

Contents

About the Author *ix*

Foreword by Professor Longtu Li *xi*

Foreword by Professor Jürgen Rödel *xiii*

Preface *xv*

1	Fundamentals of Piezoelectricity	1
1.1	Introduction	1
1.2	Piezoelectric Effects and Related Equations	2
1.3	Ferroelectric Properties and Its Contribution to Piezoelectricity	3
1.4	Piezoelectric Parameters	7
1.4.1	Piezoelectric Constants	7
1.4.1.1	Piezoelectric Charge (Strain) Constant	7
1.4.1.2	Piezoelectric Voltage Coefficient (G-constant)	8
1.4.2	Piezoelectric Coupling Coefficient	8
1.4.3	Mechanical Quality Factor	9
1.5	Issues for Measuring Piezoelectric Properties	10
1.5.1	Measurement of Direct Piezoelectric Coefficient Using the Berlincourt Method	10
1.5.2	Measurement of Converse Piezoelectric Coefficient by Laser Interferometer	12
1.5.3	Resonance and Anti-resonance Method	14
	References	16
2	High-Performance Lead-Free Piezoelectrics	19
2.1	Introduction	19
2.2	BaTiO ₃	21
2.3	(K,Na)NbO ₃	23
2.4	(Bi _{1/2} Na _{1/2})TiO ₃	25
2.5	BiFeO ₃	27
2.6	Summary	28
	References	28

3	(K,Na)NbO₃ System	33
3.1	Introduction of (K,Na)NbO ₃	33
3.1.1	History of (K,Na)NbO ₃	33
3.1.2	Crystal Structure and Phase Diagram	33
3.1.3	Current Development of KNN-Based Materials	36
3.2	Synthesis	37
3.2.1	Calcination	37
3.2.2	Sintering	38
3.2.2.1	Normal Sintering	39
3.2.2.2	Hot Pressing, Spark Plasma Sintering, and Microwave Sintering	41
3.2.3	Texturing	43
3.3	Approaches to Piezoelectricity Enhancement	44
3.3.1	Phase Engineering	45
3.3.1.1	O-T Phase Boundary	45
3.3.1.2	R-T Phase Boundary	47
3.3.2	Thermal Stability	49
3.3.3	Multiscale Heterogeneity	53
3.3.4	Poling Techniques	57
3.4	Fatigue and Mechanical Properties	57
3.4.1	Fatigue	57
3.4.2	Mechanical Properties	60
3.5	KNN Thin Films	62
3.5.1	Sol-Gel-Processed Films	63
3.5.2	KNN Films Prepared by Physical Methods	65
3.6	Single Crystals	67
3.7	Summary	68
	References	69
4	(Bi_{1/2}Na_{1/2})TiO₃ System	85
4.1	Introduction of BNT System	85
4.2	Extensive Research on Phase Diagram of (Bi _{1/2} Na _{1/2})TiO ₃ -BaTiO ₃ System	86
4.2.1	Relaxor or Antiferroelectric?	86
4.2.2	MPB and Complex Phase Structure	90
4.3	High Converse Piezoelectricity	93
4.3.1	Electric-Field-Induced Phase Transition	95
4.3.2	Ergodic and Nonergodic Relaxor	98
4.3.3	Modulation of Depolarization Temperature	103
4.3.3.1	Compositional Modification Approach	103
4.3.3.2	Composite Approach	104
4.3.3.3	Stress Approach	105
4.4	Thin Films	106
4.5	Single Crystals	109
4.6	High-Power Application	110
4.7	Summary and Outlook	112
	References	112

5 BaTiO₃ System 123

- 5.1 Brief Introduction of History 123
- 5.2 BaTiO₃-Based Ceramics and Single Crystals 125
 - 5.2.1 Ceramics 125
 - 5.2.2 Single Crystal 128
- 5.3 BaTiO₃-Based Solid Solution Ceramics 129
 - 5.3.1 (Ba,Ca)(Ti,Zr)O₃ 130
 - 5.3.2 (Ba,Ca)(Ti,Sn)O₃ 132
 - 5.3.3 (Ba,Ca)(Ti,Hf)O₃ 134
- 5.4 Piezoelectricity Enhancement 135
 - 5.4.1 Phase Engineering 135
 - 5.4.2 Domain Engineering 137
 - 5.4.3 Texturing 139
- 5.5 Key Issues of Sintering Processes 139
 - 5.5.1 Li-containing Sintering Additives 140
 - 5.5.2 Glass Compositions 141
- 5.6 Mechanical Property 142
- 5.7 Summary and Outlook 144
- References 145

6 BiFeO₃ System 157

- 6.1 Introduction 157
- 6.2 Brief Introduction to Multiferroic Materials 157
- 6.3 Multiferroicity of BiFeO₃ 159
 - 6.3.1 Ferroelectricity 159
 - 6.3.2 Antiferromagnetism and Weak Ferromagnetism 159
 - 6.3.3 Magnetoelectric Coupling 161
 - 6.3.3.1 Antiferromagnetic Switching on Electric Field 161
 - 6.3.3.2 Ferroelectricity on Magnetic Field 162
- 6.4 Phase Diagram of BiFeO₃ 163
 - 6.4.1 High Curie Temperature and Processing Issues 163
 - 6.4.2 Influence of Pressure on Phase Diagram 165
 - 6.4.3 Thin Film and Strain Effect on Phase Structure 166
- 6.5 Dielectric Permittivity, Electrical Conductivity, and Domain Wall Conductivity of BiFeO₃ 169
 - 6.5.1 Dielectric Permittivity 169
 - 6.5.2 Electrical Conductivity and Defects 170
 - 6.5.3 Domain Wall Conductivity 172
- 6.6 Ion Substitutions in BiFeO₃ 174
 - 6.6.1 On Ferroelectricity (P_r) and Piezoelectricity (d_{33}) 175
 - 6.6.2 On Phase Transformation 177
 - 6.6.3 On Magnetic Properties 177
- 6.7 BiFeO₃-Based Solid Solutions 178
 - 6.7.1 BiFeO₃-BaTiO₃ 178
 - 6.7.2 Other Solid Solutions 180
- 6.8 Application of BiFeO₃: Potentials and Status 180

6.8.1	Ferroelectricity and Electronics	181
6.8.2	Magnetoelectric Coupling and Spintronics	182
6.8.3	Domain Wall Based Electronics	184
6.9	Summary	184
	References	185
7	Applications	197
7.1	Introduction	197
7.2	Representative Applications of Lead-Free Piezoelectric Ceramics	199
7.2.1	Piezoelectric Multilayer Actuators	199
7.2.2	KNN-Based Actuation Structure in Inkjet Printhead	201
7.2.3	Ultrasonic Transducers	202
7.2.4	KNN-Based Knocking Sensors	205
7.3	Other Potential Applications	206
7.3.1	Energy Harvesting	206
7.3.2	High-Frequency Medical Imaging Transducers Using 1–3 Composites	208
7.3.3	High-Temperature Piezoelectrics and Applications	210
7.4	Summary and Outlooks	210
	References	211
	Index	217