RSC Smart Materials

Semiconductor Nanowires

From Next-Generation Electronics to Sustainable Energy

Edited by Wei Lu and Jie Xiang

ROYAL SOCIETY OF CHEMISTRY

Semiconductor Nanowires:
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Preface

The history of semiconductor wire or whisker growth dates back to the 1960s. The term nanowire, however, was first introduced in the late 1990s when semiconductor wires with diameters down to the 10 nm scale were successfully synthesized on a large scale. Interest in this fascinating material has truly taken off ever since then. The science and technology of semiconductor nanowires have been at the forefront of nanomaterial and nanodevice research and have been advancing at an amazing pace. During the past decade, we have witnessed an explosion of nanowire research in areas from the development of new material synthesis techniques, understanding of growth mechanism, engineering of heterostructure nanowire design to the exploration of fundamentally new electrical, optical and mechanical properties offered by these substantially defect-free, one-dimensional nanostructures. More importantly, exciting applications of nanowires in the field of electronics, optoelectronics, energy generation and storage have now emerged and are poised to enter the commercial market and change people's everyday lives in the near future. The goal of this book is to present a summary of these latest developments in this important field as well as an outlook as to what might be in store in the next decade based on these exciting developments.

This book contains nine chapters, covering topics from nanowire growth and integration, to high performance electronic devices (transistors and memory), biosensors, optoelectronic devices and energy devices such as photovoltaics, mechanical nanogenerators, thermoelectric harvesters and lithium-ion batteries. The book can serve as a reference book for experts and graduate student researchers aspiring to work in related fields, as well as industry watchers interested in learning how nanotechnology is transforming electronics and energy devices. It may also serve as a textbook for senior undergraduate and graduate students in materials science and

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engineering, chemistry or electrical engineering, taught chapter by chapter; or as an introduction or reference book to a class on electronic materials, by selecting an according subset of the chapters as the chapters are relatively self-contained.

The chapters are written by experts in the field of nanotechnology and, in particular, recognized leaders in semiconductor nanowire research. We would particularly like to thank Professors Charles Lieber, Peidong Yang and Zhong Lin Wang, who are pioneers of this field, for their valuable contributions despite their busy schedules, and also thank Professors Yi Cui, Song Jin, Ritesh Agarwal, Bozhi Tian and Renkun Chen, who have become major players in nanowire research, for their contributions. We wish also to thank L. Chen and Dr Y. Yang for their help in editing the book.

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CHAPTER 1

Semiconductor Nanowire Growth and Integration

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1.1 Introduction

To date, numerous studies have been carried out to explore nanowires as new building blocks in electronics,[1–11] photonics,[12–24] solar-cells,[25–29] batteries,[30–34] nanogenerators,[35,36] and biological/chemical sensors.[37–44] Commonly cited properties of nanowires in these studies that can be advantageous are the small diameters, large surface area and smooth surfaces of the nanowire materials. For example, the large surface area and small diameters enabled nanowire electrodes to outperform thin-film electrodes in battery applications in terms of rate of charging/discharging and stability (*e.g.*, small diameters can better sustain strain without cracking), while the nearly-perfect material quality has enabled optical and electrical pumped nanowire lasers. Controlled nanowire growth has also enabled biosensors with integrated detectors and electrodes,[38,39,43] all achieved in a single nanowire during growth. Another aspect that sets the "bottom-up" nanowire system apart is the ability to obtain high quality nanowire heterostructures during

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growth, including core/shell radial heterostructures and superlattice axial heterostructures. Such heterostructures are extremely difficult if not impossible to obtain using conventional fabrication methods, while the small size and volumetric similarity of nanowire structures can produce coherently strained heterostructures free from interfacial dislocations even for materials with relatively large lattice mismatch (*e.g.*, Ge and Si). This ability to grow high-quality heterostructures has in turn led to the demonstration of several high-performance electrical and photonic devices that have only been demonstrated in the nanowire form.

This chapter will review fundamental growth topics for semiconductor nanowires, particularly focusing on the nanocluster-mediated VLS growth mechanism that has been widely employed and proven to be extremely flexible. The general concept of VLS growth will be introduced, followed by discussions of how the basic growth mode can be expanded to realize more complex and functional nanowire structures, such as radial and axial heterojunctions, as well as dopant incorporation. Factors affecting the growth dynamics and growth models will then be presented, followed by discussions of recent advances in increasing structural complexity, for example, through controlled formation of merged nanowires and kinks.

1.2 Basics of Nanocluster-Mediated VLS Nanowire Growth

Interest in nanowires was largely driven by the successful growths of 10 nm scale nanowires using the VLS method in the late 1990s.[45] The history of VLS growth can be traced back to the 1960s by Wagner,[46] who successfully employed this method to grow silicon microwires (whiskers). Whisker research remained a productive field; however, the relatively large size (>0.1 μm in diameter) of the whiskers produced in these early days offer few real practical advantages compared with fabricated structures. In fact, nanometer scale nanowires were not thought to be possible until the experimental demonstrations in 1998 by Morales *et al.*[45] The early demonstrations employed laser ablation to generate the source vapor needed for VLS growth to obtain single-crystalline Si and Ge nanowires. Soon the process was expanded to more controllable methods such as chemical deposition (CVD) and VLS, which has become the dominant option for nanowire growth due to its simple realization and flexible and excellent control over many aspects of the synthesis process. Figure 1.1 highlights some of the notable applications for nanowire devices.[45,47–49]

In a typical VLS growth process, as schematically illustrated in Figure 1.2, metal nanoparticles (either elemental particles such as Au, Ag, Cu, Al, Au or their alloys[50]) are employed as a catalyst to initiate and define nucleation, as well as facilitate activation/decomposition the molecular reactants (if used). During the growth process, the metal nanoparticles are first heated up above the eutectic temperature for the target metal–semiconductor system to create