Contents

List of Contributors xi
Preface xiii
Contents of Volumes 1–23 xvii

1. Spin Glasses 1
H. Kawamura and T. Taniguchi

1. Introduction 2
1.1 What is Spin Glass? 2
1.2 Spin Glass Materials 4
1.3 A Brief Historical Survey 7
1.4 Organization of the Chapter 21
2. Experimental Features of Spin Glass 22
2.1 Magnetic Properties 22
2.2 Importance of Time Scales—Equilibrium versus Nonequilibrium 29
2.3 Thermal Properties 31
2.4 Transport Properties 34
2.5 Effects of Magnetic Anisotropy 38
2.6 In-Field Properties and Magnetic Phase Diagram 41
2.7 Critical Properties of the Spin Glass Transition 47
3. Theoretical Features of Spin Glass 54
3.1 Edwards–Anderson Model 54
3.2 Mean-Field Model 57
3.3 Replica-Symmetry Breaking 63
3.4 Numerical Results of the Ising Spin Glass 64
3.5 Numerical Results on the Heisenberg Spin Glass 70
3.6 Numerical Results on the *XY* Spin Glass 78
3.7 Phenomenological Analysis 80
4. Chirality in Spin Glasses 83
4.1 Chirality Scenario of the Spin Glass Ordering 83
4.2 Relation to Experiments 90
5. Off-Equilibrium Dynamics of Spin Glasses 96
5.1 Aging 96
5.2 Memory and Rejuvenation 99
5.3 Noise Measurements 101
5.4 Breaking of the FDT and Relation to RSB 104

6. **A Variety of Spin Glass Families** 108
   6.1 Reentrant Spin Glass 108
   6.2 Spin Glass Behaviors in Geometrically Frustrated Magnets 112
   6.3 Multiferroic Behaviors in Spin Glass 115
   6.4 Spin Glass in Multidegree-Coupled System 116
   6.5 Coupling to the Conduction Electrons in Metallic Spin Glasses 119
   6.6 Spin Glass Behaviors in Magnetic Nanoparticles 120
   6.7 Spin Glass Behaviors in Relaxors 121
   6.8 Spin Glass Behaviors in Granular Superconductors 123
7. **Concluding Remarks** 127
Acknowledgments 128
References 129

2. Advances in Giant Magnetoimpedance of Materials 139

A. Zhukov, M. Ipatov and V. Zhukova

1. **Introduction** 140
2. **Longitudinal and Off-Diagonal GMI** 143
3. **Tailoring of Magnetic Properties and GMI** 149
   3.1 Fabrication of Soft Magnetic Materials Suitable for GMI-Related Applications 151
   3.2 Effect of Composition and Magnetoelastic Anisotropy on MI of Amorphous Wires 155
   3.3 Effect of Annealing on GMI Effect of Amorphous Wires. Correlation with the Magnetostriction Constant 171
   3.4 Tailoring of GMI Effect by Nanocrystallization 177
4. **Asymmetry and Hysteresis of MI Caused by the Helicoidality** 181
   4.1 Determination of the Equilibrium Magnetization State and Calculation of the MI in Wire with a Helical Magnetic Anisotropy 183
   4.2 Surface Domain Structure and Magnetoimpedance in Microwires with Circumferential and Helical Magnetic Anisotropy 196
   4.3 Effect of Static Bias Current on MI 199
   4.4 Impedance as a Function of Bias Current, Model, and Experiment 204
   4.5 Application of Bias Field in Wires with Helical Magnetic Anisotropy for Enhancing MI Sensor Performance 208
5. **Asymmetry and Hysteresis in GMI Induced by Core–Shell Interaction** 216
6. **Novel Applications of the MI Effect** 223
   6.1 Application of MI Hysteresis in Magnetic Memory 224
   6.2 Metamaterials 227
   6.3 Applications of the GMI Effect for Sensors 230
7. **Concluding Remarks and Future Perspectives** 230
Acknowledgments 232
References 232

3. Advances in Magnetoelectric Materials and Their Application 237

L.E. Fuentes-Cobas, J.A. Matutes-Aquino, M.E. Botello-Zubiate, A. González-Vázquez, M.E. Fuentes-Montero and D. Chateigner

1. **Introduction** 238
2. **Physics of Crystal Magnetoelectricity** 242
   2.1 Summary of Constitutive Equations and Units 242
   2.2 Properties and Magnetic Symmetry 242
   2.3 Magnetoelectric Longitudinal Surfaces 243
   2.4 Magnetoelectricity and the Material Properties Open Database 243
   2.5 Superexchange Interaction 256
   2.6 Ferroelectricity in Spiral Magnets 258
   2.7 Dzyaloshinskii–Moriya (DM) Interaction 259
   2.8 A Note on the Modern Theory of Polarization 261
   2.9 Magnetoelectricity and the Electron Electric Dipole 264
3. **Representative Magnetoelectric Crystals** 264
   3.1 $BiFeO_3$ and Related Perovskites 264
   3.2 $RFeO_3$ Orthoferrites 271
   3.3 A Magnetoelectric *Cubic* Perovskite 272
   3.4 Double Perovskites 273
   3.5 Aurivillius Phases 275
   3.6 Doped ZnO 276
   3.7 $TbMnO_3$ and Its Cycloidal Spin Ordering 277
4. **Single-Phase Polycrystal Magnetoelectrics** 277
   4.1 Macroscopic Anisotropy of Magnetoelectric Polycrystals 277
   4.2 Experimental Investigation of Textured Magnetoelectric Thin Films 279
   4.3 Single-Phase Polycrystal Magnetoelectrics: In Silico Case Studies 280
5. **Composite Magnetoelectrics** 288
   5.1 General Issues on Magnetoelectric Composites 288
   5.2 Magnetoelectric Coefficients Measurement Methods 290
   5.3 Magnetoelectric Effect Enhancement in Composites by Resonances 291
   5.4 Electromechanical Resonance 292
   5.5 Magnetic Resonance 294
   5.6 Magnetoacoustic Resonance 294
   5.7 Influence of Type of Connectivity and Electrical Resistance on the Magnetoelectric Effect 296
6. **Applications of Magnetoelectricity** 298
   6.1 Microwave and Millimeter-Wave Applications of Magnetoelectric Composites 298
   6.2 Sensor Applications of Magnetoelectric Composites 300
   6.3 Current Sensors 302
   6.4 Energy Harvesting Applications of Magnetoelectric Composites 303

6.5 Spintronic Applications of Magnetoelectric Composites 304
6.6 Magnetoelectric Composites for Medical Application 306
6.7 Magnetoelectric Nanoparticles to Enable Field-Controlled High-Specificity Drug Delivery to Eradicate Ovarian Cancer Cells 308
6.8 Externally Controlled On-Demand Release of Anti-HIV Drug Using Magnetoelectric Nanoparticles as Carriers 309

Appendix: Texture and Physical Properties 311
Crystallographic Texture 311
Polycrystal Physical Properties. Voigt, Reuss, and Hill Approximations 312
Geometric Average 315

Acknowledgments 317

References 317

4. Advances in Magnetic Hysteresis Modeling 323

Ermanno Cardelli

1. Introduction 325
2. The Stoner and Wohlfarth Model 326
2.1 The Classical Stoner–Wohlfarth Model 327
2.2 The Cubic Anisotropy Cut in the (100) Plane 332
2.3 The Cubic Anisotropy Cut in the (110) Plane 335
3. The Equivalent Ellipse Model 338
3.1 Definition of the Model 338
3.2 Magnetic Field and Eddy Currents Distribution 339
4. The Jiles–Atherton Model 341
4.1 Effective Field and Isotropic Materials 341
4.2 Extension to Anisotropic Materials 343
4.3 Vector Extension 344
5. The Play Model 346
5.1 The Play Operator 346
5.2 The Vector Play Model 347
6. The Preisach Model 349
6.1 The Preisach Bistable Operator 349
6.2 Identification of the Preisach Function 350
7. Vector Extension of the Classical Preisach Model 353
7.1 Superposition of Rotated Scalar Models 353
7.2 Vector Preisach Function and Its Identification 354
8. The Vector Preisach Hysteron 354
8.1 The Preisach Operator in 3D 354
8.2 Properties 356
8.3 Numerical Identification Techniques 358
9. The Magnetic Accommodation 363
9.1 Accommodation and Vector Model 363
9.2 Examples 363

10. The Magnetic Aftereffect 365
10.1 Magnetic Viscosity and Vector Model 365
10.2 Magnetization Decay 366
11. The Vector Moving Model 367
11.1 The Moving Hysteron 367
12. Artificial Neural Networks Modeling 369
12.1 Introduction to the Artificial Neural Networks 369
12.2 Scalar Magnetic Hysteresis 371
12.3 Extension to Dynamic Processes in 1D 372
12.4 2D Magnetic Hysteresis 373
13. The Coupling with FEM Solvers 375
13.1 The Magnetostatic Field Problem 375
13.2 The Eddy Currents Field Problem 376
13.3 The Use of the Potentials 378
13.4 The Magnetic Scalar Potential and the Magnetostatic Problem 379
13.5 The Magnetic Scalar Potential and the Eddy Current Problem 380
13.6 FEM Formulations for Magnetic Problems 381
13.7 Iterative Solvers 384

Appendix 1—Determination of the Discrete Probability Density Distribution Function of the Vector Hysterons for a Nongrain-Oriented Electrical Steel by Scalar Measurements 387
Appendix 2—Determination of the Probability Density Distribution Function of the Vector Hysterons in Case of Lorentian Approximation and Comparison with Experimental Results 389
Appendix 3—An Example of Application of the Moving Vector Hysterons Modeling to the Static Analysis of Nongrain-Oriented and Grain-Oriented Electrical Steels 393
Appendix 4—Determination of the Magnetic Induction Distribution in a Magnetostatic Problem 396
Acknowledgments 398
References 398

Author Index 411
Subject Index 427
Material Index 435