Fenichel, M. Gershenson, H. Grunbaum, and Z. Ovadyahu</i> ..	573
Electron Localization in Granular Metals. <i>B. Abeles and Ping Sheng</i>	578

5. Phonons

Strong Coupling Superconductivity. <i>J. P. Carbotte</i>	587
Phonon Spectrum of La. <i>L. F. Lou and W. J. Tomasch</i>	599
A Simple Experiment for the Determination of the BCS Parameter in Normal Metals. <i>G. Deutscher and C. Valette</i>	603
Variations of Cutoff Phonon Frequencies in Strong-Coupling Superconductors. <i>A. Rothwarf, F. Rothwarf, C. T. Rao, and L. W. Dubeck</i>	607
The Electron-Phonon Enhancement Factor for Some Transition Metals. <i>G. S. Knapp, R. W. Jones, and B. A. Loomis</i>	611
Neutron Scattering, Phonon Spectra, and Superconductivity. <i>H. G. Smith, N. Wakabayashi, R. M. Nicklow, and S. Mihailovich</i>	615
Superconductivity and Anomalous Phonon Dispersion in TaC. <i>Philip B. Allen and Marvin L. Cohen</i>	619
Soft Transverse Phonons in an Amorphous Metal. <i>B. Golding, B. G. Bagley, and F. S. L. Hsu</i>	623
Lattice Structure and Instabilities and Electron-Phonon Coupling in Superconductors with High Transition Temperatures. <i>P. Hertel</i>	627

6. Fluctuations

One-Dimensional Superconductivity in Bismuth Films. <i>T. Shigi, Y. Kawate, and T. Yotsuya</i>	633
Evidence for Magnetic-Field-Induced Reduction of the Fluctuation Dimensionality in Bulk Type II Superconductors Just Above the Upper Critical Field H_{c2} . <i>R. R. Hake</i>	638
Fluctuation Conductivity of Superconductors. <i>Bruce R. Patton</i>	642
Critical Fluctuation Behavior in the Resistive Transition of Superconducting Bi Films. <i>M. K. Chien and R. E. Glover III</i>	649
A Study of Fluctuation Effects on Resistive Transition to Superconductivity in Thin Indium Films. <i>Anil K. Bhatnagar and Belkis Gallardo</i>	654
Fluctuation Effects in the AC Impedance of One-Dimensional Superconductors. <i>John R. Miller and John M. Pierce</i>	659
Functional Integral Method for Superconducting Critical Phenomena. <i>Hajime Takayama</i>	664
Isothermal Superconducting Transitions in Milligauss Fields. <i>R. Schreiber and H. E. Rorschach</i>	669
Fluctuation-Induced Diamagnetism above T_c in Al and Al-Ag Alloys. <i>H. Kaufman, F. de la Cruz, and G. Seidel</i>	673
Fluctuation-Induced Diamagnetism in Bulk Al and Al Alloys above the Superconducting Transition Temperature. <i>J. H. Claassen and W. W. Webb</i>	677
Thermodynamic Fluctuations in "Zero-Dimensional" Superconductors. <i>R. A. Buhrman, W. P. Halperin, and W. W. Webb</i>	682

Size Effects in the Fluctuation Diamagnetic Susceptibility of Indium Powders above T_c . <i>D. S. McLachlan</i>	687
Fluctuations in a Small Superconducting Grain. <i>G. Deutscher, Y. Imry, and L. Gunther</i>	692
Coherent Behavior in Josephson Junction Arrays. <i>A. Saxena, J. E. Crow, and Myron Strongin</i>	696
Instabilities in the Voltage-Current Characteristics of Current-Carrying One-Dimensional Superconductors. <i>J. Meyer and G. v. Minnigerode</i>	701
Intrinsic Fluctuations in a Superconducting "Flux Detector" Ring Closed by a Josephson Junction: Theory and Experiment. <i>L. D. Jackel, J. Kurkijärvi, J. E. Lukens, and W. W. Webb</i>	705
The Pair-Field Susceptibility of Superconductors. <i>J. T. Anderson, R. V. Carlson, A. M. Goldman, and H.-T. Tan</i>	709

7. Superconductivity Phenomena

High-Resolution Magneto-optical Experiments on Magnetic Structures in Superconductors. <i>H. Kirchner</i>	717
Growth and Current-Induced Motion of the Landau Domain Structure. <i>R. P. Huebener, R. T. Kampwirth, and David F. Farrell</i>	728
Investigation of Possibilities for Raising the Critical Temperature of Superconductors. <i>G. F. Zharkov</i>	729
Resistance of Superconducting Alloys Near T_c As Caused by Vortex Structure Motion. <i>L. P. Gor'kov and N. B. Kopnin</i>	735
The Anisotropy of the Static Magnetic Field Penetration Depth in Superconducting Tin. <i>P. C. L. Tai, M. R. Beasley, and M. Tinkham</i>	740
Ultrasonic Attenuation in Superconducting Indium and Indium-Tin Alloys. <i>F. G. Brickwedde, David E. Binnie, and Robert W. Reed</i>	745
Low-Temperature Anomalies in Pure Niobium Studied Ultrasonically. <i>J. R. Leibowitz, E. Alexander, G. Blessing, and T. Francavilla</i>	750
Ultrasonic Absorption in Superconducting Single Crystals of $Nb_{1-x}Mo_x$. <i>L. L. Lacy</i>	756
The Volume Change at the Superconducting Transition of Lead and Aluminum above 0.3°K. <i>H. R. Ott</i>	760
Nuclear Spin-Lattice Relaxation in Impure Superconducting Indium. <i>J. D. Williamson and D. E. MacLaughlin</i>	763
Electronic Part of the Thermal Conductivity of a Thin, Superconducting Film Composed of Lead and Gadolinium. <i>D. M. Ginsberg and B. J. Mrstik</i>	767
Thermoelectrostatic Effects in Superconductors. <i>A. Th. A. M. de Waele, R. de Bruyn Ouboter, and P. B. Pipes</i>	772
Structure of Superconductors with Dilute Magnetic Impurities. <i>Reiner Kümmel</i>	777
Bose Condensation in Superconductors and Liquid ^4He . <i>M. D. Girardeau and S. Y. Yoon</i>	781

Enhanced Plasticity in the Superconducting State. <i>G. Kosterz</i>	785
Relation between Superconducting Energy Gaps and Critical Magnetic Fields. <i>D. U. Gubser and R. A. Hein</i>	790
Theory of Superconductors with Spatially Varying Order Parameter. <i>Reiner Kümmel</i>	794
Observation of Pair-Quasiparticle Potential Difference in Non-equilibrium Superconductors. <i>John Clarke</i>	798
Electric Potential Near a Superconducting Boundary. <i>M. L. Yu and J. E. Mercereau</i>	799
Contents of Other Volumes	805
Index to Contributors	826
Subject Index	833

SUPERCONDUCTIVITY

1

Plenary Topics

A Survey of Superconducting Materials

J. K. Hulm and R. D. Blaugher

*Westinghouse Research Laboratories
Pittsburgh, Pennsylvania*

Introduction

This paper provides an overview of superconducting materials for nonspecialists in this currently very active field of research. Several new classes of materials have emerged in the past two or three years, and some of them offer promise of higher critical temperatures—although new records have not yet been achieved. Several of the hydrides of the transition metals have recently been found to be superconducting, for example, thorium hydride, Th_4H_{15} , discovered by Satterthwaite and co-workers¹ at the University of Illinois. Hydrogen has also been introduced into palladium by ion implantation; the system becomes superconducting close to 10°K.² Another interesting class of superconductors involves layer compounds, such as tantalum disulfide, which were shown to have very interesting asymmetric superconducting characteristics by Geballe and co-workers at Stanford.³ Recently Matthias and co-workers⁴ have discovered a new ternary group, typified by LiTiS_2 , in which critical temperatures as high as 17°K have already been achieved. All these materials are discussed elsewhere in this volume and we shall not elaborate on them here.

We have chosen instead to focus most of our attention on the β -tungsten or A15 group of superconductors, for two reasons. First, these materials still offer the highest critical temperatures known at the present time. Second, they offer a fascinating set of electronic, lattice, crystallographic, and defect properties which impact directly upon superconductivity. These properties have been investigated to a greater extent than for any other class of superconducting compounds. We can expect to find similar behavior in other high- T_c compounds as more detailed studies are made, but for the most part this has not yet been done.

In order to obtain a proper perspective on superconducting materials, it is also necessary to have some idea of potential uses. Therefore, we include a few comments on what has to be done to go from a raw superconducting material to a wire or cable which is of value to electrical technology.

A simplified historical overview of the subject is provided by Fig. 1. By about 1940 most of the high- T_c elements had been identified and some pioneering work on sodium chloride-structure carbides and nitrides had been done by Meissner and Franz⁵ in Germany. In 1950 Matthias and Hulm^{6,7} began some experiments which led to the discovery of the high- T_c A15 superconductors, such as V_3Si and Nb_3Sn , and also superconducting alloys of transition metals, typified by niobium-titanium.*

*See Ref. 7 for a detailed list of references on high- T_c materials.

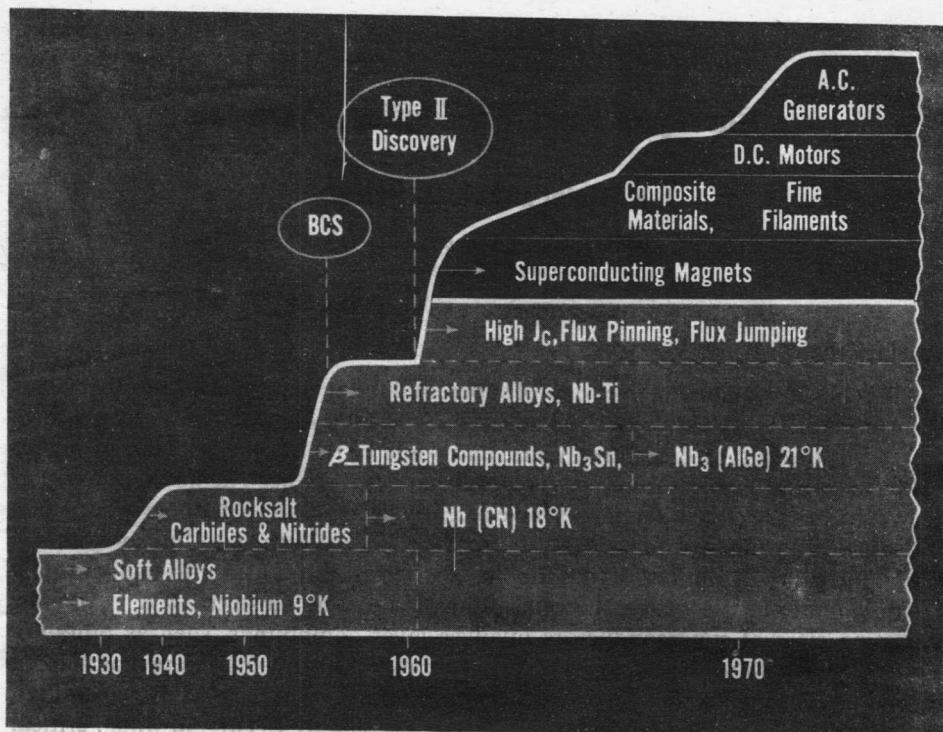


Fig. 1. History of superconducting materials and their applications.

A study of the magnetoresistance properties of Nb₃Sn by Kunzler and co-workers⁸ in 1961 revealed the dramatic high-field and high-current-density properties of this class of materials, and triggered a whole new field of technology.

After 1961 the role of metallurgical defects in controlling the critical current density of type II materials was explored and the concept of flux pinning by defects became well known. The first application of these materials was in the construction of superconducting magnets. In this connection it was found to be good practice to form the superconductor into a composite structure with a good normal conductor such as copper. A further improvement was obtained by dividing the superconductor itself into a large number of fine filaments. The resulting "filamentary composite" conductors have proved to be eminently satisfactory for large magnet construction.

Recently an application of much greater industrial importance has emerged. In May 1972 it was reported at the Applied Superconductivity Conference in Annapolis that several prototype ac generators of a few MVA capacity were under construction. At the recent Cryogenic Engineering Conference in Boulder the successful completion and testing of a 5-MVA, 60-Hz generator was reported by Westinghouse.⁹ The way is now clear for the construction of a much larger machine, in the 50–75-MW class. It appears that with a major effort a prototype machine of this class could be placed in a central power station by the middle or late seventies. At last superconductivity is on its way to practical application in a major industrial market. We may anticipate a

large return on the investment in basic research which has already taken place, and a greater willingness to fund more research in the future.

Superconducting materials appear to hold great promise for future technological development. As far as ac machine applications are concerned, it would be useful to have materials with much higher critical temperatures, say 25 or 30°K. This would certainly ease refrigeration requirements. At the same time it must be emphasized that we have not yet been able to fully exploit the 21°K critical temperature already available to us. Present technological developments are based upon ductile alloys with T_c 's around 10°K. This restriction is primarily due to the poor mechanical properties of the higher T_c compounds.

As far as basic understanding is concerned, the primary aim is, of course, to determine why certain special materials and certain crystal classes are favorable to the occurrence of high critical temperatures. Over the years some progress has been made toward this goal. Following the advent of the BCS theory, the theory of superconducting interactions was gradually refined. It is now possible to make reasonably good calculations of T_c for certain simple materials. For the most part, however, theory has tended to lag well behind experiment in this field.

The reasons for theoretical difficulty are not hard to find. High- T_c materials are really quite complex systems. Their electronic and lattice structures are quite inaccessible experimentally, and they are rarely well characterized in a materials science sense. This is not to imply any "alchemical" attributes to these materials, but merely to say that we seldom have exact knowledge of factors such as composition, secondary phases, vacancy content, degree of long-range ordering, and so on. These parameters are known to affect T_c , and sometimes even dominate it.

We believe that the creation of a satisfactory general theory for all materials is an illusory goal. Progress will best be made by painstakingly building up a series of quasiempirical models specialized to various material situations. Our aim here is to discuss some of the experimental factors which seem to be important in influencing T_c and which should presumably enter into such models. We hope to indicate some of the areas of ignorance and to give some guidance as to what might be done in future experimental work to close these gaps.

High- T_c Superconductors

Due to their restricted numbers, the elements are of quite limited interest from a superconducting materials viewpoint, and we have to deal mainly with alloys or compounds. Superconducting binaries and ternaries are readily formed all over the periodic system, but as far as high T_c is concerned, the greatest interest is centered around the transition metals, in particular niobium and vanadium.

The most prominent transition metal systems are: (1) body-centered cubic alloys such as Nb-Ti, $T_c \sim 10^\circ\text{K}$; (2) B1 (rocksalt) structure compounds such as NbN and Nb(C,N), $T_c \sim 18^\circ\text{K}$; (3) A15 (β -tungsten) structure compounds such as V_3Si and $\text{Nb}_3(\text{Al,Ge})$, $T_c \sim 21^\circ\text{K}$.

The first two classes have been discussed quite extensively in recent reviews,^{7,10} and will not be further analyzed here. We have chosen instead to focus our attention upon the third group, which has so far offered the most spectacular examples of