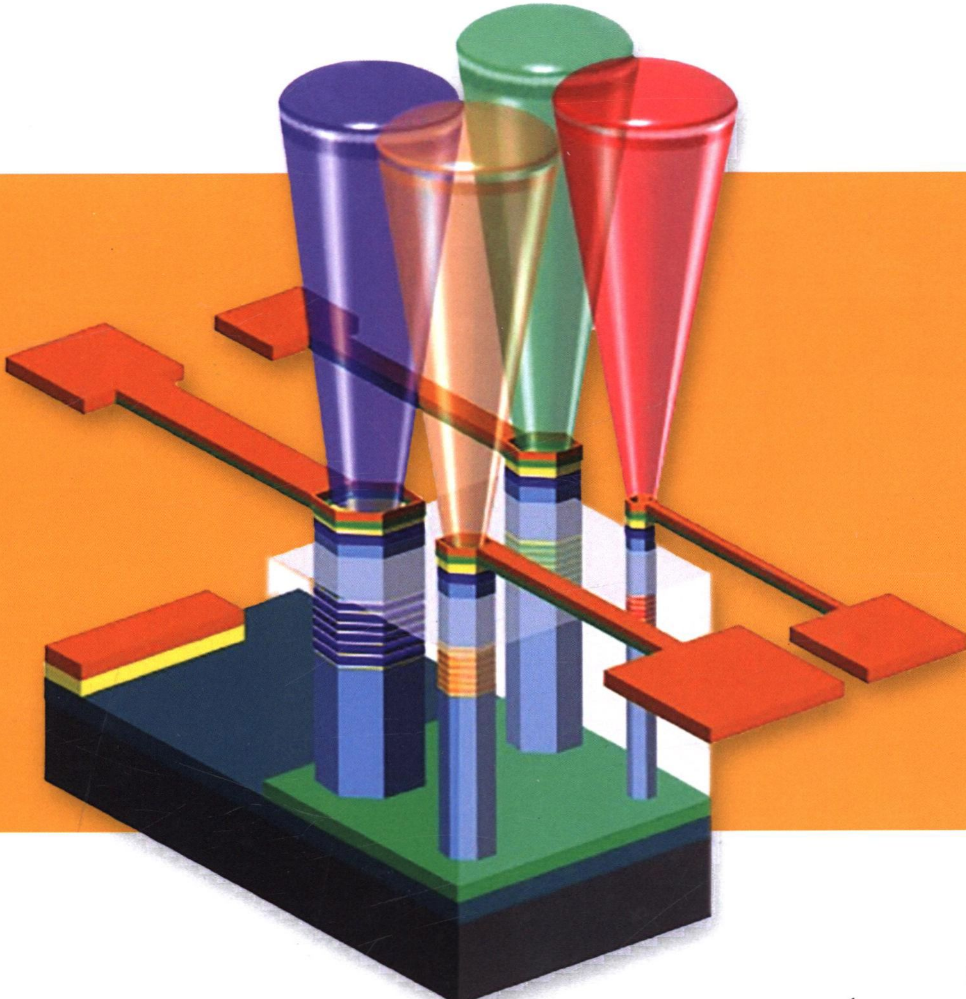
SERIES IN OPTICS AND OPTOELECTRONICS

Handbook of GaN Semiconductor Materials and Devices



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CRC Press
Taylor & Francis Group

Electrical Engineering / Optics

SERIES IN OPTICS AND OPTOELECTRONICS

SERIES EDITORS: ROBERT G W BROWN AND E ROY PIKE

Handbook of GaN Semiconductor Materials and Devices

This book addresses material growth, device fabrication, device application, and commercialization of energy-efficient white light-emitting diodes (LEDs), laser diodes, and power electronics devices. It begins with an overview on the basics of semiconductor materials, physics, growth, and characterization techniques, followed by a detailed discussion of the advantages, drawbacks, design issues, processing, applications, and key challenges for state-of-the-art GaN-based devices. It includes state-of-the-art material synthesis techniques with an overview on growth technologies for emerging bulk or free-standing GaN and AlN substrates and their applications in electronics, detection, sensing, optoelectronics, and photonics.

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K27029

CRC Press
Taylor & Francis Group
an informa business
www.crcpress.com

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Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

ISBN: 978-1-4987-4713-4
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9 781498 747134

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-1-4987-4713-4 (Hardback)

Library of Congress Cataloging-in-Publication Data

Names: Bi, Wengang, editor.
Title: Handbook of GaN semiconductor materials and devices / Wengang (Wayne) Bi, Hao-chung (Henry) Kuo, Pei-Cheng Ku, Bo Shen, editors.
Description: Boca Raton : Taylor & Francis, CRC Press, 2017. | Series: Series in optics and optoelectronics | Includes bibliographical references.
Identifiers: LCCN 2017011253 | ISBN 9781498747134 (hardback : alk. paper)
Subjects: LCSH: Semiconductors--Handbooks, manuals, etc. | Gallium nitride--Handbooks, manuals, etc.
Classification: LCC TK7871.15.G33 H36 2017 | DDC 621.3815/2--dc23
LC record available at https://lccn.loc.gov/2017011253

Visit the Taylor & Francis Web site at
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Series Preface

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Proposals for new volumes in the series may be directed to Lu Han, senior publishing editor at CRC Press, Taylor & Francis Group (lu.han@taylorandfrancis.com).

Foreword

III-nitride semiconductors and devices have emerged as a rising star in numerous electronic and optoelectronic applications. The breakthrough in epitaxial growth and p-type doping back in the early 1990s transformed the once unremarkable material into one of the most important for the worldwide semiconductor industry. The unique properties of GaN, AlN, InN, and related compounds presented us with both opportunities and challenges. Their large energy bandgaps enabled highly energy efficient ultraviolet and visible wavelength lasers, and pyro- and piezoelectric properties have been utilized to generate two-dimensional electron gas in high-power, high-frequency, high-electron mobility transistors. Light-emitting diodes (LEDs), in particular, promise a revolution in lighting efficiency unprecedented in the past hundred years. The ubiquity of LEDs in flat-panel displays and increasing popularity in general lighting, the advent of visible and ultraviolet lasers for optical data storage, and the superior power-handling performance of GaN-based transistors are just a few examples of how III-nitride materials and devices have been utilized in many fields.

Thanks to research and development efforts in both industry and academia in the past two decades, I believe we are just seeing the beginning of the GaN revolution. There are still many challenges to overcome before we can fully uncover the potential of III-nitride materials. These include fundamental understandings of the droop mechanism, continuing advancement of epitaxial technologies for both short-wavelength and long-wavelength applications, as well as the development of better substrates for improved materials quality and device performance. However, holistic approaches toward system-level solutions are needed as well. For example, the use of III-nitride lasers instead of LEDs for lighting can be just as efficient but without the issue of droop. It was the persistent efforts by only a handful of researchers in the early days that brought about the revolution we enjoy today. It is equally important that we keep the enthusiasm going forward, which is why I think this book serves an important role for this endeavor.

This book is devoted to the latest development of III-nitride materials and technologies. It compiles the latest results in materials growth, understanding of electronic and optical properties, and device physics and architectures from experts in this field. These developments are important as they not only continue to improve the performance of existing devices but establish a solid foundation to new capabilities and new applications of III-nitride materials. This book strikes a good balance between fundamental materials science and technology developments with diverse topics ranging from epitaxial growth of high-aluminum and high-indium composition III-nitride thin-film and nanostructural materials to development of native GaN substrates, from fundamental understandings of electronic and optical properties to processing techniques, which are of central importance to improve device performance, and from a continued push to new emitter wavelengths to new frontiers in solar cells, intersubband (ISB) optoelectronics, lighting communications, and quantum light emitters. These topics and their promising results reassert my belief that the potential of nitride materials and technologies are only limited by our creativity.

I believe this book will be a great resource to researchers and engineers, in both academia and industry, to learn and be inspired by the latest developments and potentials of III-nitride materials and devices. I thank the editors and CRC Press/Taylor & Francis Group for their efforts in putting everything together. I am happy to contribute this Foreword, and I sincerely wish the success of this book.

Shuji Nakamura
University of California, Santa Barbara
2014 Nobel Laureate in Physics

Preface

Gallium nitride (GaN) and related alloys or GaN materials in short possess remarkable electronic and optoelectronic properties, unparalleled in other semiconductors, including an extremely tunable direct bandgap from 0.7 to 6.2 eV, a large exciton binding energy, a high-electron mobility (>10^4 cm^2/V s in InN), and a large saturation velocity (10^8 cm/s in InN). The research and development of the GaN-based devices in the past 25 years have created an enormous impact on our daily life, leading to a revolution in energy-efficient lighting and electronic displays, resilient power electronic systems for vehicle electrification, and ultracompact semiconductor lasers in the ultraviolet, blue, and green wavelengths for data storage as well as many scientific and industrial applications. However, it has also become clear to the research community that what has been unearthed is only the tip of the iceberg. Many potential applications of GaN have yet to be realized. These include—but are not limited to—deep ultraviolet, deep visible, and near-infrared light-emitting diodes (LEDs) and lasers; next-generation power transistors; sensors that operate in harsh environments; and sources for quantum photonics. Grand challenges must be overcome to achieve breakthroughs in these emerging applications and require continued push on several research frontiers, including epitaxial growths, materials science, manufacturing technologies, characterization techniques, device architecture, and modules as well as system optimizations. This book is devoted to gathering the latest developments in these areas, presented by renowned researchers from both academia and industry.

The book is organized into sections with a total of 22 chapters. Thanks to our contributors, the breadth and depth of this book are incredible. Section I (Chapters 1 through 4) focuses on the fundamental properties of GaN materials, encompassing their structural, electronic, and optical properties. Section II (Chapters 5 through 8) is devoted to the latest developments in GaN and related material growth and device fabrication technologies. Section III (Chapters 9 through 12) covers research frontiers in the area of GaN power electronics. Section IV (Chapters 13 through 18) presents the state-of-the-art developments of GaN-based light emitters including both LEDs and lasers. Section V (Chapters 19 through 22) includes a diverse range of emerging applications of GaN-based materials and devices. We think readers from both academia and industry will find this book beneficial. We also put our best efforts to make each chapter independent on its own so that readers who are specifically interested in certain topics can easily navigate through selected chapters across different parts with ease.

A more detailed overview of this book is following. Updates on the fundamental properties of GaN materials will be presented in Section I. In Chapter 1, Shen et al. give a comprehensive overview of the basic physical properties of GaN materials and discuss various growth and characterization techniques. In Chapter 2, Ponce discusses in more detail on the microstructures and polarization properties of GaN materials, including the evolution of microstructures, characteristics of dislocations, and polarization effects. In Chapter 3, Paskov and Monemer give an in-depth overview for the optical properties of GaN and related materials, including both band-to-band absorption and emission as well as emission properties from structural defects. In Chapter 4, Wu will review electronic band structures and carrier transport in GaN materials and how they are influenced by strain, alloy, and quantization.

Section II presents the latest developments in GaN and related material growth and processing technologies, which have been the key to the successful commercialization of GaN devices. In Chapter 5, Paskova et al. review recent advances in substrate technologies and discuss the relationship between growth techniques and substrates. In Chapter 6, Dr. Koleske gives a comprehensive overview on metal–organic vapor-phase epitaxy of GaN materials with an emphasis on the chemistry, growth mechanisms, and material properties that transformed a once backwater research topic into the ultimate resolution of solid-state lighting industry we have witnessed in recent years. In Chapter 7, Mi et al. discuss recent advances made in molecular beam epitaxy of GaN nanostructures, which have helped pushing GaN materials toward both deep visible and deep ultraviolet wavelengths. In Chapter 8, Jiang describes the state-of-the-art GaN device fabrication technologies with a focus on LEDs.

Sections III through V focus on devices and applications of GaN materials, including power electronics (Section III), light emitters (Section IV), and emerging applications (Section V). Section III covers a wide range of topics in GaN power devices, including material properties, device physics, and device architecture as well as reliability. In Chapter 9, Huang et al. review the fundamental properties of GaN-based heterostructures for electronic devices, including both depletion and enhancement mode transistors. In Chapter 10, Chowdhury presents the latest developments of GaN power devices, including vertical transistors. In Chapter 11, Chen and Yang discuss the status and challenges of GaN transistors on silicon. In Chapter 12, Zanoni et al. present an overview of the characterization methodologies and the latest results on the understanding of parasitic effects and reliability of GaN power devices.

Light emitters, including both LEDs and lasers, are perhaps the most researched applications for GaN materials. As Nakamura, the Nobel laureate in Physics in 2014 for his seminal contributions in GaN LEDs, points out in the Foreword, the breakthroughs in epitaxial growth and p-type doping back in the early 1990s led to the revolution in GaN-based LEDs and lasers. In Section IV, we gather six chapters to present the latest developments in this area. In Chapter 13, Zhang et al. summarize recent progress in continuing to push for a higher efficiency for GaN LEDs and introduce several novel concepts recently developed in this area. In Chapter 14, Wang et al. report the state-of-the-art white light emitters based on blue LEDs. In Chapter 15, Dr. J. Wang et al. summarize the progress in the growth and fabrication of indium-rich InGaN green LEDs with discussions on various substrate orientations. At the shorter end of the spectrum, Kim et al. present the challenges facing UV LEDs and recent efforts to overcome them in Chapter 16. Chapters 17 and 18 include the latest developments in GaN-based lasers. In Chapter 17, Bhattacharya et al. pave a new ground with low-threshold red-emitting GaN lasers by using the quantum dot to replace a more conventional quantum-well active region. In Chapter 18, Lu et al. present the latest developments in GaN surface-emitting lasers and their unique challenges as well as properties compared to their III–V counterparts.

GaN materials possess unique optical and electronic properties. Section V covers a series of emerging yet exciting opportunities for GaN-related materials and devices. In Chapter 19, Lin et al. discuss the potential application of GaN in photovoltaic cells by exploiting the small bandgap of InN and bandgap tunability of InGaN. In Chapter 20, Monroy et al. describe optoelectronic devices based on intersubband transitions in GaN. Unique applications toward ultrafast near-infrared devices and room-temperature terahertz lasers are discussed. In Chapters 21 and 22, the applications of GaN light emitters for novel forms of data networks are presented. In Chapter 21, Lin et al. discuss free-space communication using GaN transmitters. In Chapter 22, Ku et al. present scalable GaN quantum light emitters exploiting the large exciton binding energy in GaN.

We take this opportunity to thank all the authors, professors, researchers, and students for their contributions. Without them, this book would not be possible. We are grateful for their efforts in

delivering the manuscripts in a very tight schedule. We hope this book will not only be useful for the GaN research community, but most importantly will benefit students who are just entering this field. It is by no means an encyclopedia, but the diverse range of topics will likely stimulate the next-generation engineers and scientists to discover something new. Seasoned engineers should also find new insight and opportunity presented by the latest developments of GaN devices.

We also thank Prof. Shuji Nakamura, a pioneer in this field, for delivering an insightful and inspiring foreword. If the readers have any suggestion or criticism, please feel free to let us know. *Enjoy Reading!*

Editors

Wengang (Wayne) Bi is distinguished chair professor and associate dean in the College of Information and Electrical Engineering, chief scientist in the State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin, People's Republic of China. He earned his PhD in applied physics in the department of electrical and computer engineering at the University of California-San Diego, California. He has worked in industry for over two decades, including at Hewlett-Packard Laboratory (Palo Alto, California), Agilent Technologies Laboratory (Palo Alto, California), and Philips Lumileds (San Jose, California), developing cutting-edge optoelectronic and photonic materials and device structures by molecular beam epitaxy and metal–organic vapor-phase epitaxy with their applications to optoelectronic and electronic devices. Previously, he was chief engineer and senior vice president of Nanjing Technology (Hangzhou, Zhejiang, People's Republic of China)/NNCrystal (Fayetteville, Arkansas). Dr. Bi has authored or coauthored over 60 refereed journal publications, has presented numerous conference talks, and is the inventor of 20 patents. He is an elected fellow of the Optical Society of America.

Hao-Chung (Henry) Kuo is distinguished professor and associate director of the Photonics Center at National Chiao-Tung University, Hsin-Tsu, Taiwan, where he has supervised more than 40 PhD and Master's-level scientists and engineers. He earned his doctorate in the department of electrical and computer engineering at the University of Illinois at Champaign Urbana, Champaign, Illinois. He has worked in industry for many years, including at Bell Labs (Murray Hill, New Jersey), Lucent Technologies (Murray Hill, New Jersey), Agilent Technologies (San Jose, California), and LuxNet Corporation (Fremont, California). He has more than 20 years of experience in the field of III–V optical devices and materials, solid-state lighting process development, and fabrication and measurement of quantum devices. He is an associate editor of the *IEEE Journal of Selected Topics in Quantum Electronics* and *Journal of Lightwave Technology*. He has published more than 300 papers in peer-reviewed journals and is an elected fellow of the International Society for Optics and Photonics (SPIE), the Optical Society of America, and the Institution of Engineering and Technology.

Pei-Cheng Ku is an associate professor in the department of electrical engineering and computer science at the University of Michigan, Ann Arbor, Michigan. He earned his PhD in electrical engineering and computer science from the University of California-Berkeley, California, and worked at Intel Corporation, Santa Clara, California, prior to joining the University of Michigan faculty. He co-founded Arborlight (Ann Arbor, Michigan) in 2011, a solid-state lighting technology company.

Bo Shen is a Cheung Kong professor at Peking University, Beijing, People's Republic of China. He received his PhD from Tohoku University, Sendai, Japan, and obtained the Outstanding Youth Foundation of the National Science Foundation of China in 2003. His main research field is III-nitride wide bandgap semiconductor physics, materials, and devices. He has published more than 160 contributed papers and owned 18 invention patents in this field.