

NanoScience and Technology

Anqi Zhang
Gengfeng Zheng
Charles M. Lieber

Nanowires

Building Blocks for Nanoscience and
Nanotechnology

 Springer

NanoScience and Technology

Series editors

Phaedon Avouris, Yorktown Heights, USA

Bharat Bhushan, Columbus, USA

Dieter Bimberg, Berlin, Germany

Klaus von Klitzing, Stuttgart, Germany

Cun-Zheng Ning, Tempe, USA

Roland Wiesendanger, Hamburg, Germany

The series NanoScience and Technology is focused on the fascinating nano-world, mesoscopic physics, analysis with atomic resolution, nano and quantum-effect devices, nanomechanics and atomic-scale processes. All the basic aspects and technology-oriented developments in this emerging discipline are covered by comprehensive and timely books. The series constitutes a survey of the relevant special topics, which are presented by leading experts in the field. These books will appeal to researchers, engineers, and advanced students.

More information about this series at <http://www.springer.com/series/3705>

Anqi Zhang · Gengfeng Zheng
Charles M. Lieber

Nanowires

Building Blocks for Nanoscience
and Nanotechnology

 Springer

Anqi Zhang
Department of Chemistry and Chemical
Biology
Harvard University
Cambridge, MA
USA

Charles M. Lieber
Department of Chemistry and Chemical
Biology
Harvard University
Cambridge, MA
USA

Gengfeng Zheng
Department of Chemistry, Collaborative
Innovation Center of Chemistry
for Energy Materials
Fudan University
Shanghai
China

and
Harvard John A. Paulson School
of Engineering and Applied Sciences
Harvard University
Cambridge, MA
USA

ISSN 1434-4904
NanoScience and Technology
ISBN 978-3-319-41979-4
DOI 10.1007/978-3-319-41981-7

ISSN 2197-7127 (electronic)
ISBN 978-3-319-41981-7 (eBook)

Library of Congress Control Number: 2016945143

© Springer International Publishing Switzerland 2016

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

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.

We thank Yongjie Hu (University of California, Los Angeles), Wei Lu (University of Michigan) and Yat Li (University of California, Santa Cruz) for reviewing early drafts of several chapters.

Cambridge
Shanghai
Cambridge
Jun 2016

Anqi Zhang
Gengfeng Zheng
Charles M. Lieber

Contents

1	Emergence of Nanowires	1
1.1	Introduction: Motivation for Nanowires	1
1.1.1	Importance of One-Dimensional Materials	2
1.1.2	Synthetic Challenges and Initial Design	4
1.1.3	Top-Down and Bottom-Up Nanotechnology	5
1.2	Micron-Scale Whiskers: VLS Concept	6
1.2.1	Concept and Key Results	6
1.2.2	Limitations	8
1.3	Other Early Works	8
1.3.1	Top-Down Lithography-Based Si Nanopillars	8
1.3.2	Carbide Nanorods	9
1.3.3	Nanowiskers by Vapor Phase Epitaxy	9
1.4	Beginning of Rapid Growth: Vapor-Phase Nanocluster Catalyzed Growth	10
	References	11
2	General Synthetic Methods	15
2.1	Introduction	15
2.2	Vapor Phase Growth	16
2.2.1	Laser-Assisted Catalytic Growth	16
2.2.2	Chemical Vapor Deposition	18
2.2.3	Chemical Vapor Transport	20
2.2.4	Molecular Beam Epitaxy	21
2.2.5	Vapor-Solid-Solid Growth	22
2.2.6	Vapor-Solid Growth	22
2.2.7	Oxide-Assisted Growth	23
2.3	Templated Growth	24
2.3.1	Formation Inside Nanopores	24
2.3.2	Templating Against Self-assembled Structures	25
2.3.3	Construction on Existing Nanostructures	25
2.3.4	Superlattice Nanowire Pattern Transfer	26

2.4	Solution-Based Methods	27
2.4.1	Solution-Liquid-Solid Growth	27
2.4.2	Supercritical Fluid-Liquid-Solid Growth	28
2.4.3	Solvothermal/Hydrothermal Synthesis	29
2.4.4	Directed Solution Phase Growth.	30
2.5	Future Directions and Challenges.	31
	References	32
3	Structure-Controlled Synthesis	39
3.1	Introduction.	39
3.2	Homogeneous Nanowires	40
3.3	Axial Modulated Structures.	42
3.3.1	Early Work	42
3.3.2	Semiconductor Heterojunctions	43
3.3.3	Metal-Semiconductor Heterostructures	43
3.3.4	<i>p-n</i> Homojunctions.	45
3.3.5	Ultrashort Morphology Features.	48
3.4	Radial/Coaxial Modulated Structures	48
3.4.1	Semiconductor Radial Structures	49
3.4.2	Coaxial Modulated Structures	52
3.5	Branched/Tree-Like Structures.	53
3.5.1	Sequential Catalyst-Assisted Growth.	54
3.5.2	Solution Growth on Existing Nanowires	56
3.5.3	Phase Transition Induced Branching	56
3.5.4	One-Step Self-catalytic Growth	58
3.5.5	Screw Dislocation Driven Growth	58
3.6	Kinked Structures	60
3.6.1	Undersaturation/Supersaturation-Induced Kinking.	60
3.6.2	Confinement-Guided Kinking	62
3.7	Future Directions and Challenges.	63
	References	64
4	Hierarchical Organization in Two and Three Dimensions	69
4.1	Introduction.	69
4.2	Post-growth Assembly	70
4.2.1	Fluidic Method	70
4.2.2	Langmuir-Blodgett Method	72
4.2.3	Blown Bubble Method	77
4.2.4	Chemical Interactions for Assembly	78
4.2.5	Assembly at Interfaces	79
4.2.6	Electric/Magnetic Field-Based Methods.	81
4.2.7	PDMS Transfer Method	82
4.2.8	Printing.	85
4.2.9	Nanocombing-Based Assembly	87
4.2.10	Other Assembly Methods	89

- 4.3 Patterned Growth 90
 - 4.3.1 Epitaxial Growth from Patterned Nanocluster Catalysts 90
 - 4.3.2 Substrate-Step-Directed Growth 95
- 4.4 Future Directions and Challenges 97
- References 97
- 5 Nanoelectronics, Circuits and Nanoprocessors 103**
 - 5.1 Introduction and Historical Perspective 103
 - 5.2 Basic Nanoelectronic Devices 104
 - 5.2.1 Field-Effect Transistors 104
 - 5.2.2 p-n Diodes 112
 - 5.3 Simple Circuits 115
 - 5.3.1 Logic Gates 115
 - 5.3.2 Ring Oscillators 120
 - 5.3.3 Demultiplexers 121
 - 5.3.4 Nonvolatile Memory 122
 - 5.4 Nanoprocessors 129
 - 5.4.1 Logic Tiles 129
 - 5.4.2 Arithmetic Logic 131
 - 5.4.3 Sequential Logic 132
 - 5.4.4 Basic Nanocomputer 133
 - 5.5 Future Directions and Challenges 136
 - References 137
- 6 Nanophotonics 143**
 - 6.1 Introduction 143
 - 6.2 Optical Phenomena 144
 - 6.2.1 Photoluminescence from Nanowire Structures 144
 - 6.2.2 Nonlinear Processes 146
 - 6.3 Photonic Devices 152
 - 6.3.1 Nanowire Waveguides 152
 - 6.3.2 Nanoscale Light-Emitting Diodes 153
 - 6.3.3 Optically-Pumped Nanowire Lasers 156
 - 6.3.4 Electrically-Pumped Nanowire Lasers 166
 - 6.3.5 Photodetectors 167
 - 6.4 Future Directions and Challenges 168
 - References 169
- 7 Quantum Devices 177**
 - 7.1 Introduction 177
 - 7.2 Quantum Dot Systems in Semiconductor Nanowires 179
 - 7.2.1 Configurations of Quantum Dot Systems in Nanowires 179
 - 7.2.2 Basic Electronic Properties of Quantum Dots 181

7.2.3	Single Quantum Dots in Nanowires	182
7.2.4	Coupled Quantum Dots in Nanowires	184
7.2.5	g -Factor and Spin-Orbit Interaction	187
7.3	Hybrid Superconductor-Semiconductor Devices	192
7.3.1	Josephson Junctions	192
7.3.2	Majorana Fermions	194
7.4	Topological Insulators	196
7.5	Future Directions and Challenges	197
	References	198
8	Nanowire-Enabled Energy Storage	203
8.1	Introduction	203
8.2	Lithium-Ion Batteries	204
8.2.1	Anodes	205
8.2.2	Cathodes	211
8.3	Electrochemical Capacitors	214
8.4	Sodium-Ion Batteries	219
8.5	Future Directions and Challenges	219
	References	220
9	Nanowire-Enabled Energy Conversion	227
9.1	Introduction	227
9.2	Photovoltaics	228
9.2.1	Nanowire Arrays for Enhanced Light Absorption	229
9.2.2	Radial Junction Nanowires for Enhanced Carrier Separation	233
9.2.3	Tuning Band Gaps of III-V Compounds	236
9.3	Photoelectrochemical Conversion/Photocatalysis	238
9.3.1	Si Nanowire-Based Photoelectrochemical Water Splitting	239
9.3.2	Dual-Band Gap Artificial Photosynthesis	240
9.4	Thermoelectrics	244
9.5	Piezoelectric Effects	246
9.6	Future Directions and Challenges	248
	References	248
10	Nanowire Field-Effect Transistor Sensors	255
10.1	Introduction	255
10.2	Fundamental Principles of Field-Effect Transistor Sensors	256
10.3	Examples of Nanoelectronic Sensors	258
10.3.1	Protein Detection	258
10.3.2	Nucleic Acid Detection	260
10.3.3	Virus Detection	261
10.3.4	Small Molecule Detection	262

- 10.4 Methods for Enhancing the Sensitivity of Nanowire Sensors 263
 - 10.4.1 3D Branched Nanowires for Enhanced Analyte Capture Efficiency 263
 - 10.4.2 Detection in the Subthreshold Regime 263
 - 10.4.3 Reducing the Debye Screening Effect 265
 - 10.4.4 Electrokinetic Enhancement 267
 - 10.4.5 Frequency Domain Measurement 267
 - 10.4.6 Nanowire–Nanopore Sensors 269
 - 10.4.7 Double-Gate Nanowire Sensors 270
 - 10.4.8 Detection of Biomolecules in Physiological Fluids 270
- 10.5 Future Directions and Challenges 271
- References 272
- 11 Nanowire Interfaces to Cells and Tissue 277**
 - 11.1 Introduction 277
 - 11.2 Nanowire/Cell Interfaces and Electrophysiological Recording 278
 - 11.2.1 Traditional Extracellular Electrophysiological Recording 278
 - 11.2.2 Nanowire Transistors for Extracellular Recording 280
 - 11.2.3 Intracellular and Intracellular-like Electrophysiological Recording 284
 - 11.3 Nanowire-Tissue Interfaces and Electrophysiological Recording 290
 - 11.3.1 Acute Brain Slice Studies with Nanowire Transistors 291
 - 11.3.2 Cardiac Tissue Studies with Nanowire Transistors 291
 - 11.3.3 3D Nano–Bioelectronic Hybrids 293
 - 11.3.4 Injectable Electronics 298
 - 11.4 Future Directions and Challenges 300
 - References 301
- 12 Conclusions and Outlook 307**
 - References 309
- Curriculum Vitae 311**
- Index 315**