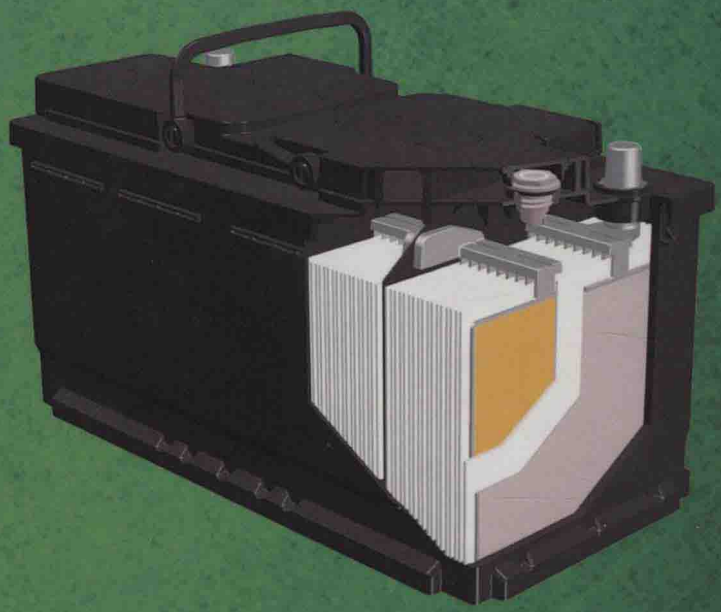
LEAD-ACID BATTERY TECHNOLOGIES

Fundamentals, Materials, and Applications



Edited by
Joey Jung • Lei Zhang
Jiujun Zhang

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ELECTROCHEMICAL ENERGY STORAGE AND CONVERSION

Series Editor: Jiujun Zhang
National Research Council Institute for Fuel Cell Innovation
Vancouver, British Columbia, Canada

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Series Preface

The goal of the *Electrochemical Energy Storage and Conversion* book series is to provide comprehensive coverage of the field, with titles focusing on fundamentals, technologies, applications, and the latest developments, including secondary (or rechargeable) batteries, fuel cells, supercapacitors, CO_2 electroreduction to produce low-carbon fuels, electrolysis for hydrogen generation/storage, and photoelectrochemistry for water splitting to produce hydrogen, among others. Each book in this series is self-contained, written by scientists and engineers with strong academic and industrial expertise who are at the top of their fields and on the cutting edge of technology. With a broad view of various electrochemical energy conversion and storage devices, this unique book series provides essential reads for university students, scientists, and engineers, and allows them to easily locate the latest information on electrochemical technology, fundamentals, and applications.

Jiujun Zhang
National Research Council of Canada
Richmond, British Columbia

Preface

Currently, energy storage and conversion have become one of the most important topics in ongoing research and development aimed at achieving a clean and sustainable world. Electrochemical energy technologies such as batteries, fuel cells, and electrochemical supercapacitors have been recognized as the most important part of the various energy storage and conversion technologies. Among electrochemical energy technologies, lead-acid rechargeable battery technology is the most popular, mature, reliable, safe, and cost-effective electrochemical technology with much wider applications than other electrochemical devices, although it still has several challenges such as relatively low specific energy density, insufficient cycle life, and possible environmental impacts from the manufacturing process (lead dust). Recently, the technology has found rapidly increasing applications in emerging technologies, in particular, in ground transportation applications including electric bicycles, low-speed electric vehicles, and microhybrid vehicles. Recent materials advancements have produced substantial improvements in lead-acid battery performance characteristics, especially energy density. These improvements have come about by enhancing battery utilization or adapting lighter materials, bringing attention to the relevance of lead-acid battery technology in a wider range of applications. For example, in the development of electric vehicles, with the realization of lithium-ion batteries due to the high cost and safety concerns, lead-acid rechargeable batteries have been reconsidered as a feasible technology as long as their energy density can be further increased.

This book is primarily intended to present an overview of lead-acid rechargeable batteries, including fundamentals, applications, and their advancements as energy storage devices in recent years. In particular, the fundamental sciences involved in their operation and the technological developments in materials science and engineering for materials fabrication are summarized in this book. An in-depth analysis of their integration with other primary power systems and their benefits toward current applications is provided. In addition, several other advanced lead-acid rechargeable battery technologies are described in this book. A group of top lead-acid battery scientists and engineers with not only excellent academic records, but also strong industrial expertise, have contributed chapters, sharing their knowledge, information, and insights on recent advances in fundamental theories, experimental methodologies, and research achievements in lead-acid battery technology.

We believe that this book will be a resource that benefits researchers, students, industrial professionals, and manufacturers by providing a systematic overview of the materials, system design, and related issues for the development of lead-acid rechargeable battery technology. The information in this book will be very helpful to readers as they select existing materials/technologies and develop new materials/technologies to improve the performance of lead-acid rechargeable batteries.

We acknowledge and express our sincere thanks for the contributions of all those involved in preparing and developing the chapters of this book. We also express our

appreciation to CRC Press for inviting us to lead this book project, and we thank Allison Shatkin for her guidance and support in smoothing the book preparation process. We acknowledge with deep appreciation Wirtz Manufacturing Company Inc. and Mac Engineering Inc. for their strong support.

If there are any technical errors in the book, we would deeply appreciate readers constructive comments for further improvement.

Joey Jung
Lei Zhang
Jiujun Zhang

Editors

Joey Jung is the founder and president of EVT Power Inc., a company focusing on lithium-ion and lead-acid battery current collector development, and the operations manager of Kemetco Research Inc., a company that provides service in the field of specialty analytical chemistry, chemical processes, and extractive metallurgy. Jung, a registered professional engineer, earned his MASc degree from the University of British Columbia in 2000. From 2000 to 2004, he was a research officer specializing in battery and fuel cell technology for BC Research Inc. From 2004 to 2007, he served as the vice president and CTO of Power Technology Inc, a public company specializing in advanced lead-acid battery development, and as the principal scientist at MagPower Systems Inc., a company engaged in developing metal-air fuel cells. Jung has more than 15 years of R&D experience in applied electrochemistry and electrochemical engineering, including lead-acid battery R&D, lithium-ion battery R&D, fuel cell R&D, rechargeable metal-air battery and metal-air fuel cells, electroplating/electrowinning R&D, catalyst development for electrochemical production of sodium chlorate, electrochemical production of lithium chlorate, electroreduction of carbon dioxide R&D, and development of a process to recycle waste polyurethane to polyols. He has published many papers and authored a book chapter on lead-acid battery technology. He holds 11 U.S. patents/patent applications in the fields of lead-acid batteries, lithium-ion batteries, and fuel cells.

Lei Zhang is a research council officer at the National Research Council of Canada. She earned her BSc in materials science and engineering from Wuhan University of Technology in 1990, her first MSc in materials chemistry from Wuhan University in 1993, and her second MSc in physical chemistry from Simon Fraser University in Canada 2000. After completing her second MSc, Zhang took a position as a research scientist at Membrane Reactor Technologies Inc. in Vancouver, British Columbia, Canada, for 3 years. In 2004 Zhang joined NRC as a research council officer, where she undertook various national and industrial projects as a project manager. Zhang's main research interests include PEM fuel cell electrocatalysis, catalyst layer/electrode structure, metal-air batteries, supercapacitors, and molecular sieve membranes. Zhang has coauthored more than 100 refereed journal papers with more than 5000 citations, 30 conference and invited keynote presentations, 1 book chapter, 2 books, and 40 industrial technical reports. She holds three U.S. patent applications. Zhang is an adjunct professor of the Federal University of Maranhao, Brazil, and Zhengzhou University, China. She is also a member of the NSERC Industrial R&D Fellowships College of Reviewers, Canada (2012–present) and an international advisory member of the Seventh IUPAC International Conference on Novel Materials and Their Synthesis (NMS-VII).

Jiujun Zhang is a principal research officer at the National Research Council of Canada and a fellow of the International Society of Electrochemistry (ISE). His technical expertise areas are electrochemistry, photoelectrochemistry, spectroelectrochemistry, electrocatalysis, fuel cells (PEMFC, SOFC, and DMFC), batteries, and supercapacitors. Dr. Zhang earned his BS and MSc degrees in electrochemistry from Peking University in 1982 and 1985, respectively, and his PhD in electrochemistry from Wuhan University in 1988. 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 holds more than 10 adjunct professorships, including one at the University of Waterloo, one at the University of British Columbia, and one at Peking University. Dr. Zhang has approximately 400 publications with more than 12,000 citations, including 230 refereed journal papers, 13 edited/coauthored books, 32 book chapters, 110 conference oral and keynote/invited presentations, and more than 10 U.S./EU/WO/JP/CA patents. He has produced in excess of 90 industrial technical reports. Dr. Zhang serves as the editor or editorial board member for several international journals as well as editor for the CRC Press book series on electrochemical energy storage and conversion.

Contributors

Isidor Buchmann
Cadex Electronics Inc.
Richmond, British Columbia, Canada

Hongyu Chen
South China Normal University
Guangzhou, China

Mikaël Cugnet
Université Grenoble Alpes
INES, F-73375
Le Bourget du Lac, France

and

CEA, LITEN, F-38054
Grenoble, France

Joey Jung
EVT Power Inc.
and
Kemetco Research Inc.
Richmond, British Columbia, Canada

Zhongqi Li
South China Normal University
Guangzhou, China

Bor Yann Liaw
Hawaii Natural Energy Institute
University of Hawaii at Manoa
Honolulu, Hawaii

Vladimir Neburchilov
National Research Council
Vancouver, British Columbia, Canada

R. David Prengaman
RSR Technologies, Inc.
Dallas, Texas

J. Kevin Whear
Daramic LLC
Charlotte, North Carolina

Jiujun Zhang
National Research Council
Vancouver, British Columbia, Canada

Yufeng Zhang
South China Normal University
Guangzhou, China

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1 Fundamentals of Lead-Acid Rechargeable Batteries

Joey Jung

CONTENTS

1.1 HISTORY

The lead-acid battery was the first secondary (rechargeable) battery to be developed. Since French physicist Gaston Planté invented the lead-acid battery in 1859, its 155 years of development have resulted in numerous applications, for example, as starting batteries, backup power batteries, telecommunication batteries, and traction