

Contents

Preface *xiii*

1	Flexible All-Solid-State Supercapacitors and Micro-Pattern Supercapacitors	1
	<i>Yuqing Liu, Chen Zhao, Shayan Seyedin, Joselito Razal, and Jun Chen</i>	
1.1	Introduction	1
1.2	Potential Components and Device Architecture for Flexible Supercapacitors	4
1.2.1	Flexible Electrode Materials	5
1.2.1.1	Carbon Materials	5
1.2.1.2	Conducting Polymers	6
1.2.1.3	Composite Materials	7
1.2.2	Solid-State Electrolytes	7
1.2.3	Device Architecture of Flexible Supercapacitor	8
1.3	Flexible Supercapacitor Devices with Sandwiched Structures	10
1.3.1	Freestanding Films Based Flexible Devices	10
1.3.2	Flexible Substrate Supported Electrodes Based Devices	14
1.4	Flexible Micro-Supercapacitor Devices with Interdigitated Architecture	18
1.4.1	In situ Synthesis of Active Materials on Pre-Patterned Surfaces	18
1.4.2	Direct Printing of Active Materials	21
1.4.3	Patterning of Well-Developed Film Electrodes	24
1.5	Performance Evaluation and Potential Application of Flexible Supercapacitors	27
1.5.1	Performance Evaluation of Flexible Supercapacitors	28
1.5.2	Integration of Flexible Supercapacitors	29
1.6	Conclusions and Perspectives	32
	References	32
2	Fiber/Yarn-Based Flexible Supercapacitor	37
	<i>Yang Huang and Chunyi Zhi</i>	
2.1	Introduction	37
2.2	Supercapacitor with Intrinsic Conductive Fiber/Yarn	40
2.2.1	Carbolic Fiber/Yarn-Based Supercapacitor	41
2.2.2	Metallic Fiber/Yarn-Based Supercapacitor	44

2.2.3	Hybrid Conductive Fiber/Yarn-Based Supercapacitor	48
2.3	Supercapacitors with Intrinsic Nonconductive Fiber/Yarn	51
2.3.1	Fiber/Yarn Modified by Carbon Materials	52
2.3.2	Fiber/Yarn Modified by Metallic Materials	54
2.4	Integrated Electronic Textiles	57
2.5	Conclusion and Outlook	61
	References	62
3	Flexible Lithium Ion Batteries	67
	<i>Xuli Chen and Yingying Ma</i>	
3.1	Overview of Lithium Ion Battery	67
3.1.1	General Principle	67
3.1.2	Cathode	70
3.1.2.1	LiCoO ₂ with Layered Structure	70
3.1.2.2	LiMn ₂ O ₄ with a Spinel Structure	70
3.1.2.3	LiFePO ₄ with an Olivine Structure	70
3.1.3	Anode	71
3.1.3.1	Carbonaceous Anodes	71
3.1.3.2	Metal Alloy Anodes	71
3.1.4	Electrolyte	72
3.2	Planar-Shaped Flexible Lithium Ion Batteries	73
3.2.1	Bendable Planar Lithium Ion Batteries	73
3.2.1.1	Bendable Carbon-Based Planar Lithium Ion Battery	73
3.2.1.2	Thin Metal Material-Based Lithium Ion Battery	77
3.2.1.3	Polymer-Based Lithium Ion Battery	79
3.2.1.4	Special Structural Design-Based Flexible Lithium-Ion Battery	82
3.2.2	Stretchable Planar Flexible Lithium Ion Batteries	84
3.3	Fiber-Shaped Flexible Lithium Ion Batteries	87
3.3.1	Bendable Fiber-Shaped Lithium Ion Battery	87
3.3.2	Stretchable Fiber-Shaped Lithium Ion Battery	93
3.4	Perspective	94
	References	95
4	Flexible Sodium Ion Batteries: From Materials to Devices	97
	<i>Shengyang Dong, Ping Nie, and Xiaogang Zhang</i>	
4.1	Introduction to Flexible Sodium Ion Batteries (SIBs)	97
4.2	The Key Scientific Issues of Flexible SIBs	98
4.2.1	Design of Advanced Active-Materials	99
4.2.2	Design of Flexible Substrates and Electrodes	99
4.2.3	Developing Novel Processing Technologies	101
4.3	Design of Advanced Materials for Flexible SIBs	101
4.3.1	Inorganic Anode Materials for Flexible SIBs	101
4.3.2	Inorganic Cathode Materials for Flexible SIBs	110
4.3.3	Organic Materials for Flexible SIBs	114
4.3.4	Other Major Components for Flexible SIBs (Electrolyte, Separators, etc.)	115
4.4	Design of Full Cell for Flexible SIBs	117

4.5	Summary and Outlook	121
	References	123
5	1D and 2D Flexible Carbon Matrix Materials for Lithium–Sulfur Batteries	127
	<i>Tianyi Wang, Yushu Liu, Dawei Su, and Guoxiu Wang</i>	
5.1	Introduction	127
5.2	The Working Mechanism and Challenges of Li–S Batteries	128
5.3	Flexible Cathode Hosts for Lithium–Sulfur Batteries	129
5.4	Electrolyte Membranes for Flexible Li–S Batteries	138
5.4.1	Solid Polymer Electrolytes for Flexible Li–S Batteries	139
5.4.2	Gel Polymer Electrolytes for Flexible Li–S Batteries	142
5.4.3	Composite Polymer Electrolytes for Flexible Li–S Batteries	143
5.5	Separator for Flexible Li–S Batteries	144
5.6	Summary	148
	References	149
6	Flexible Electrodes for Lithium–Sulfur Batteries	155
	<i>Jia-Qi Huang, Meng Zhao, Rui Xu, and Qiang Zhang</i>	
6.1	Introduction	155
6.2	Lithium–Sulfur Battery and Flexible Cathode	156
6.2.1	Lithium–Sulfur Battery	156
6.2.2	Flexible Cathode for Lithium–Sulfur Battery	156
6.3	The Flexible Cathode of Lithium–Sulfur Battery	157
6.3.1	Flexible Cathode Based on One-dimensional Materials	157
6.3.1.1	Flexible Cathode Based on CNTs	157
6.3.1.2	Flexible Cathode Based on Carbon Nanofibers	163
6.3.1.3	Flexible Cathode Based on Polymer Fibers	166
6.3.2	Flexible Cathode Based on Two-dimensional Materials	167
6.3.2.1	Flexible Cathode Based on Graphene Paper	167
6.3.2.2	Flexible Cathode Based on Graphene Foam	169
6.3.3	Flexible Cathode Based on Three-dimensional Materials	172
6.3.3.1	Flexible Cathode Based on Three-dimensional Carbon Foam Materials	172
6.3.3.2	Flexible Cathode Based on Carbon/Binder Composites Materials	174
6.3.3.3	Flexible Cathode Based on Three-dimensional Metal Materials	176
6.4	Summary and Prospect	177
	References	178
7	Flexible Lithium–Air Batteries	183
	<i>Qing-Chao Liu, Zhi-Wen Chang, Kai Chen, and Xin-Bo Zhang</i>	
7.1	Motivation for the Development of Flexible Lithium–Air Batteries	183
7.2	State of the Art for Flexible Lithium–Air Batteries	184
7.2.1	Overview of Flexible Energy Storage and Conversion Devices	184
7.2.2	Overview of Flexible Lithium–Air Batteries	185

7.2.2.1	Similarities Between Coin Cell/Swagelok Batteries with Flexible Battery	187
7.2.2.2	Differences Between Coin Cell/Swagelok Batteries with Flexible Battery	188
7.2.3	Current Status of Flexible Lithium–Air Battery	190
7.2.3.1	Planar Battery	190
7.2.3.2	Cable-type Battery	199
7.2.3.3	Woven-type Battery Pack	202
7.2.3.4	Battery Array Pack	203
7.3	Challenges and Future Work on Flexible Lithium–Air Batteries	206
7.4	Concluding Remarks	207
	References	208

8 Nanodielectric Elastomers for Flexible Generators 215

Li-Juan Yin and Zhi-Min Dang

8.1	Introduction	215
8.2	Electro-Mechanical Principles	216
8.2.1	Electro-Mechanical Conversion	216
8.2.2	Equations of DE Generators	217
8.3	Increasing the Performance of Dielectric Elastomers from the Materials Perspective	218
8.3.1	Increasing the Relative Permittivity of DEs	219
8.3.1.1	Elastomer Composites	219
8.3.1.2	Elastomer Blends	222
8.3.1.3	Chemical Modification	223
8.3.2	Decreasing Young's Modulus	225
8.3.3	Complex Network Structure	225
8.4	Circuits and Electro-Mechanical Coupling Methods	227
8.5	Examples of Dielectric Elastomer Generators	230
8.6	Conclusion and Outlook	231
	Acknowledgments	232
	References	232

9 Flexible Dye-Sensitized Solar Cells 239

Byung-Man Kim, Hyun-Gyu Han, Deok-Ho Roh, Junhyeok Park, Kwang Min Kim, Un-Young Kim, and Tae-Hyuk Kwon

9.1	Introduction	239
9.2	Materials and Fabrication of Electrodes for FDSCs	242
9.2.1	Photo-electrode	242
9.2.1.1	Flexible Substrate for Photo-electrode	242
9.2.1.2	Nanostructured-photoactive Film	243
9.2.1.3	Fiber-type FDSCs	249
9.2.2	Counter-electrode	251
9.3	Sensitizers in FDSCs and Thin Photoactive Film DSCs	254
9.3.1	State-of-the-Art Review of Sensitizers in FDSCs	254
9.3.2	Sensitizers in Thin Photoactive Film DSCs	258
9.4	Electrolyte and Hole-Transporting Materials for FDSCs	270

9.5	Conclusion and Outlook	276
	References	278
10	Self-assembly in Fabrication of Semitransparent and Meso-Planar Hybrid Perovskite Photovoltaic Devices	283
	<i>Ravi K. Misra, Sigalit Aharon, Michael Layani, Shlomo Magdassi, and Lioz Etgar</i>	
10.1	Introduction	283
10.1.1	Semitransparent Perovskite Solar Cells Through Self-assembly of Perovskite in One Step	285
10.1.1.1	Cell Architecture and Morphology	286
10.1.1.2	Transparency and Photovoltaic Performance of the Cells	288
10.1.1.3	Recombination Behavior of the Charges in Cells	291
10.1.2	Mesoporous-Planar Hybrid Perovskite Devices Through Mesh-assisted Self-assembly of Mesoporous-TiO ₂	292
10.1.2.1	Cell Architecture and Morphology	293
10.1.2.2	Photovoltaic Performance of the Solar Cells	297
10.1.2.3	Study of Recombination Behavior Through Charge Extraction	300
10.2	Summary and Future Perspective	302
	References	302
11	Flexible Organic Solar Cells	305
	<i>Lin Hu, Youyu Jiang, and Yinhua Zhou</i>	
11.1	Introduction	305
11.1.1	Working Principle	306
11.1.2	Performance Characterization of OSCs	307
11.1.3	Device Structure	308
11.1.3.1	Conventional Device Structure	308
11.1.3.2	Inverted Device Structure	308
11.2	Active Layer	308
11.2.1	Donor Materials	310
11.2.1.1	Poly(Phenylenevinylene) (PPV) and Polythiophene (PT) Derivatives	310
11.2.1.2	D-A Conjugated Polymers	311
11.2.2	Acceptor Materials	313
11.2.2.1	Fullerene Derivatives	313
11.2.2.2	Non-fullerene Acceptors	315
11.3	Flexible Electrode	317
11.3.1	Conductive Polymer (PEDOT:PSS)	317
11.3.2	Metal Nanowires and Grids	318
11.3.3	Hybrid Carbon Material	319
11.4	Interfacial Layer	320
11.4.1	Hole Transporting Layer (HTL)	320
11.4.2	Electron Transporting Layer (ETL)	320
11.5	Tandem Organic Solar Cells	321
11.5.1	Interconnecting Layer	322
11.5.2	Low Bandgap Polymer Sub-cell	324
11.6	Fabrication Technology for Flexible Organic Solar Cells	326

11.7	Summary	328
	References	329
12	Flexible Quantum Dot Sensitized Solar Cells	339
	<i>Yueli Liu, Keqiang Chen, Zhuoyin Peng, and Wen Chen</i>	
12.1	Introduction	339
12.2	Basic Concepts	340
12.2.1	Quantum Dots (QDs)	340
12.2.1.1	Quantum Size Effect	341
12.2.1.2	Multiple Exciton Generation	341
12.2.1.3	Ultrafast Electron Transfer	342
12.2.1.4	Large Specific Surface Area	343
12.2.2	Quantum Dots Sensitized Solar Cells (QDSSCs)	344
12.2.2.1	Schematic of the Structure and Charge Circulation of QDSSCs	344
12.2.2.2	Evaluation of the Photovoltaic Performances of QDSSCs	345
12.3	Development of the Flexible QDSSCs	347
12.3.1	Choosing of the Types of QDs	347
12.3.1.1	Cd-based QDs	347
12.3.1.2	Pb-based QDs	348
12.3.1.3	Cu-based QDs	349
12.3.2	Fabrication of the Flexible Photo-anode Films	350
12.3.3	TiO ₂ -Based Photo-anodes	351
12.3.3.1	Photo-anodes of TiO ₂ Nanoparticles	351
12.3.3.2	Photo-anodes of TiO ₂ Nanoarray Structures	352
12.3.3.3	Designing of Novel TiO ₂ Architecture as Photo-anodes	354
12.3.4	ZnO based Photo-anodes	354
12.3.5	Other Metal Oxide Based Photo-anodes	355
12.3.6	Development of the Sensitization Method	355
12.3.6.1	In situ Sensitization Techniques	356
12.3.6.2	Ex situ Techniques	358
12.3.6.3	Co-sensitization Techniques	360
12.3.7	Interfacial Engineering in QDSSCs	360
12.3.7.1	Surface Passivation by Large-bandgap Semiconductors	361
12.3.7.2	Surface Passivation by Metal Oxides	361
12.3.7.3	Surface Passivation by Molecular Dipoles	362
12.3.7.4	Surface Passivation by Dye Molecules	362
12.3.7.5	Surface Passivation by Molecular Relays	362
12.3.7.6	Combined Interfacial Engineering Methods	363
12.3.8	Optimization of the Counter Electrodes	363
12.3.8.1	Noble Metal Counter Electrodes	365
12.3.8.2	Carbon Counter Electrodes	365
12.3.8.3	Metallic Compound Counter Electrodes	366
12.3.8.4	Polymer Counter Electrodes	370
12.4	Conclusion and Future Outlook	370

Acknowledgments 371

References 371

13 Flexible Triboelectric Nanogenerators 383

Fang Yi, Yue Zhang, Qingliang Liao, Zheng Zhang, and Zhuo Kang

13.1 Introduction 383

13.1.1 Motivation for the Development of Flexible Triboelectric Nanogenerators 383

13.1.2 Basic Working Mechanism and Working Modes of Flexible Triboelectric Nanogenerators 385

13.2 Materials Used for Flexible Triboelectric Nanogenerators 387

13.3 Flexible Triboelectric Nanogenerators for Harvesting Ambient Energy 388

13.3.1 Harvesting Biomechanical Energy 388

13.3.2 Harvesting Wind Energy 391

13.3.3 Harvesting Water Energy 392

13.4 Flexible Triboelectric Nanogenerators for Self-Powered Sensors 393

13.4.1 Self-Powered Touch/Pressure Sensors 393

13.4.2 Self-Powered Motion Sensors 397

13.4.2.1 Sensing Motion of Human Body 397

13.4.2.2 Sensing Motion of Objects 399

13.4.3 Self-Powered Acoustic Sensors 399

13.4.4 Self-Powered Liquid/Gas Flow Sensors 402

13.5 Flexible Triboelectric Nanogenerators for Self-Charging Power Units 405

13.5.1 Self-Charging over a Period of Time to Power Electronics 406

13.5.2 Sustainably Powering Electronics 406

13.6 Flexible Triboelectric Nanogenerators for Hybrid Energy Cells 409

13.7 Service Behavior of Triboelectric Nanogenerators 411

13.8 Summary and Prospects 414

References 415

14 Flexible Thermoelectric Materials and Devices 425

Radhika Prabhakar, Yu Zhang, and Je-Hyeong Bahk

14.1 Introduction 425

14.2 Thermoelectric Energy Conversion Basics 426

14.3 Flexible Thermoelectric Materials 429

14.3.1 Conducting Polymers 431

14.3.2 Graphene and Carbon Nanotube Based TE Materials 434

14.4 Flexible Thermoelectric Energy Harvesters 435

14.4.1 Energy Management 439

14.4.2 Architecture of Thermoelectric Modules 440

14.5 Transverse TE Devices 441

14.5.1 Simulations of Transverse TEG 444

14.6	Thermoelectric Sensors	446
14.7	Summary and Outlook	447
	References	448
15	Carbon-based Electrocatalysts for Water-splitting	459
	<i>Guoqiang Li and Weijia Zhou</i>	
15.1	Introduction	459
15.2	Nonmetal-doped Carbon for HER	460
15.2.1	Nitrogen-doped Carbon-based Catalysts for HER	460
15.2.2	Other Heteroatom (B, S)-doped Carbon-based Catalysts for HER	462
15.2.3	Dual- or Treble-doped Carbons in Metal-free Catalysis	463
15.2.4	Metal-doped Carbon for HER	464
15.3	Metals Embedded in Carbon for HER	466
15.3.1	Core–Shell Structure for Carbon Nanotube and Nanoparticle	468
15.3.2	Metal Organic Frameworks for HER	471
15.4	Electrochemistry	474
15.4.1	Overpotential/Onset Potential and Calibration	474
15.4.2	Current Density and Electrochemical Surface Area	475
15.4.3	Tafel Plot and Exchange Current Density	476
15.4.4	Electrochemical Impedance	476
15.4.5	HER Durability and H ₂ Production	477
15.4.6	Activation	477
15.5	Outlook and Future Challenges	479
15.5.1	HER Mechanism for Carbon-based Catalysts	479
15.5.2	Electrochemistry, Especially for Activation Process	480
15.5.3	OER in Acidic Electrolyte	480
	References	480

Index	485
--------------	------------