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微型燃料电池
原理与应用

Micro Fuel Cells
Principles and Applications

T. S. Zhao

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前　言

在我们的前一本专著《燃料电池的进展》取得成功的基础上，本书将继续对燃料电池领域最新和最重要的进展进行深度概述，这一次将尤其关注微型燃料电池的关键领域进展。本书的每一章都关注一个重要的和新兴的主题，首先介绍基本的物理化学问题，然后按照逻辑顺序介绍最近的研究进展和今后的挑战。所有的分章作者都是该领域中冉冉升起的青年专家和成就卓著的领导者。

越来越多的便携式消费电子产品，如个人数字助手（PDA）、笔记本电脑、手机等都需要功率密度高和能量存储量大但是体积小、重量轻的电源。为了满足上述要求，在过去的几年中，多种不同类型的微型燃料电池得到了快速发展。本书对这些最新的发展给予特别关注，包括长寿命、超低功率直接甲醇燃料电池用电解质，基于微电子机械系统（MEMS）的微型燃料电池，微流体燃料电池，微型管状固体氧化物燃料电池，酶生物燃料电池和糖尿病管理领域用的葡萄糖生物传感器。

本书编委非常感激本书的所有作者，他们保持了《燃料电池进展》一书中建立起来的高标准。在此编者要感谢梁振兴博士和王二东博士在本书准备过程中给予的帮助。另外，编者还要感谢 Elsevier 的专业团队提供的编辑方面的帮助。

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（邵志刚 译）

编 者 简 介

赵天寿博士是香港科技大学机械工程系教授和可持续能源技术研究中心主任。赵博士是国际知名的能源技术专家，目前的研究方向为燃料电池，伴随电化学反应的多尺度、多相传热、传质过程以及计算机模拟。赵博士在机械工程、物理和燃料电池领域的著名期刊上发表了多篇论文，而且在国际会议上做了多次大会报告和主题报告。在学术界，赵博士是 *Advances in Fuel Cells* 的主编，*Applied Thermal Engineering* 亚洲区编辑，而且是 12 种国际期刊的编委。由于其在研究和教育方面的突出贡献，赵博士获得了多项奖励，包括 2004 年香港科技大学贝克特尔基金会工程教育优秀奖，2006 年中国国家自然科学基金海外杰出青年基金。他还是 2007 年以来的美国机械工程学会（ASME）会员，并且在 2008 年获得了裘槎基金会的高级研究成就奖。

（邵志刚 译）

分章作者介绍

Robert L. Arechederra　于1980年出生在美国。2007年在圣路易斯大学获得了化学硕士学位，并且继续在Shelley D. Minteer博士的指导下攻读博士学位。他目前的研究集中在制备电极表面基底的人工代谢途径用于发电。

Michael Beilke　在2005年获得了南密苏里州立大学化学学士学位，又在2007年获得了圣路易斯大学的化学硕士学位。他在2009年秋季进入俄亥俄州立大学攻读分析化学博士学位。

Frank Davis　是英国克兰菲尔德大学克兰菲尔德健康中心的一名研究人员。他在兰卡斯特大学获得了博士学位，然后在曼彻斯特大学、谢菲尔德大学和英国吉列研究实验室继续研究工作。从2002年起，Davis博士在克兰菲尔德从事基于酶和抗体的生物传感器，作为共同作者发表90多篇文章。

Ned Djilali　在赫特福德大学和帝国理工学院获得了航空学学士和硕士学位。在取得英属哥伦比亚大学的机械工程博士学位后，他首先在庞巴迪公司（Bombardier）的先进航空动力学部门工作，然后进入了维多利亚大学。Djilali博士是机械工程系的教授，是集成能源系统研究所（IESVic）的活跃会员，而且是能源系统设计和计算机模拟的加拿大首席科学家。

Marguerite Germain　是圣路易斯大学化学系的在读博士。她在罗克赫斯特（Rockhurst）大学开始了她的学术生涯，并且获得了法语文学学士学位。她目前的研究方向是聚亚甲基绿和开发使用线粒体作为催化剂，丙酮酸盐为燃料的自供电爆炸生物传感器。

Séamus P. J. Higson　主讲生物和电分析，他目前是英国克兰菲尔德（Cranfield）大学药物和生物科学系主任。Higson教授是牛津大学出版社的教科书《分析生物技术》的作者，他还是在其实验室研究成果基础上建立的微阵列（Microarray）公司的研究主任，该公司是克兰菲尔德（Cranfield）大学的衍生公司。

Erik Kjeang　来自瑞典，于2007年在加拿大维多利亚大学获得了机械工程

博士学位。他的研究实现了多种独特的微流体燃料电池的结构，得到了具有高性能和高效率的实用小装置，并且由于其出色的博士论文获得了总督金质奖章。此后，Kjeang 博士在巴拉德公司担任研发工程师，目前也是西蒙弗雷泽（Simon Fraser）大学机电一体化系统工程系的助理教授。

Tamara Klotzbach　在 2007 年春天获得了圣路易斯大学的化学学士学位。她目前正在俄亥俄州立大学师从 Malcolm Chisholm 教授攻读无机化学博士学位。她的工作集中在使用钙催化剂打开环状酯的聚合作用，以此来开发可生物降解的聚合物。

Paul A. Kohl　是佐治亚理工学院化学和生物分子工程系杰出教授（Regents' Professor）和赫拉克勒斯/托马斯戈西奇公司主席。他在得克萨斯大学奥斯汀分校获得了化学博士学位，并且在 AT&T Bell 实验室工作过。他的研究兴趣包括电化学和电子材料。

Shelley D. Minteer　在 1995 年获得了西伊利诺伊大学的化学学士学位，然后在 2000 年获得了爱荷华大学的分析化学博士学位。此后，在 2000 年秋季进入圣路易斯大学化学系作为助理教授，并且在 2005 年晋升为副教授，在 2008 年成为全职教授。她的研究兴趣为酶生物燃料电池。

Michael J. Moehlenbrock　于 1982 年出生在美国。他在 2007 年获得了圣路易斯大学的化学硕士学位。同样在 2007 年，他开始在 Shelley D. Minteer 博士的指导下攻读化学博士学位。他目前的研究方向为非固定化酶生物燃料电池和生物传感器的小型化以及检验生物燃料电池代谢络合物的物质传递通道。

William E. Mustain　目前是康涅狄格大学化学、材料和生物分子工程系的化学工程助理教授。Mustain 博士在 2006 年获得了伊利诺伊理工学院的博士学位。在随后的两年里，他在佐治亚理工学院进行博士后研究工作。他的专业方向为电化学工程和电催化。

Tristain Pichonat　于 1975 年出生在法国米根尼斯（Migennes）。他在 1998 年获得了第戎大学的图像处理和医学影像学士学位，而后在 1999 年获得了鲁昂大学的光学、激光和信号处理的硕士学位。在贝桑松（Besancon）的法国国家科学研究中心物理和振荡器实验室（LPMO-CNRS）从事微型加速计的研究工作，在 2004 年获得了工学博士学位，研究方向为微型燃料电池。然后他在法国国家科学研究中心微纳电子技术研究所（IEMN-CNRS）从事博士后研究工作。他目前作为微纳电子技术研究所的研发工程师，从事自动导航仪网络节点所需的微型

电源的研发工作。

Shruti Prakash　出生在印度巴特纳。她在威斯康辛大学获得了化学工程学士学位，在佐治亚理工学院获得了化学工程博士学位。她目前正在劳伦斯伯克利国家实验工作。

David Sinton　在2003年获得了多伦多大学的博士学位，从事微尺度流动的可视化研究。他目前是维多利亚大学的机械工程副教授，并且是维多利亚大学集成能源系统研究所（IESVic）的成员。Sinton博士领导了出色的科研项目，目的是面向生物医学和能源应用的微流体和纳米流体的研究和开发。

Daria Sokic-Lazic　于1980年出生在波黑图兹拉（Tuzla）。她在2008年获得了圣路易斯大学的化学学士学位。同年，开始师从Shelley D. Minteer博士攻读化学博士学位。她目前的工作集中在生物燃料电池代谢途径的酶仿生学研究。

Toshio Suzuki　是日本名古屋先进工业科学和技术（AIST）国家研究所的科学家，从事微型管状SOFC的研究。在加入AIST之前，他在密苏里大学罗拉分校担任助理研究教授，从事单管SOFC和SOFC部件（电解质和电极）的低温（低于1000℃）陶瓷处理研究。他在日本仙台的东北大学获得了学士学位，在密苏里大学罗拉分校获得了陶瓷工程博士学位。

Becky L. Treu　是密苏里州人，在2008年获得了圣路易斯大学的集成和应用科学（侧重化学）博士学位。她的专业是生物电化学，具体是用于生物燃料电池的吡咯喹啉醌（PQQ）依赖的脱氢酶的分离和提纯。在这项研究中，她已经发表了多篇文章和专利。她目前在密苏里科技大学（前身是密苏里大学罗拉分校）材料研究中心从事博士后研究工作，开发环境友好的太空用稀土基涂层。

Janice Wildrick　从事逻辑和计算机工作15年后，在密苏里大学圣路易斯分校获得了化学学士学位。她在2007年加入Shelley Minteer的课题组，从事最引人注目的可再生能源的研究。她的研究集中在空气自呼吸阴极的开发和优化。

（邵志刚 译）

Preface

Following the success of our previous book, *Advances in Fuel Cells*, this closely related volume continues to provide in-depth coverage of the newest, most important developments in the general field of fuel cells, this time specifically focusing on the pivotal area of Micro Fuel Cells. Each chapter in this book deals with a significant, emerging topic by beginning with fundamental physiochemical considerations and then proceeding in a logical fashion to the forefront of recent developments and future challenges. The contributing authors are a combination of young, upcoming experts and well-established leaders in the field.

A growing number of increasingly ubiquitous portable consumer electronics, such as personal digital assistants (PDAs), laptop computers, and cellular phones, demand small, lightweight power sources with high power density and energy capacity. Over the past few years, a number of different types of micro fuel cells have been developing at a rapid pace in order to meet this demand. This book pays particular attention to these recent developments, including electrolytes for long-life, ultra low-power direct methanol fuel cells, MEMS-based micro fuel cells, microfluidic fuel cells, micro tubular solid oxide fuel cells, enzymatic fuel cells, and glucose biosensors that mainly focus on diabetes management.

The editorial board expresses their appreciation to the contributing authors of this volume, who have maintained the high standards established in *Advances in Fuel Cells*. The editor is grateful to Dr. Zhenxing Liang and Dr. Erdong Wang for their assistance in preparing this book. Last, but not least, the editor acknowledges the efforts of the professional staff at Elsevier for providing invaluable editorial assistance.

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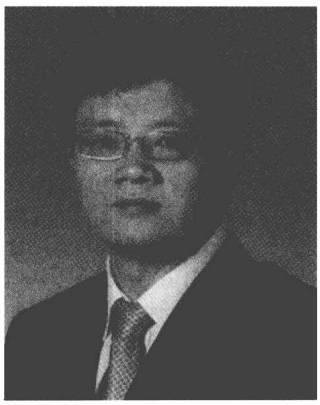
About the Editor



Dr. T.S. Zhao is a Professor of Mechanical Engineering and Director of the Center for Sustainable Energy Technology at the Hong Kong University of Science & Technology (HKUST). As an internationally renowned expert in energy technology, he presently focuses his research on fuel cells, multiscale multiphase heat/mass transport with electrochemical reactions, and computational modeling. He has published many important papers in prestigious journals in the fields of mechanical engineering, physics, and fuel cells and has presented numerous plenary/keynote lectures at international conferences. In the international community, Dr. Zhao serves as Editor-in-Chief of *Advances in Fuel Cells*, Asian Regional Editor of *Applied Thermal Engineering*, and as a member of the Editorial Board for more than 12 international journals. He has received a number of recognitions for his research and teaching, including the Bechtel Foundation Engineering Teaching Excellence Award at HKUST in 2004, the Overseas Distinguished Young Scholars Award by the Natural Science Foundation of China in 2006, Fellow of the American Society of Mechanical Engineers (ASME) since 2007, and the Croucher Senior Fellowship award from the Croucher Foundation in 2008.

About the Contributors

Robert L. Arechederra was born in the United States in 1980. He received his M.S. in Chemistry from Saint Louis University in 2007 and continued to pursue his doctoral degree under the supervision of Dr. Shelley D. Minteer. His current research efforts are focused on creating artificial metabolic pathways for substrates on electrode surfaces for generating electricity.

Michael Beilke earned his B.S. in Chemistry at Missouri Southern State University in 2005. He also obtained a M.S. in Chemistry from Saint Louis University in 2007. He will be attending the Ohio State University in the fall of 2009 to work on a Ph.D. in Analytical Chemistry.

Frank Davis is a researcher within Cranfield Health, located at Cranfield University, UK. He initially graduated and gained a Ph.D. from Lancaster University, which was then followed by research positions at Manchester University, Sheffield University, and Gillette UKRDL. Dr. Davis has worked on biosensors based on enzymes and antibodies at Cranfield since 2002 and is co-author of over 90 publications.

Ned Djilali obtained B.S. and M.S. degrees in Aeronautics from Hertfordshire University and Imperial College. After completing a Ph.D. in Mechanical Engineering at the University of British Columbia, he first worked with the Advanced Aerodynamics Department of Bombardier (Canadair Aerospace Division) and then joined the University of Victoria. Dr. Djilali is a Professor in the Department of Mechanical Engineering, an active member of the Institute for Integrated Energy Systems (IESVic), and a Canada Research Chair in Energy Systems Design and Computational Modelling.

Marguerite Germain is a Ph.D. candidate in the Department of Chemistry at Saint Louis University. She started her collegiate career at Rockhurst University where she graduated with a B.A. in French. She is currently studying poly(methylene green) and developing a self-powered explosive biosensor that uses mitochondria as catalysts and pyruvate as fuel.

Séamus P. J. Higson holds a chair in Bio- and Electro-analysis and is currently Dean of the Faculty of Medicine and Biosciences at Cranfield University in the United Kingdom. Professor Higson also is author of a major Oxford University Press textbook, *Analytical Biotechnology,* and acts as Research Director of Microarray Ltd., a University spin-off company based on research from his laboratory.

Erik Kjeang, originally from Sweden, completed his Ph.D. in Mechanical Engineering at the University of Victoria, British Columbia, Canada, in 2007. His

research demonstrated several unique microfluidic fuel cell architectures resulting in practical miniature devices with high performance and high efficiency, and was awarded with the Governor General's Gold Medal for Outstanding Dissertation. Since then, Dr. Kjeang has worked as a research engineer at Ballard Power Systems, Inc., and is presently an Assistant Professor at Simon Fraser University in Mechatronic Systems Engineering.

Tamara Klotzbach received her B.S. in Chemistry from Saint Louis University in spring of 2007. She is currently attending the Ohio State University where she is working toward a Ph.D. in Inorganic Chemistry under the direction of Professor Malcolm Chisholm. Her work focuses on using calcium catalysts for the ring opening polymerization of cyclic esters for the development of biodegradable polymers.

Paul A. Kohl is Regents' Professor and Hercules Inc./Thomas L. Gossage Chair in Chemical and Biomolecular Engineering at Georgia Institute of Technology. He received a Ph.D. in Chemistry at the University of Texas at Austin and was previously employed at AT&T Bell Laboratories. His research interests include electrochemistry and electronic materials.

Shelley D. Minteer received her Ph.D. in Analytical Chemistry from the University of Iowa in 2000 after receiving her B.S. in Chemistry at Western Illinois University in 1995. After getting her Ph.D., she took a position as an Assistant Professor of Chemistry at Saint Louis University in the fall of 2000. She was promoted to Associate Professor in 2005 and to Full Professor in 2008. Her research interests are in the area of enzymatic biofuel cells.

Michael J. Moehlenbrock was born in the United States in 1982. He received his M.S. in Chemistry from Saint Louis University in 2007. In 2007, he also began his pursuit of his Ph.D. in Chemistry under the supervision of Dr. Shelley D. Minteer. His current research efforts are focused on the miniaturization of immobilized enzymatic biofuel cells and biosensors and the examination of substrate channeling in metabolic complexes for use in biofuel cells.

William E. Mustain is currently an Assistant Professor of Chemical Engineering at the University of Connecticut in the Department of Chemical, Materials and Biomolecular Engineering. Dr. Mustain received his Ph.D. from the Illinois Institute of Technology in 2006. He then spent two years as a Postdoctoral Fellow at Georgia Institute of Technology. His areas of expertise are electrochemical engineering and electrocatalysis.

Tristan Pichonat was born in Migennes, France, in 1975. He received the M.S. in Image Processing and Medical Scanning in 1998 from the University of Dijon, Burgundy, and the M.S. in Optics, Laser, and Signal Processing from the University of Rouen in 1999. After working on micro accelerometers at the LPMO-CNRS in Besançon, he received a Ph.D. in Engineering Sciences in 2004 working on micro fuel cells. He then moved on to a post-doctorate position, working on micro resonators at the IEMN-CNRS, in Villeneuve d'Ascq. He currently works as a research engineer IEMN, in Villeneuve d'Ascq, on micro power sources for autonomous networks nodes supply.

Shruti Prakash was born in Patna, India. She did her B.S. in Chemical Engineering from University of Wisconsin, Madison. She received her Ph.D. in Chemical Engineering from Georgia Institute of Technology, Atlanta. She is currently employed by the Lawrence Berkeley National Laboratory in Berkeley, California.

David Sinton obtained his Ph.D. from the University of Toronto, focusing on microscale flow visualization in 2003. He is currently an Associate Professor in Mechanical Engineering at the University of Victoria, and member of the Institute for Integrated Energy Systems, University of Victoria (IESVic). Dr. Sinton leads an award- winning research program focused on the study and application of microfluidics and nanofluidics for biomedical and energy applications.

Daria Sokic-Lazic was born in Tuzla, Bosnia and Herzegovina, in 1980. She received her M.S. in Chemistry from Saint Louis University in 2008. In 2008, she also began her pursuit of Ph.D. in Chemistry under the supervision of Dr. Shelley D. Minteer. Her current research efforts are focused on enzymatic biomimics of metabolic pathways for use in biofuel cells.

Toshio Suzuki is a research scientist in the National Institute of Advanced Industrial Science and Technology (AIST), Nagoya, Japan, working on the development of micro tubular SOFCs. Before joining AIST, he worked as an Assistant Research Professor at the University of Missouri-Rolla, on single chamber SOFCs and low temperature (under 1000°C) ceramic processing for SOFC components (electrolyte and electrodes). He earned his M.S. in Applied Physics at Tohoku University, Sendai, Japan, and his Ph.D. in Ceramic Engineering at the University of Missouri-Rolla.

Becky L. Treu is a native Missourian who earned her Ph.D. in integrated and Applied Sciences with an emphasis in Chemistry from Saint Louis University in 2008. Her field of expertise is bioelectrochemistry, namely the isolation and purification of PQQ-dependent dehydrogenates for biofuel cell applications. From this research she has generated numerous publications and patents. She currently holds a position as a postdoctoral fellow at Missouri University of Science and Technology in the Graduate Center for Materials Research, researching environmentally friendly rare earth-based coating systems for aerospace applications.

Janice Wildrick finished her B.A. in Chemistry at University of Missouri-St. Louis after working in the legal and computer industries for 15 years. She joined Dr. Shelley Minteer's research group at St. Louis University in 2007 to contribute to the most compelling issue of our time-renewable energy. Ms. Wildrick's research focuses on the development and optimization of an air-breathing cathode.

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（邵志刚 译）

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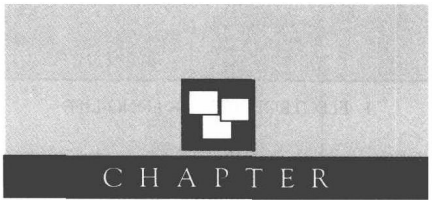

CHAPTER

1

Electrolytes for Long-Life, Ultra Low-Power Direct Methanol Fuel Cells

Shruti Prakash, William E. Mustain, and Paul A. Kohl

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