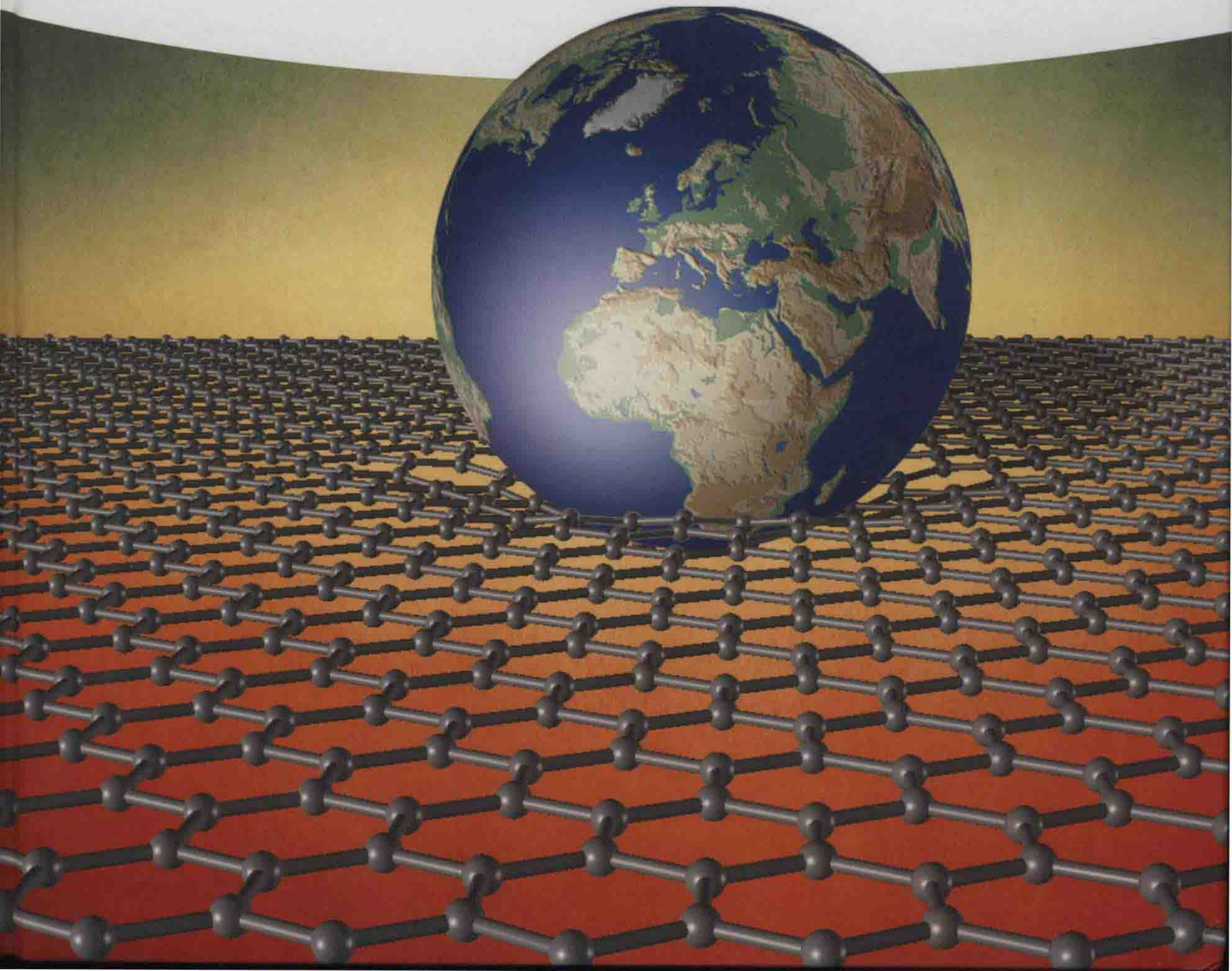
WILEY-VCH

Edited by A. Rashid bin Mohd Yusoff

Graphene Optoelectronics

Synthesis, Characterization, Properties, and Applications



Edited by A. Rashid bin Mohd Yusoff

Graphene Optoelectronics

Synthesis, Characterization, Properties, and Applications

WILEY-VCH
Verlag GmbH & Co. KGaA

Editor

Prof. A. Rashid bin Mohd Yusoff
Kyung Hee University
Information Display
Dongdaemoon-ku
130-701 Seoul
South Korea

Cover
Globe. Source: Geoatlas © Graphi-Ogre

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-33634-0
ePDF ISBN: 978-3-527-67781-8
ePub ISBN: 978-3-527-67780-1
Mobi ISBN: 978-3-527-67779-5
oBook ISBN: 978-3-527-67778-8

Cover-Design Grafik-Design Schulz, Fußgönheim, Germany
Typesetting Laserwords Private Limited, Chennai, India
Printing and Binding Markono Print Media Pte Ltd, Singapore

Printed on acid-free paper

Edited by
A. Rashid bin Mohd Yusoff

Graphene Optoelectronics

Related Titles

Georgakilas, V. (ed.)

Functionalization of Graphene

2014
Print ISBN: 978-3-527-33551-0
also available in digital formats

Roth, S., Carroll, D.

One-Dimensional Metals
Conjugated Polymers, Organic Crystals, Carbon Nanotubes and Graphene 3 Edition

2014
Print ISBN: 978-3-527-33557-2
also available in digital formats

Malic, E., Knorr, A.

Graphene and Carbon Nanotubes
Ultrafast Relaxation Dynamics and Optics

2013
Print ISBN: 978-3-527-41161-0
also available in digital formats

Rao, C.N., Sood, A.K. (eds.)

Graphene
Synthesis, Properties, and Phenomena

2013
Print ISBN: 978-3-527-33258-8
also available in digital formats

Hu, W. (ed.)

Organic Optoelectronics

2013
Print ISBN: 978-3-527-32968-7
also available in digital formats

Monthioux, M.M. (ed.)

Carbon Meta-Nanotubes - Synthesis, Properties and Applications

2012
Print ISBN: 978-0-470-51282-1
also available in digital formats

Wallace, G.G., Moulton, S., Kapsa, R.M., Higgins, M.

Organic Bionics

2012
Print ISBN: 978-3-527-32882-6
also available in digital formats

Yang, X. (ed.)

Semiconducting Polymer Composites
Principles, Morphologies, Properties and Applications

2012
Print ISBN: 978-3-527-33030-0
also available in digital formats

Schubert, U.S., Winter, A., Newkome, G.R.

Terpyridine-based Materials
For Catalytic, Optoelectronic and Life Science Applications

2012
Print ISBN: 978-3-527-33038-6
also available in digital formats

Jorio, A., Dresselhaus, M.S., Saito, R., Dresselhaus, G.

Raman Spectroscopy in Graphene Related Systems

2011
Print ISBN: 978-3-527-40811-5
also available in digital formats

Liu, B., Bazan, G.C. (eds.)

Conjugated Polyelectrolytes
Fundamentals and Applications

2012
Print ISBN: 978-3-527-33143-7
also available in digital formats

List of Contributors

Jintao Bai
Northwest University
State Key Lab Incubation Base of Photoelectric Technology and Functional Materials
International Cooperation Center of Photoelectric Technology and Functional Materials
and Institute of Photonics and Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Zhaoqiang Bai
National University of Singapore
Department of Physics
2 Science Drive 3
Singapore 117542
Singapore

Mimouna Baitoul
University Sidi Mohamed Ben Abdellah
Faculty of Sciences, Dhar el Mahraz
Laboratory of Solid State Physics
Group of Polymer and Nanomaterials
Avenue Mohamed bel arbi Alaoui
P.O. Box 1796
Atlas, Fez 30,000
Morocco

Jeong-Woo Choi
Sogang University
Department of Chemical and Biomolecular Engineering
Seoul
35 Baekbeom-ro(Sinsu-dong)
Mapo-gu, Seoul 121-742
Korea

Yi Cui
National Center for Nanoscience and Technology
Laboratory of Nanodevices
11 Beiyotoao Zhongguancun
Beijing, 100190
P.R. China

Haiming Fan
Northwest University
State Key Lab Incubation Base of Photoelectric Technology and Functional Materials
International Cooperation Center of Photoelectric Technology and Functional Materials
and Institute of Photonics and Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Yuan P. Feng
National University of Singapore
Department of Physics
2 Science Drive 3
Singapore 117542
Singapore

Jing Guo
University of Florida
Department of Electrical and Computer Engineering
Gainesville
1064 Center Drive
FL 32611
USA

Bao-Hang Han
National Center for Nanoscience and Technology
Laboratory of Nanodevices
11 Beiyotoao Zhongguancun
Beijing, 100190
P.R. China

Junji Haruyama
Aoyama Gakuin University
Faculty of Science and Engineering
5-10-1 Fuchinobe
Sagamihara
Kanagawa, 252-5258
Japan

Antonio Hill
Universität Augsburg
Institute of Physics
Augsburg D-86135
Germany

Mohammed Khenfouch
University of South Africa
UNESCO Africa Chair in Nanosciences-Nanotechnology
College of Graduate Studies
Preller street
Muckleneuk ridge, P.O. Box 392
Pretoria-South 0003
Africa

and

University Sidi Mohamed Ben Abdellah
Faculty of Sciences, Dhar el Mahraz
Laboratory of Solid State Physics
Group of Polymer and Nanomaterials
Avenue Mohamed bel arbi Alaoui
P.O. Box 1796
Atlas, Fez 30,000
Morocco

and

Nanosciences African Network
(NANOAFNET)
iThemba LABS-National
Research Foundation
1 Old Faure Road
P.O. Box 722, Somerset West
Western Cape Province 7129
South Africa

Seong C. Jun
Yunsei University
School of Mechanical
Engineering
262 Seongsanno
Seodaemun-gu
Seoul, 120-749
Korea

Tae-Hyung Kim
Rutgers
The State University of New
Jersey
Department of Biomedical
Engineering
599 Taylor Road
Piscataway
NJ 08854
USA

and

Rutgers
The State University of New
Jersey
Department of Chemistry and
Chemical Biology
610 Taylor Road
Piscataway
NJ 08854
USA

Kai-Tak Lam
University of Florida
Department of Electrical and
Computer Engineering
Gainesville
1064 Center Drive
FL 32611
USA

Ki-Bum Lee
Rutgers
The State University of New
Jersey
Department of Biomedical
Engineering
599 Taylor Road
Piscataway
NJ 08854
USA

and

Rutgers
The State University of New
Jersey
Department of Chemistry and
Chemical Biology
610 Taylor Road
Piscataway
NJ 08854
USA

Jiayuan Li
Northwest University
State Key Lab Incubation Base of
Photoelectric Technology and
Functional Materials
International Cooperation
Center of Photoelectric
Technology and Functional
Materials
and Institute of Photonics and
Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Malik Maaza
University of South Africa
UNESCO Africa Chair in
Nanosciences-Nanotechnology
College of Graduate Studies
Preller street
Muckleneuk ridge, P.O. Box 392
Pretoria-South 0003
Africa

and

Nanosciences African Network
(NANOAFNET)
iThemba LABS-National
Research Foundation
1 Old Faure Road
P.O. Box 722, Somerset West
Western Cape Province 7129
South Africa

Mei Qi
Northwest University
State Key Lab Incubation Base of
Photoelectric Technology and
Functional Materials
International Cooperation
Center of Photoelectric
Technology and Functional
Materials
and Institute of Photonics and
Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Zhaoyu Ren
Northwest University
State Key Lab Incubation Base of
Photoelectric Technology and
Functional Materials
International Cooperation
Center of Photoelectric
Technology and Functional
Materials
and Institute of Photonics and
Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Lei Shen
National University of Singapore
Department of Physics
2 Science Drive 3
Singapore 117542
Singapore

Andreas Sinner
Universität Augsburg
Institute of Physics
Augsburg D-86135
Germany

Mohd Asri bin Mat Teridi
Universiti Kebangsaan Malaysia
Solar Energy Research Institute
(SERI)
Bangi
Selangor, 43600
Malaysia

Qingyun Wu
National University of Singapore
Department of Physics
2 Science Drive 3
Singapore 117542
Singapore

Xinlong Xu
Northwest University
State Key Lab Incubation Base of
Photoelectric Technology and
Functional Materials
International Cooperation
Center of Photoelectric
Technology and Functional
Materials
and Institute of Photonics and
Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Perry T. Yin
Rutgers
The State University of New
Jersey
Department of Biomedical
Engineering
599 Taylor Road
Piscataway
NJ 08854
USA

A. Rashid bin Mohd Yusoff
Kyung Hee University
Department of Information
Display
Advanced Display Research
Center
Dongdaemoon-gu
Seoul 130-701
South Korea

Minggang Zeng
National University of Singapore
Department of Physics
2 Science Drive 3
Singapore 117542
Singapore

Ding Zhou
National Center for Nanoscience
and Technology
Laboratory of Nanodevices
11 Beiyotoao Zhongguancun
Beijing, 100190
P.R. China

Yixuan Zhou
Northwest University
State Key Lab Incubation Base of
Photoelectric Technology and
Functional Materials
International Cooperation
Center of Photoelectric
Technology and Functional
Materials
and Institute of Photonics and
Photon-Technology
No. 229 Taibai North Road
Xi'an, 710069
P.R. China

Klaus Ziegler
Universität Augsburg
Institute of Physics
Augsburg D-86135
Germany

Preface

Back in the 1920s, graphene was recognized as a carbon sheet one atom thick and consisting of a two-dimensional honeycomb lattice. It is now considered as the thinnest material in the world. It can also be considered as the basic unit for other carbon materials. The first report by A. K. Geim and his coworkers utilizing a simple micromechanical cleavage to extract graphene has received huge attention and earned them the Nobel Prize in physics in the year 2010. Since their first report, graphene has created a surge in research activities due to its high current density, ballistic transport, chemical inertness, high thermal conductivity, optical transmittance, and super hydrophobicity at the nanometer scale. In this sense, this book aims to present an overview of recent advances in research in the field of graphene, specifically in the areas of synthesis, characterization, properties, and applications, including high-frequency devices, sensors, spintronics, bandgap engineering, and photonics. Researchers from various fields, including physics, chemistry, materials, chemistry, biology, and engineering, have prepared their contributed chapters based on their research expertise in these wide fields.

The book is organized into 10 chapters. Chapter 1 is an introduction to the fundamental properties of graphene, including transport theory in the absence of an external magnetic field. The electronic properties of mono and bilayer graphene are strongly related to the existence of a quasiparticle spectrum that consists of two bands that touch each other at two Dirac nodes. Moreover, Chapter 1 also discusses the diffusion in graphene, which implies a characteristic metallic behavior in mono and bilayer graphene as well as the AC conductivity. In the end, Chapter 1 deals with the behavior of plasmons in graphene which is similar to that of plasmons in a conventional two-dimensional electron gas.

Chapter 2 deals with the synthesis techniques of graphene that have been employed, with "top-down" and "bottom-up" approaches. The top-down approach consists of mechanical cleavage, liquid-phase exfoliation, oxidation–reduction, and exfoliation of graphite intercalation compounds. This technique can be considered as a kind of exfoliation technique that produces graphene from graphite through breaking of the weak van der Waals force. On the other hand, the bottom-up approach consists of chemical vapor deposition (CVD), epitaxial growth, and chemical synthesis. Traditional CVD methods usually require high temperatures of about 1000 °C; however, in the case of graphene the CVD method has been modified to achieve high-speed, low-temperature deposition using plasma-enhanced CVD (PECVD), without the need of any special surface preparation or catalyst deposition. Finally, the modification and functionalization of graphene is also discussed in this chapter.

Chapter 3 deals with optical characterization of freestanding, diamond-like carbon and zinc oxide nanorod–graphene nanocomposite. The freestanding carbon is deposited by means of pulsed lased deposition, and Raman, ultraviolet–visible–near infrared, infrared, and photoluminescence spectroscopic techniques are used in these investigations. Finally, Chapter 3 also discusses possible LED applications based on zinc oxide nanorod–graphene nanocomposites.

Chapter 4 deals with graphene metallic and passive components. The chapter starts with a brief history of grapheme, followed by an extensive review on various applications such as transparent and flexible electrodes, liquid crystal displays, flexible smart windows and bistable displays, light emitting devices, and touch panel devices. Because of its promising features such as high charge mobility, transparency, mechanical strength, and flexibility, graphene plays a vital role as the transparent electrode in many electronic devices. In Chapter 4, the question as to why graphene can be a potential candidate to replace the commonly used transparent electrode indium tin oxide (ITO) is answered. In the end, Chapter 4 also deals with photovoltaic devices that have received huge attention in terms of anode and cathode buffer layers.

Chapter 5 deals with large-scale graphene growth, which offers a viable route toward high-frequency devices. Although a major issue is to synthesize and fabricate high-frequency devices with high carrier mobility, this chapter discusses the current efforts to understand and control the growth mechanism and fabrication of the devices. Graphene transistor, graphene functional circuit, and self-aligned electrode are also discussed comprehensively in this chapter. Finally, graphene dielectrophoresis, which handles the phenomenology of the particles subjected to an electric and a magnetic field, is also discussed.

Chapter 6 deals with bandgap engineering of graphene, which can be divided into three categories, namely surface bonding, isoelectronic codoping, and alternating electrical/chemical environment. The surface bonding usually lifts the top σ valence bands over the π valence states, and consequently opens an sp^3 bandgap of graphene. By breaking the equivalence of the sublattices, isolectronic codoping and alternating chemical environment would effectively open the $\pi-\pi^*$ bandgap of graphene. In Chapter 6, bandgap engineering in bilayer and multilayer graphene, as well as in graphene nanoribbons, is discussed. Finally, bandgap engineering by strain is also dealt with in this chapter.

Chapter 7 deals with spintronics in graphene. In spintronics, there are three major parts: generation, detection, and manipulation, among which spin generation is the most important one. It can be considered as the basis of the other two. Thus, Chapter 7 mostly discusses spin generation and manipulation in graphene. Driving spin into graphene is also discussed by various methods, including magnetic field, tunneling, and heat. Finally, Chapter 7 ends with the functionalization of spin current by spin logics.

Chapter 8 deals with magnetism and spin phenomenon arising from pore edge spins in graphene nanomeshes. It discusses ferromagnetism, non-lithographic fabrication of graphene nanomeshes with zigzag pore edges, and defect-dependent, spin-related phenomena in magnetoresistance measurement. At the end of the chapter, recent advances in spin-based phenomena (SHE) are also discussed.

Chapter 9 deals with the manipulation terahertz waves in graphene. Basically, there are several terahertz properties and applications of grapheme, such as unique terahertz response, terahertz lasers, terahertz device concepts, and the reconfigurable terahertz optoelectronics. In this chapter, extensive discussions on the static terahertz properties and new concepts to manipulate terahertz waves, ranging from electrooptic and magnetooptic to all-optic modulation based on the intrinsic terahertz properties, are given. Finally, advanced terahertz wave manipulation and the concept of plasmons and metamaterials with graphene are discussed.

Chapter 10 deals with chemical and biological sensors. Chemical and biosensors are becoming an indispensable part of our society with wide usage across various fields, including biomedical, chemical processing, clinical, environmental, food, military, pharmaceutical, and security applications. In general, sensors are composed of two fundamental constituents: (i) a recognition element that is designed to be sensitive to a particular stimulus, and (ii) a transduction element that is responsible for generating a signal whose magnitude can then be used to determine the concentration of the analyte. This chapter discusses the latest developments in the application of graphene-based materials to chemical and biosensors. It starts with electronic and electrochemical sensors, which also include biosensors, and ends with a discussion based on optical sensors.

This book contains materials from various sources including the authors' previously published articles, their latest experiments, and their lecture notes. All materials in this book have been organized, reviewed, and now presented in a consistent and more readable way because they have been reviewed very thoroughly and reformulated where necessary. It has been a great pleasure contributing to and at the same time editing this book on the device physics of graphene. For me, this book was a labor of love, and the adventure involved in compiling the content along a unifying theme was a great enriching experience and sufficient reward in and of itself. I hope that all readers will similarly find great enrichment and understanding as they explore the pages of this book. Finally, I would like to thank my lovely wife Sharifah Nurilyana and my family for their support and understanding. Special thanks also are due to my students, colleagues, and, last but not least, my director, Jin Jang, for fruitful discussions and help.

A. Rashid bin Mohd Yusoff