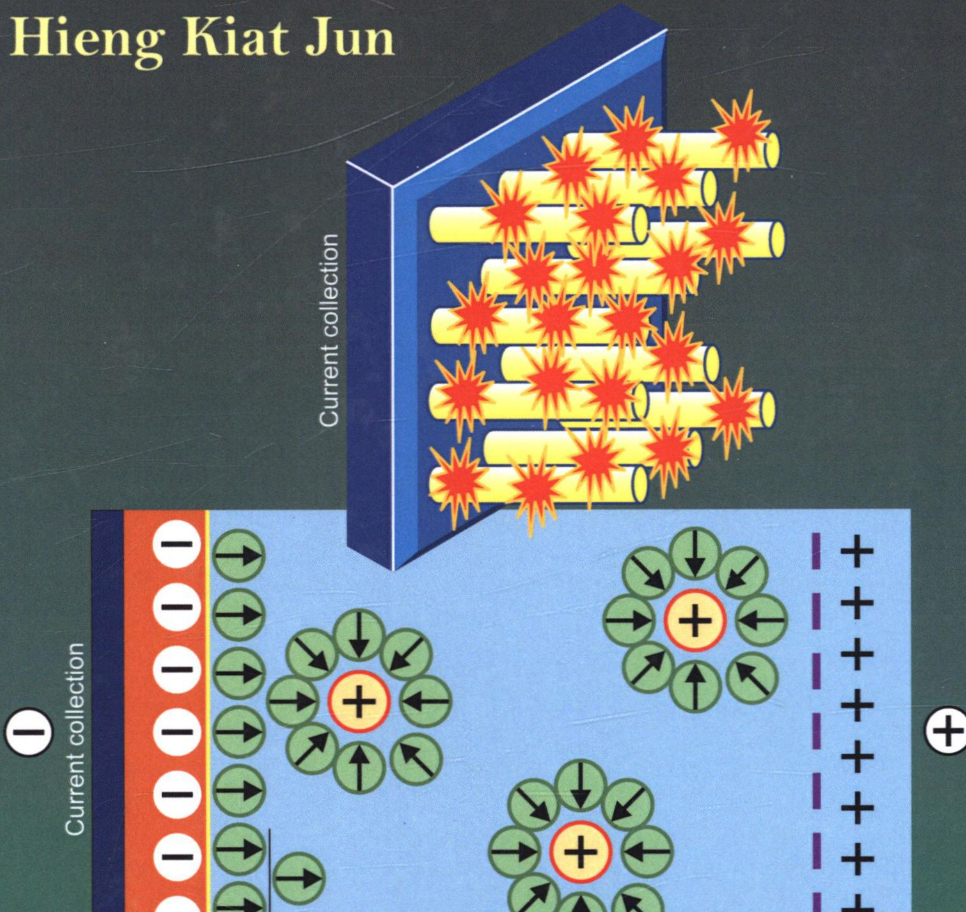
Nanomaterials in Energy Devices

Energy Storage Derivatives and Emerging Solar Cells

Editor

Hieng Kiat Jun



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This book provides up-to-date information on the application of nano-sized materials in energy devices. A brief overview on the properties of nano-sized materials introduces the readers to the basics of the application of such materials in energy devices. Among the energy devices covered are third generation solar cells, batteries, and supercapacitors. The book places emphasis on the optical, electrical, morphological, and spectroscopic properties of the materials. It contains both experimental as well as theoretical aspects of different types of nano-sized materials (nanoparticles, nanowires, thin film, etc.).

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Preface

We live in a technological era. Without doubt, our lives are bound up with computer science, telecommunication, manufacturing and energy, whether directly or indirectly. The energy field is one of the most discussed and researched area nowadays. When nanotechnology and nanoscience are applied in the field of energy, we have a very promising and high potential for application in a wide range of energy devices. Such potential is seen in production or conversion and storage of energy by utilizing the fundamental of nanotechnology.

This book is intended to bring forth some important developments in the research of nanoscaled materials for the application in energy devices. It aims to summarize the fundamentals and novel techniques of nanoscale materials applied in energy devices. Since the field is developing and accelerating at a fast pace, it is impossible for this book to cover all types of energy devices (production or storage); and it is not the intention of the editors to cram everything into a single volume as well.

In this volume, the central theme is energy storage and conversion. This narrows down to the application of batteries and their derivatives as well as light-to-electric conversion devices. Each chapter presents not just different applications but also different methods of fabrication as well as the material's characteristics. All the chapters are a unique combination of these approaches. This is because each application itself can have a diverse fabrication method and nanomaterials used. Nevertheless, the focus is on the application of nanoscale materials which are responsible for the process and functionality of the energy devices. More importantly, all the chapters are contributed by prominent researchers from academia.

It is hoped that this book will serve as a general introduction to anyone who is just entering the field of energy devices utilizing nanoscaled materials. It is also for experts who are seeking up-to-date information in this field. This book is not a handbook or a comprehensive review of a particular subject. In brief, Chapter 1, which is an introduction, gives an overview of the field of nanomaterials in energy devices. The following chapter focuses on the application of biopolymer materials as solid electrolytes in dye-sensitized solar cell. Chapter 3 gives a short review on the current status of nanomaterials in lithium ion batteries while the subsequent chapter brings us the specific application in electric double layer capacitors. Chapter 5 introduces the various nanomaterials used in emerging solar cells. This is followed by the introduction of metal-organic frameworks for the application of hydrogen storage. Finally, the last chapter delves into general application of nanomaterials in electrochemical capacitors.

The editor would like to express his sincere gratitude to all the contributors of this book, whose excellent support resulted in the successful realization of this collaboration. Their passion and support in sharing of knowledge are commendable. The editor would also like to thank the publisher, Science Publishers, an imprint of CRC Press, for recognizing the demand for such niche theme for the book.

August 2017 **Hieng Kiat Jun**

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1

Introduction to Nanomaterials in Energy Devices

Hieng Kiat Jun

1. A Brief Introduction to Current Scenario

According to the report released by the World Energy Council, global energy demand will increase from year to year. In fact, the demand for energy will double by the year 2060. However, the primary energy demand will peak until year 2030. This primary energy source includes energy derived from coal, oil and gas. The slow growth of the primary energy is forecast due to the disruptive trends of the emerging energy sources. Coupled with environmental concern like global warming, the adoption of emerging energy sources is beginning to encroach into the dominance of the primary energy source. Generally, these emerging energy sources are referred to as alternative energy resources which are not derived from fuel and coal. Some examples of such alternative energy sources include (but not limited to) solar energy, hydro energy and wind energy. The ultimate purpose of the energy demand is to be able to power up various equipments, be it portable or stationary, in order to achieve certain tasks. Therefore, it is the goal of each inventor and researcher to design an efficient energy device where maximum useful energy can be extracted.

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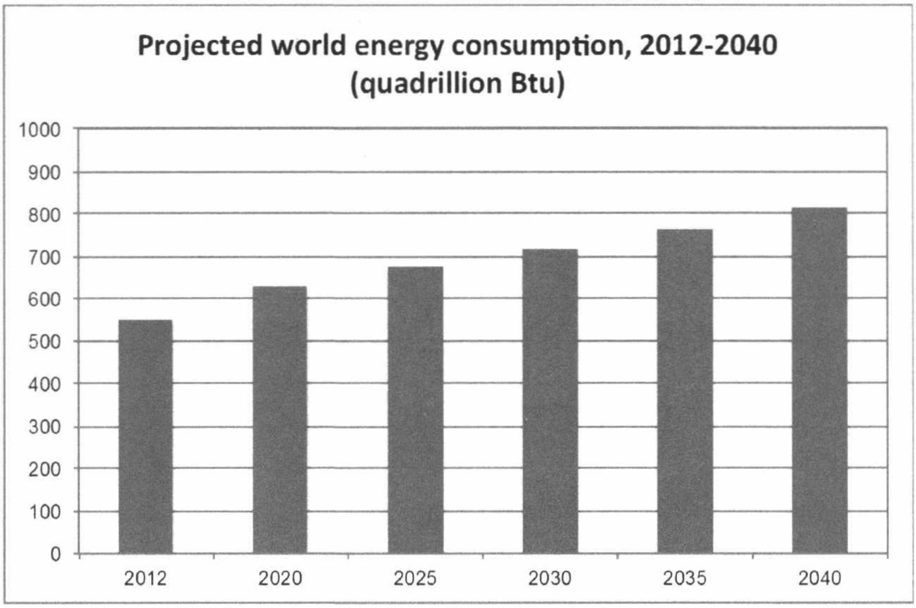

Figure 1. Projected world energy consumption (source: EIA, International Energy Outlook 2016).

2. Energy Devices

The ability of a system to produce useful energy is tantamount to an efficient energy converter system. Such energy converter system usually produces ready-to-use energy. Energy can be in various forms such as chemical energy, thermal energy, kinetic energy and electric energy. These types of energies are useful for performing work. In some cases, there will be surplus energy. In such an event, we may need to store the energy for future use. The system that allows us to convert, produce and store a specific energy type is termed as an energy device. Generally, the energy device will be connected externally for the supply of electric energy. In a reverse process, external circuit maybe connected to the device as well for converting and storing the energy into the device.

Due to a rising need for low cost, reliable and accessible energy, low-priced and efficient energy devices are the key for the mass adoption. Such avenues could reduce our dependency on fossil fuels (i.e., coal, petroleum and natural gas). It could also transform the current way of production, delivery and utilization of energy. In the long run, it will bring benefits to the environment due to low or near zero green house gases emission. Therefore, the development of new or improved energy devices plays an important role for the energy revolution.

A desirable energy system should be able to convert a raw energy source into useful energy. For example, a solar cell is used to convert

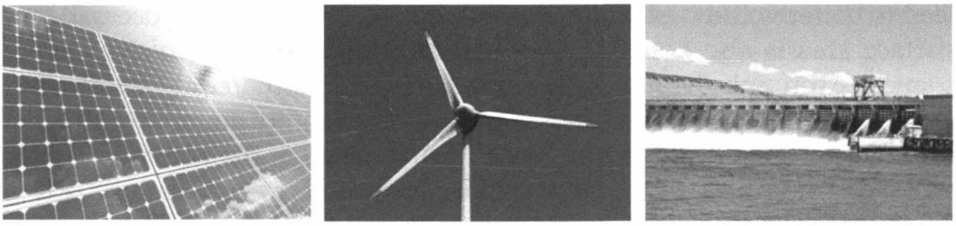

Figure 2. Types of energy devices used to convert and supply energy. From left to right: solar panel, wind turbine and hydro dam.

sunlight into electric energy. Generally, the working mechanism of an energy device is based on fundamental physical principles. From the definition of thermodynamics, energy cannot be created or destroyed in a system. It can only be converted from one form to another form. The law also states that the flow within the system is unidirectional until the achievement of equilibrium at the final state. These approaches are applied in every energy device system.

The requirement for large effective area of an energy device prompts the researchers to look for a system that is cost effective yet efficient. This is particularly important when portable energy device is in demand. One of the methods is to scale down the size of the active layer in the energy device where it is responsible for energy production and conversion processes. Such technique involves the application of nanotechnology.

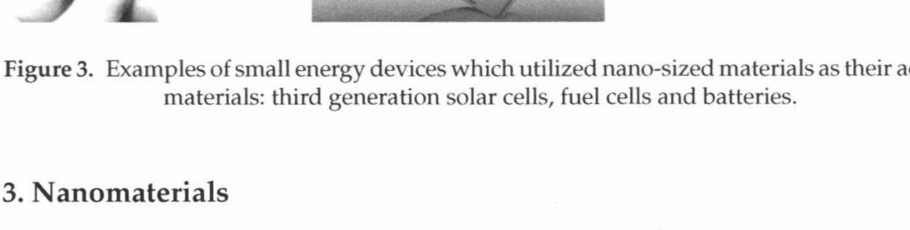

Figure 3. Examples of small energy devices which utilized nano-sized materials as their active materials: third generation solar cells, fuel cells and batteries.

3. Nanomaterials

Nanotechnology is a general term used to define the technology of design, fabrication and application of nano-sized materials (also known as nanomaterials). Typically, nanomaterials involve the manipulation of the materials properties at extremely small scale, ranging from 1–100 nm. As the size of the materials reduced, the surface area is increased which could lead to better volume exchange for the chemical reaction or process. Large surface area is also beneficial for creating effective pathway for charge transport through the interfaces. When nano-sized materials are applied into energy devices, especially for devices that require energy conversion through porous membrane or layer, the nano-size of the active materials will have an impact on the performance of the energy conversion. This is evidenced from the varying performance result in nanostructured solar cell (Jun et al. 2014). For instance, in dye-sensitized solar cell, the porosity of the titania on the working electrode is crucial for the penetration and the attachment of dye molecules onto the titania. The porosity in this case can be manipulated by reducing the particle size of the titania (Fig. 4).

In another example of semiconductor quantum dot-sensitized solar cell, the size of the semiconductor quantum dot will determine the band gap energy of the semiconductor itself due to quantum confinement effect (Jun et al. 2013). This will indirectly influence the light absorption range of the semiconductor materials as well. Thus, solar cells which have different sizes of semiconductor quantum dots will produce different range of performance. Apart from altering the particle size, the surface properties of the particles can be engineered where different functional groups could be attached onto the particles. The addition of functional groups could elevate or improve the physico-chemical properties of the materials. Essentially, the overall performance of that energy device will change.

The effect of the nano-size materials can be demonstrated from the following example where different commercial brands of titania were used to prepare the same type of dye-sensitized solar cell (DSSC). DSSC is an emerging solar cell technology where molecular structure of dye is used as light harvester. During the dye attachment process, the dye molecules will penetrate the porous titania and attach onto the titania particles. The challenge in this device structure is to have a good level of porosity to enable

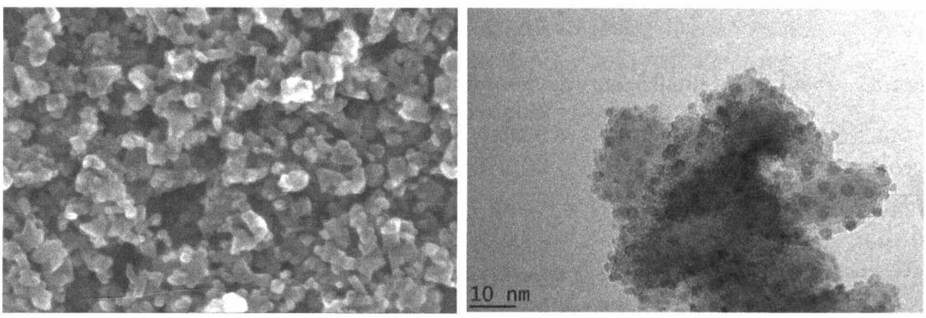

Figure 4. Left: FESEM image of titania structure at 200 k magnification. Right: The same titania structure as viewed from TEM. The "dots" attached on the titania particles are quantum dot semiconductor.

large amount of dye molecules attached onto the titania structure. Different commercial brands of titania exhibited different average titania particle size and its porosity level (Fig. 5). Thus, when all the titania electrodes are further processed for dye attachment under the same condition, it was assumed that the same amount of dye molecules would be attached on the titania surface. However, upon verification of the assembled DSSC, all the samples had different cell performance (Fig. 6 and Table 1). Such difference

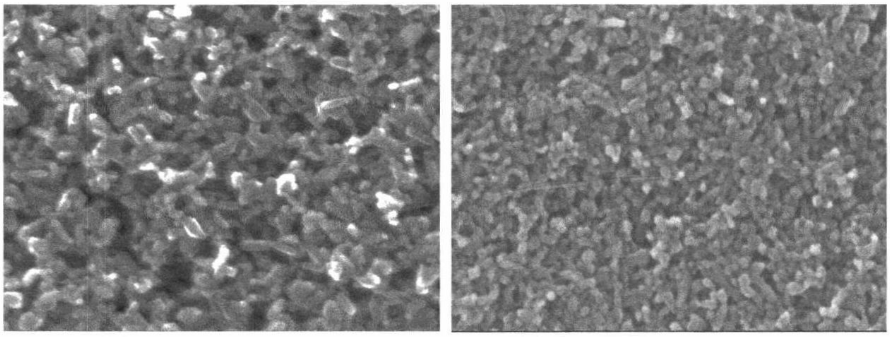

Figure 5. FESEM images (200 k magnification) of titania structure of two different commercial brands.

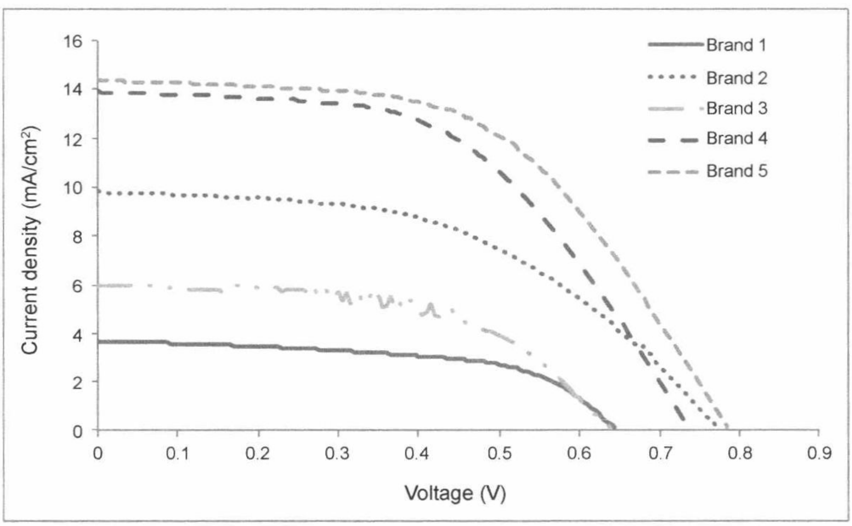

Figure 6. Current density vs. potential for dye-sensitized solar cells with various brands of titania used.

Table 1. Efficiency of dye-sensitized solar cells with various brands of titania used.

	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5
Efficiency (%)	1.4	3.7	2.0	5.4	6.1

in terms of cell performance could be attributed to distinct nanostructure properties of the titania used.

In this book, five chapters are dedicated to the application of nanomaterials in different types of energy devices. It is not the intention of this book to cover every type of energy devices but rather on the selected few based on the impact in recent years. The content of this book is mainly focused on energy conversion devices such as third generation solar cells, lithium ion batteries, and electric double layer capacitors. One chapter is dedicated to fuel storage. In this case, hydrogen fuel is referred. All the devices discussed in the following chapters utilized the intrinsic properties of the nanomaterials. In most cases, polymer materials have a substantial role in energy devices as they can be applied as electrolyte and electrode materials due to their versatility and ease of manipulating the properties *via* alteration of the nanostructure. The engineering of polymer electrolyte promotes the performance enhancement of the related energy devices.

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