

Contents

Volume 1

Preface *xiii*

- 1 Piezoelectric Coefficients and Crystallographic Symmetry** *1*
Semën Gorfman and Nan Zhang
- 1.1 Introduction *1*
- 1.2 On the Anisotropy of Piezoelectricity and Its Role in the Understanding of Structures of Crystalline Materials *1*
- 1.3 Simplified Definitions of Piezoelectric Coefficients *2*
- 1.3.1 Direct Piezoelectric Effect *3*
- 1.3.2 Converse Piezoelectric Effect *3*
- 1.3.3 On the Equivalence of Direct and Converse Piezoelectric Coefficients *4*
- 1.3.4 Typical Values of Piezoelectric Coefficients *5*
- 1.4 Description of Piezoelectricity by Third-rank Tensor *5*
- 1.4.1 Tensor of Piezoelectric Coefficients *5*
- 1.4.2 Voigt/Matrix Notation for Piezoelectric Coefficient *6*
- 1.5 Symmetry Considerations *7*
- 1.5.1 Neumann Principle for the Piezoelectric Effect *7*
- 1.5.2 The Choice of the Cartesian Coordinate System *9*
- 1.5.3 How to Use the Space Symmetry Group Information to Find the List of Independent Piezoelectric Coefficients *10*
- 1.5.4 The Shapes of Piezoelectric Tensors for Different Crystal Classes *14*
 References *14*
- 2 Piezoelectric Effects and Crystallographic Structures** *17*
Semën Gorfman and Nan Zhang
- 2.1 X-ray Diffraction in Single Crystals *17*
- 2.1.1 Geometry of Single-Crystal X-ray Diffraction Experiment *17*
- 2.1.2 Strain and Rotation in Real and Reciprocal Space *18*
- 2.1.3 Angular Displacement of Bragg Peaks *20*
- 2.1.4 Example: Determination of Piezoelectric Coefficients in BiB_3O_6 *20*
- 2.2 Observation of Piezoelectric Effect in Multidomain Ferroelectrics *23*

2.2.1	Ferroelectrics	23
2.2.2	Piezoelectric Effect in Polycrystalline Ferroelectric Ceramics	24
2.2.3	Quadratic Electrostriction and Piezoelectricity	26
2.2.4	Extrinsic and Domain-Wall Motion Mechanisms of Piezoelectricity in Ferroelectrics	28
2.2.5	Piezoelectricity at the Morphotropic Phase Boundary	30
	References	31
3	Lead-Based Piezoelectric Materials	33
	<i>Fei Li</i>	
3.1	Introduction	33
3.2	Brief History of Lead-Based Piezoelectric Materials	33
3.2.1	Lead Zirconate Titanate, PZT	33
3.2.2	Lead-based Relaxor Ferroelectrics	35
3.3	Recent Progress on Lead-Based Piezoelectric Materials	36
3.3.1	Local Structure Heterogeneity to Boost Piezoelectricity	36
3.3.2	Texture Technology (Templated Grain Growth)	37
3.3.3	Solid-state Crystal Growth (SSCG)	41
3.3.4	Piezoelectric Metamaterials	42
3.4	Recent Progress on the Applications of Lead-Based Piezoelectrics	43
3.5	Challenges and Prospects	46
	References	47
4	Lead-free Perovskite Piezoelectric Materials – Part One	51
	<i>Jiagang Wu</i>	
4.1	Potassium Sodium Niobate (KNN)	51
4.1.1	KNN-Based Ceramics	51
4.1.1.1	Synthesis of KNN Ceramics	51
4.1.1.2	Piezoelectric Properties	53
4.1.1.3	Temperature Stability	62
4.1.1.4	Other Emerging Phenomena	63
4.1.2	KNN-based Thin Films	65
4.1.3	KNN-based Single Crystals	66
4.2	Barium Titanate	66
4.3	Summary	77
	References	78
5	Lead-Free Perovskite Piezoelectric Materials – Part Two	85
	<i>Jiagang Wu</i>	
5.1	Sodium Bismuth Titanate	85
5.1.1	Phase Boundaries Versus Piezoelectricity	85
5.1.2	Depolarization Phenomenon	86
5.1.3	Depolarization Temperature T_d Versus Piezoelectricity d_{33}	89
5.1.4	Large and Reversible Electro-strain	89
5.1.4.1	Underlying Mechanism Behind the Large Electro-strain	90

5.1.4.2	New Designing Strategy for Enhancing the Electro-strain	91
5.1.5	Emerging Novel Research Topics in BNT-Based Materials	95
5.2	Bismuth Ferrite	96
5.2.1	Crystal Structure	96
5.2.2	Domain Configuration	98
5.2.2.1	Domain Structure Versus Electrical Properties	99
5.2.2.2	Domain Walls Conductivity Versus Electrical Properties	102
5.2.3	Electrical Properties	102
5.2.3.1	Piezoelectricity	102
5.2.3.2	Ferroelectricity	104
5.2.3.3	Electro-strain	105
5.2.3.4	Energy Storage Property	105
5.3	Summary	106
	References	107
6	Piezoelectricity in Molecular Ferroelectrics	115
	<i>Yu-Meng You</i>	
6.1	Introduction	115
6.2	Piezoelectricity in Molecular Ferroelectrics	116
6.2.1	Piezoelectricity in Crystals	116
6.2.2	Piezoelectricity in Crystalline Thin Films	119
6.2.3	Piezoelectricity in Plastic Polycrystals	120
6.2.4	Piezoelectricity in Composites	122
6.2.4.1	PDMS-Based Composites	123
6.2.4.2	PU-Based Composites	125
6.2.4.3	Hydrogel-Based Composites	126
6.2.5	Piezoelectricity in Molecular Solid Solutions	126
6.2.6	Piezoelectricity in Nanoparticles	127
6.3	PFM-Aided Characterization and Design	128
6.4	Conclusions	131
	References	132
7	High-Temperature BiScO₃-PbTiO₃ Piezoelectric Ceramics	139
	<i>Yazhu Dong and Zhiyong Zhou</i>	
7.1	Introduction	139
7.2	The Characteristics of BS-PT Piezoelectric Ceramics	142
7.2.1	The Revision of Phase Diagram	142
7.2.2	Preparation Methods of BS-PT Ceramics	143
7.2.2.1	Synthetic Method	144
7.2.2.2	Sintering Process	145
7.3	The Modifications of BS-PT-Based Ceramics Near MPB	148
7.3.1	A-Site and B-Site Doping	148
7.3.2	Bi-Based End-Member Mixing	149
7.3.3	Pb-Based Compound Treatment	150

- 7.3.4 Influence of Grain Size Effect 153
- 7.4 Applications of BS-PT-Based Ceramics 156
 - 7.4.1 Transducers Application 156
 - 7.4.2 Actuators Application 158
 - 7.4.3 Energy Harvester Application 159
- 7.5 Summary and Challenge 160
- References 162

8 **Bi₄Ti₃O₁₂-Based High-temperature Piezoelectric Ceramics and Their Applications** 167

Yanyan Zhang, Jianfeng Huang, Yangyang Zhou, Chun Guo, and Zhiyong Zhou

- 8.1 Introduction 167
- 8.2 Crystal Structure and Phase Transition of BIT Compounds 168
- 8.3 Fabrications of BIT Powders and Ceramics 170
 - 8.3.1 Synthesis of BIT Powders 170
 - 8.3.2 Fabrication of BIT Ceramics 172
 - 8.3.2.1 Preparation Process Based on an External Field 172
 - 8.3.2.2 Preparation Process Based on Templates 175
 - 8.4 Ferroelectric Domain Structure of BIT Compounds 177
 - 8.4.1 Space Group Analysis of BIT Domain Boundaries 177
 - 8.4.2 Ferroelectric Domain Structure of BIT Crystal 178
 - 8.4.3 Ferroelectric Domain Structure of BIT Ceramics 179
 - 8.5 Electrical Properties of BIT Compounds 182
 - 8.6 Endurance of BIT Under Different Applied Fields 191
 - 8.6.1 Mechanical Fatigue Behavior of BIT Compounds 191
 - 8.6.2 Thermal Depoling Behavior of BIT Compounds 191
 - 8.6.3 Irradiation Effect on BIT Compounds 192
 - 8.7 High-Temperature Applications Based on BIT Ceramics 192
 - 8.8 Conclusions 195
 - Acknowledgment 196
 - References 196

9 **Textured Piezoceramics: Processing, Properties and Applications** 201

Yunfei Chang, Yuan Sun, and Liangliang Liu

- 9.1 Introduction 201
- 9.2 Fundamentals of Texture Development in Piezoceramics 202
 - 9.2.1 Thermodynamic and Kinetic Aspects of Templated Grain Growth 202
 - 9.2.2 Texture Analysis 207
- 9.3 Processings for Producing Grain Orientations in Piezoceramics 209
 - 9.3.1 Template Selection and Synthesis 209
 - 9.3.1.1 Perovskite-Structured Templates 209
 - 9.3.1.2 Non-Perovskite Structured Templates 211
 - 9.3.2 Techniques for Template Alignments and Inducing Texture 212

9.3.2.1	Tape Casting	213
9.3.2.2	Magnetic Slip Casting	214
9.3.2.3	Additive Manufacturing	214
9.3.3	Densification and Texture Evolution During Sintering	216
9.4	Recent Progress on Enhancing Electrical Properties of Textured Piezoceramics	219
9.4.1	Textured Perovskite-Structured Piezoelectrics	219
9.4.1.1	Lead-Based Piezoelectrics	219
9.4.1.2	Lead-Free Based Piezoelectrics	222
9.4.2	Textured Piezoelectrics with Other Structures	231
9.5	Device Applications of Textured Piezoceramics	233
9.5.1	Ultrasonic Transducers	233
9.5.2	Piezoelectric Actuators	235
9.5.3	Energy Harvesters	237
9.6	Summary and Future Directions	239
	References	240
10	Piezoelectric Thin Films	253
	<i>Huajun Liu</i>	
10.1	Introduction	253
10.1.1	Applications of Piezoelectric Thin Film Devices	253
10.1.2	Thin Films as Unique Playgrounds for New Science	255
10.2	Growth of Piezoelectric Thin Films	258
10.2.1	Pb(Zr,Ti)O ₃ Thin Films	258
10.2.2	(K,Na)NbO ₃ Thin Films	259
10.3	Measurements of Piezoelectric Coefficients in Thin Films	261
10.3.1	Direct Piezoelectric Effect	261
10.3.2	Reverse Piezoelectric Effect	263
10.4	Conclusions	264
	References	264
11	Lead-free KNN and KTN Single Crystals: Piezoelectric and Electro-Optic Properties	269
	<i>Chengpeng Hu, Yu Wang, and Hao Tian</i>	
11.1	Introduction	269
11.2	KNN and KTN-Based Single Crystals	270
11.2.1	Top-seeded Solution Crystal Growth	270
11.2.2	Crystal Growth of KNN and KTN Single Crystals	271
11.2.3	Segregation Effect of KNN and KTN Crystals	274
11.2.3.1	Segregation Effect of KNN Crystals	274
11.2.3.2	Equal-diameter Growth of KTN Crystal	277
11.2.4	Structure of KNN Single Crystals	278
11.3	Piezoelectric Properties of KNN Single Crystal	281
11.3.1	Dielectric Properties of KNN Single Crystal	281
11.3.2	Piezoelectric and Ferroelectric Properties of KNN Crystals	282

11.3.3	Giant Electro-strain of KNN Single Crystal	286
11.4	The Electro-Optic Effect and Applications of KTN Crystal	292
11.4.1	The Electro-Optic Effect of KTN Crystal	292
11.4.2	The Evolution of Polarization in KTN Crystals Near Curie Temperature	295
11.4.3	The Structure Origin of Electro-Optic Effect in KTN Single Crystal	298
11.4.3.1	The Relationship Between Linear Electro-Optic Effect and Ferroelectric Domains Structure	298
11.4.3.2	The Relationship Between Quadratic Electro-Optic Effect and Polar Nano-regions	301
11.4.4	The Electro-Optic Modulation Devices Based on KTN Crystal	304
11.4.4.1	High-Speed Large-Angle Beam Scanner Based on Gradient Refractive Index KTN Crystal	304
11.4.4.2	Controllable Deflection Devices Based on Photorefractive Effect of Manganese-Doped KTN Crystals	306
11.4.4.3	Static Volumetric Three-Dimensional Display Based on an Electric-Field-Controlled Two-Dimensional Optical Beam Scanner	307
11.5	Conclusion	308
	References	309

Volume 2

Preface xi

12	Electrostrictive Effect	311
	<i>Chunlin Zhao, Yanli Huang, and Jiagang Wu</i>	
13	Ferroelectric Materials for Dielectric Energy Storage: Fundamentals and Applications	341
	<i>Haibo Zhang, Hua Tan, Shuaikang Huang, and Mohsin A. Marwat</i>	
14	Ferroelectric Materials for Dielectric Energy Storage: Progress and Material Design	363
	<i>Haibo Zhang, Hua Tan, Shuaikang Huang, and Mohsin A. Marwat</i>	
15	Electrocaloric Effect in Ferroelectric Ceramics	423
	<i>Guangzu Zhang, Kailun Zou, and Shenglin Jiang</i>	
16	Piezo-bioelectronic Materials and Emerging Applications	455
	<i>Yaojin Wang, Yang Liu, Lisha Liu, and Xiaolong Tang</i>	

- 17 Porous Piezoelectric Materials for Energy Applications 495**
Yan Zhang
- 18 Piezoelectric Flexible Devices 521**
Yejing Dai and Zhihao Zhao
- 19 Ferroelectrics Under Compression and Applications 553**
Zhipeng Gao, Zhengwei Xiong, Hongliang He, Jun Li, and Ke Jin
- 20 Piezoelectricity in Biomedical Applications 573**
Laiming Jiang and Jiagang Wu
- Index 599**

