Contents

1. Introduction 1

2. High-T_c Superconductors: Limitations and Applications . . 5
2.1 Critical-Current Limitations 6
2.1.1 Flux Pinning 7
2.1.2 The Role of Grain Boundaries 8
2.1.3 Percolation 10
2.2 Material Processing 11
2.3 Possible Applications 11
2.3.1 Magnet Technology 11
2.3.2 Energy Technology 12

Part I. Fundamentals

3. Fundamentals of Material Processing 17
3.1 Crystal Structure 18
3.1.1 The Rare-Earth Compounds 18
3.1.2 The Bismuth Compounds 19
3.1.3 Lattice Parameters, Anisotropy and Microstructure . . . 20
3.2 Phase Diagrams and Phase Formation 22
3.2.1 Basic Concepts 22
3.2.2 Binary Phase Diagrams 24
3.2.3 Ternary Phase Diagrams 26
3.2.4 The Phase Diagram of Y–Ba–Cu–O 28
3.2.5 The Phase Diagram of Bi(Pb)–Sr–Ca–Cu–O 30
3.2.6 Oxygen Content 33
3.3 Melt Processing of $YBa_2Cu_3O_{7-\delta}$ 34
3.3.1 Melt Growth Processes 35
3.3.2 Top-Seeding Technique 38
3.4 Tape and Wire Fabrication 38
3.4.1 Conductor Fabrication Processes 38
3.4.2 Green-Wire Fabrication Using the PIT Process 39
3.4.3 Phase Development of Pb,Bi–Sr–Ca–Cu–O in Silver . . 42
3.4.4 YBaCuO-Coated Conductors 46

4. Physical Properties of High-T_c Superconductors 51
4.1 Normal-State Properties of HTSCs 51
4.2 Superconducting Properties 52
4.2.1 Microscopic Description 52
4.2.2 Macroscopic Description 54
4.3 Electromagnetic Properties of HTSCs 57
4.3.1 Type II Superconductor in an External Magnetic Field 57
4.3.2 Elastic Properties of the Flux Line Lattice 59
4.3.3 Phase Transitions in the Vortex Lattice 60
4.4 Flux Line Dynamics 62
4.4.1 Flux Pinning and the Bean Critical-State Model 62
4.4.2 Thermally Activated Flux Creep 65

Part II. Recent Achievements

5. Conductor Preparation and Phase Evolution 71
5.1 Preparation of Wires, Tapes and Bulk HTSCs 71
5.1.1 Preparation of Bi-2223 Tapes 71
5.1.2 Preparation of Bi-2212 Tapes and Wires 74
5.1.3 YBCO-Coated-Conductor Preparation 75
5.1.4 Melt Processing of Bulk REBCO 76
5.2 Phase Formation and Microstructure 76
5.2.1 Observation of Phase Evolution of Bi-2223 76
5.2.2 Microstructure and Grain Boundaries 77

6. Characterization of Conductors and Bulk HTSCs 79
6.1 Electromagnetic Characteristics 79
6.2 Superconducting Magnetic Levitation 80
6.3 Imaging of Magnetic Flux in Type II Superconductors 80
6.3.1 Scanning Hall Probe Experiments 81
6.3.2 Magneto-Optical Imaging 81

Part III. Phase Formation and Microstructure

7. Preparation of BSCCO Conductors 85
7.1 Fabrication of Green Wires and Tapes 85
7.2 Thermal Processing of Bi-2212/Ag Conductors 88
7.2.1 Processing Scheme 89
7.2.2 Void Formation 89
7.2.3 Microstructure Development 92
7.3 Thermo-Mechanical Processing of Bi-2223/Ag Tapes 93
7.3.1 Precursor Powder 94
7.3.2 Number of Processing Steps 95

7.3.3 First Thermal Processing Step 96
7.3.4 Further Processing Steps 99

8. Overpressure Processing of Bi-2212 Conductors 101
8.1 Void Reduction in Bi-2212/Ag Wires 101
8.1.1 Processing Scheme 101
8.1.2 Critical Current Density 102
8.1.3 Microstructure 102
8.2 Overpressure Processing of Bi-2212/Ag Tapes 103
8.2.1 Thickness Dependence of the Critical Current Density 104
8.2.2 Magneto-Optical Imaging 105
8.2.3 Microstructural Analysis 105
8.2.4 X-ray Results 107
8.2.5 Interpretation 108

9. Processing of Bi-2223/Ag Tapes at Reduced Final Temperature 109
9.1 Processing Schemes 109
9.2 Critical Current Density 110
9.3 X-ray Analysis 110
9.4 Microstructural Examination 112
9.5 Ac Susceptibility Results 112
9.6 Discussion 114

10. Preliminary Results on YBCO-Coated Conductors 117
10.1 Metallurgy of the Metallic Substrates 117
10.1.1 Recrystallization Procedure 117
10.1.2 Texture Analysis 120
10.2 Buffer Layers 122
10.2.1 Buffer Layers on Nickel Substrates 122
10.2.2 Buffer Layers on Ni–Cu Composite Tapes 124
10.3 Y–Ba–Cu–O Coating 124

Part IV. Electromagnetic Properties

11. Magnetotransport and Vortex Dynamics 129
11.1 Magnetic-Field Dependence of the Critical Current Density . . 129
11.2 Scaling of the I–V Characteristics 130
11.3 Critical-Current Anisotropy 133
11.4 Flux Creep Resistivity 135
11.5 Irreversibility Field 136

12. Superconducting Magnetic Levitation 139
12.1 Levitation Force Experiments on Various Superconductors . . . 139
12.1.1 Experimental Setup 139
12.1.2 Experimental Parameters 140
12.1.3 Comparison of Various Superconductors 146
12.1.4 Spatial Distribution of Levitation Force 149
12.2 Understanding Force–Distance Hysteresis 151
12.2.1 Interpretation Within the Bean Critical-State Model . . 152
12.2.2 Magnetic-Field-Dependent Critical Current Density . . . 156
12.3 Interpretation of Vertical-Stiffness Experiments 157
12.3.1 Vertical Magnetic Stiffness as a Bearing Parameter . . . 158
12.3.2 Stiffness and Labusch Parameter 159
12.4 Experiments on Stacks of Epitaxial Thin Films 163
12.4.1 Force–Distance Characteristics 163
12.4.2 Magnetic Stiffness 164

13. Remanent Flux Distribution and Critical Current Density 167
13.1 Experimental Details 167
13.1.1 The Hall Sensor 167
13.1.2 Resolution of the Hall Probe 168
13.1.3 Imaging of the Remanent Flux Distribution 169
13.2 Calculation of the Critical Current Density 169
13.3 Epitaxial YBCO Films 171
13.3.1 Experimental Details 171
13.3.2 Results and Discussion 172
13.4 Bi-2223/Ag Tapes 172
13.4.1 Lateral Resolution 173
13.4.2 Results from Bi-2223/Ag Tapes 175
13.4.3 Quality Control of Long Tapes 178

Part V. Concluding Remarks

14. Concluding Remarks 181
14.1 Summary 181
14.2 Conclusion 182

References 187

Index 203