

Contents

Preface *xi*

Editors' Bio *xiii*

- 1 Nanostructured Multiferroics: Current Trends and Future Prospects** *1*
P.M. Visakh and B. Raneesh
 - 1.1 Single-phase Multiferroics *1*
 - 1.2 Multiferroic Study of Pure BiFeO₃ Synthesized Using Various Complexing Agents by Sol–Gel Method *2*
 - 1.3 Nanostructured Multiferroics *3*
 - 1.4 Multiferroic Systems of BiFeO₃ and BaTiO₃ Nanostructures: New Ideas and Insights from Recent Magnetoelectric Advancements *5*
 - 1.5 Effective Properties of Multilayered Nanomultiferroics *6*
 - 1.6 Correlation between Grain Size, Transport, and Multiferroic Properties of Ba-doped BiFeO₃ Nanoparticles *7*
 - 1.7 Specific Heat and Magnetocaloric Properties of Some Manganite-Based Multiferroics for Cryo Cooling Applications *8*
 - 1.8 Preparations, Characterization, and Applications of Multiferroic Nanocomposites *10*
 - 1.9 Conclusions *11*
References *11*

- 2 Single-Phase Multiferroics** *23*
Piotr Graczyk and Emerson Coy
 - 2.1 Introduction *23*
 - 2.1.1 Considerations on Single-phase Multiferroics *26*
 - 2.1.2 Ferroelastic Multiferroics *29*
 - 2.2 Analysis of the Multiferroicity in the Hexagonal Manganites *30*
 - 2.2.1 Ferromagnetism in Hexagonal Manganites *30*
 - 2.2.2 Ferroelectricity in Hexagonal Manganites *32*
 - 2.3 Investigation of Charge States and Multiferroicity in Doped Systems *32*
 - 2.3.1 Sensitive Ordering-doped Perovskite Manganites *32*

2.3.2	Frustrated LuFe_2O_4 – Multiferroism in Controversy	35
2.3.3	From the Dzyaloshinskii–Moriya Interaction to the Exchange Striction	37
2.4	Multiferroic Phases of Lone-pair Ferroelectrics: Bismuth-Based Compounds	38
2.5	Studies on Proper Geometric Ferroelectrics	41
2.6	Conclusions	44
	Acknowledgments	44
	References	45
3	Multiferroic Study of Pure BiFeO_3 Synthesized Using Various Complexing Agents by Sol–Gel Method	51
	<i>Vivek Verma, Neelam Singh, and Jarnail Singh Bangruwa</i>	
3.1	Introduction	51
3.2	Experimental	52
3.3	Results and Discussion	53
3.3.1	Structural Analysis	53
3.3.2	Morphological Analysis	54
3.3.3	FTIR Analysis	55
3.3.4	Magnetic Analysis	57
3.3.5	Ferroelectric Analysis	58
3.3.6	Dielectric Analysis	59
3.3.7	Leakage Current Analysis	60
3.4	Conclusions	61
	References	62
4	Nanostructured Multiferroics	63
	<i>Heng Wu and Xinhua Zhu</i>	
4.1	Introduction	63
4.2	Multiferroic Nanoparticles	64
4.2.1	Solid-state Reactions	65
4.2.2	Molten-salt Synthesis (MSS)	66
4.2.3	Mechanochemical Synthesis	66
4.2.4	Wet Chemical Methods	68
4.2.4.1	Sol–Gel Process	68
4.2.4.2	Hydrothermal/Solvothermal Process	69
4.2.4.3	Microwave–Hydrothermal (M–H) Process	70
4.3	Nanocomposites	73
4.4	Core–Shell Nanostructures	75
4.5	Nanostructures and Thin Films for Multifunctional Applications: Technology, Properties, and Devices	77
4.5.1	Fabrication Technologies	78
4.5.2	Physical Properties	79
4.5.2.1	Ferroelectric Properties	79

4.5.2.2	Magnetic Properties	81
4.5.2.3	Photocatalytic Properties	82
4.5.3	Multiferroic Devices	82
4.6	Thin Films for Photovoltaic Applications	84
4.7	Conclusions	87
	Acknowledgments	88
	References	88
5	Multiferroic Systems of BiFeO₃ and BaTiO₃ Nanostructures: New Ideas and Insights from Recent Magnetoelectric Advancements	95
	<i>K.C. Verma, R. K. Kotnala, and Navdeep Goyal</i>	
5.1	Introduction to Multiferroics	95
5.1.1	Multiferroic Approaches Toward Magnetoelectric Memories	96
5.1.2	Multiferroic Perovskites	97
5.1.3	Multiferroic Systems of BaTiO ₃ and BiFeO ₃ Nanostructures	99
5.1.3.1	BaTiO ₃	99
5.1.3.2	BiFeO ₃	100
5.1.3.3	Lone Pairs and Charge Ordering of Ferroelectric Activity	101
5.2	Crystalline Structure and Phase Transition	102
5.2.1	X-ray Diffraction (XRD) of BaTM _{0.01} Ti _{0.99} O ₃ [TM = Cr, Mn, Fe, Co, Ni, Cu (1 mol% Each)] Nanoparticles	102
5.2.2	Crystalline Structure of BiFeO ₃ Nanostructures with Pb Doping	103
5.2.3	Nanostructural Approach Toward Multiferroics	105
5.2.3.1	Nanostructural Influence on Ferroelectric Polarization	106
5.2.3.2	Nanosize-dependent Phase Structure	106
5.2.3.3	Lattice Defects-related Nanostructures	107
5.2.4	Magnetic Ordering	108
5.2.4.1	TM Ion-substituted BaTiO ₃	108
5.2.4.2	Magnetic Ordering in BiFeO ₃	110
5.2.5	Multiferroicity and Magnetoelectric Coupling: How to Enhance	112
5.2.5.1	Multiferroic Composites	112
5.2.5.2	Multiferroic Thin Films and Nanostructures	116
5.3	Synthesis Methods of BaTiO ₃ and BiFeO ₃ Multiferroics	122
5.3.1	Sol–Gel: Synthesis	122
5.3.2	Chemical Combustion	123
5.3.3	Liquid-phase Deposition Route	123
5.3.4	Hydrothermal Synthesis	123
5.3.5	Metallo-organic Decomposition Method (MOD) for Thin-Film Preparation	123
5.3.6	Modified Pechini Method	124
5.4	Conclusions	124
	Acknowledgments	124
	References	125

6	Effective Properties of Multilayered Nanomultiferroics	133
	<i>Ivan A. Starkov and Alexander S. Starkov</i>	
6.1	Introduction	133
6.2	Matrix Homogenization Method	134
6.2.1	Justification of the Matrix Homogenization Method	135
6.3	Laminate Nanocomposites	138
6.4	Fiber Nanocomposites	144
6.4.1	Basic Equations	144
6.4.2	Anti-plane Elasticity	147
6.4.3	Axial-symmetry Case	149
6.4.4	Maxwell–Garnett Theory	152
6.5	Core–Shell Nanostructures	153
6.5.1	Basic Equations	154
6.5.2	Homogenization Procedure for the Layered Hollow Sphere	156
6.6	Summary and Conclusions	159
	Acknowledgments	159
	References	160
7	Correlation Between Grain Size, Transport, and Multiferroic Properties of Ba-doped BiFeO₃ Nanoparticles	163
	<i>M. M. El-Desoky and M. S. Ayoub</i>	
7.1	Introduction	163
7.2	Characterization of Ba-doped BiFeO ₃ Multiferroic Nanoparticles	165
7.2.1	X-ray Diffraction (XRD)	165
7.2.2	Scanning Electron Microscope (SEM)	167
7.2.3	Transmission Electron Microscope (TEM)	167
7.2.4	Fourier Transform Infrared (FTIR) Spectra	169
7.3	Transport Properties of Ba-doped BiFeO ₃ Multiferroic Nanoparticles	170
7.3.1	Nature of Conduction Mechanism	172
7.3.2	Relation Between Activation Energy and Mean Distance Between Iron Ions	174
7.3.3	Nature of Small Polaron-hopping (SPH) Conduction	176
7.3.4	Small Polaron-hopping (SPH) Parameters	176
7.3.5	Hopping Carrier Mobility and Density	177
7.4	Multiferroic Properties of Ba-doped BiFeO ₃ Multiferroic Nanoparticles	178
7.4.1	Ferromagnetic Properties	178
7.4.1.1	Molar Magnetic Susceptibility (λ_M)	178
7.4.1.2	Néel Temperature (T_N)	180
7.4.2	Ferromagnetic Hysteresis Loop	180
7.4.3	Ferroelectric Properties	184
7.4.3.1	Temperature Dependence	184
7.4.3.2	Frequency Dependence	187

7.4.4	Ferroelectric Hysteresis Loop	188
7.5	Conclusion	189
	References	190
8	Specific Heat and Magnetocaloric Properties of Some Manganite-Based Multiferroics for Cryo Cooling Applications	193
	<i>N. Pavan Kumar, Elle Sagar, and P. Venugopal Reddy</i>	
8.1	Introduction	193
8.1.1	Magnetic Refrigeration	193
8.1.2	Magnetocaloric Effect	194
8.1.3	Magnetocaloric Effect and Magnetic Transition	195
8.1.4	Manganites as Magnetocaloric Materials	195
8.1.5	Magnetocaloric Effect in Rare Earth-Based Multiferroic Manganites	196
8.1.6	Methods for the Determination of Magnetocaloric Effect	196
8.1.6.1	Direct Measurements	196
8.1.6.2	Indirect Measurements	197
8.1.7	Properties of an Ideal Magnetic Refrigerator Material	198
8.2	Multiferroic Materials and Their Structure	198
8.2.1	Rare Earth-Based Multiferroic Manganites Based on Their Structures	198
8.2.1.1	Hexagonal Manganite Multiferroics	199
8.2.1.2	Orthorhombic Manganite Multiferroics	199
8.3	Specific Heat and Estimation of Magnetic Entropy	200
8.3.1	Specific Heat	200
8.3.1.1	RMnO_3 (R = Sm, Eu, Gd, Tb, and Dy)	200
8.3.1.2	$\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ ($x = 0, 0.1, 0.2, 0.3,$ and 0.4)	204
8.3.1.3	RMn_2O_5 (R = Tb, Dy, and Ho)	205
8.3.2	Estimation of Magnetic Entropy	208
8.3.2.1	RMnO_3 (R = Sm, Eu, Gd, Tb, and Dy)	208
8.3.2.2	$\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ ($x = 0, 0.1, 0.2, 0.3,$ and 0.4)	211
8.3.2.3	RMn_2O_5 (R = Tb, Dy, and Ho)	211
8.4	Magnetocaloric Properties	213
8.4.1	RMnO_3 Series	214
8.4.1.1	Orthorhombic NdMnO_3 , SmMnO_3 , and EuMnO_3	214
8.4.1.2	Orthorhombic GdMnO_3 , TbMnO_3 , and DyMnO_3	216
8.4.1.3	Hexagonal DyMnO_3	220
8.4.1.4	Hexagonal HoMnO_3	220
8.4.2	Group 2 Series (Doped Rare-earth Manganites)	221
8.4.2.1	Orthorhombic Dy-doped TbMnO_3	221
8.4.2.2	h- YbMnO_3 Doped with Transition Metals and Rare Earths	223
8.4.3	RMn_2O_5 (R = Tb, Dy, and Ho) Series	224
8.5	Conclusions	227
	References	228

9	Preparations, Characterization, and Applications of Multiferroic Nanocomposites	233
	<i>P.M. Visakh</i>	
9.1	Introduction	233
9.2	Preparation of Multiferroic Nanocomposites	235
9.3	Characterizations of Multiferroic Nanocomposites	238
9.4	Applications of Multiferroic Nanocomposites	240
9.5	Conclusions	241
	References	241
	Index	249