

Contents

Preface *xiii*

Part I Sensing 1

1	Wearable Organic Nano-sensors	3
	<i>Wei Huang, Liangwen Feng, Gang Wang, and Elsa Reichmanis</i>	
1.1	Introduction	3
1.2	Wearable Organic Sensors Based on Different Device Architectures	4
1.2.1	Resistor-Based Sensors	5
1.2.1.1	Definitions and Important Parameters	5
1.2.1.2	Materials and Applications	5
1.2.2	Organic Field-Effect Transistor Based Sensors	11
1.2.2.1	Definitions and Important Parameters	11
1.2.2.2	Strategy and Applications	11
1.2.3	Electrochemical Sensors	17
1.2.3.1	Definitions and Important Parameters	17
1.2.3.2	Strategy and Applications	17
1.2.4	Diode-Based Sensors	20
1.2.4.1	Definitions and Important Parameters	20
1.2.4.2	Strategy and Applications	20
1.2.5	Other Devices and System Integration	21
1.3	Summary and Perspective	24
	References	25
2	Stimuli-Responsive Electronic Skins	29
	<i>Zhouyue Lei and Peiyi Wu</i>	
2.1	Introduction	29
2.2	Materials for Electronic Skins	29
2.2.1	Liquid Metals	30
2.2.2	Hydrogels	30
2.2.3	Ionogels	33
2.2.4	Elastomers	33

2.2.5	Conductive Polymers	34
2.2.6	Inorganic Materials	34
2.3	Stimuli-Responsive Behaviors	35
2.3.1	Electrical Signals in Response to Environmental Stimuli	35
2.3.2	Stimuli-Responsive Self-healing	37
2.3.3	Stimuli-Responsive Optical Appearances	38
2.3.4	Stimuli-Responsive Actuations	40
2.3.5	Improved Processability Based on Stimuli-Responsive Behaviors	40
2.4	Understanding the Mechanism of Stimuli-Responsive Materials Applied for Electronic Skins	41
2.5	Conclusion	44
	References	45

3 Flexible Thermoelectrics and Thermoelectric Textiles 49

Fei Jiao

3.1	Introduction	49
3.2	Thermoelectricity and Thermoelectric Materials	49
3.3	Thermoelectric Generators	51
3.4	Wearable Thermoelectric Generators for Smart Clothing	53
3.4.1	Flexible Thermoelectrics	54
3.4.1.1	Inorganic Thermoelectric Materials Related	54
3.4.1.2	Organic Thermoelectric Materials Related	56
3.4.1.3	Carbon-Based Thermoelectric Materials Related	58
3.4.2	Fiber and Textile Related Thermoelectrics	60
3.5	Prospects and Challenges	63
	References	64

Part II Energy 67

4 Textile Triboelectric Nanogenerators for Energy Harvesting 69

Xiong Pu

4.1	Introduction	69
4.2	Fundamentals of Triboelectric Nanogenerators (TENGs)	70
4.2.1	Theoretical Origin of TENGs	70
4.2.2	Four Working Modes	71
4.2.3	Materials for TENGs	72
4.3	Progresses in Textile TENGs	73
4.3.1	Materials for Textile TENGs	74
4.3.2	Fabrication Processes for Textile TENGs	74
4.3.3	Structures of Textile TENGs	75
4.3.3.1	1D Fiber TENGs	75
4.3.3.2	2D Fabric TENGs	77
4.3.3.3	3D Fabric TENGs	80
4.3.4	Washing Capability	81

4.3.5	Self-charging Power Textiles	83
4.4	Conclusions and Perspectives	83
	References	85
5	Flexible and Wearable Solar Cells and Supercapacitors	87
	<i>Kai Yuan, Ting Hu, and Yiwang Chen</i>	
5.1	Introduction	87
5.2	Flexible and Wearable Solar Cells	88
5.2.1	Flexible and Wearable Dye-Sensitized Solar Cells	88
5.2.2	Flexible and Wearable Polymer Solar Cells	93
5.2.3	Flexible and Wearable Perovskite Solar Cells	98
5.2.4	Flexible and Wearable Supercapacitors	104
5.2.5	Flexible and Wearable Electric Double-Layer Capacitors (EDLCs)	108
5.2.6	Flexible and Wearable Pseudocapacitor	111
5.2.7	Integrated Solar Cells and Supercapacitors	115
5.3	Conclusions and Outlook	118
	Acknowledgments	119
	References	120
6	Flexible and Wearable Lithium-Ion Batteries	131
	<i>Zhiwei Zhang, Peng Wang, Xianguang Miao, Peng Zhang, and Longwei Yin</i>	
6.1	Introduction	131
6.2	Typical Lithium-Ion Batteries	131
6.3	Electrode Materials for Flexible Lithium-Ion Batteries	133
6.3.1	Three-Dimensional (3D) Electrodes	133
6.3.2	Two-Dimensional (2D) Electrodes	134
6.3.2.1	Conductive Substrate-Based Electrodes	134
6.3.2.2	Freestanding Film-Based Electrodes	136
6.3.2.3	Graphene Papers	136
6.3.2.4	CNT Papers	137
6.3.2.5	Fabrication of Carbon Films by Vacuum Filtration Process	138
6.3.2.6	Fabrication of Carbon Nanofiber Films by Electrospinning	140
6.3.2.7	Fabrication of Carbon Films by Vapor-Phase Polymerization	141
6.3.3	One-Dimensional (1D) Electrodes	141
6.4	Flexible Lithium-Ion Batteries Based on Electrolytes	143
6.4.1	Liquid-State Electrolytes	143
6.4.1.1	Aprotic Organic Solvent	143
6.4.1.2	Lithium Salts	144
6.4.1.3	Additives	144
6.4.2	Solid-State Electrolytes	144
6.4.2.1	Inorganic Electrolytes	145
6.4.2.2	Organic Electrolytes	145
6.4.2.3	Organic/Inorganic Hybrid Electrolytes	146
6.5	Inactive Materials and Components of Flexible LIBs	148
6.5.1	Separators	148
6.5.1.1	Types of Separators	148

- 6.5.1.2 Physical and Chemical Properties of Separators 149
- 6.5.1.3 Manufacture of Separators 150
- 6.5.2 Casing/Packaging 151
 - 6.5.2.1 Casing/Package Components 152
 - 6.5.2.2 Casing/Packaging Structure 152
- 6.5.3 Current Collectors 152
- 6.5.4 Electrode Additive Materials 153
 - 6.5.4.1 Binders 153
 - 6.5.4.2 Conductive Additives 155
- 6.6 Conclusions and Prospects 155
- References 156

Part III Interacting 163

7 Thermal and Humidity Management for Next-Generation Textiles 165

Junxing Meng, Chengyi Hou, Chenhong Zhang, Qinghong Zhang, Yaogang Li, and Hongzhi Wang

- 7.1 Introduction 165
- 7.2 Passive Smart Materials 166
- 7.3 Energy-Harvesting Materials 171
- 7.4 Active Smart Materials 177
- 7.5 Conclusion 180
- References 180

8 Functionalization of Fiber Materials for Washable Smart Wearable Textiles 183

Yunjie Yin, Yan Xu, and Chaoxia Wang

- 8.1 Introduction 183
 - 8.1.1 Conductive Textiles 183
 - 8.1.2 Waterproof Conductive Textiles 184
 - 8.1.3 Washable Conductive Textiles 184
 - 8.1.4 Evaluation of Washable Conductive Textiles 184
- 8.2 Fiber Materials Functionalization for Conductivity 185
 - 8.2.1 Conductive Fiber Substrates Based on Polymer Materials 185
 - 8.2.1.1 Dip Coating 185
 - 8.2.1.2 Graft Modification 186
 - 8.2.1.3 In Situ Chemical Polymerization 188
 - 8.2.1.4 Electrochemical Polymerization 190
 - 8.2.1.5 In Situ Vapor Phase Polymerization 190
 - 8.2.2 Conductive Fiber Substrates Based on Metal Materials 191
 - 8.2.2.1 Electroless Plating 191
 - 8.2.2.2 Metal Conductive Ink Printing 196
 - 8.2.3 Conductive Fiber Substrates Based on Carbon Material 197

8.2.3.1	Vacuum Filtration	197
8.2.3.2	Dip Coating	197
8.2.3.3	Printing	201
8.2.3.4	Dyeing	202
8.2.3.5	Ultrasonic Depositing	202
8.2.3.6	Brushing Coating	203
8.2.4	Conductive Fiber Substrates Based on Graphene Composite Materials	203
8.2.4.1	Dip Coating	203
8.2.4.2	In Situ Polymerization	204
8.3	Waterproof Modification for Conductive Fiber Substrates	204
8.3.1	Dip-Coating Method	205
8.3.2	Sol–Gel Method	205
8.3.3	Chemical Vapor Deposition	206
8.4	Washing Evaluations of Conductive Textiles	206
8.5	Conclusions	208
	References	209
9	Flexible Microfluidics for Wearable Electronics	213
	<i>Dachao Li, Haixia Yu, Zhihua Pu, Xiaochen Lai, Chengtao Sun, Hao Wu, and Xingguo Zhang</i>	
9.1	Introduction	213
9.2	Materials	213
9.3	Fabrication Technologies	215
9.3.1	Layer Transfer and Lamination	215
9.3.2	Soft Lithography	217
9.3.3	Inkjet Printing	218
9.3.4	3D Printing	218
9.3.4.1	3D Printing Sacrificial Structures	219
9.3.4.2	3D Printing Templates	220
9.3.5	Fabrication of Open-Surface Microfluidics	220
9.3.5.1	Fabrication of Paper-Based Microfluidic Device	220
9.3.5.2	Fabrication of Textile-Based Microfluidic Device	223
9.4	Applications	223
9.4.1	Wearable Microfluidics for Sweat-Based Biosensing	224
9.4.2	Wearable Microfluidics for ISF-Based Biosensing	226
9.4.3	Wearable Microfluidics for Motion Sensing	228
9.4.4	Other Flexible Microfluidics	229
9.4.4.1	Soft Robotics	229
9.4.4.2	Drug Delivery	229
9.4.4.3	Implantable Devices	231
9.4.4.4	Flexible Display	232
9.5	Challenges	234
	References	234

Part IV Integrating and Connecting 237

- 10 Piezoelectric Materials and Devices Based Flexible Bio-integrated Electronics 239**
Xinge Yu
 - 10.1 Introduction 239
 - 10.2 Piezoelectric Materials 240
 - 10.3 Piezoelectric Devices for Biomedical Applications 242
 - 10.4 Conclusion 247
 - References 247

- 11 Flexible and Printed Electronics for Smart Clothes 253**
Yu Jiang and Nan Zhu
 - 11.1 Introduction 253
 - 11.2 Printing Technology 253
 - 11.2.1 Non-template Printing 253
 - 11.2.2 Template-Based Printing 256
 - 11.3 Flexible Substrates 257
 - 11.3.1 Commercially Available Polymers 257
 - 11.3.1.1 Polyethylene Terephthalate (PET) 257
 - 11.3.1.2 Polydimethylsiloxane (PDMS) 258
 - 11.3.1.3 Polyimide (PI) 260
 - 11.3.1.4 Polyurethane (PU) 261
 - 11.3.1.5 Others 262
 - 11.3.2 Printing Papers 262
 - 11.3.3 Tattoo Papers 265
 - 11.3.4 Fiber Textiles 265
 - 11.3.5 Others 268
 - 11.4 Application 268
 - 11.4.1 Wearable Sensors/Biosensors 269
 - 11.4.2 Noninvasive Biofuel Cells 272
 - 11.4.3 Wearable Energy Storage Devices 275
 - 11.5 Prospects 281
 - References 281

- 12 Flexible and Wearable Electronics: from Lab to Fab 285**
Yuanyuan Bai, Xianqing Yang, Lianhui Li, Tie Li, and Ting Zhang
 - 12.1 Introduction 285
 - 12.2 Materials 286
 - 12.2.1 Substrates 286
 - 12.2.2 Functional Materials 286
 - 12.3 Printing Technologies 287
 - 12.3.1 Jet Printing 287
 - 12.3.1.1 Inkjet Printing 288
 - 12.3.1.2 Aerosol Jet Printing 288
 - 12.3.1.3 Electrohydrodynamic Jet (e-Jet) Printing 289
 - 12.3.2 Screen Printing 290

12.3.3	Other Printing Techniques	291
12.4	Flexible and Wearable Electronic Products	292
12.4.1	Flexible Force Sensors	292
12.4.2	Paper Battery	294
12.4.3	Flexible Solar Cell	295
12.4.4	Flexible Display	298
12.5	Strategy Toward Smart Clothing	299
12.6	Summary and Perspective	300
	References	300
13	Materials and Processes for Stretchable and Wearable e-Textile Devices	305
	<i>Binghao Wang and Antonio Facchetti</i>	
13.1	Introduction	305
13.2	Materials for e-Textiles	306
13.2.1	Conducting Materials	306
13.2.1.1	Metal Nanomaterials	306
13.2.1.2	Carbon Nanomaterials	307
13.2.1.3	Conducting Polymers	307
13.2.2	Passive Textile Materials	308
13.3	Device Applications	309
13.3.1	Interconnects and Electrodes	309
13.3.2	Strain Sensors	312
13.3.3	Heaters	318
13.3.4	Supercapacitors	319
13.3.5	Energy Generators	322
13.3.5.1	Thermoelectric Generators	322
13.3.5.2	Triboelectric Generators	323
13.4	Summary and Perspectives	325
	References	327
	Index	335

