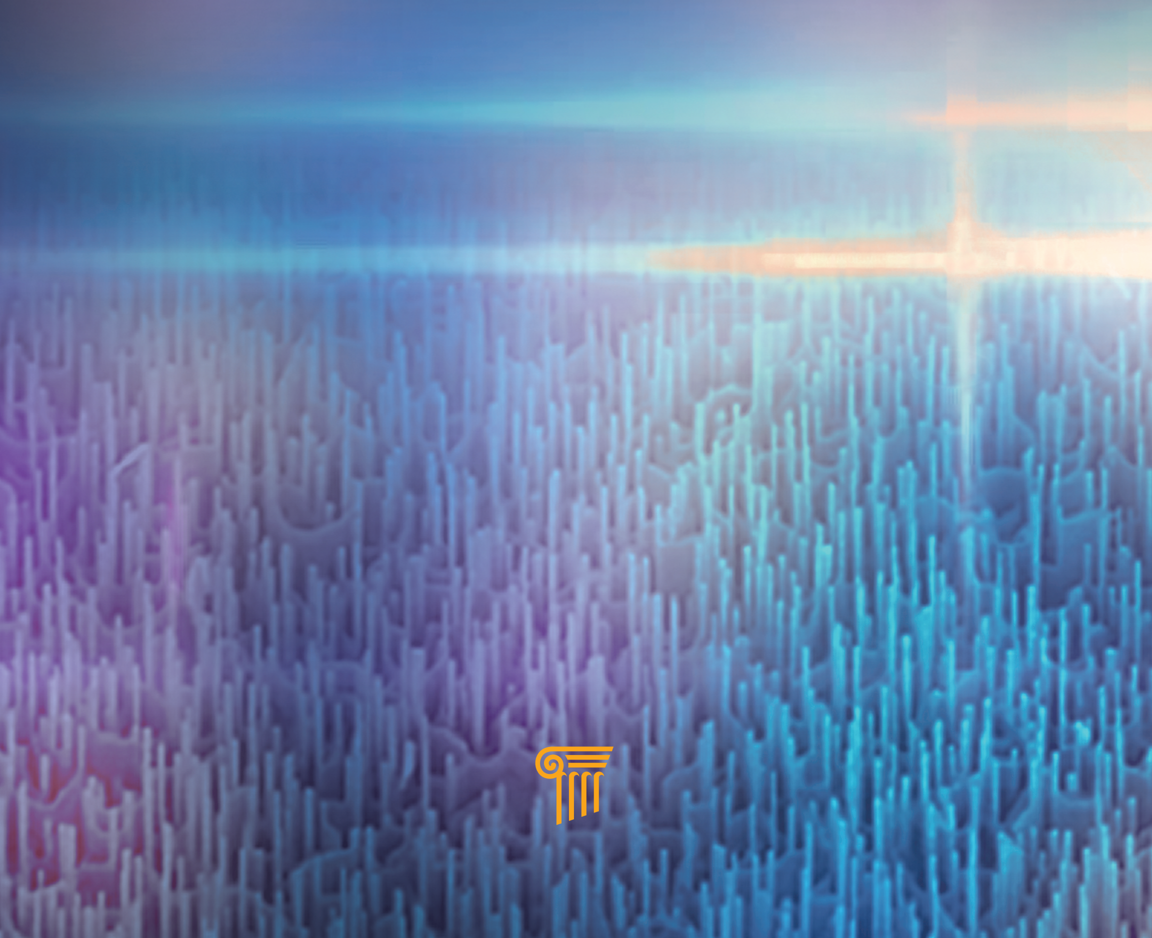
Novel Compound Semiconductor Nanowires

Materials, Devices, and Applications

edited by

Fumitaro Ishikawa
Irina A. Buyanova



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Foreword

As a researcher working on semiconductor nanostructures for about 50 years, it is my great pleasure to write a foreword for this book, which has been edited by Drs F. Ishikawa and I. Buyanova to cover recent research accomplishments on the epitaxial growth, physics, and device applications of semiconductor nanowire structures.

As is well known, most of key semiconductor devices, such as field-effect transistors (FETs) and laser diodes (LDs) make use of very thin layers as their core parts, since the control of channel conductance in FETs by gate voltage and that of optical gains in LDs by injected carriers can be efficiently achieved only if the channel layer of FETs and the active layer of LDs are sufficiently thin. These core layers, however, cannot be made too thin, since the quantum confinement of carriers in such layers leads to an excessive rise of the carrier energy and possibly weakens the carrier confinement.

As a result, these layers are formed with the thickness of a few to 10 nm by employing advanced epitaxy and other semiconductor techniques so that carriers are well confined and move freely only along the layer, while their motion normal to the layer is quantized. The two-dimensional (2D) nature of these carriers has induced a variety of important consequences, such as the formation of a series of 2D sub-bands with a step-like density of states, and the enhancement of excitonic effects. Consequently, various new devices, such as resonant tunneling diodes and inter-sub-band photo-detectors and lasers, have been realized and new phenomena, such as quantum Hall effect, have been discovered.

While the thinning of these core layers has allowed the progress of advanced devices and the exploration of new physics of 2D carriers, the width reduction of such layers or films to form wire structures, such as narrow FET channels, has been done mainly in the field of LSIs to shrink devices for higher integration and to reduce the current and power consumption. It is also noted that the use of nanowire channels reduces the short-channel effect of FETs, as the gate around the wire acts more effectively than that in planar FETs. Although this down-scaling has been widely done, the typical width of FETs is set still at 100 nm or above to keep enough current drive capabilities.

Possibilities of squeezing the wire width down to 10 nm to confine electrons quantum mechanically and to use such 1D electrons for possible device applications had not been discussed until 1975, when I analyzed electron transport in coupled nanowire or planar superlattice structures. In 1980, potentials of quantum nanowire FETs were studied also by me. In 1982, Arakawa and I proposed and studied the possible use of quantum wires and quantum dots as gain media of semiconductor lasers.

Although such nanowire structures could not be formed in those early years, several groups started exploratory works to develop various methods that have enabled the formation of nanowire structures. The attempts are categorized into the three groups:

(a) top-down approach, based on the lithographic film patterning and the passivation
(b) bottom-up approach, based on the wire growth on self-assembled nanoparticles
(c) hybrid approach, which combine various patterning and selective growth processes

This book covers key results on the epitaxial growth of nanowires that belong to either group (b) or group (c).

Thanks to the progress of these fabrication methods, the formation of nanowires has been greatly facilitated, though there are still a lot of problems to be taken care of. As a consequence, a large number of studies have been made to clarify the physics and chemistry of various nanowire structures and to disclose unexplored potentials of nanowire-based devices, such as nanowire LEDs and solar cells.

I wish to close this foreword by wishing that this book promotes more research activities and accelerates the progress in the field.

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President, Toyota Technological Institute
Nagoya, Japan
July 2017

Preface

The area of nanoscale science and technology is currently gaining increasing attention because of intriguing fundamental physics at the nanoscale, as well as potential applications of the low-dimensional structures in nanoscale electronics, optics, energy storage, and biology. The fabrication of these structures from crystalline semiconductors is now possible with a high degree of complexity, due to impressive developments in epitaxial growth techniques. Molecular beam epitaxy and metalorganic vapor phase epitaxy approaches are among the representative techniques utilized for the growth of low-dimensional semiconductor heterostructures with an atomic structural accuracy and precision. High-quality, single-crystalline III-V one-dimensional (1D) nanowire heterostructures are an example, promising for the next-generation nanoscale photonic and electronic devices, such as highly efficient nanowire light-emitting diodes, lasers and solar cells, as well as high-speed transistors. The key advantages of employing III-V semiconductor materials (i.e., nitride-, phosphide-, and arsenide-related heterostructure systems) for the realization of these devices include a high carrier mobility and superior optical properties. Furthermore, the developed epitaxial growth techniques enable electronic carrier control through the formation of quantum structures and precise doping, which can be introduced into a nanowire system. Most recently, it also became possible to fabricate III-V nanowires from highly mismatched alloys formed from III-V compounds with a large miscibility gap, or, alternatively, by the formation of hybrid heterostructures between a semiconductor and another material system based on, for instance, magnetic half metals and oxides. This book reviews the recent progress of such novel III-V semiconductor nanowires, covering a wide range of aspects from the epitaxial growth to the device applications. The prospects of such advanced 1D structures for nanoscience and nanotechnology are also discussed.

The book is organized as follows. A general overview of the area of one-dimensional structures is provided in Chapters 1 and 2. Specifically, Chapter 1 reviews the nanowire heterostructures for electrical and optical applications, focusing on the basic concepts and growth methods and the challenges of controlling the structure and the composition, and providing examples of selected nanowire devices. Chapter 2 describes the historical progress of molecular beam epitaxy of nitride nanocolumns and related nanocolumn emitters. The authors of this chapter have pioneered the growth of high-quality, metastable InGaN nanocolumns and related devices, which has opened the possibility of their applications in optical devices.

Chapters 3–9 review the properties of nanowires derived from novel strategic materials fabricated by epitaxial growth techniques.

Chapters 3–5 describe the highly mismatched dilute nitride and dilute bismide systems, which allow increased tunability in the band gap energy and lattice constants compared with conventional III-V semiconductor compounds and alloys. In Chapter 3, the structural and optical properties of GaNP nanowires are discussed along with their potential for future optoelectronic applications. In addition to significant improvements in the radiative efficiency, defect engineering via alloying with nitrogen is shown to be advantageous for the realization of polarized nano light sources and also for improving energy harvesting. In Chapter 4, structural and optical properties as well as the possible applications of GaNAs nanowires are reviewed. It is shown that alloying with nitrogen leads to the passivation of the nanowire surface and the formation of embedded quantum dot-like emitters. The existing research on dilute III-V-Bi nanowires, particularly dilute GaAsBi nanowires, is reviewed in Chapter 5. These novel alloys are of potential importance as infrared emitters with suppressed intrinsic non-radiative recombination losses at high temperature.

Chapters 6 and 7 are devoted to the characterization of nanowires based on novel spintronic materials. Chapter 6 describes experimental results from hybrid structures of ferromagnetic MnAs and non-magnetic III-V compounds and demonstrates their potential for magneto–nanoelectronic or spintronic device applications. In Chapter 7, the results from the GaAs–Fe_3Si semiconductor-ferromagnetic hybrid nanowires are presented. A high Curie temperature is a prerequisite for the application of these materials in spintronic devices, and the binary Heusler alloy Fe_3Si is a promising material in this sense.

Chapters 8 and 9 discuss hybrid nanowires consisting of GaAs and oxides. In Chapter 8, the synthesis of GaAs/$AlGaO_x$ nanowires combining molecular beam epitaxy and subsequent wet oxidation is presented. The characteristic broad visible light emission from the $AlGaO_x$ materials is demonstrated. Chapter 9 describes the growth and properties of GaAs/$SrTiO_3$ core–shell nanowires providing strategies for the synthesis of these high-quality hybrid structures. It demonstrates the feasibility of monolithical integration between the monocrystalline epitaxial shell of functional oxides and the nanowire, promising for the development of heterostructures that couple light emission/absorption and piezoelectricity or ferroelectricity.

The recent progress in device applications of nanowires is reviewed in Chapters 10–14. An overview of growth and applications of GaN nanowires together with a brief history of the related discoveries is given in Chapter 10. Both top-down and bottom-up approaches for the formation of nanowire arrays are presented. Additionally, the applications of these materials as quantum light emitters and nano-transistors are discussed. In Chapter 11, the potential of InP-related light-emitting devices is reviewed based on the in-depth investigations of the nanowire growth and device fabrication. The growth and the future prospect of InP/InAs nanowires for applications in field-effect transistors are described in Chapter 12. The achieved reproducible low-temperature synthesis of radial InP/InAs structures grown with top-down patterning and the demonstrated use of these structures as field-effect transistors highlight the potential of these materials in beyond-CMOS technologies. Chapter 13 describes the growth of InGaN nanowires and their applications in green light-emitting diodes, in lasers with a photonic crystal cavity, and also in photovoltaic devices. Chapter 14, the last chapter, provides a comprehensive overview of the historical development and the state-of-the-art of semiconductor nanowire transistors and solar cells. The emphasis is on the progress of III-V nanowires grown via metalorganic vapor phase epitaxy and their applications. This chapter also summarizes the most representative achievements in nanowire device applications for a wide range of III-V and group-IV materials and oxides.

We would like to express our gratitude to all contributors for their willingness to share with the readers their experience and in-depth insights into the exciting area of semiconductor nanowires. We hope that the comprehensive collection of the review articles on the current status of novel nanowire materials and systems provided in the book will stimulate further research efforts in this exciting field. F. I acknowledges the transfer of the experience and growth techniques at the initial stage of the nanowire study from Masahito Yamaguchi (who sadly passed away in 2013) and Yoshio Honda.

We are grateful to Stanford Chong and Arvind Kanswal of Pan Stanford Publishing for the invitation of this book editing and continuous support during the preparation.

Fumitaro Ishikawa, Matsuyama
Irina A. Buyanova, Linköping
July 2017