

Edited by François Béguin and Elzbieta Frackowiak

Supercapacitors

Materials, Systems, and Applications

Series Editor:
G.Q. Max Lu



Materials for Sustainable Energy and Development

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Edited by François Béguin and Elżbieta Frąckowiak

Supercapacitors

Materials, Systems, and Applications



**WILEY-
VCH**

WILEY-VCH Verlag GmbH & Co. KGaA

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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>>.

© 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12,
69469 Weinheim, Germany

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Print ISBN: 978-3-527-32883-3

ePDF ISBN: 978-3-527-64669-2

ePub ISBN: 978-3-527-64668-5

mobi ISBN: 978-3-527-64667-8

oBook ISBN: 978-3-527-64666-1

Materials for sustainable energy and development
(Print) ISSN: 2194-7813

Materials for sustainable energy and development
(Internet) ISSN: 2194-7821

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Series Editor Preface

The Wiley Series on New Materials for Sustainable Energy and Development

Sustainable energy and development is attracting increasing attention from the scientific research communities and industries alike, with an international race to develop technologies for clean fossil energy, hydrogen and renewable energy as well as water reuse and recycling. According to the REN21 (Renewables Global Status Report 2012 p. 17) total investment in renewable energy reached \$257 billion in 2011, up from \$211 billion in 2010. The top countries for investment in 2011 were China, Germany, the United States, Italy, and Brazil. In addressing the challenging issues of energy security, oil price rise, and climate change, innovative materials are essential enablers.

In this context, there is a need for an authoritative source of information, presented in a systematic manner, on the latest scientific breakthroughs and knowledge advancement in materials science and engineering as they pertain to energy and the environment. The aim of the *Wiley Series on New Materials for Sustainable Energy and Development* is to serve the community in this respect. This has been an ambitious publication project on materials science for energy applications. Each volume of the series will include high-quality contributions from top international researchers, and is expected to become the standard reference for many years to come.

This book series covers advances in materials science and innovation for renewable energy, clean use of fossil energy, and greenhouse gas mitigation and associated environmental technologies. Current volumes in the series are:

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In presenting this volume on Supercapacitors, I would like to thank the authors and editors of this important book, for their tremendous effort and hard work in completing the manuscript in a timely manner. The quality of the chapters reflects well the caliber of the contributing authors to this book, and will no doubt be recognized and valued by readers.

Finally, I would like to thank the editorial board members. I am grateful to their excellent advice and help in terms of examining coverage of topics and suggesting authors, and evaluating book proposals.

I would also like to thank the editors from the publisher Wiley-VCH with whom I have worked since 2008, Dr Esther Levy, Dr Gudrun Walter, and Dr Bente Flier for their professional assistance and strong support during this project.

I hope you will find this book interesting, informative and valuable as a reference in your work. We will endeavour to

bring to you further volumes in this series or update you on the future book plans in this growing field.

Brisbane, Australia

G.Q. Max Lu

31 July 2012

Preface

Currently, our planet faces huge challenges related to energy. How to reduce CO₂ emissions and fossil fuel consumption? How to introduce renewable energies in the energy mix? Of course these are not new questions, but simply, until the end of the last century, no one cared about the scarcity of fossil fuels even if some warnings appeared during the successive oil crises.

The answer to the above questions is energy saving as well as energy management. It is exactly the role that can be played by electrochemical capacitors, so-called supercapacitors, because of their ability to store larger amounts of energy than the traditional dielectric capacitors. Such exceptional properties originate from the nanometric scale capacitors built from the polarized electrode material and a layer of attracted ions on its surface. The thickness of the electrode-electrolyte interface is directly controlled by the size of ions. Supercapacitors are able to harvest energy in very short periods (less than one minute) and to subsequently provide burst of energy when needed. They are now a reality in the market, where they are applied in automotive and stationary systems, and allow energy savings ranging from 10 to 40%. They can also play a role in the stabilization of current when intermittent renewable energies are introduced in the energetic mix.

Although supercapacitors are now commercially available, they still require improvements, especially for enhancing their energy density. It requires a fundamental understanding of their properties and exact operating principles, in addition to improving electrode materials, electrolytes past and integration in systems. All these topics

led to a very strong motivation of academics and industry during the decade.

When Max Lu invited us to suggest a book in his series Materials for Sustainable Energy and Development, we immediately thought about Supercapacitors. Indeed, since the fantastic pioneer book Electrochemical supercapacitors: Scientific Fundamentals and Technological Applications published by B.E. Conway in 1999, no other comprehensive book was dealing extensively with the topic of supercapacitors, and until now the book is generally referred in almost all scientific publications concerning this subject. During the past 10 years new ideas appeared, such as a better description of what is really the double-layer in these systems and hybrid and asymmetric capacitors, requiring a comprehensive review.

Our book entitled Supercapacitors: materials and systems does not intend to substitute but be a complement to the Conway's book taking advantage of the developments which appeared in the past decade. It is dedicated to researchers and engineers involved with supercapacitor science, its developments, and implementation. The book is also intended for graduate and undergraduate students wanting to special in energy storage systems.

For these reasons, it has been written in collaboration with scientists world-wide renowned in supercapacitors science and also with contributors from the industry. The book includes 14 chapters: 3 being dedicated to general principles of electrochemistry, electrochemical characterization techniques and general properties of supercapacitors in order to allow reading the book without any prerequisite knowledge; 3 to fundamentals, general properties, and modelling of electrical double-layer capacitors, and pseudo-capacitors; 3 to new trends such as asymmetric and hybrid capacitors, and the use of ionic liquid electrolytes; 2 to manufacturing and modules sizing; 3

to testing, reliability, and applications of supercapacitors. Each chapter aims at giving the most detailed information using familiar terms.

We are very happy and proud that we could gather, in this book, the greatest names in supercapacitors science and technology. All are colleagues and friends who we met in international conferences or with whom we have had the pleasure to collaborate. They all kindly accepted to devote their time for contributing chapters; we sincerely and warmly thank them for their help. We also would like to thank our friend Max Lu for giving us this wonderful opportunity and also the Wiley staff for being patient. Finally, we would like to dedicate this book to our solve parents who would be very proud to see our small contribution in helping solve humanity problems.

Poznan

François Bèguin and Elzbieta Frackowiak

November 2012

About the Series Editor



Professor Max Lu

Editor, New Materials for Sustainable Energy and Development Series

Professor Lu's research expertise is in the areas of materials chemistry and nanotechnology. He is known for his work on nanoparticles and nanoporous materials for clean energy and environmental technologies. With over 500 journal publications in high-impact journals, including *Nature*, *Journal of the American Chemical Society*, *Angewandte Chemie*, and *Advanced Materials*, he is also coinventor of 20 international patents. Professor Lu is an Institute for Scientific Information (ISI) Highly Cited Author in Materials Science with over 17 500 citations (h-index of 63). He has received numerous prestigious awards nationally and internationally, including the Chinese Academy of Sciences International Cooperation Award (2011), the Orica Award, the RK Murphy Medal, the Le Fevre Prize, the ExxonMobil Award, the Chemeca Medal, the Top 100 Most Influential Engineers in Australia (2004, 2010, and 2012), and the Top 50 Most Influential Chinese in the World (2006). He won the Australian Research Council Federation Fellowship twice (2003 and 2008). He is an elected Fellow of the Australian Academy of Technological Sciences and

Engineering (ATSE) and Fellow of Institution of Chemical Engineers (IChemE). He is editor and editorial board member of 12 major international journals including *Journal of Colloid and Interface Science and Carbon*.

Max Lu has been Deputy Vice-Chancellor and Vice-President (Research) since 2009. He previously held positions of acting Senior Deputy Vice-Chancellor (2012), acting Deputy Vice-Chancellor (Research), and Pro-Vice-Chancellor (Research Linkages) from October 2008 to June 2009. He was also the Foundation Director of the ARC Centre of Excellence for Functional Nanomaterials from 2003 to 2009.

Professor Lu had formerly served on many government committees and advisory groups including the Prime Minister's Science, Engineering and Innovation Council (2004, 2005, and 2009) and the ARC College of Experts (2002-2004). He is the past Chairman of the IChemE Australia Board and former Director of the Board of ATSE. His other previous board memberships include Uniseed Pty Ltd., ARC Nanotechnology Network, and Queensland China Council. He is currently Board member of the Australian Synchrotron, National eResearch Collaboration Tools and Resources, and Research Data Storage Infrastructure. He also holds a ministerial appointment as member of the National Emerging Technologies Forum.

About the Volume Editors



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François Béguin is a professor at the Poznan University of Technology (Poland), where he was recently awarded the WELCOME stipend from the Foundation for Polish Science. His research activities are devoted to chemical and electrochemical applications of carbon materials, with special attention to the development of nanocarbons with controlled porosity and surface functionality for applications to energy conversion/storage and environment protection. The main topics investigated in his research group are lithium batteries, supercapacitors, electrochemical hydrogen storage, and reversible electrosorption of water contaminants. He published over 250 publications in high-ranking international journals, and his works are cited in 8300 papers, with Hirsch index 46. He is also involved in several books dealing with carbon materials and energy

storage. He is a member of the International Advisory Board of the Carbon Conferences and has launched the international conferences on Carbon for Energy Storage and Environment Protection (CESEP). He is a member of the editorial board of the journal *Carbon*. He was Professor of materials science in the Orléans University (France) until 2012 and was Director of national programmes on Energy Storage (Stock-E), Hydrogen and Fuel Cells (H-PAC), and electricity management (PROGELEC) in the French Agency for Research (ANR).



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Elżbieta Frąckowiak is a full professor at the Institute of Chemistry and Technical Electrochemistry at the Poznan University of Technology. Her main research topics are devoted to energy storage in electrochemical capacitors, Li-ion batteries, and hydrogen electrosorption. She is especially interested in the development of electrode materials (nanoporous carbons, template carbons, carbon nanotubes, graphene, etc.), composite electrodes from conducting polymers, and doped carbons and transition-

metal oxides for supercapacitors, as well as in new concepts of supercapacitors based on the carbon/redox couples interface.

She serves as Chair of Division 3 “Electrochemical Energy Conversion and Storage” of the International Society of Electrochemistry (2009–2014). She is a member of International Advisory Boards - *Electrochimica Acta* from 2011 and *Energy & Environmental Science* from 2008. She was chair/cochair of a few international conferences (12th International Symposium on Intercalation Compounds (ISIC 12) Poznań, Poland, 1–5 June 2003; 2nd International Symposium on Enhanced Electrochemical Capacitors (ISEECap'11), Poznań, Poland, 12–16 June 2011; and the World CARBON conference in Krakow, 17–22 June 2012). She was the winner of the Foundation for Polish Science Prize, the so-called Polish Nobel (December 2011) and was also decorated with the Order of Polonia Restituta (December 2011) and the Order Sapiienti Sat (October 2012).

She is the author of 150 publications, a few chapters, and tens of patent applications. The number of her citations is about 6000, with Hirsch index 36.

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