ELECTROCHEMICAL ENERGY STORAGE AND CONVERSION

Carbon Nanomaterials for Electrochemical Energy Technologies

Fundamentals and Applications

Edited by
Shuhui Sun • Xueliang Sun • Zhongwei Chen
Yuyu Liu • David P. Wilkinson • Jiujun Zhang

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Carbon Nanomaterials for Electrochemical Energy Technologies: Fundamentals and Applications offers comprehensive coverage of carbon-based nanomaterials and electrochemical energy conversion and storage technologies such as batteries, fuel cells, supercapacitors, and hydrogen generation and storage, as well as the latest material and new technology development. It addresses a variety of topics such as electrochemical processes, materials, components, assembly and manufacturing, degradation mechanisms, challenges, and strategies. With in-depth discussions ranging from electrochemistry fundamentals to engineering components and applied devices, this all-inclusive reference offers a broad view of various carbon nanomaterials and technologies for electrochemical energy conversion and storage devices.

- Features the most recent advances in electrochemical energy
- Covers cutting-edge carbon nanomaterials and technology for electrochemical energy storage and conversion
- Includes both experimental and theoretical modeling that can be used to guide and promote materials as well as technology development for electrochemical energy
- Written by international-leading scientists and engineers active in electrochemical energy and device manufacturing

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Preface

With increasing demand on global energy production and the highly negative impact of fossil fuel combustion on the environment, exploring clean and sustainable energy sources and developing associated technologies have become necessary for modern society's sustainability. To address this, advanced technologies for both energy conversion and storage are being extensively studied around the world and are becoming the most critical elements in overcoming fossil fuel exhaustion and global pollution. Among these, electrochemical energy technologies are considered the most feasible, environmentally friendly, and sustainable. However, in both the aspects of materials and technologies, there are still challenges in terms of the performance, cost, and applications of the energy systems.

Nanotechnology has opened up new frontiers in materials science and engineering to meet these challenges by creating new materials, particularly carbon nanomaterials, for efficient electrochemical energy conversion and storage. Compared with conventional energy materials, carbon nanomaterials possess unique size-/surface-dependent properties (e.g., morphological, electrical, optical, and mechanical) that are useful for enhancing the energy-conversion and storage performance. Over the past few decades, considerable efforts have been made to utilize the unique properties of carbon nanomaterials. These energy materials include fullerenes, carbon nanotubes, graphene, and so on, through which tremendous progress has been achieved in developing high-performance electrochemical energy conversion and storage devices. To accelerate further development, a book covering all important areas of carbon materials and technologies of electrochemical energy storage and conversion should be highly desired.

This book gives a comprehensive description of carbon-based nanomaterials (CNTs, graphene, and other carbon materials) and their associated electrochemical energy conversion and storage technologies, such as batteries, fuel cells, supercapacitors, and hydrogen generation and storage, as well as the latest material and modern technology development. It addresses a variety of topics, such as electrochemical processes, materials, components, assembly and manufacturing, and degradation mechanisms, as well as challenges and perspectives. This book includes in-depth discussions, ranging from comprehensive understanding to engineering of components and applied devices. We believe that a broader view of various carbon nanomaterials and technologies for electrochemical energy conversion and storage devices makes this book unique and an essential read for scientists and engineers working in related fields.

This book consists of 13 chapters: Chapters 1–5 are devoted to carbon materials for various batteries (Li-ion, Li–S, Na-ion, metal–air), Chapter 6 describes carbon materials for supercapacitors, Chapters 7 and 8 discuss carbon materials for Li–O2 and Na–O2 batteries, Chapters 9–11 introduce carbon materials for fuel cells (catalyst, support, membrane), Chapter 12 focuses on carbon materials in electrolysis and hydrogen, and Chapter 13 is about graphene-based sensors.

We would like to thank all those who have been helpful in the writing of this book, including our colleagues who kindly devoted their time to contribute chapters, and the staff at Taylor & Francis for giving us this opportunity.

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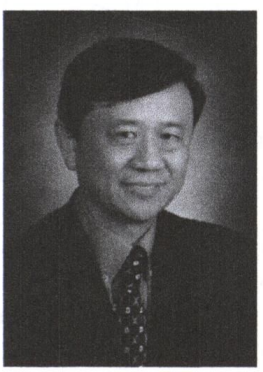
Shuhui Sun is a Professor at the National Institut de la Recherche Scientifique, Center for Energy, Materials, and Telecommunications (INRS–EMT) in Montreal, Canada, where he directs the laboratory of sustainable nanotechnology. His current research interests focus on the development of multifunctional nanomaterials (graphene, CNTs, MOF, metal, and metal oxides) for energy and the environment, including PEM fuel cells (low-Pt and Pt-free catalysts), Li-ion and Na-ion batteries, metal–air batteries, as well as wastewater treatment. He received his PhD in materials engineering from the University of Western Ontario, Canada, and MSc/PhD in physics from the Chinese Academy of Sciences. He has published 10 book chapters, one book, and over 100 peer-reviewed articles in journals including *Advanced Materials, Angewandte Chemie, Advanced Energy Materials, Advanced Functional Materials, and Nano Energy*, and also holds two U.S. patents. He has been invited to present his research findings at over 100 conferences, workshops, seminars, and institutions worldwide. He is the recipient of various prestigious fellowships and awards, such as the ECS Toyota Young Investigator Fellow (2017), Fellow of the Global Young Academy (2017), the Canada Governor General's Academic Gold Medal (2012), NSERC-Alexander Graham Bell Canada Fellowship (2009), the 1st Prize of Natural Science Award of Anhui Province (2014), and the Quebec Merits Fellowship (2007). He is the Vice President of the International Academy of Electrochemical Energy Science (IAOEES). He serves as Executive Editor-in-Chief of *Electrochemical Energy Reviews (EER)* (Springer–Nature), and an editorial board member for another five journals related to nanomaterials and energy.

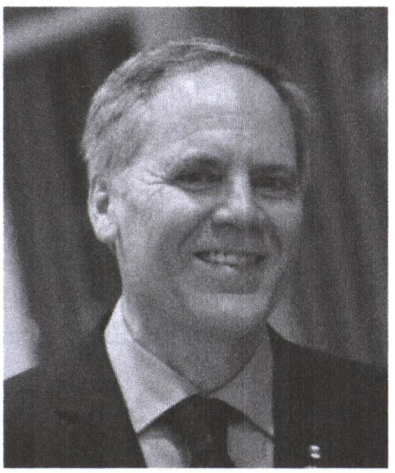


Xueliang Sun is a Professor and Canada Research Chair (Tier I) for the development of nanomaterials for clean energy at the University of Western Ontario, Canada. He was elected as a Fellow of the Canadian Academy of Engineering and a Fellow of the Royal Society of Canada in 2016. His current research interests are associated with electrochemical energy storage and conversion. Dr. Sun received his PhD in materials chemistry at the University of Manchester, United Kingdom, in 1999. After his PhD, he worked as a Postdoctoral Fellow in the University of British Columbia, Canada, from 1999 to 2001. He was a research associate at the National Institut de la Recherche Scientifique (INRS), Quebec, Canada, from 2001 to 2004 before joining the University of Western Ontario in 2004. Dr. Sun is an author and co-author of over 280 refereed journals, two books, and 15 book chapters, including *Nature Communications*, *Advanced Materials*, *Angewandte Chemie International Edition*, *Journal of the American Chemical Society (JACS)*, *Nano Letters*, and *Energy and Environmental Science*. His work has been cited over 13,000 times with an h-index of 60. He holds 10 U.S. patents. Dr. Sun is actively collaborating with industries and government labs such as Ballard Power Systems, General Motors, Lithium Phostech Inc., 3M, and China Automotive Battery Institute Inc. Dr. Sun received various awards such as Early Researcher Award (2006), University Faculty Scholar Award (2010), and the Western Engineering Prize for Achievement in Research (2013).

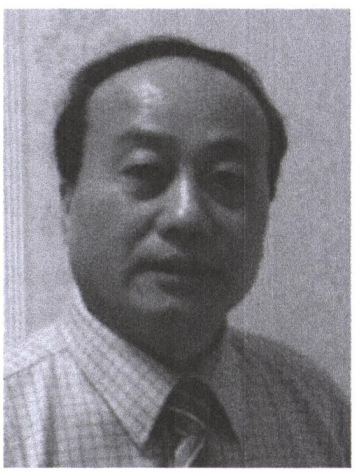
He also serves as Editor-in-Chief for *Electrochemical Energy Reviews* (Springer–Nature) and an Associate Editor for Frontiers of Energy Storage (2013–present). Dr. Sun is a Vice Chairman of the International Academy of Electrochemical Energy (IAOEES).

Zhongwei Chen is a Professor and Canada Research Chair in advanced materials for clean energy, Director of the collaborative graduate program in nanotechnology, and Director of the applied nanomaterials and clean energy laboratory at University of Waterloo, Ontario, Canada. His current research interests are the development of advanced energy materials for metal–air batteries, lithium-ion batteries, and fuel cells. He received his PhD in chemical and environmental engineering from the University of California–Riverside. Prior to joining the faculty at Waterloo in 2008, he focused on the advanced catalysts research by the Chancellor's Dissertation Fellowship in the Los Alamos National Laboratory (LANL) in New Mexico. His current research is on advanced materials for fuel cells, batteries, and sensors. He has published one book, six book chapters, and more than 170 peer-reviewed journal articles in publications including *Nature Nanotechnology*, *Nature Communications*, *JACS*, *Angewandte Chemie*, *Advanced Materials*, *Advanced Energy Materials*, *Energy & Environmental Science*, *Nano Letters*, and *ACS Nano*. To date, these publications have earned him over 10,000 citations with an h-index of 50 (Google Scholar). He is also listed as inventor on 18 U.S./international patents, with three start-up companies in the United States and Canada. Dr. Chen also serves as an editorial board member for peer-reviewed journals including *Scientific Reports* (Nature Publishing) and is Vice President of the International Academy of Electrochemical Energy Science (IAOEES). In 2107, he was elected a Fellow of the Canadian Academy of Engineering, in recognition of his outstanding abilities. He was also recipient of the 2016 E.W.R. Steacie Memorial Fellowship and member of the Royal Society of Canada's College of New Scholars, Artists and Scientists in 2016, which followed several other prestigious honors, including the Ontario Early Researcher Award, an NSERC Discovery Supplement Award, and the Distinguished Performance and Research Excellence Awards from the University of Waterloo.

Yuyu Liu is a Vice-Dean and Professor at the Institute of Sustainable Energy, Shanghai University, China. He received his PhD in environmental engineering from Yamaguchi University, Japan, in 2003. Then, he worked at Kyushu Environmental Evaluation Association, Osaka Institute of Technology, Tokyo University of Agriculture and Technology, Yokohama National University as Postdoctoral and Research Fellow. From 2010 to 2016, he was Assistant Professor and Associate Professor of the Graduate School of Environmental Studies, Tohoku University, Japan. Dr. Liu has more than 20 years of experience in environmental/electrochemical science and technology, particularly in the areas of air quality monitoring, water and soil research, and their associated instrument development. Recently, his research interest has moved to the electrochemical reduction of CO_2 to low-carbon fuels. As the first author and corresponding author, he has published over 60 research papers in peer-reviewed journals, 20 conferences, and keynote/invited/oral presentations, as well as three co-authored/edited books and seven book chapters (including *Electrochemical Reduction of Carbon Dioxide: Fundamentals and Technology* by CRC Press and *Environmental Bioengineering: Volume 11 [Handbook of Environmental Engineering]* by Humana Press). He is also a member of the Japan Society on Water Environment, Japan Society of Material Cycles and Waste Management, and a Board Committee Member of the International Academy of Electrochemical Energy Science.



David P. Wilkinson is a Professor and Canada Research Chair (Tier 1) in clean energy and fuel cells in the Department of Chemical and Biological Engineering at the University of British Columbia (UBC), Canada. He has received a number of awards and is a fellow of several organizations, including the Engineering Institute of Canada, the Canadian Academy of Engineering, the Chemical Institute of Canada, and the Royal Society of Canada. Dr. Wilkinson's main research interests are in electrochemical and photochemical devices, energy conversion and storage materials, and processes to create clean and sustainable energy and water. He has more than 80 issued patents and 160 refereed journal articles covering innovative research in these fields. Dr. Wilkinson received his BASc in chemical engineering from the University of British Columbia (UBC) in 1978 and his PhD in physical chemistry from the University of Ottawa in 1987, where his graduate work was done with Professor Brian Conway in electrochemistry. Prior to joining the university in 2004, Dr. Wilkinson had more than 20 years of industrial experience in the areas of fuel cells and advanced lithium batteries. He has held a variety of leadership positions, including being Associate Department Head, Executive Director of the UBC Clean Energy Research Center, Principal Research Officer and Senior Adviser with the National Research Council of Canada Institute for Fuel Cell Innovation, Director and Vice President of Research and Development at Ballard Power Systems, and Section Leader for Chemistry at Moli Energy (now E-One Moli Energy). Dr. Wilkinson is a Board Member of the International Academy of Electrochemical Energy Science (IAOEES), a Board Member of the Canadian Hydrogen and Fuel Cells Association, and a Board Member of Mangrove Water Technologies Ltd, a company he recently cofounded.



Jiujun Zhang is a Professor and Dean in the College of Sciences/ Institute for Sustainable Energy at Shanghai University and a Principal Research Officer (Emeritus) at the National Research Council of Canada (NRC). Dr. Zhang is a Fellow of the Canadian Academy of Engineering (CAE), Fellow of The Academy of Science of The Royal Society of Canada (FRSC), Fellow of The Engineering Institute of Canada (EIC), Fellow of International Society of Electrochemistry (ISE), and Fellow of the Royal Society of Chemistry (RSC), and Chairman/President of International Academy of Electrochemical Energy Science (IAOEES). Dr. Zhang received his BS and MSc in electrochemistry from Peking University in 1982 and 1985, respectively, and his PhD in electrochemistry from Wuhan University in 1988. After completing his PhD, he took a position as an Associate Professor at the Huazhong Normal University for two years. Starting in 1990, he carried out three terms of postdoctoral research at the California Institute of Technology, York University, and the University of British Columbia. Dr. Zhang has over 35 years of research and development (R&D) experience in theoretical and applied electrochemistry, including over 18 years of fuel cell R&D (including six years at Ballard Power Systems, 14 years at NRC, and three years of electrochemical sensor experience, respectively). Dr. Zhang holds more than 15 adjunct/honorable professorships, including one at the University of Waterloo, one at the University of British Columbia, and one at Peking University. Up to now, Dr. Zhang has co-authored more than 450 publications, including 250 refereed journal papers with approximately 23,000 citations, 19 edited /co-authored books,

11 conference proceeding papers, and 43 book chapters, as well as 140 conference and invited oral presentations. He also holds over 16 US/EU/WO/JP/CA patents, 11 U.S. patent publications, and has produced more than 90 industrial technical reports. Dr. Zhang serves as Editor-in-Chief of *Electrochemical Energy Reviews* (Springer–Nature), Associate Editor of *Green Energy & Environment* (KeAi), Editor of *International Journal of Electrochemistry* (Hindawi), and editorial board member for several international journals, as well as Editor for the book series of *Electrochemical Energy Storage and Conversion* (CRC Press). Dr. Zhang is an active member of The Electrochemical Society (ECS), the International Society of Electrochemistry (ISE, Fellow Member), the American Chemical Society (ACS), and the Canadian Institute of Chemistry (CIC), as well as the International Academy of Electrochemical Energy Science (IAOEES, Board Committee Member).

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