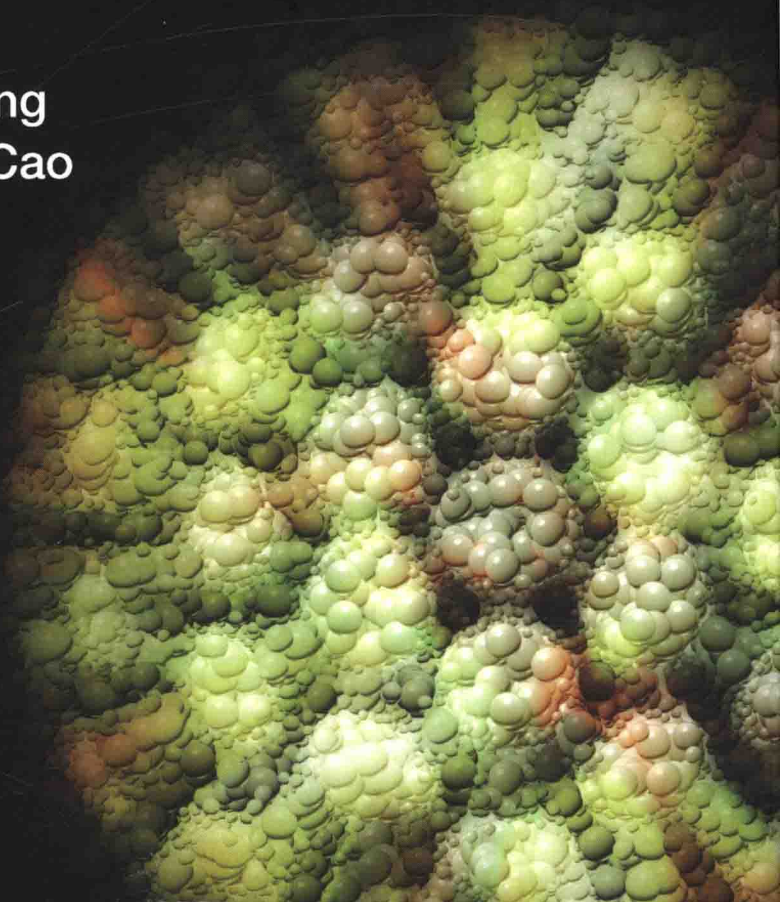
Nanomaterials for Energy Conversion and Storage



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Editors

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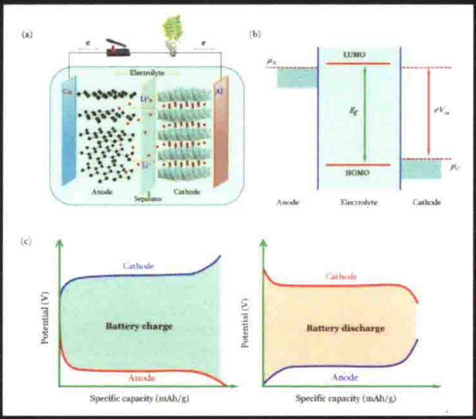

Nanomaterials for Energy Conversion and Storage

The use of nanomaterials in energy conversion and storage represents an opportunity to improve the performance, density and ease of transportation in renewable resources. This book looks at the most recent research on the topic, with particular focus on artificial photosynthesis and lithium-ion batteries as the most promising technologies to date. Research on the broad subject of energy conversion and storage calls for expertise from a wide range of backgrounds, from the most fundamental perspectives of the key catalytic processes at the molecular level to device scale engineering and optimization. Although the nature of the processes dictates that electrochemistry is a primary characterization tool, due attention is given to advanced techniques such as synchrotron studies *in operando*. These studies look at the gap between the performance of current technology and what is needed for the future, for example how to improve on the lithium-ion battery and to go beyond its capabilities.

Suitable for students and practitioners in the chemical, electrochemical, and environmental sciences, *Nanomaterials for Energy Conversion and Storage* provides the information needed to find scalable, economically viable and safe solutions for sustainable energy.

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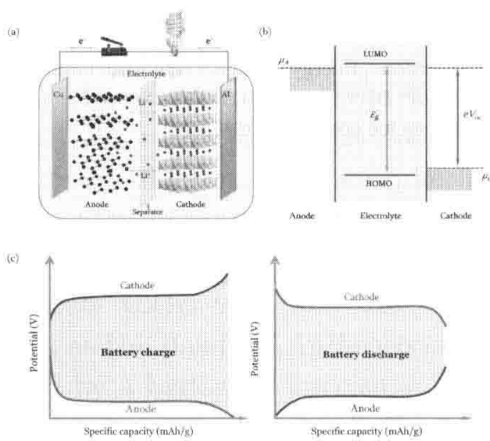

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PREFACE

Human beings, as a single species, consume 40% of plants grown in any given year. Our activities contribute close to 40 gigatons (10^9 tons) of CO_2 and over 160 tons of atmospheric SO_2 every year, impacting more than 60% of land surfaces and 40% of marine environments. Our impact to the environment has been so significant that recently geologists voted to define the post-war boom of the late 1940s and 1950s as the dawn of *Anthropocene*,[a] a new geological era primarily shaped by a biological species, a first in the 4.5 billion years of history of this lone planet. At the heart of the impacts by human activities is the brilliant way we have developed in consuming energy, chiefly supplied by high energy-density media of fossil fuels. The entire worldwide energy infrastructure is based on the premise that fossil fuels are endless, they are nearly free and, most important of all, using it has few consequences. The formal recognition of *Anthropocene* presents an imperative challenge to the scientific community: What is the best way to preserve the convenience offered by civilization while minimizing our footprints within the biosphere?

It dawns upon us that the key may lie in the replacement of fossil fuels from our energy infrastructure. Further examination of the existing energy schemes provides more insights. First, it is important to preserve several key benefits inherent to fossil fuels, including high

[a] *Science* **2016**, *353*, 852.

energy density, ease of transportation, and convenience in energy release. From the perspective of high energy density, we see that storing energy in chemical bonds makes good sense. Furthermore, recognizing that the ultimate source of fossil fuel energy actually comes from the Sun, we can easily conclude that direct energy conversion from light to chemical potentials will play a critical role in a renewables-powered future. It is within this context that we compiled a collection of nine chapters on the topic of artificial photosynthesis. The promises and challenges associated with the idea of direct solar-to-chemical energy conversion are detailed by authors who have made significant progresses. Notwithstanding, as we will see from writings by these top researchers, there is still a long way to go before the idea can be developed into an economically competitive technology. For instance, the sluggish kinetics inherent to the breaking and formation of chemical bonds sets an upper limit on the round-trip efficiencies one can achieve in terms of energy storage. Take hydrogen as an example. A minimum of 400 mV overpotential is needed to achieve a meaningful current density during water splitting that produces hydrogen. Conversely, the reverse process of burning hydrogen in a fuel cell requires a minimum of 200 to 300 mV overpotential, as well. Knowing that the equilibrium potential of water splitting is 1.2 V, we obtain an upper limit of the overall round-trip efficiency not much higher than 50% (i.e., $(1.2 - 0.3\ \text{V})/(1.2 + 0.4\ \text{V}) = 56\%$). These considerations lead us to the second important insight.

For high round-trip efficiencies, to adapt to a diverse renewable supply scheme, and to support an increasingly electrified society, the demand for batteries has never been greater than today. As far as energy and power densities are concerned, Li-ion battery represents the state-of-the-art, which has become the key component of the coolest gadgets and cars we see today and in the foreseeable future. Yet, we all know too well how disappointed we are by the gap between what the best batteries can offer and what we hope they should be able to do. Within this context, we compiled a collection of five chapters to share the principles that govern the state-of-the-art batteries and what we can do to break the barriers and go beyond the Li-ion technology.

While the topics of this book are diverse and cover a wide spectrum, there share an important commonality. The length scales of the key materials all fall in the nanometer range. It is so for a good reason, because most charge behaviors critical to energy conversion and storage feature relevant characteristic lengths. With this consideration in mind, we highlight the contents of this book with the keyword "nanomaterials" in the title. As manifested by the diverse affiliations and trainings of the authors, research on the broad subject of energy conversion and storage calls for expertise from a wide range of backgrounds, from the most fundamental perspectives of the key catalytic processes at the molecular level to device scale engineering and optimization. Although the nature of the processes (electrochemical) dictate that electrochemistry is a primary characterization tool, due attention is given by our authors to advanced techniques such as synchrotron studies in *operando*. We expect that this book will catalyze new, innovative approaches to the various challenges the field faces, leading to concerted efforts by the broad community to the eventual realization of a renewables-powered future.

Prof. Guozhong Cao, University of Washington
Prof. Dunwei Wang, Boston College

ABOUT THE EDITORS

Dr. Guozhong Cao is Boeing-Steiner Professor of Materials Science and Engineering, Professor of Chemical Engineering, and Adjunct Professor of Mechanical Engineering at the University of Washington, Seattle, Washington. He received his B.S. degree from East China University of Science and Technology, M.S. from Shanghai Institute of Ceramics, Chinese Academy of Sciences, and Ph.D. from Eindhoven University of Technology, the Netherlands.

Dr. Cao has published over 580 technical papers with over 420 SCI papers including over 30 comprehensive review papers, and authored and edited eight books, book conference proceedings and contributed 29 book chapters, and received 16 US patents. He is one of the Thomson Reuters Highly Cited Researchers with a total citation of over 23,000 and an h-index of 74. His book *Nanostructures and Nanomaterials: Synthesis, Properties and Applications* has been used as a textbook or a reference book in many universities worldwide and also been translated and published in Russian and Chinese.

Dr. Dunwei Wang graduated from the University of Science and Technology of China in 2000 with a B.S. degree in Chemistry. He was then trained at Stanford University (with Hongjie Dai) between 2000 and 2005, where his Ph.D. thesis was awarded the Prize for Young Chemists by the *International Union of Pure and Applied Chemistry* (2006). After two years of post-doctoral study with James R. Heath at Caltech, he joined the faculty of Boston College where he is currently an Associate Professor of Chemistry. His research concerns the development of new materials that can be used for efficient solar energy conversion and storage. He is a recipient of an NSF CAREER award (2011), a Sloan Research Fellowship (2012), a Massachusetts Clean Energy Center (MassCEC) Catalyst award (2011), and a Japan Society for Promotion of Science Fellowship (2016). He has published close to 100 peer-reviewed journal papers that have been collectively cited over 12,000 times with an h-index of 44.

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