

## Contents

Preface *xiii*

About the Companion Website *xvii*

<b>1</b>	<b>Nature and Types of Solid Materials</b>	<b>1</b>
1.1	Introduction	1
1.2	Defining Properties of Solids	1
1.2.1	Electrical Conductance ( $G$ )	1
1.2.2	Bandgap, $E_g$	2
1.2.3	Permeability, $\epsilon$	3
1.3	Fundamental Nature of Electrical Conductivity	4
1.4	Temperature Dependence of Electrical Conductivity	4
1.4.1	Case of Metals	5
1.4.2	Case of Semiconductors	5
1.4.3	Frequency Spectrum of Permittivity (or Dielectric Constant)	6
1.5	Essential Elements of Quantum Mechanics	7
1.5.1	Planck's Radiation Law	7
1.5.2	Photoelectric Effect	8
1.5.3	Bohr's Theory of Hydrogen Atom	10
1.5.4	Matter–Wave Duality: de Broglie Hypothesis	11
1.5.5	Schrödinger's Wave Equation	12
1.5.6	Heisenberg's Uncertainty Principle	13
1.6	Quantum Numbers	13
1.7	Pauli Exclusion Principle	14
1.8	Periodic Table of Elements	15
1.9	Some Important Concepts of Solid-State Physics	18
1.9.1	Ceramic Superconductivity	18
1.9.2	Superconductivity and Technology	19
1.10	Signature Properties of Superconductors	19
1.10.1	Thermal Behavior of Resistivity of a Superconductor	20
1.10.2	Magnetic Nature of Superconductivity: Meissner–Ochsenfeld Effect	20
1.10.3	Josephson Effect	22
1.11	Fermi–Dirac Distribution Function	24
1.12	Band Structure of Solids	27
	Glossary	29
	Problems	30
	References	31
	Further Reading	31
<b>2</b>	<b>Processing of Electroceramics</b>	<b>33</b>
2.1	Introduction	33
2.2	Basic Concepts of Equilibrium Phase Diagram	33

2.2.1	Gibbs' Phase Rule	34
2.2.2	Triple Point and Interfaces	34
2.2.3	Binary Phase Diagrams	35
2.2.3.1	Totally Miscible Systems	35
2.2.3.2	Systems with Limited Solubility in Solid Phase	37
2.3	Methods of Ceramic Processing	38
2.3.1	Room Temperature Uniaxial Pressing (RTUP)	38
2.3.2	Other Methods for Powder Compaction and Densification	41
2.3.2.1	Hot Isostatic Pressing (HIP)	41
2.3.2.2	Cold Isostatic Pressing (CIP)	41
2.3.2.3	Low Temperature Sintering (LTP)	42
2.3.3	Nanoceramics	42
2.3.4	Thin Film Ceramics	42
2.3.5	Methods for Film Growth	43
2.3.5.1	Solgel Method	43
2.3.5.2	Pulsed Laser Deposition (PLD) Method	44
2.3.5.3	Molecular Beam Epitaxy (MBE) Method	46
2.3.5.4	RF Magnetron Sputtering Method	47
2.3.5.5	Liquid Phase Epitaxy (LPE) Method	49
2.3.6	Single Crystal Growth Methods for Ceramics	49
2.3.6.1	High Temperature Solution Growth (HTSG) Method or Flux Growth Method	50
2.3.6.2	Czochralski Growth Method	51
2.3.6.3	Top Seeded Solution Growth (TSSG) Method	52
2.3.6.4	Hydrothermal Growth	53
2.3.6.5	Some Other Methods of Crystal Growth	53
	Glossary	54
	Problems	55
	References	55
<b>3</b>	<b>Methods for Materials Characterization</b>	<b>57</b>
3.1	Introduction	57
3.2	Methods for Surface and Structural Characterization	57
3.2.1	Optical Microscopes	58
3.2.2	X-ray Diffraction Analysis (XRD)	60
3.2.2.1	XRD Diffractometer: Intensity vs. $2\theta$ Plot	60
3.2.2.2	Laue X-ray Diffraction Method	61
3.2.3	Electron Microscopes	63
3.2.3.1	Transmission Electron Microscope (TEM)	64
3.2.3.2	Scanning Electron Microscope (SEM)	65
3.2.3.3	Scanning Transmission Electron Microscope (STEM)	65
3.2.3.4	X-ray Photoelectron Spectroscopy (XPS)	66
3.2.4	Force Microscopy	68
3.2.4.1	Atomic Force Microscope (AFM)	68
3.2.4.2	Magnetic Force Microscope (MFM)	69
3.2.4.3	Piezoelectric Force Microscope (PFM)	69
	Glossary	70
	Problems	71
	References	71
<b>4</b>	<b>Binding Forces in Solids and Essential Elements of Crystallography</b>	<b>73</b>
4.1	Introduction	73
4.2	Binding Forces in Solids	73
4.2.1	Ionic Bonding	74
4.2.2	Covalent Bonding	74

4.2.3	Metallic Bonding	74
4.2.4	Van der Waals Bonding	75
4.2.5	Polar-molecule-induced Dipole Bonds	75
4.2.6	Permanent Dipole Bonding	75
4.3	Structure–Property Relationship	75
4.4	Basic Crystal Structures	77
4.4.1	Bravais Lattice	78
4.4.2	Miller Indices for Planes and Directions	79
4.4.2.1	Rule for Indexing a Crystal Direction	80
4.5	Reciprocal Lattice	81
4.6	Relationship Between $d^*$ and Miller Indices for Selected Crystal Systems	81
4.7	Typical Examples of Crystal Structures	82
4.7.1	Sodium Chloride, NaCl	82
4.7.2	Perovskite Calcium Titanate	82
4.7.3	Diamond Structure	83
4.7.4	Zinc Blende (Also Wurtzite)	84
4.8	Origin of Voids and Atomic Packing Factor (apf)	84
4.8.1	apf for a Primitive Cubic Structure (P)	85
4.9	Hexagonal and Cubic Close-packed Structures	85
4.10	Predictive Nature of Crystal Structure	86
4.11	Hypothetical Models of Centrosymmetric and Noncentrosymmetric Crystals	87
4.12	Symmetry Elements	88
4.13	Classification of Dielectric Materials: Polar and Nonpolar Groups	89
4.14	Space Groups	90
	Glossary	91
	Problems	92
	References	93
	Further Reading	93
<b>5</b>	<b>Dominant Forces and Effects in Electroceramics</b>	<b>95</b>
5.1	Introduction	95
5.2	Agent–Property Relationship	95
5.3	Electric Field ( $E$ ), Mechanical Stress ( $X$ ), and Temperature ( $T$ ) Diagram: Heckmann Diagram	96
5.3.1	Piezoelectric Zone	97
5.3.2	Pyroelectric Zone	97
5.3.3	Thermoelastic Zone	98
5.4	Electric Field, Mechanical Stress, and Magnetic Field Diagram	99
5.5	Multiferroics Phenomena and Materials	101
5.6	Magnetolectric (ME) Effect and Associated Issues	103
5.6.1	Basic Formulations Governing the ME Effect	103
5.6.2	Composite ME Materials	104
5.6.3	ME Integrated Structures	104
5.6.4	Experimental Determination	104
5.7	Applications of Multiferroics	105
5.7.1	Ferroelectric and Ferromagnetic Coupled Memory	105
5.7.2	Multiferroic Tunnel Junctions (MTJ)	106
5.8	Magnetostriction and Electrostriction	106
5.8.1	Magnetostriction	106
5.8.2	Electrostriction	107
5.9	Piezoelectricity	108
5.9.1	Crystallographic Considerations for Piezoelectricity	108
5.9.2	Mathematical Representation of Piezoelectric Effects	109
5.9.3	Constitutive Equations for Piezoelectricity	110
5.10	Experimental Determination of Piezoelectric Coefficients	111

5.10.1	Charge Coefficient, $d$	111
5.10.2	Stress Coefficient, $e$	112
5.10.3	Piezoelectric Devices and Applications	113
5.10.3.1	Piezoelectric Transducers	114
5.10.3.2	Generation of Sound and an AC Signal	114
5.10.3.3	Surface Acoustic Wave (SAW) Device	115
5.10.3.4	Piezoelectric Acoustic Amplifier	116
5.10.3.5	Piezoelectric Frequency Oscillator	116
5.10.4	MEMS Actuator	116
	Glossary	118
	Problems	119
	References	120
<b>6</b>	<b>Coupled Nonlinear Effects in Electroceramics</b>	<b>121</b>
6.1	Introduction	121
6.2	Historical Perspective	123
6.3	Signature Properties of Ferroelectric Materials	123
6.3.1	Hysteresis Loop: Its Nature and Technical Importance	124
6.3.2	Temperature Dependence of Ferroelectric Parameters	125
6.3.3	Temperature Dependence of Dielectric Constant	125
6.3.4	Ferroelectric Domains	126
6.3.5	Electrets	126
6.3.6	Relaxor Ferroelectrics	126
6.4	Perovskite and Tungsten Bronze Structures	127
6.4.1	Perovskite Structure	127
6.4.2	Tungsten Bronze Structure	130
6.5	Landau–Ginsberg–Devonshire Mean Field Theory of Ferroelectricity	130
6.6	Experimental Determination of Ferroelectric Parameters	134
6.6.1	Poling of Samples for Experiments	134
6.6.2	Polarization vs. Electric Field	135
6.6.3	Capacitance Measurement and $C$ – $V$ Plot	136
6.6.4	Ferroelectric Domains (Experimental Determination)	137
6.7	Recent Applications of Ferroelectric Materials	138
6.8	Antiferroelectricity	139
6.9	Pyroelectricity	143
6.9.1	Historical Perspective	143
6.9.2	Pyroelectric Effect	143
6.9.3	Experimental Determination of Pyroelectric Coefficient	145
6.9.4	Applications of Pyroelectricity	146
6.10	Pyro-optic Effect	147
	Glossary	148
	Problems	150
	References	150
	Further Reading	151
<b>7</b>	<b>Elements of A Semiconductor</b>	<b>153</b>
7.1	Introduction	153
7.2	Nature of Electrical Conduction in Semiconductors	153
7.3	Energy Bands in Semiconductors	155
7.4	Origin of Holes and n- and p-Type Conduction	156
7.5	Important Concepts of Semiconductor Materials	158
7.5.1	Mobility, $\mu$	158
7.5.2	Direct and Indirect Bandgap, $E_g$	159
7.5.3	Effective Mass, $m^*$	160
7.5.4	Density of States and Fermi Energy	161

7.6	Experimental Determination of Semiconductor Properties	162
7.6.1	Determination of Resistivity, $\rho$	162
7.6.2	Four-Point Probe (van der Pauw) Method	163
7.6.3	Two-Point Probe Method	163
7.6.4	Determination of Bandgap, $E_g$	164
7.6.5	Determination of N- and P-Type Nature: Seebeck Effect	164
7.6.6	Determination of Direct and Indirect Bandgap, $E_g$	166
7.6.7	Determination of Mobility, $\mu$	166
7.6.7.1	Haynes–Shockley Method	167
7.6.7.2	Hall Effect	168
	Glossary	170
	Problems	170
	References	171
	Further Reading	171
<b>8</b>	<b>Electroceramic Semiconductor Devices</b>	<b>173</b>
8.1	Introduction	173
8.2	Metal–Semiconductor Contacts and the Schottky Diode	174
8.2.1	Metal–Metal Contact	174
8.2.2	Metal Semiconductor Contact	175
8.2.3	Schottky Diode	176
8.2.4	Determination of Contact Potential and Depletion Width	178
8.2.5	Oxide Semiconductor Materials and Their Properties	179
8.2.6	In Search of UV-blue LED	181
8.2.7	Determination of $I$ – $V$ Characteristics of a LED	182
8.2.8	Thin-film Transistor (TFT)	183
8.3	Varistor Diodes	184
8.3.1	Metal Oxide Varistors	185
8.4	Theoretical Considerations for Varistors	186
8.4.1	Equivalent Circuit of a Varistor	186
8.4.2	Idealized Model of Varistor Microstructure	186
8.4.3	Energy Band Diagram: Grain–Grain Boundary–Grain (G–GB–G) Structure	188
8.5	Varistor-Embedded Devices	190
8.5.1	Voltage Biased Varistor and Embedded Voltage Biased Transistor (VBT)	190
8.5.1.1	Frequency Dependence of IHC 45 VBT Device	194
8.5.1.2	Comparison Between a VBT, BJT, and Schottky Transistor	195
8.5.2	Electric Field Tuned Varistor and Its Embedded Electric Field Effect Transistor ( $E$ -FET)	196
8.5.2.1	Frequency Dependence of IHC 45 $E$ -FET Device	198
8.5.3	Magnetically Tuned Varistor and Embedded Magnetic Field Effect Transistor ( $H$ -FET)	198
8.6	Magnetic Field Sensor	202
8.7	Thermistors	206
8.7.1	Heating Effects in Thermistors	207
	Glossary	210
	Problems	212
	References	213
	Further Reading	214
<b>9</b>	<b>Electroceramics and Green Energy</b>	<b>215</b>
9.1	Introduction	215
9.2	What is Green Energy?	215
9.3	Energy Storage and Its Defining Parameters	217
9.3.1	Capacitor as an Energy Storage Device	218
9.3.2	Battery-Supercapacitor Hybrid (BSH) Devices	220
9.3.3	Piezoelectric Energy Harvester	220
9.3.4	MEMS Power Generator	222

9.3.5	Ferroelectric Photovoltaic Devices	222
9.3.6	Solid Oxide Fuel Cells (SOFC)	224
9.3.7	Antiferroelectric Energy Storage	225
	Glossary	227
	Problems	227
	References	228
<b>10</b>	<b>Electroceramic Magnetics</b>	<b>229</b>
10.1	Introduction	229
10.2	Magnetic Parameters	229
10.3	Relationship Between Magnetic Flux, Susceptibility, and Permeability	230
10.4	Signature Properties of Ferrites	231
10.4.1	Temperature Dependence of Magnetic Parameters	234
10.5	Typical Structures Associated with Ferrites	234
10.6	Essential Theoretical Concepts	235
10.7	Magnetic Nature of Electron	235
10.7.1	Molecular Field Theory	236
10.7.2	Antiferromagnetism and Ferrimagnetism	237
10.7.3	Quantum Mechanics and Magnetism	238
10.8	Classical Applications of Ferrites	239
10.9	Novel Magnetic Technologies	239
10.9.1	GMR Effect	240
10.9.2	CMR Effect	241
10.9.3	Spintronics	241
	Glossary	242
	Problems	243
	References	245
	Further Reading	245
<b>11</b>	<b>Electro-optics and Acousto-optics</b>	<b>247</b>
11.1	Introduction	247
11.2	Nature of Light	247
11.2.1	Fundamental Optical Properties of a Crystal	248
11.2.2	Electro-optic Effects	249
11.2.3	Selected Electro-optic Applications	251
11.2.3.1	Optical Waveguides	251
11.2.3.2	Phase Shifters	252
11.2.3.3	Electro-optic Modulators	252
11.2.3.4	Night Vision Devices (NVD)	252
11.2.4	Acousto-optic Effect and Applications	253
	Glossary	254
	Problems	255
	References	255
	Further Reading	255
<b>Appendix A</b>	<b>Periodic Table of the Elements</b>	<b>257</b>
<b>Appendix B</b>	<b>Fundamental Physical Constants and Frequently Used Symbols and Units (Rounded to Three Decimal Points)</b>	<b>259</b>
<b>Appendix C</b>	<b>List of Prefixes Commonly Used</b>	<b>261</b>
<b>Appendix D</b>	<b>Frequently Used Symbols and Units</b>	<b>263</b>
	<b>Index</b>	<b>265</b>