

Superconductor Applications: SQUIDs and Machines

Edited by

Brian B. Schwartz and Simon Foner

Francis Bitter National Magnet Laboratory

M. I. T.

Cambridge, Massachusetts

PLENUM PRESS • NEW YORK AND LONDON

Published in cooperation with NATO Scientific Affairs Division

**Physikalische Bibliothek
der Technischen Hochschule
Darmstadt**

TF 1969

CONTENTS

PART I - SQUIDS

CHAPTER 1:	THE HISTORICAL CONTEXT OF JOSEPHSON'S DISCOVERY A. B. Pippard	
HISTORY		1
<hr/>		
CHAPTER 2:	MACROSCOPIC QUANTUM PHENOMENA IN SUPER-CONDUCTORS R. de Bruyn Ouboter	
I.	INTRODUCTION	21
	A. Meissner Effect and Flux Quantization	21
	B. The dc Josephson Effect	26
	C. The Critical Current Through a Double Point Contact as a Function of the Applied Magnetic Field	32
II.	AC QUANTUM EFFECTS	42
	A. Extension of the Two-Fluid Interpretation of the London Theory	42
	B. The ac Josephson Effect	46
III.	RESISTIVE STATES IN WEAK LINK JUNCTIONS	49
	A. The Current-Voltage Characteristics and the Resistive-Superconductive Region of a Single Superconducting Weak Link	49
	B. The Double Point Contact in the Resistive Superconducting Region, the dc SQUID	56

CHAPTER 3:	SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES FOR LOW FREQUENCY MEASUREMENTS	
	J. Clarke	
I.	INTRODUCTION	67
II.	SUPERCONDUCTIVITY AND THE JOSEPHSON EFFECTS	68
	A. Flux Quantization	68
	B. The Josephson Equations	69
	C. Types of Josephson Junctions, and their Current-Voltage Characteristics	69
III.	DC SQUID	71
	A. Theory of the dc SQUID	71
	B. Operation of the dc SQUID	76
	C. Theory of Noise in the dc SQUID	79
	D. Practical dc SQUIDS: Fabrication and Performance	82
	E. Future Improvements in the dc SQUID	89
IV.	RF SQUID	90
	A. Theory of the rf SQUID	90
	B. Operation of the rf SQUID	97
	C. Noise in the rf SQUID	97
	D. Practical rf SQUIDS: Fabrication and Performance	103
	E. Future Improvements in the rf SQUID	106
V.	SQUIDS AS MAGNETOMETERS, GRADIOMETERS, SUSCEPTOMETERS, AND VOLTMETERS	108
	A. Flux Transformer	108
	B. Measurement of Magnetic Field	110
	C. Measurement of Magnetic Field Gradient	112
	D. Measurement of Magnetic Susceptibility	113
	E. Measurement of Voltage	116
VI.	PRACTICAL APPLICATIONS OF SQUID-BASED DEVICES	118

CHAPTER 4:	EQUIVALENT CIRCUITS AND ANALOGS OF THE JOSEPHSON EFFECT	
	T. A. Fulton	
I.	INTRODUCTION	125
II.	SMALL JUNCTIONS	126
	A. Model of the Supercurrent Flow	126
	B. Voltage Biased Model	127
	C. Stewart-McCumber Model	127
	1. Circuit equations	127
	2. Mechanical analogues	130
	3. I - $\langle V \rangle$ curves	132
	4. Plasma oscillations	136
	5. Punchthrough	136
	6. Interaction with rf currents	138
	D. Inductively-Connected External Elements	143
	1. Circuit and mechanical analogues	143
	2. Resistive shunts	144
	3. Capacitive shunts	146
	4. ac SQUID	153
	E. The dc SQUID	155
III.	LARGE JUNCTIONS	160
	A. Two-Dimensional Systems	160
	1. Circuit models	160
	2. Two-dimensional mechanical analog	164
	B. One-Dimensional Junctions	165
	1. Circuit equations	165
	2. Mechanical analogue	165
	3. Small oscillations and displacements	166
	4. Magnetic diffraction and Fiske modes for $l \ll \lambda_J$	167
	5. Junctions having $l \gg \lambda_J$ -vortices and critical currents	168
	6. Magnetic field behavior for $l \gg \lambda_J$	172
	7. Vortex motion	174
	8. Resonant vortex propagation	177
	9. Finite $\langle V \rangle$ behavior for $l \gg \lambda_J$	179
	10. Vortex oscillations	179
IV.	CONCLUSIONS	182

CHAPTER 5: SUPERCONDUCTING DEVICES FOR
METROLOGY AND STANDARDS

R. A. Kamper

I.	INTRODUCTION	189
II.	VOLTAGE STANDARDS	190
	A. The SI Volt	190
	B. Standard Cells and the Defined Volt	191
	C. The Josephson Effect and e/h	191
	D. Practical Josephson Voltage Standards	193
	E. The Microwave Signal Source	193
	F. The Josephson Junction	193
	G. Shielding, Filtering, and Tempering	196
	H. Theoretical Uncertainty	196
	I. Present Activities	197
III.	CURRENT COMPARATORS AND RATIO MEASUREMENTS	198
	A. Resistive Networks	198
	B. Inductive Devices	200
	C. Cold Resistive Dividers	203
	D. Superconducting Inductive Current Comparators	205
IV.	MEASUREMENTS OF RF POWER AND ATTENUATION	208
	A. Some General Remarks on RF and Microwave Measurements	208
	B. The SQUID as an RF Measuring Device	210
	C. Practical SQUIDS for RF Metrology	213
	D. The Measurement of Attenuation	217
	E. The Measurement of Power	219
	F. Systematic Errors	220
V.	THERMOMETRY	227
	A. The Kelvin Scale Below 1 K	227
	B. Noise Thermometry with SQUID Sensors	228
	C. Magnetic Thermometry with SQUIDS	237
	D. Superconducting Fixed Points	238
VI.	MEASUREMENTS OF FREQUENCY	238
	A. The Stability of Oscillators	238
	B. Oscillators with Superconducting Cavity Resonators	241
	C. Far Infrared Frequency Synthesis	243
	D. Recent Work	244

CHAPTER 6: HIGH FREQUENCY PROPERTIES
AND APPLICATIONS OF JOSEPHSON
JUNCTIONS FROM MICROWAVES
TO FAR-INFRARED

R. Adde and G. Vernet

I.	GENERAL PROPERTIES OF JOSEPHSON JUNCTIONS FOR HIGH FREQUENCY APPLICATIONS	249
A.	High Frequency Fundamental Properties of the Ideal Josephson Junction	249
B.	The Parallel Impedance of Real Josephson Junctions	249
C.	Limiting Factors of Josephson Junctions at High Frequencies	251
1.	Frequency limitation related to the physical mechanism	251
2.	Geometrical structure and coupling	257
3.	Thermal effects	258
4.	Noise	258
D.	The Main Detection Mechanism	259
1.	Wide band detection	259
2.	Narrow band detection (linear)	260
E.	The Josephson Junction and Parametric Amplification	261
F.	The Real JJ Analyzed with the RSJ Model	263
1.	Voltage source model	263
2.	The current source model	264
3.	An important example: the Josephson heterodyne mixer with an external oscillator	266
G.	Noise	268
1.	Physical origin of fluctuations in Josephson junctions	268
2.	Josephson junction response in the presence of fluctuations	272
H.	Noise Temperature, Minimum Detectable Temperature, NEP	275
1.	Noise temperatures	275
2.	System sensitivity	277
I.	Coupling and Impedance Matching	279
1.	General remarks	279
2.	Impedance matching	279
3.	Signal input coupling	281

II. ANALYSIS AND PERFORMANCES OF HIGH-FREQUENCY JOSEPHSON DEVICES	284
A. Generation of Radiation	285
B. Bolometer	286
1. Bolometer characteristics	286
2. SNS and superconducting transition edge bolometers	287
3. Comparison of devices	290
C. Video Detection	290
1. Junction quadratic response	290
2. Voltage response in the general case	291
3. Noise equivalent power	293
4. Discussion of experimental results and comparison with other video detectors	293
D. Heterodyne Detection	295
1. External local oscillator	296
2. Internal local oscillator	302
3. Discussion of the results and comparative performances of other mixers	306
E. Parametric Amplification	311
1. Parametric amplification with self-pumped JJ	312
2. Externally pumped JJ parametric amplifier	314
3. Discussion	315
F. Conclusions	315

CHAPTER 7: FABRICATION OF JOSEPHSON JUNCTIONS
B. T. Ulrich and T. Van Duzer

I. INTRODUCTION	321
II. FABRICATION TECHNOLOGY	323
A. Evaporation Masks	323
B. Photolithography	324
C. Electron Lithography	327
D. Thin-Film Deposition and Ion Etching	329
III. SANDWICH-TYPE JUNCTIONS	332
A. Oxide-Barrier Junctions	333
B. Evaporated Semiconductor Barrier Junctions	337
C. Single-Crystal Silicon-Membrane Junctions	337

IV. JUNCTIONS WITH COPLANAR ELECTRODES	341
A. Variable-Composition Junctions	342
B. Semiconductor Bridge	346
C. Microbridges	347
V. POINT CONTACTS	350

CHAPTER 8: BIOMAGNETISM
 S. J. Williamson, L. Kaufman
 and D. Brenner

I. INTRODUCTION	355
II. FORWARD AND INVERSE PROBLEMS	357
III. SQUID MEASUREMENT TECHNIQUES	360
IV. MAGNETOCARDIOGRAM	371
V. FETAL MAGNETOCARDIOGRAM	383
VI. MAGNETOMYOGRAM	384
VII. MAGNETO-OCULOGRAM	386
VIII. MAGNETOENCEPHELOGRAM	387
IX. VISUALLY EVOKED FIELD	392
X. EXPECTATIONS	396

CHAPTER 9: A PROGRESS REPORT ON COMMERCIAL
 SUPERCONDUCTING INSTRUMENTS
 IN THE UNITED STATES
 M. B. Simmonds

I. INTRODUCTION	403
II. SQUID SENSORS	404
III. LABORATORY PROBES	405
IV. GEOPHYSICAL MAGNETOMETERS	406
V. MAGNETIC ANOMALY DETECTORS	407

VI.	BIOMEDICAL MAGNETOMETERS	409
VII.	SAMPLE MEASURING INSTRUMENTS	411
VIII.	SHIELDED ENVIRONMENTS	412
IX.	CONCLUSIONS	413

CHAPTER 10: RESISTIVE DEVICES
J. G. Park

I.	INTRODUCTION	415
II.	THE 'CORRESPONDING' SQUID	417
III.	THE RSQUID AND ITS 'CORRESPONDING' SQUID	422
IV.	BEHAVIOR WHEN MODULATION CURRENTS I and i_m ARE ABSENT	426
	A. Stable and Unstable Equilibrium	426
	B. Deviations from the Standard Behavior	427
	C. The Form of $I_k(\Theta_j)$	427
	D. Fluctuations about Equilibrium	430
	E. Behavior when I is small	430
V.	EXPERIMENTS WITH EXTERNAL CURRENT I (AC OR DC)	431
VI.	APPLICATIONS OF RSQUIDS	437
	A. Types of RSQUIDS	437
	B. Picovoltmeters	439
	C. The RSQUID Noise Thermometer	441
	D. Heat Current Measurement	443

CHAPTER 11: "HOT SUPERCONDUCTORS": THE PHYSICS AND APPLICATIONS OF NONEQUILIBRIUM SUPERCONDUCTIVITY
J. -J. Chang and D. J. Scalapino

I.	INTRODUCTION	447
II.	RELAXATION PROCESSES AND THE KINETIC EQUATIONS	454

III.	MAGNITUDES AND THE ROTHWARF-TAYLOR EQUATIONS	468
IV.	SOLUTIONS OF THE BOLTZMANN EQUATIONS	473

CHAPTER 12: COMPUTER APPLICATIONS OF
 JOSEPHSON JUNCTIONS
 P. Wolf

I.	HISTORICAL NOTES	487
II.	THE JOSEPHSON JUNCTION AS A SWITCHING DEVICE	487
III.	DEVICE FABRICATION	489
IV.	CIRCUITS	489
	A. Logic Circuits	489
	B. Memory Circuits	490

CHAPTER 13: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN CANADA
 J. A. Blackburn

PROGRAMS		495
----------	--	-----

CHAPTER 14: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN FRANCE
 R. Adde

PROGRAMS		501
----------	--	-----

CHAPTER 15: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN GERMANY
 S. Ern 

PROGRAMS		505
----------	--	-----

CHAPTER 16:	PROGRAMS ON SMALL-SCALE SUPERCONDUCTING DEVICES IN ITALY M. Cerdonio	
PROGRAMS		509
<hr/>		
CHAPTER 17:	PROGRAMS ON SMALL-SCALE SUPERCONDUCTING DEVICES IN THE NETHERLANDS R. de Bruyn Ouboter	
PROGRAMS		513
<hr/>		
CHAPTER 18:	PROGRAMS ON SMALL-SCALE SUPERCONDUCTING DEVICES IN THE UNITED KINGDOM J. G. Park	
PROGRAMS		515
<hr/>		
CHAPTER 19:	PROGRAMS ON SMALL-SCALE SUPERCONDUCTING DEVICES IN THE UNITED STATES R. Brandt and E. A. Edelsack	
I.	SUMMARY	521
II.	INTRODUCTION	521
III.	BIOMEDICAL	525
IV.	METROLOGY	527
V.	GEOPHYSICAL	529
VI.	DETECTION AND RADIATION	531
VII.	DIGITAL PROCESSING	535
VIII.	DEVICE PROPERTIES	537
IX.	TRENDS	540
<hr/>		

PART II - MACHINES

CHAPTER 20: LARGE-SCALE APPLICATIONS OF SUPERCONDUCTIVITY

G. Bogner

I.	INTRODUCTION	547
II.	SUPERCONDUCTING MATERIALS AND MAGNETS	549
	A. Introduction	549
	B. High-Field Superconductors	550
	1. Superconducting materials	550
	C. Stabilized High Field Superconductors	553
	1. Cryostatic stabilization	554
	2. Adiabatic stabilization	554
	3. Dynamic stability	554
	D. Conductors for dc and ac Magnets	555
	E. Irradiation Effects in Composite Superconductors	565
	F. General Design Aspects of Superconducting Magnets	567
	1. Intrinsically stable coils	567
	2. Fully or cryostatically stabilized coils	572
	3. Current leads and coil protection	574
	G. Superconducting Magnets for Laboratory Application	575
	H. Magnets for High Energy Physics	579
	I. Superconducting Magnets for Fusion Reactors and MHD Generators	586
	1. Fusion reactors	586
	2. MHD generators	594
	J. Superconducting Magnets for Inductive Energy Storage	596
	K. Superconducting Magnets for Magnetic Separation	604
III.	LEVITATED VEHICLES WITH SUPERCONDUCTING MAGNETS	608
	A. Introduction	608
	B. Basic Features of the Electrodynamic Flight	609
	C. Principle of the Electrodynamic Levitation System	609
	D. Various Lift and Guidance Systems	610
	E. Damping	613
	F. Propulsion Systems	615
	G. On-Board Cooling Systems	617

H.	Magnetic Shielding of the Passengers	619
I.	Electrodynamic Levitation Projects	619
	1. FRG - the Erlangen test carrier and track	619
	2. The Japanese National Railway magnetic levitation project	627
	3. The Canadian Maglev-project	632
	4. Work on magnetic levitation in Great Britain	633
	5. The US program on magnetic levitation	633
IV.	ELECTRIC MACHINES	636
	A. Introduction	636
	B. Limits of Conventional Machines	636
	C. Superconducting Machines: General Remarks	638
	D. DC Machines	640
	1. Heteropolar machines	640
	2. Homopolar machines	645
	E. Synchronous Machines	654
	1. Technical limits of conventional turbogenerators	656
	2. Potential advantages of supercon- ducting generators	656
	3. Basic construction of supercon- ducting generators	657
	4. Cooling system	662
	5. Armature winding (stator)	666
	6. Machine screening	667
	7. Electrical operating behavior and characteristic data	667
	8. Economic considerations	669
	9. Superconducting turbine-generator projects	670
V.	SUPERCONDUCTING CABLES	672
	A. Introduction	672
	B. Superconducting Cable Concepts	673
	1. Mechanical construction	673
	2. Conductor configurations	673
	3. Comparison between superconducting direct current and alternating current cables	675
	C. Cryogenic Envelope	677
	D. Superconducting Material	678
	1. Direct current superconductors	678
	2. Alternating current superconductors	679

CONTENTS

xxi

E. Cable Core	684
F. Electrical Insulation	687
G. Cable Cooling	694
H. Cable Terminations	699
I. Superconducting Cable Projects	701
J. The Economics of Superconducting Cables	705
K. Future Development of Superconducting Cables	709

SUBJECT INDEX

PART I - SQUIDS	719
PART II - MACHINES	731