

# Contents

<b>1</b>	<b>The Phenomenon: Occurrence and Characteristics</b>	<b>1</b>
1.1	Marching Towards Absolute Zero	1
1.2	Discovery of Superconductivity	2
1.3	Occurrence of Superconductivity	3
1.3.1	Elemental Superconductivity	3
1.3.2	Alloys	3
1.3.3	Binary Compounds (A-15 Materials)	3
1.3.4	Heavy Fermion Superconductors	4
1.3.5	Organic Superconductors	4
1.3.6	C <sub>60</sub> -Based Superconductors	6
1.4	The Superconducting State	7
1.5	Phase Coherence	9
1.6	Coherence Length	10
1.6.1	Pippard's Equation and Coherence Length	11
1.6.2	The Size of an Electron Pair	12
1.6.3	Analogy Between Long Range Spatial Order in a Solid and Phase-Order in a Superconductor	13
1.7	Critical Magnetic Field	13
1.8	Meissner Effect	14
1.9	Comparison Between a Superconductor and a Very Good (or Ideal) Conductor	15
1.10	Isotope Effect	17
1.11	Isotope Effect in HTSCs	18
1.11.1	Optical Behaviour Study	18
1.11.2	Elastic and Ultrasonic Studies	18
1.12	The Energy Gap	19
1.13	Thermodynamics of Superconductors	21
1.13.1	Latent Heat of Superconducting Transitions	24
1.13.2	Heat Capacity of Superconductors	24
1.13.3	Strong Coupling Case	26
1.14	London Equations and Penetration Depth	27

1.15	Ginzberg–Landau Theory .....	29
1.16	Type-I and Type-II Superconductors .....	32
1.16.1	How a Normal Core is Formed in Mixed State? .....	35
1.17	Why Materials with High $T_c$ Tend to Fall in Type-II Category? .....	37
1.18	Why It is Extremely Difficult to Obtain Higher $T_c$ ? .....	38
	References .....	39
<b>2</b>	<b>Crystal Structure of High Temperature Superconductors ..</b>	<b>41</b>
2.1	Introduction .....	41
2.1.1	Perovskite Structure .....	41
2.2	The Structure of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ .....	41
2.2.1	Variation of $T_c$ with Oxygen Stoichiometry .....	43
2.3	The Structure of $\text{La}_{2-x}\text{M}_x\text{CuO}_4$ .....	46
2.4	The Structure of Bi-Based Cuprate Superconductors .....	46
2.5	Structure of Thallium-Based Cuprate Superconductors .....	48
2.5.1	Comparison of Bismuth and Thallium Based Cuprates ..	49
2.6	Mercury Based Cuprate Superconductors .....	51
2.7	Characteristics of High Temperature Superconductors .....	53
2.7.1	Resemblance Between HTSC and Conventional Superconductors .....	54
2.7.2	Unusual Properties of HTSCs .....	54
2.8	Fermi Energy and Fermi Velocity of Superconductors .....	55
2.9	Comparison of High $T_c$ Cuprates with Typical Metals in Relation to Normal State Resistivity .....	57
	References .....	57
<b>3</b>	<b>Critical Current .....</b>	<b>59</b>
3.1	Introduction .....	59
3.2	Critical Current of a Wire .....	60
3.3	Critical Current in Mixed State .....	61
3.4	Flux Pinning .....	61
3.4.1	Role of Inhomogeneties .....	62
3.4.2	Flux Pinning (Pinning of Flux-Vortices in Conventional Superconductors) .....	63
3.5	Depinning of Flux Vortices .....	63
3.6	Critical Current in High Temperature Superconductors .....	65
3.6.1	Effect of Structure .....	65
3.7	RSJ Model of an HTSC (High $T_c$ Superconductor) .....	66
3.8	Effect of Granularity on Superconductivity .....	68
3.9	Measurement for $J_c$ .....	69
3.10	Flux Flow and Defining $J_c$ .....	70
3.11	Anisotropies in High $T_c$ Superconductors .....	71
3.12	Flux Pinning in High Temperature Superconductors .....	73
3.13	Columnar Defects and Flux Pinning .....	74
3.13.1	Flux Pinning in HTSCs by Vortex Pancakes .....	75

3.14	Experimental Results on Introduction of Flux Pinning Centers in HTSCs .....	77
3.14.1	Melt Textured Growth .....	77
3.14.2	Introduction of Second Phase (Chemical Inhomogeneity) .....	78
3.14.3	Extended Defects (Columnar Defects) .....	78
3.15	Magnetic Phase Diagrams of HTSCs .....	78
3.16	Melting of the FLL Because of Reduced Size of $\xi_{GL}(T)$ .....	80
3.16.1	Effect of Reduced Size of $\xi_{GL}(T)$ .....	81
3.17	Kosterlitz–Thouless–Berezinski Transition .....	81
3.18	Anisotropy and Change Over from a 2D to 3D Behaviour .....	82
3.18.1	High Field Regime ( $B \gg B_{cr}$ ) .....	83
3.18.2	Weak Field Region ( $B \ll B_{cr}$ ) .....	83
3.18.3	The Cross-Over Field $B_{cr}$ .....	84
3.19	The Effect of Anisotropy Parameter $\gamma$ on the Vortex Phase Transitions .....	84
3.20	Desired Microstructure Synthesis for High Critical Current Density in High $T_c$ Superconductors .....	85
3.20.1	Some Inherent Problems (Weak-Links and “Flux Lattice Melting”) .....	85
3.20.2	Possible Ways Out of “Weak-Links” .....	87
3.20.3	Provision of Flux Pinning Sites .....	91
3.20.4	Desired Microstructure for High $J_c$ .....	93
3.21	High $T_c$ Technology .....	94
3.21.1	Advantage of Weak Pinning .....	95
3.22	Comparison Between Non-Uniform Order in a Solid and that in a Superconductor .....	95
	References .....	96
<b>4</b>	<b>Synthesis of High <math>T_c</math> Superconductors</b> .....	<b>99</b>
4.1	Synthesis of $Y_1Ba_2Cu_3O_7$ in Bulk Form .....	99
4.2	Why Thin Films of High $T_c$ Superconductors? .....	100
4.3	Techniques for Thin Film Preparation .....	101
4.3.1	Chemical Deposition Methods .....	103
4.3.2	Chemical Vapour Deposition (CVD) .....	103
4.3.3	Spray Pyrolysis .....	103
4.4	Basic Thin film Processes for HTSC Films .....	104
4.5	Various Techniques for Deposition of Films of High Temperature Superconductors .....	106
4.6	Preparation of Thin Films of HTSC- $YBa_2Cu_3O_{7-x}$ : An Introduction .....	108
4.6.1	Choice of the Substrate for Thin Film Deposition .....	108
4.6.2	YBCO Film/Substrate Interaction .....	109
4.7	Techniques Employed for Synthesis of YBCO Thin Films .....	112

4.7.1	Electron Beam Evaporation.....	112
4.7.2	Molecular Beam Epitaxy .....	113
4.7.3	Sputter Deposition .....	114
4.7.4	Sputter Deposition of HTSC Films .....	116
4.7.5	Pulsed Laser Deposition .....	118
4.7.6	Chemical Vapour Deposition .....	119
	References .....	120
<b>5</b>	<b>Superconductivity in Cuprates.....</b>	<b>123</b>
5.1	Mott Insulator .....	123
5.2	The First Cuprate $\text{La}_{2-x}\text{M}_x\text{CuO}_4$ .....	123
5.3	The Charge-Transfer Model of a High $T_c$ Cuprate Superconductor .....	124
5.4	Electron and Hole Doping of $\text{CuO}_2$ Layers .....	125
5.4.1	Source of Hole (Carriers) in Various Cuprate Families ..	126
5.5	The Conductions Plane in Cuprates .....	127
5.6	Octahedral Ligand Field.....	128
5.7	Jahn-Teller Effect .....	128
5.8	Energy levels for Copper .....	129
5.9	Comparison of $\text{Cu}^{3+}$ and $\text{Cu}^{2+}$ ions in the Oxide Octahedron .	130
5.10	The Hamiltonian and the Relevant Energy Levels in the Conduction Plane.....	130
5.11	Hole Superconductivity in Oxides.....	132
5.12	Two Band and One Band Hubbard Models .....	134
5.13	The Electronic Structure of Cuprates .....	134
5.14	Strong Electron Correlations .....	136
5.15	Charge Density Wave and Spin Density Wave .....	137
5.16	Variation of $T_c$ with Hole Concentration .....	138
5.16.1	Role of $\text{CuO}_2$ Planes (Effect on $T_c$ ) .....	138
5.17	Defects in Bi Based Superconductors.....	140
5.18	Effect of Oxygen Stoichiometry on $T_c$ of HTSCs Bi Based and Tl Based Superconductors .....	140
5.19	Comparison of Bi- and Tl-Cuprates .....	141
5.20	Comparison of Mercury Based and Thallium Monolayer Based Cuprate Superconductors .....	143
5.21	Mercury Based Superconductors.....	143
5.22	Mercury Doped Tl:2223 Superconductor .....	144
	References .....	145
<b>6</b>	<b>The Proximity and Josephson Effects .....</b>	<b>147</b>
6.1	DC Josephson Effects .....	147
6.2	Some Types of Josephson Junctions.....	150
6.2.1	Typical Current Voltage Characteristics for the Above Types of Junctions .....	152
6.3	Equivalent Circuit of a Josephson Junction .....	152

6.4	AC Josephson Effect .....	153
6.5	Giaever Tunnelling/Tunnelling of Quasi-Particles .....	155
6.6	Superconductive Tunnelling in a S-I-S Junction .....	159
6.7	Quasi-Particle Tunnelling for a Symmetric S-I-S Junction ....	162
6.7.1	Effect of Thickness of Insulator in S-I-S Junction ....	163
6.8	Properties of Josephson Junction .....	163
6.9	Flux Quantisation .....	165
6.10	SQUIDS .....	166
6.11	DC SQUID (A Superconducting Loop with Two Josephson Junctions) .....	167
6.11.1	The Characteristics of an Ideal DC SQUID .....	170
6.12	The rf SQUID .....	172
6.12.1	Principle .....	172
6.12.2	Working.....	173
6.13	Applications of SQUIDS .....	176
6.14	HTSC SQUIDS.....	176
6.15	Some Practical rf SQUIDS .....	177
6.15.1	Break Junction rf SQUIDS.....	177
6.15.2	Two-and One-Hole rf SQUIDS .....	177
6.16	SQUIDS Fabricated From Films .....	178
6.16.1	SQUIDS using Polycrystalline Films .....	179
6.16.2	SQUIDS using Epitaxial Films .....	180
6.17	How SQUIDS are Used for Flux Measurements .....	182
6.17.1	Superconducting Flux Transformers .....	184
6.18	Design and Noise Aspects of SQUIDS .....	186
6.18.1	Choice for Critical Current $I_c$ of J.J.....	186
6.18.2	Choice for the Inductance of the Ring .....	186
6.18.3	Noise, Noise Energy and Energy Resolution of SQUID ..	187
6.19	Proximity Effect (Induced Superconductivity) .....	190
6.19.1	S-I Junction .....	192
6.20	S-N Junction .....	192
6.20.1	Fundamental Properties of S-N Contacts .....	192
6.20.2	Boundary Conditions for Pair Amplitude (F) .....	193
6.20.3	Effect of a Finite Boundary Resistance .....	194
6.20.4	(Cuprate -S)/N Interface .....	195
6.21	Grain Boundary Junctions.....	195
6.22	Requirements for Josephson Devices .....	197
6.22.2	Test for the ac Josephson Effect .....	198
	References .....	198
<b>7</b>	<b>Theories of Superconductivity .....</b>	<b>199</b>
7.1	Microscopic Theory of Superconductivity (The BCS Theory) ..	200
7.1.1	Qualitative Ideas .....	201
7.1.2	The BCS Ground State .....	203

## XIV Contents

7.2	Anderson's Resonating Valence Bond Theory .....	210
7.2.1	Anderson's Valence Bonds .....	210
7.3	Spin-Bag Theory .....	214
7.3.1	Questions Which Remain .....	214
	References .....	214
<b>8</b>	<b>Application of Superconductivity .....</b>	<b>215</b>
8.1	Potential Applications .....	215
8.1.1	Superconducting Magnets .....	215
8.2	Applications of High- $T_c$ Oxide Superconductors .....	215
8.3	Applications of High $T_c$ Films .....	217
	<b>Index .....</b>	<b>219</b>