

Contents

Foreword	XV
Preface to the 2nd Edition	XVII
Preface to the 1st Edition	XIX
List of Contributors	XXI

Part One Sustainable Energy Production 1

1	Nanotechnology for Energy Production 3
	<i>Elena Serrano, Kunhao Li, Guillermo Rus, and Javier García-Martínez</i>
1.1	Energy Challenges in the Twenty-first Century and Nanotechnology 3
1.2	Nanotechnology in Energy Production 6
1.2.1	Photovoltaics 6
1.2.2	Hydrogen Production 14
1.2.3	Fuel Cells 20
1.2.4	Thermoelectricity 27
1.3	New Opportunities 28
1.4	Outlook and Future Trends 33
	Acknowledgments 34
	References 34
2	Nanotechnology in Dye-Sensitized Photoelectrochemical Devices 41
	<i>Augustin J. McEvoy and Michael Grätzel</i>
2.1	Introduction 41
2.2	Semiconductors and Optical Absorption 42
2.3	Dye Molecular Engineering 46
2.4	The Stable Self-Assembling Dye Monomolecular Layer 48
2.5	The Nanostructured Semiconductor 50
2.6	Recent Research Trends 52
2.7	Conclusions 54
	References 54

3	Thermal-Electrical Energy Conversion from the Nanotechnology Perspective	57
	<i>Jian He and Terry M. Tritt</i>	
3.1	Introduction	57
3.2	Established Bulk Thermoelectric Materials	58
3.3	Selection Criteria for Bulk Thermoelectric Materials	61
3.4	Survey of Size Effects	63
3.4.1	Classic Size Effects	64
3.4.2	Quantum Size Effects	65
3.4.3	Thermoelectricity of Nanostructured Materials	66
3.5	Thermoelectric Properties on the Nanoscale: Modeling and Metrology	68
3.6	Experimental Results and Discussions	70
3.6.1	Bi Nanowire/Nanorod	70
3.6.2	Si Nanowire	72
3.6.3	Engineered “Exotic” Nanostructures	74
3.6.4	Thermionics	76
3.6.5	Thermoelectric Nanocomposites: a New Paradigm	78
3.7	Summary and Perspectives	83
	Acknowledgments	84
	References	84
4	Piezoelectric and Piezotronic Effects in Energy Harvesting and Conversion	89
	<i>Xudong Wang</i>	
4.1	Introduction	89
4.2	Piezoelectric Effect	90
4.3	Piezoelectric Nanomaterials for Mechanical Energy Harvesting	91
4.3.1	Piezoelectric Potential Generated in a Nanowire	92
4.3.2	Enhanced Piezoelectric Effect from Nanomaterials	94
4.3.3	Nanogenerators for Nanoscale Mechanical Energy Harvesting	96
4.3.3.1	Output of Piezoelectric Potential from Nanowires	96
4.3.3.2	The First Prototype Nanogenerator Driven by Ultrasonic Waves	98
4.3.3.3	Output Power Estimation	99
4.3.4	Large-Scale and High-Output Nanogenerators	101
4.3.4.1	Lateral ZnO Nanowire-Based Nanogenerators	101
4.3.4.2	Piezoelectric Polymer Thin Film-Based Nanogenerators	104
4.4	Piezocatalysis—Conversion between Mechanical and Chemical Energies	109
4.4.1	Fundamental Principles of Piezocatalysis	109
4.4.2	Piezocatalyzed Water Splitting	110
4.4.3	Basic Kinetics of Piezocatalyzed Water Splitting	112
4.5	Piezotronics for Enhanced Energy Conversion	114
4.5.1	What is the Piezotronic Effect?	115
4.5.2	Band Structure Engineering by Piezotronic Effect	115

4.5.2.1	Remnant Polarization in Strained Piezoelectric Materials	115
4.5.2.2	Interface Band Engineering by Remnant Piezopotential	116
4.5.2.3	Quantitative Study of Interface Barrier Height Engineering	118
4.5.3	Piezotronics Modulated Photovoltaic Effect	120
4.5.3.1	Principle of Piezotronic Band Structure Engineering	120
4.5.3.2	Piezoelectric Polarization-Enhanced Photovoltaic Performance	122
4.6	Perspectives and Conclusion	125
	Acknowledgments	127
	References	127
5	Graphene for Energy Production and Storage Applications	133
	<i>Dale A.C. Brownson, Jonathan P. Metters, and Craig E. Banks</i>	
5.1	Introduction	133
5.2	Graphene Supercapacitors	135
5.3	Graphene as a Battery/Lithium-Ion Storage	147
5.4	Graphene in Energy Generation Devices	158
5.4.1	Fuel Cells	158
5.4.2	Microbial Biofuel Cells	161
5.4.3	Enzymatic Biofuel Cells	166
5.5	Conclusions/Outlook	167
	References	168
6	Nanomaterials for Fuel Cell Technologies	171
	<i>Antonino Salvatore Aricò, Vincenzo Baglio, and Vincenzo Antonucci</i>	
6.1	Introduction	171
6.2	Low-Temperature Fuel Cells	172
6.2.1	Cathode Reaction	172
6.2.2	Anodic Reaction	178
6.2.3	Practical Fuel Cell Catalysts	180
6.2.4	Nonprecious Catalysts	189
6.2.5	Electrolytes	189
6.2.6	High-Temperature Polymer Electrolyte Membranes	191
6.2.7	Membrane–Electrode Assembly	196
6.3	High-Temperature Fuel Cells	198
6.3.1	High-Temperature Ceramic Electrocatalysts	201
6.3.2	Direct Utilization of Dry Hydrocarbons in SOFCs	204
6.4	Conclusions	205
	References	207
7	Nanocatalysis for Iron-Catalyzed Fischer–Tropsch Synthesis: One Perspective	213
	<i>Uschi M. Graham, Gary Jacobs, and Burtron H. Davis</i>	
7.1	Introduction	213
7.2	Nanocatalyst–Wax Separation	213
7.2.1	Commercial Nanosized Iron Oxide	215

7.2.2	Nanosized Iron Oxide by Gas Phase Pyrolysis	218
7.2.3	Spray-Dried Clusters of Nanosized Iron Oxide	218
7.2.4	Precipitation of Unsymmetrical Nanosized Iron Oxide	220
7.2.5	Supported Iron Oxide Nanoparticles	221
7.2.6	Precipitation of Nanosized Iron Oxide Particles	225
7.3	Summary	229
	References	229
8	The Contribution of Nanotechnology to Hydrogen Production	233
	<i>Sambandam Anandan, Jagannathan Madhavan, and Muthupandian Ashokkumar</i>	
8.1	Introduction	233
8.2	Hydrogen Production by Semiconductor Nanomaterials	235
8.2.1	General Approach	235
8.2.2	Need for Nanomaterials	236
8.2.3	Nanomaterials-Based Photoelectrochemical Cells for H ₂ Production	237
8.2.4	Semiconductors with Specific Morphology: Nanotubes and Nanodisks	239
8.2.5	Sensitization	245
8.3	Summary	253
	Acknowledgments	254
	References	254

Part Two Efficient Energy Storage 259

9	Nanostructured Materials for Hydrogen Storage	261
	<i>Saghar Sepehri and Guozhong Cao</i>	
9.1	Introduction	261
9.2	Hydrogen Storage by Physisorption	262
9.2.1	Nanostructured Carbon	263
9.2.2	Zeolites	264
9.2.3	Metal–Organic Frameworks	265
9.2.4	Clathrates	265
9.2.5	Polymers with Intrinsic Microporosity	266
9.3	Hydrogen Storage by Chemisorption	266
9.3.1	Metal and Complex Hydrides	266
9.3.2	Chemical Hydrides	269
9.3.3	Nanocomposites	270
9.4	Summary	273
	References	273
10	Electrochemical Energy Storage: the Benefits of Nanomaterials	277
	<i>Patrice Simon and Jean-Marie Tarascon</i>	
10.1	Introduction	277
10.2	Nanomaterials for Energy Storage	280

10.2.1	From Rejected Insertion Materials to Attractive Electrode Materials	280
10.2.2	The Use of Once Rejected Si-Based Electrodes	282
10.2.3	Conversion Reactions	283
10.3	Nanostructured Electrodes and Interfaces for the Electrochemical Storage of Energy	285
10.3.1	Nanostructuring of Current Collectors/Active Film Interface	285
10.3.1.1	Self-Supported Electrodes	285
10.3.1.2	Nano-Architected Current Collectors	285
10.3.2	Nanostructuring of Active Material/Electrolyte Interfaces	290
10.3.2.1	Application to Li-Ion Batteries: Mesoporous Chromium Oxides	290
10.3.2.2	Application to Electrochemical Double-Layer Capacitors	291
10.4	Conclusion	296
	Acknowledgments	297
	References	297
11	Carbon-Based Nanomaterials for Electrochemical Energy Storage	299
	<i>Elzbieta Frackowiak and François Béguin</i>	
11.1	Introduction	299
11.2	Nanotexture and Surface Functionality of sp^2 Carbons	299
11.3	Supercapacitors	302
11.3.1	Principle of a Supercapacitor	302
11.3.2	Carbons for Electric Double-Layer Capacitors	304
11.3.3	Carbon-Based Materials for Pseudo-Capacitors	307
11.3.3.1	Pseudo-Capacitance Effects Related with Hydrogen Electrosorbed in Carbon	307
11.3.3.2	Pseudo-Capacitive Oxides and Conducting Polymers	310
11.3.3.3	Pseudo-Capacitive Effects Originated from Heteroatoms in the Carbon Network	312
11.4	Lithium-Ion Batteries	316
11.4.1	Anodes Based on Nanostructured Carbons	317
11.4.2	Anodes Based on Si/C Composites	318
11.4.3	Origins of Irreversible Capacity of Carbon Anodes	321
11.5	Conclusions	323
	References	324
12	Nanotechnologies to Enable High-Performance Superconductors for Energy Applications	327
	<i>Claudia Cantoni and Amit Goyal</i>	
12.1	Overcoming Limitations to Superconductors' Performance	327
12.2	Flux Pinning by Nanoscale Defects	329
12.3	Grain Boundary Problem	330
12.4	Anisotropic Current Properties	332
12.5	Enhancing Naturally Occurring Nanoscale Defects	335
12.6	Artificial Introduction of Flux Pinning Nanostructures	337

12.7	Self-Assembled Nanostructures	338
12.8	Effect of Local Strain Fields in Nanocomposite Films	344
12.9	Control of Epitaxy Enabling Atomic Sulfur Superstructure	347
	Acknowledgments	349
	References	350

Part Three Energy Sustainability 355

13	Green Nanofabrication: Unconventional Approaches for the Conservative Use of Energy	357
	<i>Darren J. Lipomi, Emily A. Weiss, and George M. Whitesides</i>	
13.1	Introduction	357
13.1.1	Motivation	358
13.1.2	Energetic Costs of Nanofabrication	359
13.1.3	Use of Tools	360
13.1.4	Nontraditional Materials	362
13.1.5	Scope	362
13.2	Green Approaches to Nanofabrication	364
13.2.1	Molding and Embossing	364
13.2.1.1	Hard Pattern Transfer Elements	364
13.2.1.2	Soft Pattern Transfer Elements	366
13.2.1.3	Outlook	369
13.2.2	Printing	370
13.2.2.1	Microcontact Printing	370
13.2.2.2	Dip-Pen Nanolithography	371
13.2.2.3	Outlook	372
13.2.3	Edge Lithography by Nanoskiving	372
13.2.3.1	The Ultramicrotome	374
13.2.3.2	Nanowires with Controlled Dimensions	374
13.2.3.3	Open- and Closed-Loop Structures	374
13.2.3.4	Linear Arrays of Single-Crystalline Nanowires	375
13.2.3.5	Conjugated Polymer Nanowires	378
13.2.3.6	Nanostructured Polymer Heterojunctions	379
13.2.3.7	Outlook	384
13.2.4	Shadow Evaporation	385
13.2.4.1	Hollow Inorganic Tubes	385
13.2.4.2	Outlook	387
13.2.5	Electrospinning	389
13.2.5.1	Scanned Electrospinning	390
13.2.5.2	Uniaxial Electrospinning	391
13.2.5.3	Core/Shell and Hollow Nanofibers	391
13.2.5.4	Outlook	393
13.2.6	Self-Assembly	393
13.2.6.1	Hierarchical Assembly of Nanocrystals	394

13.2.6.2	Block Copolymers	395
13.2.6.3	Outlook	397
13.3	Future Directions: Toward “Zero-Cost” Fabrication	397
13.3.1	Scotch-Tape Method for the Preparation of Graphene Films	397
13.3.2	Patterned Paper as a Low-Cost Substrate	398
13.3.3	Shrinky-Dinks for Soft Lithography	398
13.4	Conclusions	400
	Acknowledgments	401
	References	401
14	Nanocatalysis for Fuel Production	407
	<i>Gary Jacobs and Burtron H. Davis</i>	
14.1	Introduction	407
14.2	Petroleum Refining	408
14.3	Naphtha Reforming	408
14.4	Hydrotreating	420
14.5	Cracking	425
14.6	Hydrocracking	427
14.7	Conversion of Syngas	427
14.7.1	Water–Gas Shift	427
14.7.2	Methanol Synthesis	438
14.7.3	Fischer–Tropsch Synthesis	442
14.7.4	Methanation	451
14.8	Nanocatalysis for Bioenergy	454
14.9	The Future	461
	References	462
15	Surface-Functionalized Nanoporous Catalysts towards Biofuel Applications	473
	<i>Brian G. Trewyn</i>	
15.1	Introduction	473
15.1.1	“Single Site” Heterogeneous Catalysis	474
15.1.2	Techniques for the Characterization of Heterogeneous Catalysts	475
15.2	Immobilization Strategies of Single Site Heterogeneous Catalysts	476
15.2.1	Supported Materials	476
15.2.2	Conventional Methods of Functionalization on Silica Surfaces	478
15.2.2.1	Noncovalent Binding of Homogeneous Catalysts	478
15.2.2.2	Surface Immobilization of Catalysts through Covalent Bonds	480
15.2.3	Alternative Synthesis of Immobilized Complex Catalysts on the Solid Support	487
15.3	Design of More Efficient Heterogeneous Catalysts with Enhanced Reactivity and Selectivity	488
15.3.1	Surface Interaction of Silica and Immobilized Homogeneous Catalysts	488

15.3.2	Reactivity Enhancement of Heterogeneous Catalytic System Induced by Site Isolation	491
15.3.3	Introduction of Functionalities and Control of Silica Support Morphology	494
15.3.4	Selective Surface Functionalization of Solid Support for Utilization of Nanospace Inside the Porous Structure	497
15.3.5	Cooperative Catalysis by Multifunctionalized Heterogeneous Catalyst System	503
15.3.6	Tuning the Selectivity of Multifunctionalized Heterogeneous Catalysts by the Gatekeeping Effect	504
15.3.7	Synergistic Catalysis by General Acid and Base Bifunctionalized MSN Catalysts	507
15.4	Other Heterogeneous Catalyst Systems on Nonsilica Supports	512
15.5	Conclusion	512
	References	513
16	Nanotechnology for Carbon Dioxide Capture	517
	<i>Richard R. Willis, Annabelle Benin, Randall Q. Snurr, and Özgür Yazaydın</i>	
16.1	Introduction	517
16.2	CO ₂ Capture Processes	522
16.3	Nanotechnology for CO ₂ Capture	524
16.4	Porous Coordination Polymers for CO ₂ Capture	529
	References	553
17	Nanostructured Organic Light-Emitting Devices	561
	<i>Juo-Hao Li, Jinsong Huang, and Yang Yang</i>	
17.1	Introduction	561
17.2	Quantum Confinement and Charge Balance for OLEDs and PLEDs	563
17.2.1	Multilayer Structured OLEDs and PLEDs	563
17.2.2	Charge Balance in a Polymer Blended System	564
17.2.3	Interfacial Layer and Charge Injection	569
17.2.3.1	I–V Characteristics	570
17.2.3.2	Built-in Potential from Photovoltaic Measurement	571
17.2.3.3	XPS/UPS Study of the Interface	573
17.2.3.4	Comparison with Cs/Al Cathode	578
17.3	Phosphorescent Materials for OLEDs and PLEDs	579
17.3.1	Fluorescence and Phosphorescent Materials	579
17.3.2	Solution-Processed Phosphorescent Materials	580
17.4	Multi-Photon Emission and Tandem Structure for OLEDs and PLEDs	586
17.5	The Enhancement of Light Out-Coupling	587
17.6	Outlook for the Future of Nanostructured OLEDs and PLEDs	589
17.7	Conclusion	590
	References	590

18	Electrochromics for Energy-Efficient Buildings: Nanofeatures, Thin Films, and Devices	593
	<i>Claes-Göran Granqvist</i>	
18.1	Introduction	593
18.2	Electrochromic Materials	595
18.2.1	Functional Principles and Basic Materials	595
18.2.2	The Role of Nanostructure	598
18.2.3	The Cause of Optical Absorption	600
18.2.4	Survey over Transparent Conducting Thin Films	603
18.2.5	Electrolyte Functionalization	605
18.3	Electrochromic Devices	607
18.3.1	Six Challenges	607
18.3.2	Practical Constructions of Devices: a Brief Survey	608
18.3.3	Data on Foil-Based Devices with W Oxide and Ni Oxide	609
18.4	Conclusions and Remarks	612
	References	613
	 Index	 619