

Index

a

active magnetic regenerative (AMR) 195
 antiferrodistortive phase transition 43,
 44
 anti-plane elasticity 147–149
 atomic force microscopy (AFM) 119
 autoclave method 4, 69
 Avogadro's number 166

b

Ba-doped BiFeO₃ multiferroic
 nanoparticles
 characterization 165–170
 multiferroic properties of 178–189
 transport properties of 170–178
 BaMF₄ 42
 BaMnF₄ 42, 43
 barium fluorides 43
 barium titanate (BaTiO₃) 24
 paraelectric phase 24
 phase diagram 4, 24
 tetragonal ferroic phase 24
 Berry phase formulation 39
 BiBaFeO₃ multiferroic nanoparticles
 adiabatic hopping regime 173, 174
 agglomeration 168
 average distance, effect of 175
 barium content effect, on
 pre-exponential factor 175
 charge carrier concentration 164
 conduction mechanism, nature of
 172–174
 DC conductivity variation
 activation energy 170–174
 and crystallite size 170–171
 effect of barium content 171
 function of inverse of temperature 171
 Debye temperature 170
 ferroelectric properties
 frequency dependence 187–188
 hysteresis loops 188–189
 temperature dependence 184–187
 ferromagnetic properties
 hysteresis loop 180–184
 magnetization dependence 179, 181
 molar magnetic susceptibility
 178–180
 Néel temperature 180
 FTIR spectra 169–170
 grain growth 167
 hopping carrier mobility and density
 177–178
 iron ions, activation energy vs. mean
 distance 174–175
 magnetic properties 8
 non-adiabatic hopping regime 172, 173
 optical phonon frequency 169, 170
 oxygen vacancies, concentration of 8
 particle size, lattice parameters and
 density 165
 physical properties 173
 scanning electron microscope (SEM)
 167, 168
 semiconducting nature 170
 small polaron-hopping (SPH)
 parameters 176–177

- semiconducting nature (*contd.*)
 - nature of 176
 - transmission electron microscope (TEM) 167–168
 - transport properties 170–178
 - X-ray diffraction (XRD) 165–167
 - BiFeO₃ (BFO) thin films 2, 51
 - Bi(Fe_{x-1}Mn_x)O₃, (BFMO) 41
 - bismuth-based complex oxides 234
 - bismuth ferrite (BFO) nanoparticles
 - magnetoelectric device applications 64
 - mechanochemical synthesis 66–68
 - molten-salt synthesis (MSS) 66
 - solid-state reaction process 65
 - wet chemical synthesis methods
 - advantages 68
 - hydrothermal method 69–70
 - microwave–hydrothermal (M–H) process 70–73
 - sol–gel process 68–69
 - solvothermal method 69–70
 - bismuth ferrite (BiFeO₃)
 - antiferromagnetic order 27
 - autoclave method 4
 - BFO thin films 51
 - citric acid 3
 - crystallite size 4
 - Curie temperature 51
 - dielectric properties 3
 - direct mechanochemical reaction 4
 - ferroelectricity 5, 7, 37–40
 - ferroelectric transition temperature 234
 - hydrothermal method 4
 - lattice of polarization vectors 39
 - leakage current 8, 163, 164
 - magnetic hysteresis loops 3
 - magnetic order 39
 - magnetism 7
 - magnetization and coercivity 3
 - ME coefficient 51–52
 - nanoparticles, modified Pechini method 5–6
 - Néel temperature 51
 - phase transitions 38
 - at room temperature 163
 - scanning electron micrographs 10
 - sol–gel method 2, 3
 - space charges in 8
 - top-down approach 4
 - variation of leakage current 3
 - weak ferromagnetism 40
 - X-ray diffraction (XRD) pattern 3
 - BFO–graphene nanohybrids 82
 - BFO thin films
 - magnetic properties 81–82
 - bottom-up approach 78
 - electron beam direct writing (EBDW) method 78
 - ferroelectric properties 79–91
 - focused ion beam (FIB) milling method 78
 - light and dark I–V curves 85
 - photocatalytic properties 82
 - photovoltaic applications 84–87
 - top-down approach 78
- C**
- Campbell–Hausdorff formula 136
 - Carnot efficiency 193
 - ferroelectric property 80
 - charge ordering 28, 100–101
 - chemical combustion method 123
 - Co doped BaTiO₃ system 6, 109
 - collinear magnets 28
 - colossal magnetoresistance (CMR) 9, 35, 196
 - core–shell nanocomposites 7, 77, 153, 154
 - core–shell nanostructures
 - BTO 76
 - BTO– γ -Fe₂O₃ nanoparticles 76
 - CFO–BTO 76
 - CFO/PZT nanotubes 77
 - core–shell type nanotubes 4, 76
 - cubic symmetry 5, 24, 96, 99
 - cubic perovskite, crystalline structure of 25

Curie temperature 2, 7, 51, 87, 163,
184–186, 190, 195, 234

d

Debye approximation 212
Debye–Scherrer equation 165
Debye temperature 164, 169, 170, 212
deformation tensor 138
de-Gennes scaling 209
dielectric constant, of BFO pellets 64
double perovskite structure 25
DyMn₂O₅ 200, 208, 214, 215, 227
DyMnO₃
magnetic entropy values 211
MCE properties of 9

e

electron beam direct writing (EBDW)
method 4, 78
entropy 194
entropy change
of RMnO₃ (R=Gd, Tb and Dy)
multiferroics 217
Tb_{1-x}Dy_xMnO₃ multiferroic system
222
EuMnO₃ samples 201, 209, 214
exaggerated grain growth 167
exchange striction 37–38, 44, 98

f

ferrodistortive phase transition 43, 44
ferroelastic domains 2, 29
ferroelastic multiferroics 29–30
ferroelastic switching 2, 29
ferroelectric hysteresis loops 188–189
ferroelectricity
due to charge ordering 28
geometric 28
hexagonal manganites 32
ferroelectric nanostructures vs. bulk
materials 5
ferroelectric polarization 27–29, 32, 40,
75, 79, 80, 81, 82, 86, 105, 237
ferroelectric random access memory
(FeRAM) 83, 96

ferroelectric thin film-based photovoltaic
devices 86, 87

ferroic materials

hysteretic nature 23
metastable states 23
nonzero remanence 23

ferromagnetism

and ferroelectricity 2
in hexagonal manganites 30–31

fiber nanocomposites

anti-plane elasticity 147–149
axial-symmetry case 149–151
basic equations 144–147

Maxwell–Garnett approach 152–153

field cooling (FC) 109

focused ion beam (FIB) milling method
4, 78

Fourier transform infrared (FTIR)

spectra 3, 55–57, 169–170,
234–235

frustrated LuFe₂O₄ 35–37

g

gadolinium molybdate Gd₂(MoO₄)₃
(GMO)

complex phase diagram 29
sol–gel technique 29

GdMnO₃ samples

magnetic entropy values 211
MCE properties of 9

geometric ferroelectricity 28

geometric ferroelectrics 28, 41–44

Goldschmidt tolerance factor 25, 26

Goodenough–Kanamori rule 2, 26, 27

grain boundary scattering 171, 175

h

half-doped Pr_{0.5}Ca_{0.5}MnO₃

checkerboard (CB) charge-ordered state
33

orthorhombic structure 32

hexagonal manganites 28

ferroelectricity in 32

ferromagnetism in 30–31

HoMn₂O₅ sample 203

- homogenization methods 133
 Hund's rule 6, 101
 hydrothermal synthesis 5, 65, 69–71,
 123–124, 235
- i**
- inverse Dzyaloshinskii–Moriya
 interaction (DMI) 2, 98
 inverse Dzyaloshinsky–Moriya interaction
 (DMI) 28
 I-type multiferroics 2, 37
- k**
- Koop's theory 59
- l**
- $\text{La}_{0.33}\text{Ca}_{0.67}\text{MnO}_3$ 34
 $\text{La}_2\text{NiMnO}_6$ double perovskite 26
 laminate nanocomposites 138–144
 Landau–Devonshire theory 185, 186
 layered perovskites 43, 44
 liquid-phase deposition route method
 123
 lone-pair electrons 5, 7, 27, 32, 98, 99,
 101, 124, 163
 lone-pair ferroelectrics 38–41
 lone-pair model 98
 low-dimensional BFO multiferroic
 nanostructures 64
- m**
- magnetic anisotropy 8, 178
 magnetic entropy 208, 209
 of EuMnO_3 samples 209
 in perovskite manganites 8
 of RMn_2O_5 (R=Tb, Dy and Ho) samples
 211
 of SmMnO_3 samples 209
 of $\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ samples 212
 of TbMnO_3 single crystal 210
 vs. temperature plots 210
 magnetic ferroelectrics 2, 37
 magnetic random access memory
 (MRAM) 83, 96
 magnetic refrigeration 8, 9, 193–194
 magnetic refrigerator materials,
 properties of 198
 magnetocaloric effect (MCE) 9, 195
 determination methods
 direct measurements 196–197
 from heat capacity measurements
 197–198
 indirect measurements 197–198
 from magnetization measurements
 197
 and magnetic transition 195
 properties
 of Dy-doped TbMnO_3 orthorhombic
 samples 221–223
 of DyMnO_3 orthorhombic single
 crystal 219
 of hexagonal HoMnO_3 220–221
 of hexagonal- DyMnO_3 220
 of HoMn_2O_5 sample 226, 227
 of GdMnO_3 single crystal 216–220
 of Mg-doped YbMnO_3 223
 of rare-earth-elements-doped
 YbMnO_3 224
 of TbMn_2O_5 sample 216–220
 in rare earth-based multiferroic
 manganites 196
 values 213
 of doped RMnO_3 samples 223
 of DyMnO_3 216
 of EuMnO_3 samples 214
 of GdMnO_3 216
 of NdMnO_3 samples 215
 of RMn_2O_5 samples 227
 of SmMnO_3 samples 214
 of TbMnO_3 216
 magnetodielectric (MD) coupling effect
 76
 magnetoelectric coefficients 133, 138,
 143, 144, 155, 158, 159
 magnetoelectric coupling (MEC) 28, 51,
 63, 112–122, 180
 magnetoelectric (ME) effect 7, 43, 95,
 133, 134, 142
 magnetoelectric random access memory
 (MERAM) 77

- magneto-electro-elasticity equations 7, 8, 134, 138, 141, 142, 145, 147, 159
- manganite-based multiferroics
 for cryo cooling applications 8–10
 magnetic refrigeration 193–194
 magnetic transition 195
 magnetocaloric effect 194–195
 direct method 196–197
 indirect method 197–198
 in rare earth-based multiferroic manganites 196
 magnetocaloric materials 195–196
 magnetocaloric properties 213–227
 multiferroic materials and structure 198–200
 specific heat and estimation 200–213
- manganites 195–196
- matrix homogenization method (MHM)
 accuracy of 137
 advantages 154
 application of 139
 feature of 136
 justification of 135–138
 nonlinear equations 143
- Maxwell–Garnett approach 148, 152
- Maxwell–Wagner effect 35, 76, 114
- mechanochemical synthesis 3, 64–68
- metallo-organic decomposition (MOD)
 method 124, 235
- metastable states, in ferroics 23
- microwave–hydrothermal (M–H) process 4, 65, 68, 70–73, 235
- Mn-doped BFO 40
- modern theory of polarization (MTP) 38
- modified Pechini method 6, 106, 124
- molar magnetic susceptibility 178–179
- molten-salt synthesis (MSS) 65–67
- multiferroic composites 11, 112–114, 133, 233, 235–240
- multiferroic devices 77, 82–84
- multiferroicity 27, 28, 30–38, 41, 43, 63, 95, 98, 112–122
- multiferroic manganites 9, 84, 196, 198–199, 215, 220, 221, 228
- multiferroic materials 1–3, 6, 7, 24, 27, 28, 44, 51, 63, 73, 83, 87, 133, 134, 163, 164, 185, 198, 199, 233, 234
- multiferroic nanocomposites
 applications of 240–241
 characterization 10–11, 238–240
- $\text{PbZr}_{0.58}\text{Ti}_{0.42}\text{O}_3\text{-Ni}_{0.5}\text{Co}_{0.5}\text{Fe}_2\text{O}_4$ 239
 preparation 235
 $\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3\text{-Ni}_{0.8}\text{Zn}_{0.2}\text{Fe}_2\text{O}_4$
 nanofibers 238
- $\text{BaTiO}_3\text{-CoFe}_2\text{O}_4$ 236
- $\text{BaTiO}_3\text{-Ni}_{0.5}\text{Co}_{0.5}\text{Fe}_2\text{O}_4$ 236
- BCZT–CFO nanocomposites 237
- $\text{Bi}_2\text{Fe}_4\text{O}_9\text{-Fe}_3\text{O}_4$ films 236
 bilayered
 $\text{CoFe}_2\text{O}_4/0.68\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$
 0.32PbTiO_3 films 237
- BPFO–NZFO nanocomposites 237
- $\text{CoFe}_2\text{O}_4/\text{Ba}_{0.8}\text{Sr}_{0.2}\text{TiO}_3$ composites 235
- $\text{CoFe}_2\text{O}_4/\text{Pb}_{0.7}\text{Ca}_{0.3}\text{TiO}_3$ composites 235
- double-perovskite $\text{Bi}_2\text{FeCrO}_6$ thin film 238
- GdMnO_3 and CoFe_2O_4 236
- $\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3\text{-BaTiO}_3$ 238
- $\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3/\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$
 films 236, 238
- $\text{Pb}(1x)\text{Sr}x\text{TiO}_3/\text{CoFe}_2\text{O}_4$
 nanocomposites 237
- $x\text{CoFe}_2\text{O}_4\text{-(1-x)}\text{Bi}_{0.85}\text{La}_{0.15}\text{FeO}_3$
 237
- $x\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3\text{-(1-x)}$
 $\text{Pb}(\text{Zr}_{0.58}\text{Ti}_{0.42})\text{O}_3$ 236
- $x\text{ZnFe}_2\text{O}_4\text{-(1-x)}\text{BiFeO}_3$
 nanocomposites 237
- preparation methods 10
- sensitive H sensors 11
- wet chemical procedures 234
- multiferroic nanoparticles 8, 64–73, 164–189
- multiferroic nanostructures
 bottom-up approach 78
 EBDW method 78

- multiferroic nanostructures (*contd.*)
 - fabrication 78–79
 - FIB milling method 78
 - ferroelectric properties 79–81
 - photocatalytic properties 82
 - multiferroic systems
 - BaTiO₃ 99
 - BiFeO₃ 100–101
 - composites 112
 - coupling
 - 0.7BiFeO₃–0.3BaTiO₃ nanoparticles 115–116
 - magnetic and ferroelectric phase transition 116–117
 - crystalline structure and phase transition
 - BiFeO₃ nanostructures with Pb doping 104
 - X-ray diffraction 102–103
 - ferroelectric activity 100–101
 - heterostructures 112–114
 - lone pairs 101
 - magnetic ordering
 - in BaTiO₃ 110
 - nanosize-dependent magnetization 111–112
 - TM ion-doped BaTiO₃ 108–110
 - magneto-capacitive/dielectric effects 114–115
 - ME effect 95, 97
 - nanostructural approach
 - ferroelectric polarization 105
 - lattice defects related nanostructures 107–108
 - nanosize-dependent phase structure 106–107
 - perovskite 97
 - synthesis methods
 - chemical combustion method 123
 - hydrothermal synthesis 123–124
 - liquid-phase deposition route 123
 - metallo-organic decomposition method 123
 - modified Pechini method 124
 - sol-gel method 122
 - thin films and nanostructures
 - atomic force microscopy images 118
 - BaTiO₃–BiFeO₃ thin films 122
 - horizontal multilayer
 - heterostructures 118
 - multilayers heterostructures 121
 - NiFe₂O₄/BaTiO₃ 120
 - single component thin-film
 - multiferroics 117, 118
 - vertical heterostructures 118–119
 - voltage control magnetism 119–120
 - multiferroic thin film fabrication 78
 - multiferroic tunnel junction 83
 - multilayered nanomultiferroics 6–7, 133–159
- n**
- nanocomposite films
 - BTO/CFO superlattice structured films 74
 - classification 73, 74
 - epitaxial BTO–NFO on LaAlO₃ substrates 74
 - ME effect 73
 - PZT–CFO composite films 74
 - PZT–CFO multilayer thin films 75
 - nanomatryoshkas 7
 - effective characteristics, calculation of
 - basic equations 154–156
 - magneto-electro-elastic spherical shells 154
 - matrix homogenization method 135–138
 - optical parameters 154
 - Néel temperature 8, 41, 64, 87, 106, 163, 178–180, 182, 186, 190, 234
 - non-volatile ferroelectric random access memories (NFERAMs) 105
- o**
- octahedron tilting 24
 - optical phonon frequency 169, 170, 172

p

PCMO 32–35
 perovskite ferroelectric material synthesis 67
 perovskite manganites 8, 195, 196
 charge ordering-doped 32–35
 perovskite structure 1, 3, 5, 7, 24, 25, 30, 40, 43, 54, 58, 96–98, 101, 163, 234
 photovoltaic applications, thin films or 84–87
 photovoltaic effect 84–86
 piezoresponse force microscopy (PFM) 81, 119, 238, 240
 polaron-hopping conduction model 164
 polaron-hopping mechanism 164, 173
 polaron-hopping theory 164

r

rare earth based multiferroic manganites
 hexagonal manganites 199
 orthorhombic manganites 199–200
 refrigeration
 disadvantages 193
 global electric consumption 194
 ruthenium (Ru)-doped BKFO (BiKFe_2O_5)
 multiferroic nanocomposite 10

s

Scherrer's formula 54
 Schottky anomaly 203
 second ferroelectric transition 9
 selected area electron diffraction (SAED) 54
 single-phase multiferroic material 7, 28, 51, 73, 234
 small-polaron hopping (SPH) 164, 172, 173, 176–177
 SmMnO_3 samples 201
 sol-gel method 3, 122
 BFO nanoparticle synthesis 68
 pure BiFeO_3 preparation
 complexing agents 52
 dielectric relaxation 59–60
 ferroelectric analysis 58–59

FTIR spectra 55–57
 leakage current density *versus*
 applied electric field 61
 loss tangent variations 60
 magnetic analysis 57–58
 magnetic hysteresis loops of 57
 magnetic parameters of 57, 58
 morphological analysis 54–55
 scanning electron micrographs 55, 56
 selected area electron diffraction (SAED) 54
 tunneling electron micrograph 54, 55
 structural analysis 53–54
 X-ray diffraction 53, 54
 pure bismuth ferrite preparation 51
 solid-state reaction synthesis, of BFO
 nanoparticles 65
 solvothermal synthesis 4
 BFO nanoparticles 69
 space-charge relaxation effect 187
 specific heat
 of DyMnO_3 manganites 201
 of EuMnO_3 manganites 201
 of GdMnO_3 manganites 201
 RMn_2O_5 (R=Tb, Dy and Ho) samples 205
 of SmMnO_3 manganites 201
 of TbMnO_3 manganites 201
 $\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ samples 204
 spin filter device, multiferroics in 83
 spiral magnets 2, 9, 28, 37, 98, 203
 spiral spin order 40
 spontaneous polarization 2, 5, 9, 24, 30, 32, 33, 39, 42, 51, 79, 84, 98, 99, 100, 105, 107, 118, 204
 superexchange interactions, in perovskites 26, 27
 symmetry inversion breaking 27

t

$\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ samples 213
 TbMn_2O_5 samples 225
 TbMnO_3 samples 9, 203, 204

- tolerance factor 25, 26, 100, 166, 167, 189
- topological ferroelectrics 43
- total entropy
 - of RMnO_3 (R=Gd, Tb and Dy)
 - multiferroics 216
 - of SmMnO_3 and EuMnO_3 215
 - of $\text{Tb}_{1-x}\text{Dy}_x\text{MnO}_3$ multiferroic system 222
- type I multiferroics 28, 32
- type II multiferroics 28

- V**
- vapor compression technology 193, 194
- Vegard's law 166

- X**
- X-ray diffraction (XRD) 3, 5, 10, 35, 42, 53, 71, 102, 165–167, 199, 234

- Y**
- $\text{Yb}_{0.9}\text{Er}_{0.1}\text{MnO}_3$ 11, 223, 224

- YMO_3 perovskite 30, 32
 - antiferromagnetic ordering 33
 - atomic force microscopy in 30
 - centrosymmetric space group 32
 - ferroelectric transition temperature 32
 - ferromagnetic ordering 30
 - in-plane arrangement 30
 - interplane interactions 30
 - magnetic interactions 30
 - neutron diffraction 30
 - noncentrosymmetric group 32
 - paraelectric regime 32
 - second harmonic generation (SHG) measurements 30
 - spin alignments 31
 - structure 31

- Z**
- Zener polarons 34
- zero-field cooling (ZFC) 109

