

Contents

Preface *xiii*

1	Overview of High-Temperature Polymers	1
	<i>Xue-Jie Liu, Mengyu Xiao, Wenjie Huang, Xing Yang, and Jun-Wei Zha</i>	
1.1	Introduction	1
1.2	Development of High-Temperature Polymers	2
1.3	Parameters of Polymers with High Temperature Resistance	3
1.4	Thermal Analysis Technology	5
1.4.1	Differential Scanning Calorimetry (DSC)	5
1.4.2	Dynamic Thermomechanical Analysis (DMA)	5
1.4.3	Thermogravimetric Analysis (TGA)	6
1.4.4	Static Thermomechanical Analysis (TMA)	7
1.4.5	Thermal Conductivity	8
1.4.6	Dynamic Dielectric Analysis (DEA)	9
1.5	High-Temperature Polymer Materials	9
1.5.1	Commercial High-Temperature Polymer	9
1.5.2	Molecular Structure Modification of High-Temperature Polymer	11
1.5.3	High-Temperature Polymer-Based Composite Materials	13
1.6	Summary and Outlook	14
	References	15
2	Basic Principles of Dielectrics	21
	<i>Anastasios Chr. Patsidis and Georgios Chr. Psarras</i>	
2.1	Introduction	21
2.2	Definition of Dielectrics	21
2.3	Dipole Moment and Types of Dielectric Materials	22
2.4	Polarization and Dielectric Permittivity	23
2.5	Polarization Under Static Electric Field	24
2.5.1	Dielectric Permittivity and Polarizability	24
2.5.2	Dipole's Local Electric Field	27

2.5.3	Models for Static Dielectric Permittivity: Debye, Onsager, Kirkwood, and Fröhlich	29
2.6	Polarization Under Time Varying Electric Field	32
2.6.1	Frequency Dependent Dielectric Permittivity – Debye's Equations	33
2.6.2	Models of Dielectric Relaxations	34
2.6.3	Effect of Temperature	36
2.7	Conduction Phenomena in Dielectrics	38
2.8	Active Dielectrics	40
2.9	Polymers as Dielectric Materials	43
2.9.1	Dielectric Relaxations in Polymers	43
2.9.2	Heterogenous Systems – Polymer Matrix Composites	45
2.10	Thermal Properties of Dielectrics	47
2.10.1	Heat Capacity	47
2.10.2	Thermal Conduction of Dielectrics	50
2.11	Concluding Remarks	51
	Acknowledgements	51
	References	52

3 High-Temperature Energy Storage Polymer Dielectrics for Capacitors 57

Zongliang Xie, He Li, Zongren Peng, and Yi Liu

3.1	Introduction	57
3.2	Basic Parameters of High-Temperature Capacitor Materials	60
3.2.1	Electrical Characteristics of High-Temperature Capacitor Materials	60
3.2.1.1	Energy Storage Parameters	60
3.2.1.2	Dielectric Constant and Dielectric Loss	61
3.2.1.3	Dielectric Breakdown Strength	63
3.2.1.4	Electrical Conduction and Charge Injection	64
3.2.2	Thermal Characteristics of high-Temperature Capacitor Materials	65
3.2.3	Self-Clearing Abilities of High-Temperature Capacitor Materials	67
3.3	Randomly Dispersed Polymer/Inorganic Nanofiller Composites	69
3.3.1	Composites Filled with Insulating Fillers	70
3.3.1.1	Composites Filled with Metal Oxides	70
3.3.1.2	Composites Filled with Nitrides and Fluorides	71
3.3.2	Composites Filled with Conductive or Semi-Conductive Fillers	74
3.3.3	Composites Co-filled with Both Insulating and Semi-Conductive Fillers	76
3.4	Core@Shell-Structured Nanofillers for Polymer Composites	76
3.4.1	Organic Shells for Inorganic Nanoparticles	77
3.4.2	Inorganic Shells for Inorganic Nanoparticles	79
3.5	Layered Polymer Composites	80
3.5.1	Polymer Films with Inorganic Layers	80
3.5.2	Sandwich-Structured Nanocomposites	83
3.6	Novel Polymers and All-Organic Polymer Composites	85
3.6.1	Novel Polymers	86

3.6.1.1	Structural Modification of Commercial High- T_g Polymers	86
3.6.1.2	Cross-linked Polymers	87
3.6.1.3	Wide Bandgap Polymers	88
3.6.1.4	Polymers with Polar Groups	89
3.6.2	All-Organic Polymer Composites	90
3.6.2.1	Polymer Blends	90
3.6.2.2	Polymer Doped with Organic Fillers	92
3.6.2.3	All-Organic Layered Polymer Composites	92
3.7	Conclusion and Perspective	94
	References	95
4	Review on High-Temperature Polymers for Cable Insulation: State-of-the-Art and Future Developments	103
	<i>Yousef Kemari, Guillaume Belijar, Zarel Valdez-Nava, Frédéric Forget, and Sombel Diahm</i>	
4.1	Brief History of Cables Development and Insulating Materials	103
4.2	Technologies of Modern Power Cables	106
4.2.1	Designs and Manufacturing Processes	106
4.2.1.1	Wrapping Technology	106
4.2.1.2	Extrusion Technology	110
4.2.1.3	Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System	112
4.2.2	Insulating Material Considerations for High-Temperature Cables	113
4.2.2.1	Electrical Requirements	116
4.2.2.2	Thermal Requirements	117
4.2.2.3	Mechanical Requirements	118
4.2.2.4	Environmental and Functional Considerations	119
4.2.2.5	Flame Resistance	120
4.2.2.6	Smoke Evolution	121
4.2.2.7	Toxicity	121
4.2.2.8	Corrosivity	121
4.2.2.9	Heat Release	121
4.2.2.10	Radiation Resistance	122
4.2.2.11	Chemical Resistance	122
4.2.2.12	Recapitulation of Important Standards for Cables Testing	125
4.3	Review of the Most Relevant Electrical Characteristics of High Temperature Insulating Materials	125
4.3.1	Dielectric Spectroscopy	125
4.3.2	Partial Discharges	130
4.3.3	Space Charge and DC Conductivity	133
4.3.4	Aging and Degradation	137
4.4	Trends and Outlooks	140
	Author's Note	142
	References	142

5 High-Temperature Polymer-Based Dielectrics for Advanced Electronic Packaging 149

Jie Liu, Peng Li, Jianwei Zhao, and Shuhui Yu

- 5.1 Introduction 149
- 5.1.1 Development of Electronic Packaging Technology 150
- 5.1.2 Requirement of Polymer-Based Dielectrics for Advanced Electronic Packaging Application 152
 - 5.1.2.1 Dielectric Properties 155
 - 5.1.2.2 Thermal and Thermal–Mechanical Properties 157
 - 5.1.2.3 Dynamic Thermomechanical Properties 157
 - 5.1.2.4 Thermal Expansion Coefficient 157
 - 5.1.2.5 Thermal Conductivity 158
 - 5.1.2.6 Other Requirements 159
- 5.2 High-Temperature Polymer and Polymer-Based Dielectrics 160
 - 5.2.1 High-Temperature Polymer Dielectrics 160
 - 5.2.1.1 Polyimide 160
 - 5.2.1.2 Epoxy Resins 163
 - 5.2.1.3 Benzocyclobutene Resins 165
 - 5.2.1.4 Benzoxazine Resins 167
 - 5.2.1.5 Polyaryl Ether 167
 - 5.2.1.6 Organic Porous Materials 168
 - 5.2.2 High-Temperature Polymer-Based Composite Dielectrics 169
 - 5.2.2.1 Inorganic Fillers 169
 - 5.2.2.2 Inorganic Porous Fillers 171
 - 5.2.2.3 Organic Porous Fillers 171
- 5.3 Summary and Perspectives 172
- References 173

6 High-Temperature Polymer Dielectrics for Printed Circuit Board 181

Xu Wang, Xinyu Chen, Junhui Luo, Xin Wang, Yan Chen, and Xiangyang Liu

- 6.1 Epoxy Resin Used for PCB 182
 - 6.1.1 Structure of Epoxy Resins 182
 - 6.1.2 Properties and Application of Epoxy 184
 - 6.1.3 Epoxy Resin Used for CCL in PCB 185
- 6.2 Phenolic Resins Used for PCB 188
 - 6.2.1 Structure of Phenolic Resins 188
 - 6.2.2 Synthesis of Phenolic Resins 188
 - 6.2.2.1 Synthesis of Thermoplastic Phenolic Resins 189
 - 6.2.2.2 Thermosetting Phenolic Resins 190
 - 6.2.3 Properties of Phenolic Resins and Their Application in PCBs 191
 - 6.2.3.1 Application of Phenolic Resins in Copper-Clad Laminates 192
 - 6.2.3.2 Tung Oil-Modified Phenolic Resin 192
 - 6.2.3.3 Linear Phenolic Resins 193
 - 6.2.3.4 Nitrogen-Containing Phenolic Resins 194

6.2.3.5	Polybenzoxazine Used for PCB	195
6.2.4	Prospect	196
6.3	Polyimide Used for PCB	197
6.3.1	Introduction to Polyimide and its Performance Characteristics	197
6.3.2	Synthesis Method of PI	197
6.3.2.1	One-Step Method	197
6.3.2.2	Two-Step Method	198
6.3.2.3	Three-Step Method	199
6.3.3	Classification of PI	199
6.3.3.1	Non-Fusible and Insoluble PI	199
6.3.3.2	Fusible PI, Thermoplastic PI	200
6.3.4	Performance Characteristics of PI	201
6.3.5	Application of PI in CCLs	201
6.3.5.1	Application of PI in Rigid CCLs	201
6.3.5.2	Application of PI in Flexible Copper-Clad Laminate	202
6.3.5.3	Application of Thermoplastic Polyimide in Double-Sided Copper Laminates	203
6.3.6	Prospect	206
6.4	Polymer Materials Used for PCB at High Frequency	206
6.4.1	Polytetrafluoroethylene (PTFE) Used for PCB	207
6.4.1.1	Structure and Properties of PTFE	207
6.4.1.2	PTFE Used for PCB	209
6.4.2	Liquid Crystal Polymer (LCP) Used for PCB	211
6.4.2.1	Structure and Properties of LCP	211
6.4.2.2	LCP Used for PCB	213
6.4.3	Other Resins with Potential in the Field of High-Frequency Communications	215
6.4.3.1	Cyanate Ester (CE) Used for PCB	215
6.4.3.2	Polyphenylene Oxide (PPO) Used for PCB	218
6.4.4	Prospect of Polymer Resin for PBC at High Frequency	220
	References	221

7 High-Temperature Polymer Dielectrics for New Energy Power Equipment

Meng Xiao, Zhiyuan Zhang, Yuyan Chen, Xiaodan Du, and Boxue Du

7.1	Introduction	227
7.2	High-frequency Power Transformer and Dry-type Bushing	228
7.2.1	Modification of Epoxy Resin	228
7.2.1.1	Change the Molecular Chain	229
7.2.1.2	Develop the Curing Agent with Better Thermal Stability	232
7.2.1.3	Filling Modification	232
7.3	Modification of Polyimide	233
7.3.1	Filling Modification	234
7.3.2	Introduce Rigid Groups	235
7.3.3	Form the Cross-linked Structure	237

- 7.4 High-temperature Resistant Dielectric Material for Capacitor 239
 - 7.4.1 High-temperature Dielectric Polymer 240
 - 7.4.1.1 Polytetrafluoroethylene 240
 - 7.4.1.2 Polyvinylidene Fluoride 242
 - 7.4.1.3 Other Materials 243
 - 7.4.2 Nanocomposite Material 245
 - 7.4.3 Crosslinked Polymer 248
- 7.5 High-temperature Resistant Dielectric Material for IGBT 250
 - 7.5.1 Silicone Gels 251
 - 7.5.2 Engineering Plastics 252
 - 7.5.2.1 Polyphenylene Sulfide 253
 - 7.5.2.2 Polyetheretherketone 254
- 7.6 Concluding Remarks 256
- References 257

- 8 High-Temperature Polymer Dielectrics for Aerospace Electrical Equipment 269
 - Daomin Min, Xiaofan Song, Lingyu Yang, Yuanshuo Zhang, Shihang Wang, and Shengtao Li*
 - 8.1 Introduction 269
 - 8.2 Challenges of Insulating Materials Under High Temperatures 272
 - 8.2.1 Substantial Drop in Resistivity Under High Temperatures and Strong Electric Fields 272
 - 8.2.2 Greatly Increased Dielectric Loss Factor at High Temperatures 275
 - 8.2.3 Space Charge Accumulation and Electric Field Distortion Under High Temperatures and High-DC Electric Fields 276
 - 8.2.4 Reduction in Breakdown Strength Under High Temperatures and High-Frequency Voltages 277
 - 8.2.5 More Severe Partial Discharge and Accelerated Aging at High Temperatures and High Frequencies 278
 - 8.2.6 Reduction in Surface Flashover Voltage Under Electron Irradiations and Voltages 279
 - 8.3 High Temperature Resistant and Strong DC Insulating Polymer Dielectrics 280
 - 8.3.1 Polyimide Nanocomposites 280
 - 8.3.2 Polyetherimide Nanocomposites 282
 - 8.3.3 Epoxy Resin Nanocomposites 284
 - 8.3.4 Polytetrafluoroethylene Composites 285
 - 8.4 High-temperature-Resistant Polymer Dielectrics with Strong Nonlinear Conductivity 288
 - 8.4.1 Charge Accumulation and Electric Field Distortion in Polymers Under High Electric Fields 288
 - 8.4.2 Charge Accumulation Induced by High-Energy Electron Irradiation and Working Voltage 290

- 8.4.3 Nonlinear Conductivity 292
- 8.5 High-Temperature-Resistant Polymer Dielectrics Under the Coupling of Electron Irradiation and High Voltage 295
 - 8.5.1 Mechanism of Vacuum DC Surface Discharge Under the Coupling of Electron Beam Irradiation and High Voltage 296
 - 8.5.2 Effect of Electron Beam Irradiation on Vacuum DC Surface Discharge 296
 - 8.5.3 Influence of Incident Electron Beam Characteristics on Vacuum DC Surface Discharge 297
 - 8.5.4 Influence of Insulation Distance and Electrode Height on Surface Discharge 298
- 8.6 High Temperature Resistant and High-Frequency Strong Insulating Polymer Dielectrics 300
 - 8.6.1 Electrical Tree Characteristics of Epoxy Resin Under Bipolar Square Wave Voltage 301
 - 8.6.2 Micro/Nano-Doped Epoxy Resin Composites 302
 - 8.6.3 Corona Resistance Life of Polyimide Modified by Nano-Doped Multilayer Structure 304
 - 8.6.4 Characteristics of Polyimide Modified by Molecular Structure 305
- References 307

9 Smart Polymer Dielectrics 313

Xiaoyan Huang, Lu Han, Zhiwen Huang, and Qi Li

- 9.1 Introduction 313
- 9.2 Self-Adaptive Dielectrics 315
- 9.3 Self-Reporting Dielectrics 324
 - 9.3.1 Self-Reporting Materials Based on Photochromic Compounds 325
 - 9.3.2 Self-Reporting Materials Based on Conjugated Polymers 330
 - 9.3.3 Self-Reporting Materials Based on Encapsulated Systems 333
 - 9.3.4 Outlook for SRDs 335
- 9.4 Self-Healing Dielectrics 336
 - 9.4.1 Expectations and Challenges in Developing Self-Healing Dielectrics 336
 - 9.4.2 Melting Interdiffusion by Magnetic/Microwave Heating of Nanoparticles 337
 - 9.4.3 Microcapsule-Based Self-Healing Dielectrics 342
 - 9.4.3.1 Polymerization Triggered by Environmental Stimuli 342
 - 9.4.3.2 Polymerization by Latent Functionality 346
 - 9.4.4 Intrinsic Self-Healing Dielectrics by Reversible Bonds or Interactions 348
 - 9.4.5 Summary of Self-Healing Dielectrics 351
- 9.5 Outlook 352
- References 353

- 10 The Future Development of High-temperature Polymer Dielectrics 365**
Qi-Kun Feng, Yong-Xin Zhang, Xin-Jie Wang, and Zhi-Min Dang
- 10.1 Introduction 365
- 10.2 Present Development and Challenges 365
 - 10.2.1 Temperature Stability 365
 - 10.2.2 Polymer-based High-temperature Composites 367
 - 10.2.3 Cost and Scale-up Production 367
- 10.3 Future Perspectives and Trends 368
 - 10.3.1 Intrinsic High-temperature Polymers 368
 - 10.3.2 Polymer-based High-temperature Composites 369
 - 10.3.3 Large-scale Industrial Production 370
- 10.4 Summary 370
- Acknowledgments 371
- References 371

- Index 375**