RSC Nanoscience & Nanotechnology

Hierarchical Nanostructures for Energy Devices

Edited by Seung Hwan Ko and Costas P. Grigoropoulos

ROYAL SOCIETY OF CHEMISTRY

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Preface

Energy has been the major global issue in our society. Since the Fukushima nuclear disaster in 2011, future renewable energy development has been viewed through the safety prism. Non-nuclear-based, safe and sustainable energy sources have therefore attracted tremendous attention.

Research studies on energy devices have traditionally focused on the development of new materials for components such as anodes, cathodes, dyes, electrolytes and catalysts. However, in the last decade, new material development has been sluggish as it is admittedly very hard to overcome constraints posed by the materials' intrinsic structure. Therefore, researchers have been seeking new ground-breaking approaches by smart design/structuring of known materials through three-dimensional (3D) multi-scale hierarchical nano-architectures comprised of nanoscale building blocks. Recently, research in 3D branched hierarchical nanowire structures has been booming among researchers in various energy device fields, including energy conversion, storage and consumption. 3D branched hierarchical nanowire structures that possess a high surface area and offer direct transport pathways for charge carriers are especially attractive for energy applications. More specifically, 3D branched hierarchical nanowires improve light absorption due to the increased optical path as well as additional light trapping through reduced reflection and multiple scattering in comparison to 1D nanowire arrays, which are beneficial for solar energy harvesting applications. The high surface area can also increase surface activity and electrolyte infiltration in energy storage devices. The direct charge carrier transport pathway in both the trunks and branches boosts the charge collection efficiency. These fascinating properties of branched hierarchical nanowire structures have indeed many ideal characteristics for energy devices.

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This book will focus on the recent developments in hierarchical nanostructuring, especially for highly efficient energy device applications. Hierarchical nanostructures usually entail a combination of multi-scale, multi-dimensional nanostructures such as nanowires, nanoparticles, nanosheets and nanopores. Because of the ability to tailor the architecture, synergistically combine functionalities and thereby specifically tune the transport properties, hierarchical nanostructures are expected to overcome the limitations of single scale nanostructures for achieving enhanced performance. Surface characteristics are of primary concern in most energy devices where maximizing efficiency can be achieved by either new material development or functional structuring. In this respect, hierarchical functional nanostructuring is particularly effective for achieving a surface area increase and favourable electrical properties. The energy devices covered in this book are: (1) energy generation devices (solar cells [DSSCs, OPVs]), fuel cells, piezoelectric, thermoelectric, water splitting *etc.*, (2) energy storage devices (secondary batteries, super capacitors *etc.*), (3) energy efficient electronics (displays, sensors, *etc.*). The hierarchical nanostructuring routes include construction of highly porous metal–organic frameworks, nanoparticle assembly with defined pore size, and synthesis of multiple generation highly branched nanowire trees.

Hierarchical nanostructure research has a bright future in solving the current limitations of energy devices. The ultimate goal is to push energy devices towards practical applications, which requires the development of devices with high efficiency, low cost and long lifespan. We hope this book will provide an account of the state-of-the-art research trends and a perspective on hierarchical nanostructures for energy device applications.

This book would not be possible without the commitment, effort and enthusiasm of all the contributing authors whom we sincerely thank. Our gratitude is extended to the Royal Society of Chemistry (RSC) for giving us a chance to embark on this great adventure and its high standard of support in preparing the book. In particular, we would like to acknowledge the administrative help from Mrs Alice Toby-Brant and Dr Merlin Fox. Finally, Dr Ko wants to thank his family (his wife Hyun Jung Kim and his new born son Suh June Ko) for their warm support and understanding.

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Contents

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CHAPTER 1

Introduction: Hierarchical Nanostructures for Energy Devices

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1.1 Introduction

Energy has been the hottest social issue for a long time. Energy issues have been related to the problems associated with current major energy sources such as fossil and mineral energy sources: (1) their inevitable exhaustion in the near future,[1] (2) environmental problems such as global warming due to a commensurate increase in CO_2 (a prominent greenhouse gas) emissions,[2] (3) an energy shortage due to a recent dramatic increase in global energy consumption[2] (between 2004 and 2030, the annual global consumption of energy is estimated to rise by more than 50%) and thus a price increase. Renewable energy sources, such as hydroelectric, solar, wind, hydrothermal, biomass and nuclear power, are expected to solve the problems associated with fossil fuels. However, energy issues are becoming more serious global problems in the aftermath of the Fukushima catastrophe.

Despite the projected persistent increases in oil and gas prices, less than 10% of the global energy production in 2030 is predicted to come from renewable energy sources. In order to moderate global reliance on

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exhaustible natural resources and their environmentally hazardous combustion, more scientific efforts should be directed toward reducing the cost of energy production from renewable sources.[2]

Developing sustainable renewable energy sources has been a major research topic in an effort to solve the environmental problems caused by fossil fuels. Significant progress has been made in increasing the efficiency of various renewable energy technologies including solar cells, fuel cells, nuclear energy, wind power and so on.[3] Since the nuclear power plant disasters at Japan and Ukraine, the safety issue has become the most important factor.

1.2 Energy Cycle

Energy devices do not mean only energy generation devices but also include energy storage and energy consumption devices. To fully understand efficient energy usage and to increase the efficiency, the term *Energy Cycle* should be understood. *Energy Cycle* is the complete life of energy from birth to death: energy generation, energy storage and energy consumption (Figure 1.1). Efficiency is a major concern in energy devices and the total efficiency of energy devices is limited by the one with lowest efficiency (just like a chemical reaction rate is dominated by the slowest process). Even though one may develop an extremely efficient energy generation device, if the generated energy is stored in a poor efficiency energy storage device or used for a poor efficiency energy consumption device, the efficiency will be low from the total energy cycle viewpoint. Therefore, to approach the energy

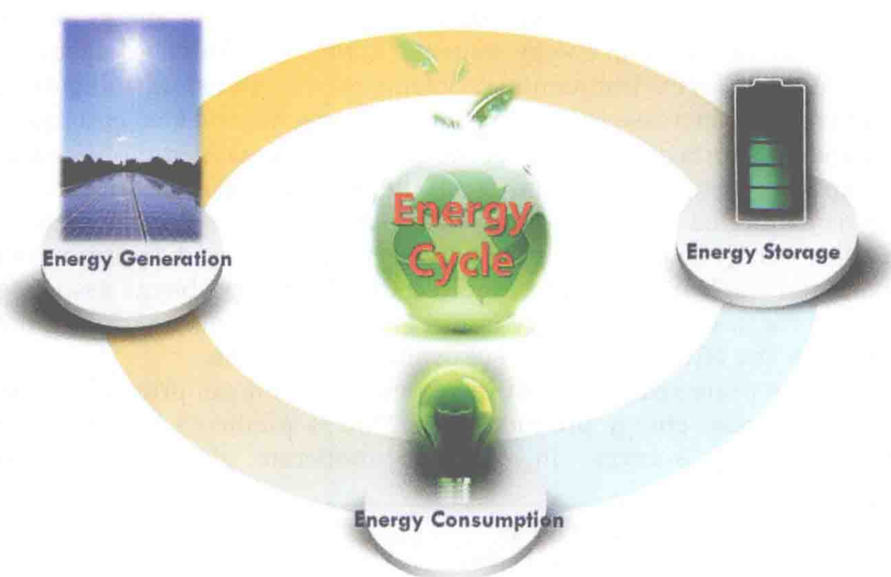

Figure 1.1 The *Energy Cycle* is the complete life cycle of energy from birth to death: energy generation, energy storage and energy consumption.