NanoScience and Technology

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Nanowires

Building Blocks for Nanoscience and Nanotechnology

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Preface

Dimensionality plays a critical role in determining the properties of materials due to, for example, the different ways that electrons interact in 3D, 2D and 1D structures. 1D nanowires (NWs), with diameters reaching to the molecular or quantum regime, have been the focus of research for two decades and today remain at the forefront of both scientific research and developing nanotechnologies. In particular, semiconductor NWs represent one of the most important and versatile nanometer-scale structures. In contrast to other classes of 1D nanostructures, such as carbon nanotubes, semiconductor NWs can be rationally and predictably synthesized in single crystal forms with all key parameters controlled, including chemical composition, diameter, length, doping and electronic properties. Thus, semiconductor NWs represent one of the best-defined classes of nanoscale building blocks, and the precise control over key variables has correspondingly enabled a wide range of devices, assembly strategies and integrated nanosystems to be pursued, as well as opening new directions at the interface with other fields. This book provides an overview of this vibrant area of nanoscience and nanotechnology research starting from early efforts that recognized the importance and began to develop this class of building blocks through to state-of-the-art directions today, including quantum devices, energy technology and interfacing to biological systems.

Chapter 1 will introduce the emergence of the semiconductor NW research platform, including the concept and importance, synthetic challenges and initial design, and the development of vapor-liquid-solid crystal growth mechanism, as well as other nanofabrication-based approaches explored in the early years of this field.

In Chap. 2, we will overview major bottom-up strategies for the synthesis of semiconductor NWs, including vapor phase, templated, and solution-based methods. Chapter 3 will further expand upon the basic synthetic methods to yield controlled growth of a host of semiconductor NWs with modulated morphologies and structures, including axial and radial heterostructures, kinked, branched, and/or modulated doped structures, where the increased complexity in the NWs can enable unique functional properties.

To utilize these NW building blocks for nanoscale devices through integrated systems, such as in electronics and photonics, requires controlled and scalable assembly of NWs on either rigid or flexible substrates. In Chap. 4, we will summarize advances in large-scale NW assembly by organizing pre-grown NWs onto target substrates and the direct growth of aligned NWs on substrates.

Electronics obtained through the bottom-up approach of molecular-level control of material composition and structure can lead to devices and fabrication strategies, as well as new architectures not readily accessible or even possible within the context of the top-down driven industry and manufacturing infrastructure. Chapter 5 will present a summary of advances in basic nanoelectronics devices, basic circuits and nanoprocessors assembled by semiconductor NWs.

In Chap. 6, we will review the advantages of the sub-wavelength diameters of NW structures and tunable energy band gaps for investigating generation, detection, amplification and modulation of light. The rational design and synthesis of NW structures together with the capability of controlling and manipulating these structures on surfaces to form single devices and networks has been crucial for realizing NW-based photonic circuitry. Progress in the area of NW photonic devices, including waveguides, light-emitting diodes, lasers, and photodetectors, will be reviewed.

When the dimensions of the NWs become comparable to the electron characteristic lengths, the fundamental quantum properties of charge carriers can dominate the charge transport and new device properties become possible. Chapter 7 will summarize studies over the past decade where quantum properties are critical to the observed behavior, including quantum dot systems in semiconductor NWs, hybrid superconductor-semiconductor NW devices, and NW topological insulators.

Substantial recent scientific effort has been focused on efficient energy storage and conversion of renewable energy sources, where semiconductor NWs represent attractive candidates since their composition, size and other factors that determine basic electronic and optical properties can be synthetically manipulated in complex ways. In Chaps. 8 and 9, the advantages of NW structures for efficient energy storage and conversion will be illustrated and discussed.

Chapter 10 will introduce research advances exploiting NWs configured as field-effect transistors for biomolecule analysis, as one of the most promising and powerful platforms for label-free, real-time, and sensitive electrical detection based upon the electrostatic gating effect on the surface. Representative examples of semiconductor NW sensors will be described, including sensitive detection of proteins, nucleic acids, viruses and small molecules.

The interface between nanosystems and biosystems is emerging as one of the broadest and most dynamic areas of science and technology, bringing together researchers and ideas from biology, chemistry, physics and many areas of engineering, biotechnology and medicine. These efforts are leading to many advances, for example, the creation of new and powerful tools that enable direct, sensitive and rapid analysis of biological species and cellular activities. Research at the interface between nanomaterials and biology could yield breakthroughs in fundamental science and lead to revolutionary technologies. In Chap. 11, we will introduce studies focused on building interfaces between NWs with cells and tissues, including extracellular and intracellular signal recording, synthetic cyborg tissues and in vivo recording.

Finally, in Chap. 12, we will conclude this book and look into the future of the exciting opportunities of NW science and technology moving forward.

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