Contents

List of Contributors *xvii* Preface *xxiii*

- 1 Principle of Low-temperature Fuel Cells Using an Ionic Membrane 1 Claude Lamy
- 1.1 Introduction 1
- 1.2 Thermodynamic Data and Theoretical Energy Efficiency under Equilibrium (j = 0) 2
- 1.2.1 Hydrogen/oxygen Fuel Cell 2
- 1.2.2 Direct Alcohol Fuel Cell 5
- 1.3 Electrocatalysis and the Rate of Electrochemical Reactions 8
- 1.3.1 Establishment of the Butler–Volmer Law (Charge Transfer Overpotential) 9
- 1.3.2 Mass Transfer Limitations (Concentration Overpotential) 11
- 1.3.3 Cell Voltage versus Current Density Curves 13
- 1.3.4 Energy Efficiency under Working Conditions $(j \neq 0)$ 15
- 1.3.4.1 Hydrogen/oxygen Fuel Cell 15
- 1.3.4.2 Direct Ethanol Fuel Cell 15
- 1.4 Influence of the Properties of the PEMFC Components (Electrode Catalyst Structure, Membrane Resistance, and Mass Transfer Limitations) on the Polarization Curves *16*
- 1.4.1 Influence of the Catalytic Properties of Electrodes 17
- 1.4.2 Influence of the Membrane-specific Resistance 17
- 1.4.3 Influence of the Mass Transfer Limitations *18*
- 1.5 Representative Examples of Low-temperature Fuel Cells 19
- 1.5.1 Direct Methanol Fuel Cell for Portable Electronics 19
- 1.5.2 Hydrogen/air PEMFC for the Electrical Vehicle 25
- 1.6 Conclusions and Outlook 30 Acknowledgments 31 References 31

۱v

- vi Contents
 - 2 Research Advancements in Low-temperature Fuel Cells 35 N. Rajalakshmi, R. Imran Jafri, and K.S. Dhathathreyan
 - 2.1 Introduction 35
 - 2.2 Proton Exchange Membrane Fuel Cells 38
 - 2.2.1 Current Scenario 41
 - 2.2.2 Ideal Properties for Electrocatalyst, Catalyst Support, and Current Collectors for Market Entry 43
 - 2.2.3 Role of Nanomaterials in Bringing Down Pt Loading 44
 - 2.2.4 Types of Catalyst Supports (Activated Carbon, CNT, Graphene, etc.) 44
 - 2.2.5 Non-Pt-Based Catalysts 46
 - 2.2.6 Catalyst Corrosion and Fuel Cell Life (Protocols for Testing) 46
 - 2.2.7 Type of Fuels (Alcohols) 46
 - 2.3 Alkaline Fuel Cells 50
 - 2.3.1 Fuels for Alkaline Membrane Fuel Cells 50
 - 2.3.2 Types of Catalysts 54
 - 2.3.3 Types of Membranes 54
 - 2.3.4 System Development 57
 - 2.4 Direct Borohydride Fuel Cells 59
 - 2.4.1 Catalyst Development 59
 - 2.4.2 System Development 61
 - 2.5 Regenerative Fuel Cells 62
 - 2.5.1 Electrocatalysts 62
 - 2.5.2 System Development 63
 - 2.6 Conclusions and Outlook 64 Acknowledgments 65 References 65
 - **3** Electrocatalytic Reactions Involved in Low-temperature Fuel Cells 75 Claude Lamy
 - 3.1 Introduction 75
 - 3.2 Preparation and Characterization of Pt-based Plurimetallic Electrocatalysts *76*
 - 3.2.1 Preparation Methods of the Catalysts 76
 - 3.2.1.1 Electrochemical Deposition 76
 - 3.2.1.2 Impregnation–Reduction Methods 77
 - 3.2.1.3 Colloidal Methods 78
 - 3.2.1.4 Carbonyl Complex Route 81
 - 3.2.1.5 Plasma-enhanced PVD 82
 - 3.2.2 Characterization of Catalysts and Determination of Reaction Mechanisms by Physicochemical Methods 82
 - 3.2.2.1 Physicochemical Characterizations 82
 - 3.2.2.2 Electrochemical Measurements: Cyclic Voltammetry and CO Stripping 83
 - 3.2.2.3 Infrared Reflectance Spectroscopy (EMIRS, FTIRS) 85
 - 3.2.2.4 Differential Electrochemical Mass Spectrometry 86
 - 3.2.2.5 Chromatographic Techniques 88

Contents vii

- 3.3 Mechanisms of the Electrocatalytic Reactions Involved in Lowtemperature Fuel Cells *90*
- 3.3.1 Electrocatalytic Oxidation of Hydrogen 91
- 3.3.2 Electrocatalytic Reduction of Dioxygen 93
- 3.3.3 Electrocatalysis of CO Oxidation 96
- 3.3.4 Oxidation of Alcohols in a Direct Alcohol Fuel Cell (DMFC, DEFC) 98
- 3.3.4.1 Oxidation of Methanol 99
- 3.3.4.2 Oxidation of Ethanol 102
- 3.4 Conclusions and Outlook 105 Acknowledgment 106 References 106
- 4 Direct Hydrocarbon Low-temperature Fuel Cell 113 Avan Mukheriee and Suddhasatwa Basu
- 4.1 Introduction 113
- 4.2 Direct Methanol Fuel Cell 114
- 4.2.1 Efficiency of DMFC *116*
- 4.2.2 Methanol Crossover 116
- 4.2.3 Catalyst for Methanol Electrooxidation 117
- 4.3 Direct Ethanol Fuel Cell 119
- 4.3.1 Proton Exchange Membrane-based DEFC 120
- 4.3.2 Anion Exchange Membrane-based DEFC 120
- 4.3.3 Ethanol Crossover 121
- 4.3.4 Catalyst for Ethanol Electrooxidation 122
- 4.4 Direct Ethylene Glycol Fuel Cell 125
- 4.4.1 Proton Exchange Membrane-based DEGFC 126
- 4.4.2 Anion Exchange Membrane-based DEGFC 126
- 4.4.3 Catalyst for Ethylene Glycol Electrooxidation 128
- 4.5 Direct Formic Acid Fuel Cell 129
- 4.5.1 Catalyst for Formic Acid Electrooxidation 130
- 4.6 Direct Glucose Fuel Cell 131
- 4.7 Commercialization Status of DHFC 132
- 4.8 Conclusions and Outlook 134
 - References 137

5 The Oscillatory Electrooxidation of Small Organic Molecules 145

- Hamilton Varela, Marcelo V.F. Delmonde, and Alana A. Zülke
- 5.1 Introduction 145
- 5.2 In Situ and Online Approaches 147
- 5.3 The Effect of Temperature 152
- 5.4 Modified Surfaces 155
- 5.5 Conclusions and Outlook 157 Acknowledgments 157 References 158

viii	Contents

6	Degradation Mechanism of Membrane Fuel Cells with Monoplatinum	
	and Multicomponent Cathode Catalysts 165	
	Mikhail R. Tarasevich and Vera A. Bogdanovskaya	
6.1	Introduction 165	
6.2	Synthesis and Experimental Methods of Studying Catalytic Systems	
	under Model Conditions 166	
6.2.1	Synthesis Methods Followed 166	
6.2.1.1	Polyol Technique of Synthesis of Pt/C Catalysts 167	
6.2.1.2	Thermochemical Method of Synthesis of Bi- and Trimetallic	
	Catalysts 167	
6.2.2	Electrochemical Research Methods 167	
6.2.3	Structural Research Methods 168	
6.3	Characteristics of Commercial and Synthesized Catalysts 169	
6.3.1	Corrosion Stability of CMs (Supports) 169	
6.3.1.1		
6.3.1.2	Chemical Corrosion Exposure 171	
6.3.2	Electrochemical and Structural Characteristics of Catalytic	
	Systems 171	
6.3.2.1	Monometallic Catalysts with Pt Content of 20 and 40 wt.% 171	
6.3.2.2	Bimetallic Catalytic Systems (PtM) 174	
6.3.2.3	Trimetallic Catalysts (PtCoCr/C) 175	
6.4	Methods of Testing Catalysts within FC MEAs 179	
6.5	Mechanism of Degradation Phenomenon in MEAs with Commercial	
	Pt/C Catalysts 181	
6.6	Characteristics of MEAs with 40Pt/CNT-T-based Cathode 187	
6.7	Characteristics of MEAs with 50PtCoCr/C-based Cathodes 188	
6.8	Conclusions and Outlook 192	
	Acknowledgments 193	
	References 193	
_		
7	Recent Developments in Electrocatalysts and Hybrid Electrocatalyst	
	Support Systems for Polymer Electrolyte Fuel Cells 197	
	Surbhi Sharma	
7.1	Introduction 197	
7.2	Current State of Pt and Non-Pt Electrocatalysts Support Systems for	
7.0	PEFC 197	
7.3	Novel Pt Electrocatalysts 199	
7.3.1	1D, 2D, and 3D Nanostructures 200	
7.4	Pt-based Electrocatalysts on Novel Carbon Supports 203	
7.4.1	Mesoporous Carbon Supports 203	
7.4.2	Carbon Nanotube Supports 204	
7.4.3	Graphene-based Supports 205	
7.5	Pt-based Electrocatalysts on Novel Carbon-free Supports 207	
7.5.1	Tungsten Oxides and Carbides 207	
7.5.2	Tin Oxide Supports 208	
7.5.3	Titanium Nitride Supports 210	
7.5.4	Doped Metal-based Supports 211	
	1 11	

viii I

- 7.5.4.1 Doped Tin Oxide *212*
- 7.5.4.2 Doped Titanium Dioxide 212
- 7.6 Pt-free Metal Electrocatalysts *213*
- 7.6.1 Metal on Novel Carbon Supports 213
- 7.6.2 Metal on Novel Carbon-free Supports 214
- 7.7 Influence of Support: Electrocatalyst–Support Interactions and Effect of Surface Functional Groups 214
- 7.7.1 Enhancing Electrocatalytic Activity 215
- 7.7.2 Enhancing CO Tolerance 216
- 7.8 Hybrid Catalyst Support Systems 218
- 7.8.1 Carbon-enriched Metal-based Supports 218
- 7.8.2 Polymers in Catalyst Support Systems 221
- 7.8.3 Polyoxometalates Liquid Catholytes 222
- 7.9 Conclusions and Outlook 223 References 224

8 Role of Catalyst Supports: Graphene Based Novel Electrocatalysts 241 Chunmei Zhang and Wei Chen

- Chunmei Zhang ana wei Ch
- 8.1 Introduction 241
- 8.2 Graphene-based Cathode Catalysts for Oxygen Reduction Reaction 243
- 8.2.1 Graphene-supported Nonnoble Metal ORR Catalysts 244
- 8.2.1.1 Transition Metal–Nitrogen (N) Graphene Catalysts 244
- 8.2.1.2 Graphene-supported Metal Oxide/Sulfide Nanocomposites 244
- 8.2.2 Graphene-supported Noble Metal Catalysts 246
- 8.2.2.1 Graphene-supported Pt/Pt-alloy ORR Catalysts 247
- 8.2.2.2 Graphene-supported Other Metal Alloys as ORR Catalysts 2508.3 Graphene-based Anode Catalysts 250
- 8.3.1 Graphene-based Catalysts for Methanol Oxidation Reaction 251
- 8.3.2 Graphene-based Catalysts for Ethanol Oxidation Reaction 253
- 8.3.3 Graphene-based Catalysts for Formic Acid Oxidation Reaction 254
- 8.4 Conclusions and Outlook 256 Acknowledgment 256 References 257
- 9 Recent Progress in Nonnoble Metal Electrocatalysts for Oxygen Reduction for Alkaline Fuel Cells 267
 - Qinggang He and Xin Deng
- 9.1 Introduction 267
- 9.1.1 Alkaline Fuel Cells 267
- 9.1.2 Oxygen Reduction Reaction 269
- 9.2 Nonnoble Metal Electrocatalysts 272
- 9.2.1 Carbon-supported Metal–N_b Matrix 272
- 9.2.1.1 Fundamental Overview 272
- 9.2.1.2 Proposed Active Sites 273
- 9.2.1.3 Synthesis Methods 276
- 9.2.2 Transition Metal Oxides 280

- **x** Contents
 - 9.2.3 Transition Metal Chalcogenides 283
 - 9.2.4 Transition Metal Carbides/Nitrides/Oxynitrides 285
 - 9.2.4.1 Transition Metal Carbides 285
 - 9.2.4.2 Transition Metal Nitrides/Oxynitrides 286
 - 9.2.5 Perovskites 287
 - 9.2.6 Metal-free Electrocatalysts 289
 - 9.2.6.1 Carbon Nanotube-based Metal-free Electrocatalysts 289
 - 9.2.6.2 Graphene-based Metal-free Electrocatalysts 293
 - 9.2.6.3 Other Types of Metal-free Carbon Electrocatalysts 294
 - 9.3 Conclusions and Outlook 296 References 299
 - 10 Anode Electrocatalysts for Direct Borohydride and Direct Ammonia Borane Fuel Cells 317

Pierre-Yves Olu, Anicet Zadick, Nathalie Job, and Marian Chatenet

- 10.1 Introduction 317
- 10.2 Direct Borohydride (and Ammonia Borane) Fuel Cells 318
- 10.2.1 Basics of DBFC and DABFC 318
- 10.2.2 Main Issues of the DBFC and DABFC 319
- 10.3 Mechanistic Investigations of BOR and BH₃OR at Noble Electrocatalysts *320*
- 10.3.1 Different Families of (Electro)Catalysts for the BOR 320
- 10.3.2 BOR Mechanism at Pt Surfaces 323
- 10.3.3 The issue of H_2 Generation (and Possible Oxidation) during the BOR 324
- 10.3.4 Effects of the Mass Transfer, Pt Loading, and Active Layer Thickness on the BOR 325
- 10.3.5 Does the BH₃OR Mechanism Differ from the BOR? 328
- 10.4 Toward Ideal Anode of DBFC and DABFC 329
- 10.4.1 Practical Benchmarks for the Evaluation of Anode Electrocatalyst Materials 330
- 10.4.1.1 Rotating Disk Electrode Studies in Half-Cell Configuration 330
- 10.4.1.2 Hydrogen Evolution and Faradaic Efficiency of the Electrocatalysts *331*
- 10.4.2 Performances of DBFC and DABFC Unit Cells 333
- 10.4.3 Toward Optimal BOR and ABOR Electrocatalysts? 335
- 10.5 Durability of DBFC and DABFC Electrocatalysts 336
- 10.5.1 From FC Studies 336
- 10.5.2 From Accelerated Stress Tests 336
- 10.6 Conclusions and Outlook 339 References 340
- 11 Recent Advances in Nanostructured Electrocatalysts for Lowtemperature Direct Alcohol Fuel Cells 347 Srabanti Ghosh, Thandavarayan Maiyalagan, and Rajendra N. Basu
- 11.1 Introduction 347
- 11.2 Fundamentals of Electrooxidation of Organic Molecules for Fuel Cells 348

- 11.3 Investigation of Electrocatalytic Properties of Nanomaterials 352
- 11.4 Anode Electrocatalysts for Direct Methanol or Ethanol Fuel Cells 353
- 11.4.1 Nobel Metal-based Nanostructured Catalysts 353
- 11.4.2 Palladium-based Nanostructured Catalysts 354
- 11.4.3 Improved Performance of Binary and Ternary Catalysts 355
- 11.4.4 Effect of Support on Catalytic Activity of Nanostructured Electrocatalysts 357
- 11.5 Anode Catalysts for Direct Polyol Fuel Cells (Ethylene Glycol and Glycerol) *359*
- 11.6 Conclusions and Outlook *361* References *362*
- 12 Electrocatalysis of Facet-controlled Noble Metal Nanomaterials for Low-temperature Fuel Cells 373

Xiaojun Liu, Wenyue Li, and Shouzhong Zou

- 12.1 Introduction 373
- 12.2 Synthesis of Shape-controlled Noble Metal Nanomaterials 374
- 12.2.1 One-pot Chemical Reduction 375
- 12.2.2 Seed-mediated Growth 377
- 12.2.3 Solvothermal and Hydrothermal Synthesis 378
- 12.2.4 Galvanic Replacement 381
- 12.2.5 Electrochemical Deposition 383
- 12.3 Applications of Shape-controlled Noble Metal Nanomaterials as Catalysts for Low-temperature Fuel Cells 383
- 12.3.1 Oxygen Reduction Reaction 383
- 12.3.2 Methanol Oxidation Reaction 385
- 12.3.3 Ethanol Oxidation Reaction 386
- 12.3.4 Formic Acid Oxidation Reaction 387
- 12.4 Conclusions and Outlook 389 Acknowledgment 390 References 390
- 13 Heteroatom-doped Nanostructured Carbon Materials as ORR Electrocatalysts for Low-temperature Fuel Cells 401

Thandavarayan Maiyalagan, Subbiah Maheswari, and Viswanathan S. Saji

- 13.1 Introduction 401
- 13.2 Oxygen Reduction Reaction and Methanol-tolerant ORR Catalysts 402
- 13.3 Heteroatom-doped Nanostructured Carbon Materials 403
- 13.3.1 Synthesis of Heteroatom-doped Carbon Materials 403
- 13.3.2 Single Heteroatom-doped Carbon Nanomaterials 403
- 13.3.2.1 N Doping 403
- 13.3.2.2 Stability of N-doped Graphene 406
- 13.3.2.3 B Doping 408
- 13.3.2.4 P Doping 408
- 13.3.2.5 S Doping 409
- 13.3.2.6 XPS Analysis 409

xii Contents

- 13.3.2.7 Halogen Doping 411
- 13.3.3 Dual Heteroatom-doped Carbon Materials 411
- 13.3.4 Multiheteroatom-doped Carbon Materials 414
- 13.4 Heteroatom-doped Carbon-based Nanocomposites 415
- 13.5 Conclusions and Outlook 416 References 417
- 14 Transition Metal Oxide, Oxynitride, and Nitride Electrocatalysts with and without Supports for Polymer Electrolyte Fuel Cell Cathodes 423 Mitsuharu Chisaka
- 14.1 Introduction 423
- 14.2 Transition Metal Oxide and Oxynitride Electrocatalysts 424
- 14.2.1 Stability 424
- 14.2.2 Activity 427
- 14.2.2.1 Evaluation of ORR Activity 427
- 14.2.2.2 Active Sites for ORR 431
- 14.3 Transition Metal Nitride Electrocatalysts 433
- 14.4 Carbon Support-Free Electrocatalysts 434
- 14.5 Conclusions and Outlook 435 Acknowledgment 436 References 436
- 15 Spectroscopy and Microscopy for Characterization of Fuel Cell Catalysts 443

Chilan Ngo, Michael J. Dzara, Sarah Shulda, and Svitlana Pylypenko

- 15.1 Introduction 443
- 15.2 Electron Microscopy 444
- 15.2.1 Scanning Electron Microscopy 444
- 15.2.2 Transmission Electron Microscopy 446
- 15.2.3 In Situ TEM 446
- 15.2.4 Scanning Transmission Electron Microscopy 449
- 15.3 Electron Spectroscopy: Energy-dispersive Spectroscopy and Electron Energy Loss Spectroscopy 449
- 15.4 X-ray Spectroscopy 451
- 15.4.1 X-ray Photoelectron Spectroscopy 452
- 15.4.2 X-ray Absorption Spectroscopy 453
- 15.5 Gamma Spectroscopy: Mossbauer 455
- 15.6 Vibrational Spectroscopy: Fourier Transform Infrared Spectroscopy and Raman Spectroscopy 456
- 15.7 Complementary Techniques 459
- 15.7.1 X-ray Diffraction and Small-angle/Wide-angle X-ray Scattering 459
- 15.7.2 Gas Adsorption/Desorption and Thermal Analysis Techniques 460
- 15.7.3 Inductively Coupled Plasma Methods 461
- 15.7.4 Nuclear Magnetic Resonance Spectroscopy 461
- 15.7.5 Atom Probe Tomography 461
- 15.8 Conclusions and Outlook 462 References 462

Contents xiii

- 16Rational Catalyst Design Methodologies: Principles and Factors
Affecting the Catalyst Design 467
 - Sergey Stolbov and Marisol Alcántara Ortigoza
- 16.1 Introduction 467
- 16.2 Oxygen Reduction Reaction 468
- 16.3 Recent Progress in Search for Efficient ORR Catalysts 469
- 16.4 Physics and Chemistry behind ORR 471
- 16.5 Rational Design of ORR Catalysts 475
- 16.5.1 Electrochemical and Thermodynamic Stability 475
- 16.5.2 Catalytic Activity toward ORR 478
- 16.6 Rationally Designed ORR Catalysts Addressing Cost-effectiveness 482
- 16.7 Conclusions and Outlook 483 References 483
- 17 Effect of Gas Diffusion Layer Structure on the Performance of Polymer Electrolyte Membrane Fuel Cell 489 Branko N. Popov, Sehkyu Park, and Jong-Won Lee
- 17.1 Introduction 489
- 17.2 Structure of Gas Diffusion Layer 490
- 17.2.1 Single-layer Macroporous Substrate 491
- 17.2.2 Dual-layer Gas Diffusion Layer 493
- 17.3 Carbon Materials 493
- 17.4 Hydrophobic and Hydrophilic Treatments 494
- 17.5 Microporous Layer Thickness 499
- 17.6 Microstructure Modification 500
- 17.7 Conclusions and Outlook 500 Acknowledgment 505 References 505
- **18 Efficient Design and Fabrication of Porous Metallic Electrocatalysts** *511 Yaovi Holade, Anaïs Lehoux, Hynd Remita, Kouakou B. Kokoh, and Têko W. Napporn*
- 18.1 Introduction 511
- 18.2 Advances in the Design and Fabrication of Mesoporous Metallic Materials *512*
- 18.2.1 Dealloying Route: the Great and Positive Aspect of Controlled Dissolution/Corrosion *512*
- 18.2.2 Nanoarchitecture Engineering by a Templating Approach: From 1D to 3D Multiscale Design 513
- 18.2.3 Controlled Radiolytic Synthesis: An Elegant Process for Designing Multispatial Nanostructures 515
- 18.2.4 Other Strategies for Tuning Porosity in Metallic Nanomaterials: Nanocages, Nanoframes, and so on 517
- 18.3 Nanoporous Metallic Materials at Work in Electrocatalysis 520
- 18.3.1 Anodic Catalysis: Electrocatalytic Oxidation of Organic Molecules 520
- 18.3.2 Cathodic Catalysis: Electrochemical Oxygen Reduction Reaction 523

xiv	Contents

18.3.3	Other Electrochemical Applications: Fuel Cells, Electroanalysis, and
	Sensing 524

- 18.4 Conclusions and Outlook 526 References 527
- 19Design and Fabrication of Dealloying-driven Nanoporous MetallicElectrocatalyst533

Zhonghua Zhang and Wang Ying

- 19.1 Introduction 533
- 19.2 Design of Precursors for Dealloying-driven Nanoporous Metallic Electrocatalysts 535
- 19.2.1 Compositions 536
- 19.2.2 Fabrication Methods of Precursors 537
- 19.3 Microstructural Modulation of Dealloying-driven Nanoporous Metallic Electrocatalysts 538
- 19.3.1 Control Over the Dealloying Process 539
- 19.3.2 Further Modification of NPMs 542
- 19.4 Catalytic Properties of Dealloying-driven Nanoporous Metallic Electrocatalysts 542
- 19.4.1 Nanoporous Metals 543
- 19.4.2 Nanoporous Alloys 545
- 19.4.3 Nanoporous Nanocomposites 547
- 19.4.4 Other Dealloyed Nanostructured Alloys 548
- 19.4.5 Density Functional Theory Calculations 550
- 19.5 Conclusions and Outlook 551 Acknowledgments 551 References 551
- 20 Recent Advances in Platinum Monolayer Electrocatalysts for the Oxygen Reduction Reaction 557 Kotaro Sasaki, Kurian A. Kuttiyiel, Jia X. Wang, Miomir B. Vukmirovic, and

Radoslav R. Adzic

- 20.1 Introduction 557
- 20.2 Pt ML on Pd Core Electrocatalysts ($Pt_{ML}/Pd/C$) 558
- 20.2.1 Synthesis, Structure, and Activity 558
- 20.2.2 Potential Cycle Tests between 0.6 and 0.9 V 560
- 20.2.3 Performance at High Current Densities 563
- 20.3 Pt ML on PdAu Core Electrocatalyst (Pt_{ML}/PdAu/C) 564
- 20.3.1 Synthesis, Characterization, and Stability 564
- 20.3.2 Potential Cycle Tests between 0.6 and 1.0 V 565
- 20.3.3 Potential Cycle Tests between 0.6 and 1.4 V 567
- 20.4 Further Improving Activity and Stability of Pt ML Electrocatalysts *570*
- 20.4.1 Nitride-stabilized Cores 570
- 20.4.1.1 PtMN (M = Fe, Co, and Ni) Core–Shell Catalysts 570
- 20.4.1.2 Pt ML on PdNiN Core Catalysts 573
- 20.4.2 Intermetallic Pd-based Nanoparticles 573

20.4.3 Iridium (Ir)-based Nanoparticle Cores 578
20.5 Conclusions and Outlook 579

Acknowledgments 579
References 580

Index 585