

Contents

About the Editor *xiii*

Preface to “Persistently Luminescent Materials: From Development to Applications” *xv*

1 Introduction to Persistently Luminescent Materials *1*

Nimai Pathak and Yuanbing Mao

1.1 Introduction *1*

1.2 PersL Processes and Emission Mechanisms *5*

1.2.1 CB-VB Model *7*

1.2.2 Energy Band Model via CB and VB Engineering *9*

1.2.3 Self-Electron/Hole Trapping–Detrapping Model *10*

1.2.4 QT Model *12*

1.2.5 Cation and Anion Vacancy Model *12*

1.3 Types of PLMs *13*

1.3.1 Inorganic PLMs *13*

1.3.1.1 UV PLMs *13*

1.3.1.2 Visible PLMs *17*

1.3.1.3 NIR PLMs *19*

1.3.2 Molecular PLMs *20*

1.3.2.1 Organics PLMs *21*

1.3.2.2 Organic–Inorganic Metal Halide Hybrid PLMs *21*

1.3.2.3 Inorganic–Organic Molecular Hybrid PLMs *22*

1.4 Synthesis Methods for IPLMs *22*

1.4.1 Solid-State Method *23*

1.4.2 Ball Milling Method *24*

1.4.3 Pulsed Laser Ablation Method *24*

1.4.4 Solution-Based Methods *25*

1.4.4.1 Hydrothermal Method *25*

1.4.4.2 Coprecipitation Method *26*

1.4.4.3 Colloidal Method *26*

1.4.4.4 Template Method *26*

1.4.4.5 Other Methods *26*

1.4.5 PersL Glass, Glass Ceramics and Composites *27*

1.5	Measurements and Characteristics of PersL	27
1.5.1	Excitation and Emission Characteristics	28
1.5.2	Trap Properties	30
1.5.2.1	Trap Depth and Optimum Temperature for Potential Applications	30
1.5.2.2	Controlling Trap Filling and Releasing Kinetics by Temperature and Pump Power	30
1.5.2.3	PersL Lifetime and Storage Capacity	32
1.5.3	Trap Manipulation	33
1.6	Summary and Challenges	34
	References	34
2	Application Advances in Display Technology Field of Long Persistent Phosphor	43
	<i>Dangli Gao, Chaoyang Jia, and Xiaojun Wang</i>	
2.1	Introduction	43
2.2	Research Progress on Afterglow Phosphors and Related Mechanisms	45
2.3	Application Advances in Display Field	47
2.3.1	Weak Light Illumination	47
2.3.2	Landscape Decoration	49
2.3.3	Application of Long Persistent Phosphors in the Field of AC-LEDs Display	51
2.3.4	Multi-Color and Multi-Mode Luminescent Display for Anticounterfeiting Applications	56
2.3.5	PersL Combined with High-Resolution Display Technology for Imaging Applications	59
2.3.5.1	Application of Long Afterglow Materials in the Field of X-ray Detection	59
2.3.5.2	Application of Long Afterglow Materials in the Field of Optical Imaging	61
2.3.5.3	Exploration of Imaging Application of Stress Responsive Afterglow Materials	62
2.4	Challenges and Opportunities	62
2.5	Summary	63
	References	64
3	Persistent Luminescence-Based Light-Emitting Diodes	71
	<i>Bingfu Lei, Shuting Liu, and Xuejie Zhang</i>	
3.1	Introduction	71
3.2	Fundamentals of AC-LEDs	73
3.2.1	The Research Background of AC-LEDs	73
3.2.2	Working Principle of AC-LEDs	74
3.2.3	Lighting Flicker	74
3.3	PersL Phosphors Applied in AC-LEDs	75
3.3.1	Properties	75

3.3.1.1	Millisecond Afterglow	75
3.3.1.2	Efficient Excitation by Blue Light and Sufficient Red Emission Range	76
3.3.2	Inorganic PersL Phosphors	76
3.3.2.1	Garnet-Structure	76
3.3.2.2	$(M_{1-x-y}Lu_xEu_y)Al_2O_4$	83
3.3.2.3	$M_{1-x-y}Si_2O_{2-w}N_{2+2w/3}:Eu_x,R_y$	85
3.3.2.4	Other Inorganic PersL Phosphors	86
3.3.3	Organic Phosphorescent Materials	86
3.4	Challenges and Outlooks	89
3.4.1	Challenges	89
3.4.2	Outlooks	89
	References	90
4	Persistently Luminescent Nanoparticles for Bioimaging and Biosensors	95
	<i>Yi Wei, Guogang Li, and Jianhua Hao</i>	
4.1	Introduction	95
4.2	Fundamental Principles	96
4.2.1	Introduction of Bioimaging and Biosensors	96
4.2.2	Fluorescent Nanoprobes	99
4.2.3	Preparation Methods of PLNPs	100
4.3	Classifications with Excitation Light Sources	102
4.3.1	n-UV or Visible Light Excitation	102
4.3.2	NIR Light Excitation	104
4.3.3	X-ray Excitation	106
4.4	Enhancing Performance of PLNPs for Biomedicine	108
4.4.1	Composition Substitution of Host	108
4.4.2	Ionic Codoping Strategy	108
4.4.3	Construction of Core-Shell Structure	110
4.4.4	Nanomaterial Processing and Surface Modification	113
4.5	Conclusions and Outlook	115
	Acknowledgments	116
	References	116
5	Persistently Luminescent Nanoparticles for Cancer Therapy	129
	<i>Shileng Chen, Zhiyang Shen, Yu Qiu, and Hongmin Chen</i>	
5.1	Introduction	129
5.2	Luminescence Nanoparticles and Persistent Luminescent Nanoparticles	130
5.2.1	Organic Fluorophore	131
5.2.2	Inorganic Nanoparticles	132
5.2.3	Fluorescent Protein	133
5.2.4	Persistent Luminescent Nanoparticles	134

5.2.4.1	Main Types of PLNPs	134
5.2.4.2	Main Characteristics of PLNPs	136
5.2.4.3	Applications of PLNPs	136
5.3	Persistently Luminescent Nanoparticles for Cancer Therapy	139
5.3.1	Photodynamic Therapy	139
5.3.1.1	PDT with Visible Light Excitation	139
5.3.1.2	PDT with NIR Excitation	140
5.3.1.3	PDT with X-Ray Excitation	143
5.3.2	Photothermal Therapy	146
5.3.3	Other Therapies	148
5.4	Biocompatibility of PLNPs	149
5.5	Conclusion	150
	Acknowledgments	151
	References	151

6 Persistently Luminescent Inorganic Materials for Anticounterfeiting 163

Luidgi Giordano, Guanyu Cai, Victor Castaing, Bruno Viana, and Cyrille Richard

6.1	Introduction	163
6.2	A Wide Range of Possible Excitation Wavelengths: from NIR to X-rays	167
6.2.1	Near Infrared Excitation	167
6.2.2	Visible Excitation	175
6.2.3	UV Excitation	176
6.2.4	X-ray Excitation	177
6.3	The Possible Emission Wavelengths Applied to Anticounterfeiting: from UV to SWIR	178
6.3.1	UV Emission	179
6.3.2	Visible Emission	180
6.3.3	NIR and SWIR Emission	183
6.4	A Particular Focus on ZGO Spinel and Garnets and Their Prospects for Optical Anticounterfeiting Applications	186
6.4.1	Persistent Luminescence Materials Based on Zinc-Gallate Spinel Toward Optical Anticounterfeiting Applications	186
6.4.2	Self-Activated Blue Emission ZGSO Spinel Phosphors for Anticounterfeiting	186
6.4.3	Blue-Green/Deep-Red PersL ZGSO:Mn ²⁺ ,Cr ³⁺ Spinel for Anticounterfeiting	188
6.4.4	ZGSO:Cr ³⁺ ,Er ³⁺ Spinel Emitting in the Green/Red/Deep-Red Range for Anticounterfeiting	188
6.4.5	Transparent Thin Films with PersL for Anticounterfeiting	190
6.4.6	Garnets Applied to Anticounterfeiting	190
6.5	Multi-Mode Imaging of Latent Fingerprints (LFP)	192

6.6	Conclusions	195
	References	196
7	Recent Advances of the Deep Trap Persistent Phosphor for Optical Data Storage	205
	<i>Dangli Gao and Chaoyang Jia</i>	
7.1	Introduction	205
7.2	The Information Storage Principle of Afterglow Materials	207
7.2.1	The Mechanism of Information Storage	207
7.2.2	The Regulation Method of Trap Energy Level	209
7.3	Enhanced Information Storage Capacity Strategy	210
7.3.1	Various Trap Regulation Strategies for Information Storage Applications	210
7.3.2	Increasing Information Storage Capacity by Intensity Multiplexing	213
7.3.3	Increasing Information Storage Capacity by Wavelength Multiplexing	216
7.3.4	Multidimensional Information Storage Through Up-conversion Wavelength Multiplexing	219
7.3.5	Multidimensional Information Storage Through Stress Multiplexing	221
7.3.6	Multidimensional Information Storage via Multidimensional Addressable Trap Through Temperature Management	224
7.4	Challenges and Opportunities of Optical Information Storage Materials	228
	References	230
8	Afterglow Thermometer Using Persistent Phosphors	237
	<i>Chuan Liao, Feng Liu, Xiaojun Wang, and Jiahua Zhang</i>	
8.1	Introduction	237
8.2	Performance of Afterglow Thermometer	238
8.2.1	Thermal Sensitivity	238
8.2.2	Time Independence	240
8.2.3	Temperature Uncertainty	240
8.2.4	Repeatability	242
8.3	Response Parameters of Afterglow Thermometer	242
8.3.1	Afterglow Intensity Ratio (AIR)	242
8.3.1.1	Thermal Coupling	245
8.3.1.2	Nonthermal Coupling	247
8.3.2	Afterglow Spectral Bandwidth	249
8.3.3	Afterglow Spectral Shift	250
8.3.4	Afterglow Decay	251
8.3.5	Afterglow Color	253
8.4	Physical Insights of Afterglow Thermometer	253
8.4.1	Charging	254

8.4.1.1	Charging by Ionizing Radiation	254
8.4.1.2	Up-Conversion Charging (UCC)	256
8.4.2	Trapping	257
8.4.2.1	Trap–Emitter Relationship	257
8.4.2.2	Trap Density	257
8.4.2.3	Trap Distribution	257
8.4.3	Emitting	259
8.4.3.1	Ultraviolet Afterglow	259
8.4.3.2	Visible Afterglow	259
8.4.3.3	Infrared Afterglow	266
8.4.4	Persistent Energy Transfer	266
8.5	Extended Thermometers Using Storage Phosphors	266
8.5.1	Photostimulated Luminescence (PSL) Thermometer	267
8.5.2	Mechanoluminescence (ML) Thermometer	268
8.6	Conclusion	268
	References	269
9	Persistent Luminescence and Applications of Molecular Materials and Their Hybrids	283
	<i>Jiahui Xu, Huifang Shi, and Zhongfu An</i>	
9.1	Introduction	283
9.2	Mechanism of Organic Persistent Luminescence	284
9.3	Afterglow Materials	285
9.3.1	Phosphorescence Materials	285
9.3.1.1	Organic Small Molecule-Based Phosphorescent Materials	287
9.3.1.2	Polymer-Based Phosphorescence Materials	293
9.3.1.3	Supramolecule-Based Phosphorescence Materials	299
9.3.1.4	Carbon Dots-Based Phosphorescence Materials	300
9.3.1.5	Organic–Inorganic Hybrid Phosphorescence Materials	303
9.3.1.6	Other Phosphorescence Materials	304
9.3.2	Thermally Activated Delayed Fluorescence Materials	304
9.3.2.1	Organic Small Molecule-Based TADF Materials	304
9.3.2.2	Polymer-Based TADF Materials	305
9.3.2.3	Carbon Dots-Based TADF Materials	306
9.3.2.4	Organic–Inorganic Hybrid TADF Materials	306
9.3.3	Organic Long Persistent Luminescence Materials	306
9.3.3.1	Organic Small Molecule-Based LPL Materials	307
9.3.3.2	Other LPL Materials	308
9.4	Applications	308
9.4.1	Information Encryption	308
9.4.2	Afterglow Display	309
9.4.3	Sensing	309
9.4.4	Afterglow OLEDs	309
9.4.5	Bioimaging	311
9.4.6	X-Ray Detection	311

9.5	Summary and Prospective	311
	Acknowledgment	312
	Abbreviation	312
	References	313
10	Summary and Perspectives on Persistently Luminescent Materials	323
	<i>Yuanbing Mao and Xiaojun Wang</i>	
10.1	Introduction	323
10.2	Other Applications	328
10.2.1	Persistent Photocatalysis	329
10.2.2	“All-weather” Fluorescent Photocatalytic Antifouling	331
10.2.3	Water Tracer Sensing	333
10.2.4	PersL Road Marking	335
10.2.5	Cryogenic Sensing	337
10.2.6	High-Temperature PersL	338
10.3	Conclusions, Challenges, and Perspectives	338
10.3.1	Controlled Synthesis of PersL NPs	342
10.3.2	Tuning Excitation and Emission Properties	342
10.3.3	Orthogonal Encoding	344
10.3.4	Photonic Engineering	345
10.3.5	Trap Engineering	346
10.3.6	Biosafety Study	346
10.3.7	Computational and Theoretical Studies	347
10.3.8	Final Thoughts	351
	Acknowledgments	351
	References	351
	Index	359