

Edited by Zhongwei Chen, Jean-Pol Dodelet,
and Jijun Zhao

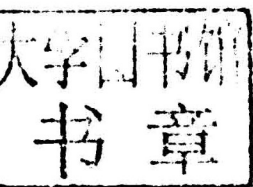
Non-Noble Metal Fuel Cell Catalysts



Edited by

Zhongwei Chen, Jean-Pol Dodelet, and Jiujun Zhang

Non-Noble Metal Fuel Cell Catalysts



WILEY-VCH
Verlag GmbH & Co. KGaA

Editors

Prof. Zhongwei Chen

University of Waterloo
Dept. of Chem. Engineering
200 University Avenue West
N2L 3G1 NK
Canada

Prof. Jean-Pol Dodelet

INRS
Energie, Matériaux et Télécommunications
Boulevard Lionel Boulet 1650
J3X 1S2 NK
Canada

Dr. Jiujun Zhang

National Res. Council Canada
Inst. for Fuel Cell Innovation
Westbrook Mall 4250
V6T 1W5 NK
Canada

All books published by **Wiley-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Print ISBN: 978-3-527-33324-0

ePDF ISBN: 978-3-527-66493-1

ePub ISBN: 978-3-527-66492-4

mobi ISBN: 978-3-527-66491-7

oBook ISBN: 978-3-527-66490-0

Cover-Design Formgeber, Mannheim, Germany

Typesetting Laserwords Private Limited, Chennai, India

Printing and Binding Markono Print Media Pte Ltd, Singapore

Printed on acid-free paper

Edited by
Zhongwei Chen, Jean-Pol Dodelet,
and Jiujun Zhang

Non-Noble Metal Fuel Cell Catalysts

Related Titles

Jiang, S. P., Yan, Y. (eds.)

Materials for High-Temperature Fuel Cells

Series: Materials for Sustainable Energy and Development

Series edited by Lu, G. Q. M.

2013

ISBN: 978-3-527-33041-6

Stolten, D., Emonts, B. (eds.)

Fuel Cell Science and Engineering

Materials, Processes, Systems and Technology

2 Volumes

2012

ISBN: 978-3-527-33012-6

Park, J.-K. (ed.)

Principles and Applications of Lithium Secondary Batteries

2012

ISBN: 978-3-527-33151-2

Zhang, J., Zhang, L., Liu, H., Sun, A., Liu, R.-S. (eds.)

Electrochemical Technologies for Energy Storage and Conversion

2011

ISBN: 978-3-527-32869-7

Daniel, C., Besenhard, J. O. (eds.)

Handbook of Battery Materials

Second, Completely Revised and Enlarged Edition

2 Volumes

2011

ISBN: 978-3-527-32695-2

Aifantis, K. E., Hackney, S. A., Kumar, R. V. (eds.)

High Energy Density Lithium Batteries

Materials, Engineering, Applications

2010

ISBN: 978-3-527-32407-1

Liu, H., Zhang, J. (eds.)

Electrocatalysis of Direct Methanol Fuel Cells

From Fundamentals to Applications

2009

ISBN: 978-3-527-32377-7

Preface

In the context of economic development and improvement in human living conditions, developing advanced technologies for energy storage and conversion has become a hot topic today. Polymer electrolyte membrane (PEM) fuel cells are one kind of important clean energy-converting devices that have drawn a great deal of attention in recent years due to their high efficiency, high energy density, and low or zero emissions, as well as their several important areas of application such as transportation, stationary and portable power, and micro-power. However, two major technical challenges, namely, high cost and low reliability/durability, have been identified as the major obstacles hindering the commercialization of PEM fuel cells. Fuel cell catalysts, such as platinum (Pt)-based catalysts and their associated catalyst layers, are the major factors related to these challenges. To overcome the challenges, exploring new catalysts, improving catalyst activity and stability/durability, and reducing catalyst cost are currently the major approaches in fuel cell technology and commercialization.

Regarding the cost reduction of Pt-based catalysts, non-noble metal catalysts, the next generation PEM fuel cell catalysts slated to replace expensive Pt, have been recognized as the sustainable solution for the commercialization of PEM fuel cells. In more recent years, intensified research and development in this area has been carried out by the world fuel cell community. To facilitate this effort, a book specifically focusing on this area is definitely necessary. This book contains comprehensive and systematic information on non-noble metal electrocatalysts for oxygen reduction reactions in both acid and alkaline PEM fuel cells with emphasis on (i) the fundamentals of electrochemical oxygen reduction catalysis with non-noble metal catalysts within acid and alkaline PEM fuel cells; (ii) the synthesis, characterization, activity validation, and modeling of various kinds of non-noble metal electrocatalysts; and (iii) the integration of the non-noble metal electrocatalysts into fuel cells and validation of their performance.

This book is written by a group of top scientists in the field of fuel cell catalysts, who not only have excellent academic records but also industrial expertise in the use of fuel cells. The book contains the latest updated information on R&D achievements and understanding in electrocatalysts for oxygen reduction reactions in both acid and alkaline PEM fuel cells. Some important R&D directions toward commercialization of both types of fuel cells are also discussed. In order to help readers understand the science and technology

of the fuel cell catalysis, some important and representative figures, tables, photographs, and a comprehensive list of reference papers are presented in this book.

We believe that this book should be extremely useful to researchers and engineers who are working in energy/fuel cell industries. We sincerely hope that through reading this book, the reader will easily be able to locate the latest information on the fundamentals and applications of the catalysis of the oxygen reduction reaction in the next generation of fuel cells. It is expected that this book could be used as a reference for college/university students including undergraduates and graduates, and scientists and engineers who work in the areas of energy, electrochemistry science/technology, fuel cells, and electrocatalysis.

We would like to acknowledge with deep appreciation all of the efforts of all the contributors in writing their chapters. We also wish to thank Dr. Heike Nöthe, Senior Project Editor at STMS Books for extensive help and support.

If technical errors are found in this book, we and all the contributors would deeply appreciate the readers' constructive comments for correction and further improvement.

January 2014

Dr. Zhongwei Chen,
Waterloo, Ontario, Canada

Dr. Jean-Pol Dodelet
Montreal, Quebec, Canada

Dr. Jiujuun Zhang
Vancouver, British Columbia,
Canada

List of Contributors

Nicolas Alonso-Vante

IC2MP-CNRS 7285
University of Poitiers 4 Michel
Brunet Street
86022 Poitiers
France

Koichiro Asazawa

Daihatsu Motor Co., Ltd.
Frontier technology R&D
Department
R&D Division
3000 Yamanoue
Ryuo
Gamo
Shiga 520-2593
Japan

Michael Bron

Martin Luther University
Halle-Wittenberg
Faculty of Natural Sciences II
Department of Chemistry
von-Danckelmann-Platz 4
06120 Halle
Germany

Rui Cai

Chinese Academy of Sciences
State Key Laboratory of Catalysis
Dalian Institute of Chemical
Physics
457 Zhongshan Road
Dalian 116023
China

Chen Chen

Wuhan University
College of Chemistry and
Molecular Sciences
LuoJia Hill Street
Wu Chang
Wuhan 430072
China

Zhongwei Chen

University of Waterloo
Department of Chemical
Engineering
Waterloo Institute for
Nanotechnology
Waterloo Institute for Sustainable
Energy
200 University Avenue West.
Waterloo
Ontario
N2L 3G1
Canada

Deryn Chu

U.S. Army Research Laboratory
Sensors and Electron Devices
Directorate
2800 Powder Mill Road
Adelphi
MD 20783-1197
USA

Wenling Chu

Chinese Academy of Sciences
State Key Laboratory of Catalysis
Dalian Institute of Chemical
Physics
457 Zhongshan Road
Dalian 116023
China

Eben Dy

National Research Council
Canada
Institute for Fuel Cell Innovation
4250 Wesbrook Mall
V6T 1W5
Vancouver BC
Canada

Drew Higgins

University of Waterloo
Department of Chemical
Engineering
Waterloo Institute for
Nanotechnology
Waterloo Institute for Sustainable
Energy
200 University Avenue West.
Waterloo
Ontario
N2L 3G1
Canada

Hideto Imai

NISSAN ARC Ltd.
Energy-Device Analysis
Department
1 Natsushima
Yokosuka
Japan

Akimitsu Ishihara

Yokohama National University
Green Hydrogen Research Center
79-5 Tokiwadai
Hodogaya-ku
Yokohama
Japan

Frédéric Jaouen

Université de Montpellier II
Institut Charles Gerhardt
Montpellier
Laboratory of Aggregates,
Interfaces and Materials for
Energy
CNRS-UMR 5253
2 Place Eugène Bataillon
34095 Montpellier
France

Rongzhong Jiang

U.S. Army Research Laboratory
Sensors and Electron Devices
Directorate
2800 Powder Mill Road
Adelphi
MD 20783-1197
USA

Jesaiah King

The Ohio State University
 Department of Chemical and
 Biomolecular Engineering
 Koffolt Laboratories
 140 W. 19th Ave.
 Columbus
 OH 43210
 USA

Kunchan Lee

Showa Denko K.K.
 Institute for Advanced and Core
 Technology
 1-1-1, Ohnodai
 Midori-ku, Chiba-shi
 Chiba 267-0056
 Japan

Qing Li

Materials Physics and
 Applications Division
 Los Alamos National Laboratory
 P.O. Box 1663
 Mailstop D429
 Los Alamos
 NM 87545
 USA

Ken-ichiro Ota

Yokohama National University
 Green Hydrogen Research Center
 79-5 Tokiwadai
 Hodogaya-ku
 Yokohama
 Japan

Umit S. Ozkan

The Ohio State University
 Department of Chemical and
 Biomolecular Engineering
 Koffolt Laboratories
 140 W. 19th Ave.
 Columbus
 OH 43210
 USA

Jing Pan

Wuhan University
 College of Chemistry and
 Molecular Sciences
 Luojia Hill Street
 Wu Chang
 Wuhan, 430072
 China

Tomokazu Sakamoto

Daihatsu Motor Co., Ltd.
 Frontier technology R&D
 Department
 R&D Division
 3000 Yamanoue
 Ryuo
 Gamo
 Shiga 520-2593
 Japan

Zheng Shi

National Research Council
 Canada
 Institute for Fuel Cell Innovation
 4250 Wesbrook Mall
 V6T 1W5
 Vancouver BC
 Canada

Deepika Singh

The Ohio State University
Department of Chemical and
Biomolecular Engineering
Koffolt Laboratories
140 W. 19th Ave.
Columbus
OH 43210
USA

Hirohisa Tanaka

Daihatsu Motor Co., Ltd.
Frontier technology R&D
Department
R&D Division
3000 Yamanoue
Ryuo
Gamo
Shiga 520-2593
Japan

Gang Wu

Materials Physics and
Applications Division
Los Alamos National Laboratory
P.O. Box 1663
Mailstop D429
Los Alamos
NM 87545
USA

Jiujun Zhang

National Research Council
Canada
Institute for Fuel Cell Innovation
Westbrook Mall 4250
Vancouver
BC V6T 1W5
Canada

Lin Zhuang

Wuhan University
College of Chemistry and
Molecular Sciences
Luoja Hill Street
Wu Chang
Wuhan, 430072
China

Contents

Preface XIII

List of Contributors XV

1	Electrocatalysts for Acid Proton Exchange Membrane (PEM) Fuel Cells – an Overview	1
	<i>Michael Bron</i>	
1.1	Introduction	1
1.2	Acid PEM Fuel Cell Background and Fundamentals	2
1.2.1	Acid PEM Fuel Cell Overview – History, Status, and Advantages	2
1.2.2	Acid PEM Fuel Cell Reactions – Thermodynamics and Kinetics	4
1.3	Acid PEM Fuel Cell Catalysis for Cathode O ₂ Reduction Reaction	9
1.3.1	Electrochemical Thermodynamics of O ₂ Reduction Reaction	10
1.3.2	Pt-Based Catalysts for the Oxygen Reduction Reaction	10
1.3.3	Electrochemical Kinetics and Mechanism of the O ₂ Reduction Reaction Catalyzed by Pt Catalysts	16
1.4	Catalyst Challenges and Perspective in Acid PEM Fuel Cells	18
1.4.1	Pt Catalyst Cost Analysis and Major Challenges	18
1.4.2	Sustainability	19
1.4.3	Major Technical Challenges for Non-noble Metal Catalysts and Mitigation Strategies	19
1.4.4	Non-noble Metal Catalyst Overview	20
1.5	Conclusion	22
	References	22
2	Heat-Treated Transition Metal-N_xC_y Electrocatalysts for the O₂ Reduction Reaction in Acid PEM Fuel Cells	29
	<i>Frédéric Jaouen</i>	
2.1	Introduction	29
2.1.1	Why the Search for Non-precious Metal Catalysts for O ₂ Reduction?	29
2.1.2	Activity, Power Performance, and Durability Constraints on Me/N/C Catalysts	33
2.1.3	Milestones Achieved by Me/N/C Catalysts over the Last 50 Years	37

2.1.3.1	Milestone 1	37
2.1.3.2	Milestone 2	38
2.1.3.3	Milestone 3	39
2.1.3.4	Milestone 4	39
2.1.3.5	Milestone 5	39
2.2	Synthesis Approaches for Heat-Treated Me/N/C Catalysts	40
2.2.1	The Supported-Macrocycle Approach	41
2.2.2	The Templating Method	42
2.2.3	The Foaming Agent Approach	43
2.2.4	The N Molecule or Metal–Ligand Approach	45
2.2.5	The N–Polymer Approach	48
2.2.6	Gaseous N-Precursor Approach (NH_3 and CH_3CN)	50
2.2.7	Thermally Decomposable Metal–Organic Frameworks (MOF)	52
2.3	Important Parameters for Highly Active Me/N/C Catalysts	54
2.3.1	Pyrolysis Temperature	54
2.3.1.1	Metal Macrocycles Supported on Carbon and Pyrolyzed in Inert Atmosphere	54
2.3.1.2	Separate Metal and Nitrogen Precursors or Metal–Ligand Complexes Impregnated on a Carbon Support and Pyrolyzed in Inert or Reactive Atmosphere	56
2.3.2	The Transition Metal	57
2.3.2.1	Binary Metal Catalysts	58
2.3.2.2	Metal Concentration	59
2.3.3	The Nitrogen Content and Speciation by X-ray Photoelectron Spectroscopy (XPS)	61
2.3.4	The Carbon Support/Host	64
2.4	Nature of the Active Sites	73
2.4.1	Time-of-Flight Secondary Ion Mass Spectroscopy	73
2.4.2	X-ray Absorption Spectroscopy and Extended X-ray Absorption Fine Structure	75
2.4.2.1	Studies on Pyrolyzed Macrocycles	76
2.4.2.2	Studies on Catalysts Synthesized from Separate Metal, N and C Precursors	77
2.4.3	Mössbauer Spectroscopy	79
2.4.3.1	Studies on FePc and Fe- Porphyrin, Unpyrolyzed or Pyrolyzed at $T < 500^\circ\text{C}$	80
2.4.3.2	Studies on Fe Macrocycles Pyrolyzed at $T \geq 700^\circ\text{C}$	81
2.4.3.3	Studies on Fe–N–C Catalysts Obtained by Pyrolysis of Separate Fe, N, and C Precursors	85
2.4.4	Turnover Frequency and Site Density	91
2.5	Electrochemical Investigation by RDE/RRDE Methods	94
2.5.1	RDE and the Thin Film Problem: Model and Experiment	94

2.5.2	Activity for H_2O_2 Reduction or Oxidation: a Major Difference from Pt-Based Catalysts	99
2.5.3	The pH Effect: Another Look at the Turnover Frequency of Different Active Sites	103
2.6	Conclusions	105
	Acronyms	106
	Acknowledgments	106
	References	107
3	Modified Carbon Materials for O_2 Reduction Reaction Electrocatalysts in Acid PEM Fuel Cells	119
	<i>Deepika Singh, Jesaiah King, and Umit S. Ozkan</i>	
3.1	Introduction	119
3.2	Doped Carbon Materials	119
3.2.1	Nitrogen-Doped Carbons	121
3.2.1.1	N-Doped CNTs and CNFs	122
3.2.1.2	N-Doped Fullerene	124
3.2.1.3	Carbon Nitrides	124
3.2.1.4	Graphitic Carbon Nitride	125
3.2.1.5	N-Doped Graphene	125
3.2.2	Doping with Other Heteroatoms	127
3.3	Doped Carbons as ORR Catalysts	130
3.3.1	Nitrogen-Doped Carbon Materials Prepared without a Metal	139
3.4	Conclusions	140
	Acknowledgment	141
	References	141
4	Transition Metal Chalcogenides for Oxygen Reduction Electrocatalysts in PEM Fuel Cells	157
	<i>Kunchan Lee, Nicolas Alonso-Vante, and Jiujuan Zhang</i>	
4.1	Introduction	157
4.2	Non-noble Metal Chalcogenide Electrocatalysts for Oxygen Reduction Reaction	160
4.3	Synthesis Methods for Non-noble Metal Chalcogenides	163
4.3.1	Nonorganic Solvent Methods	164
4.3.2	Organic Solvent Methods at Low Temperature	165
4.4	Oxygen Reduction Reaction on Non-noble Metal Chalcogenides	168
4.4.1	Mechanism of Oxygen Reduction Reaction	168
4.4.2	Theoretical Approach for ORR Mechanism	172
4.5	Methanol Tolerance	175
4.6	Fuel Cell Measurements	177
4.7	Conclusions	178
	References	179

5	Transition Metal Oxides, Carbides, Nitrides, Oxynitrides, and Carbonitrides for O₂ Reduction Reaction Electrocatalysts for Acid PEM Fuel Cells	183
	<i>Akimitsu Ishihara, Hideto Imai, and Ken-ichiro Ota</i>	
5.1	Introduction	183
5.2	Transition Metal Nitrides and Carbonitrides as Cathode Catalysts	185
5.3	Stability of Oxides in Acid Electrolyte	186
5.4	Non-noble Metal Oxide-Based Cathode Catalysts	187
5.4.1	Stability of Group 4 and 5 Metal Oxide-Based Catalysts	187
5.4.2	Formation of Complex Oxide Layer Containing Active Sites	188
5.4.3	Substitutional Doping of Nitrogen	189
5.4.4	Creation of Oxygen Defects without Using Carbon and Nitrogen	191
5.4.5	Oxidation of Compounds Including Carbon and Nitrogen	193
5.4.6	Performance of Single Cell with Oxide-Based Cathodes	197
5.5	Conclusions	198
	Acknowledgments	198
	References	199
6	Theoretical Modeling of Non-noble Metal Electrocatalysts for Acid and Alkaline PEM Fuel Cells	205
	<i>Eben Dy and Zheng Shi</i>	
6.1	Introduction	205
6.2	Mechanisms of ORR	205
6.2.1	Role of the Catalyst	206
6.2.2	Effect of pH	208
6.3	Simple Metal–N ₄ Macrocycles	212
6.4	Heat-Treated Transition Metal Nitrogen–Carbon Precursors (M–N _x /C)	216
6.5	Functionalized Graphitic Materials	221
6.5.1	Doped Graphene Materials	222
6.5.2	Doped Carbon Nanotube Materials	227
6.5.3	Metal-Functionalized Graphene Materials	229
6.6	Conducting Polymers	232
6.7	Outlook	235
	References	236
7	Membranes for Alkaline Polyelectrolyte Fuel Cells	243
	<i>Jing Pan, Chen Chen, and Lin Zhuang</i>	
7.1	Introduction	243
7.2	Two Main Challenges of APEs	244
7.2.1	Pursuing High Conductivity as well as Low Swelling Degree	244
7.2.2	High Chemical Stabilities of Cation Groups	244
7.3	APEs Reported in the Literature	245
7.3.1	Heterogeneous APE Membranes	246

7.3.1.1	Ion-Solvating Polymers	246
7.3.1.2	Organic–Inorganic Hybrid APE Membranes	247
7.3.1.3	Composite APE Membrane	248
7.3.2	Homogeneous APE Membranes	249
7.3.2.1	Film-Modified APEs	249
7.3.2.2	Polymer-Modified APEs	250
7.3.2.3	Monomer-Polymerized APE	250
7.4	Strategies for Improving the Ionic Conductivity of APE	254
7.5	Efforts of Improving the Chemical Stability of the Cationic Functional Group	258
7.5.1	Cationic Groups with Conjugated Structure	258
7.5.2	Cationic Groups with Strong Electron Donor	260
7.6	Research on the Chemical Stability of APE Backbone	261
7.7	Conclusions and Perspective	261
	References	264
8	Electrocatalysts for Alkaline Polymer Exchange Membrane (PEM) Fuel Cells – Overview	271
	<i>Rongzhong Jiang and Deryn Chu</i>	
8.1	Introduction	271
8.2	Alkaline Fuel Cell Overview – History, Status, and Advantages	272
8.3	Alkaline Fuel Cell and Alkaline PEM Fuel Cell – Thermodynamics and Kinetics	274
8.3.1	Thermodynamics of H_2/O_2 Fuel Cell Reactions in Alkaline Electrolyte	274
8.3.2	Kinetics of O_2 Reduction in Alkaline Fuel Cells	276
8.3.3	Mechanisms of Oxygen Reduction at Noble Metal Surface	279
8.3.4	Mechanisms of Oxygen Reduction at Non-noble Metal Surface	282
8.3.5	Kinetics and Mechanisms of H_2 Oxidation	284
8.4	Silver-Based Materials for Cathode Electrocatalysts in Alkaline PEM Fuel Cells	286
8.4.1	Starting Materials and Synthesis Strategies for Silver-Based Electrocatalysts	287
8.4.1.1	Chemical Synthesis of Powder Ag Catalysts	288
8.4.1.2	Some Synthetic Methods for Porous Ag Membranes and Porous Electrodes	291
8.4.2	Physical and Electrochemical Characterizations	291
8.4.2.1	X-ray Powder Diffraction (XRD)	291
8.4.2.2	X-ray Photoelectron Spectroscopy (XPS)	293
8.4.2.3	Transmission Electron Microscopy (TEM)	293
8.4.2.4	Electrochemical Method	295
8.4.3	Silver-Based Catalysts for Alkaline PEM Fuel Cells	297
8.5	Catalysts for Oxidation of a Broad Range of Fuels for Alkaline PEM Fuel Cells	298
8.5.1	Non-carbon Fuels and Specific Catalysts for Their Oxidation	298

8.5.1.1	Hydrogen	298
8.5.1.2	Borohydride	298
8.5.1.3	Hydrazine	299
8.5.1.4	Ammonia	299
8.5.1.5	Sulfide	300
8.5.2	Single-Carbon Organic Fuels and Specific Catalysts for Their Oxidation	300
8.5.2.1	Methanol	300
8.5.2.2	Formaldehyde	301
8.5.2.3	Formic Acid	301
8.5.3	Organic Fuels Containing Carbon–Carbon (C–C) Bond in the Molecules and Specific Catalysts for Their Oxidation	302
8.5.3.1	Ethanol	302
8.5.3.2	Ethylene Glycol and Dimethyl Ether	303
8.5.3.3	Other Organic Fuels Containing Two or More C–C Bonds in Their Molecules	305
8.5.4	Electrochemical Kinetics and Mechanisms of Fuel Electrooxidation in Alkaline Media	305
8.6	Major Challenges of Alkaline Fuel Cells and Alkaline PEM Fuel Cells	307
	Acknowledgments	309
	References	309
9	Carbon Composite Cathode Catalysts for Alkaline PEM Fuel Cells	319
	<i>Qing Li and Gang Wu</i>	
9.1	Introduction	319
9.2	Metal-Free Carbon Catalysts	321
9.2.1	Nitrogen Doping into Carbon	322
9.2.2	Nitrogen-Doped Carbon Nanotube Catalysts	324
9.2.3	Nitrogen-Doped Graphene Catalysts	325
9.2.4	Other Heteroatom-Doped Carbon Catalysts	328
9.3	Heat-Treated M–N–C (M: Fe, Co) Carbon Composite Catalysts	330
9.3.1	Heating Temperatures	330
9.3.2	Type of Transition Metals	332
9.3.3	Nitrogen Precursors	333
9.4	Nanocarbon/Transition Metal Compound Hybrid Catalysts	336
9.4.1	Nanocarbon/Metal Oxides Hybrid Catalysts	337
9.4.2	Carbon/Metal Chalcogenide Hybrid Catalysts	341
9.4.3	Nanocarbon/Macrocyclic Compound Catalysts	342
9.5	ORR Mechanism on NPMCs in Alkaline Media	344
9.6	NPMC Cathode Performance in Anion Exchange Membrane Fuel Cell	346
9.7	Summary and Perspective	348
	References	349