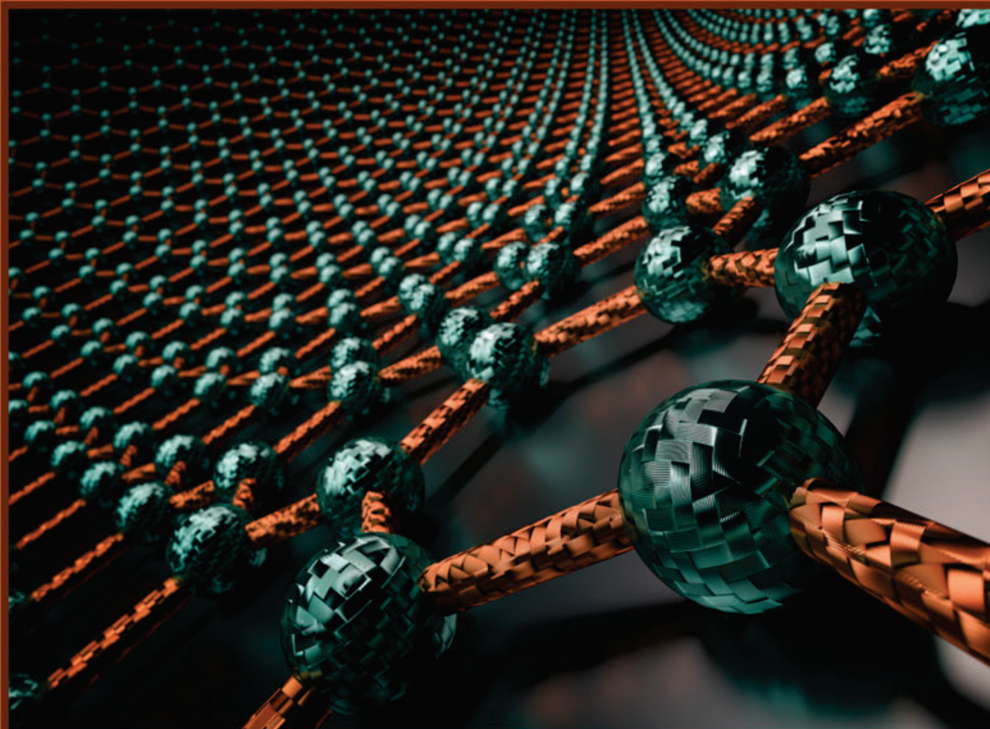
WOODHEAD PUBLISHING IN MATERIALS



GRAPHENE: SYNTHESIS, PROPERTIES, TECHNOLOGY, AND APPLICATIONS

Edited by
SARITHA APPUKUTTAN
JITHA S. JAYAN
A.S. SETHULEKSHMI

ELSEVIER

Graphene: Synthesis, Properties, Technology, and Applications

This page intentionally left blank

Woodhead Publishing in Materials

Graphene: Synthesis, Properties, Technology, and Applications

Edited by

Saritha Appukuttan

Jitha S. Jayan

A.S. Sethulekshmi

ELSEVIER

WP WOODHEAD PUBLISHING

An imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
125 London Wall, London EC2Y 5AS, United Kingdom

ISBN: 978-0-443-26627-0 (print)

ISBN: 978-0-443-26628-7 (online)

For information on all Woodhead Publishing publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Matthew Deans
Acquisitions Editor: Gwen Jones
Editorial Project Manager: Debarati Roy
Production Project Manager: Kamesh R.
Cover Designer: Gopalakrishnan Venkatraman

Typeset by MPS Limited, Chennai, India

Contents

List of contributors

Nahid Ahmadi School of Shahed Mahdieh, Education of Zanjan, Zanjan, Iran

Saritha Appukuttan Department of Chemistry, Amrita Vishwa Vidyapeetham, Kollam, Kerala, India

Mohammad Arefi Department of Solid Mechanics, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

Deeraj B.D.S. Department of Materials Engineering, Indian Institute of Science, Bengaluru, Karnataka, India

Jyoti Bhattacharjee Department of Chemical Engineering, University of Calcutta, Kolkata, West Bengal, India

Elyas Mohammad-Rezaei Bidgoli Department of Solid Mechanics, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

Suryasarathi Bose Department of Materials Engineering, Indian Institute of Science, Bengaluru, Karnataka, India

Akshatha Chandrashekar Faculty of Natural Sciences, Department of Chemistry, MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Shyam Kumar Choudhary New Material Business, Tata Steel Ltd, Jamshedpur, India

Preetam Datta CRNN, University of Calcutta, Kolkata, West Bengal, India

Kardelen Altan Ertaş Department of Chemistry, Faculty of Science, Bilecik Seyh Edebali University, Bilecik, Türkiye

Suyin Gan Faculty of Science and Engineering, University of Nottingham Malaysia, Semenyih, Selangor, Malaysia

N. Gomathi Department of Physics, Saveetha Engineering College (Autonomous), Chennai, Tamil Nadu, India

Abu Hashem Microbial Biotechnology Division, National Institute of Biotechnology, Dhaka, Bangladesh

Madhushree Hegde Faculty of Natural Sciences, Department of Chemistry, MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Billie Yan Zhang Hiew School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, Putrajaya, Malaysia

M.A. Motalib Hossain Institute of Sustainable Energy, Universiti Tenaga Nasional, Kajang, Malaysia

Jitha S. Jayan Department of Chemistry, Amrita Vishwa Vidyapeetham, Kollam, Kerala, India

A.G. Jineesh Department of Science, Alliance University, Bengaluru, Karnataka, India

Mohd Rafie Johan Nanotechnology and Catalysis Research Centre, Institute for Advanced Studies, Universiti Malaya, Kuala Lumpur, Malaysia

J. Lavanya Department of Physics, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India; Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India

Lai Yee Lee Faculty of Science and Engineering, University of Nottingham Malaysia, Semenyih, Selangor, Malaysia

Ajith R. Mallia Department of Chemistry, St Berchmans College, Changanasserry, Kottayam, India

Mohammad Al Mamun Nanotechnology and Catalysis Research Centre, Institute for Advanced Studies, Universiti Malaya, Kuala Lumpur, Malaysia; Department of Chemistry, Jagannath University, Dhaka, Bangladesh

Ab Rahman Marlinda Nanotechnology and Catalysis Research Centre, Institute for Advanced Studies, Universiti Malaya, Kuala Lumpur, Malaysia

R. Naveena Department of Chemistry, Indian Institute of Space Science and Technology, Thiruvananthapuram, Kerala, India

Jun Hong Ooi Faculty of Science and Engineering, University of Nottingham Malaysia, Semenyih, Selangor, Malaysia

Vaishali Pathak ChemX-VV Pvt. Ltd, Bharuch, Gujarat, India

T. Niranjana Prabhu Faculty of Natural Sciences, Department of Chemistry, MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Vinay Deep Punetha 2D Materials and Remote Actuation Laboratory, Centre of Excellence for Research, P P Savani University, Surat, Gujarat, India

Subhasis Roy Department of Chemical Engineering, University of Calcutta, Kolkata, West Bengal, India; CRNN, University of Calcutta, Kolkata, West Bengal, India

Vimal Kumar S. Department of Materials Engineering, Indian Institute of Science, Bengaluru, Karnataka, India

M. Saigayathri Department of Chemistry, Amrita Vishwa Vidyapeetham, Kollam, Kerala, India

Parag Sanghani 2D Materials and Remote Actuation Laboratory, Centre of Excellence for Research, P P Savani University, Surat, Gujarat, India

Montree Sawangphruk School of Energy Science and Engineering, Vidyasirimedhi Institute of Science and Technology, Rayong, Rayong Province, Thailand

A.S. Sethulekshmi Department of Chemical Technology, Chulalongkorn University, Bangkok, Thailand

Abdul Aziz Shaikh CRNN, University of Calcutta, Kolkata, West Bengal, India

Hülya Silah Department of Chemistry, Faculty of Science, Bilecik Seyh Edebali University, Bilecik, Türkiye

Suchithra Thangalazy-Gopakumar Faculty of Science and Engineering, University of Nottingham Malaysia, Semenyih, Selangor, Malaysia

Archana Vinod Department of Chemistry, Amrita Vishwa Vidyapeetham, Kollam, Kerala, India

Yasmin Abdul Wahab Nanotechnology and Catalysis Research Centre, Institute for Advanced Studies, Universiti Malaya, Kuala Lumpur, Malaysia

This page intentionally left blank

About the editors

Dr. Saritha Appukuttan is an professor in the Department of Chemistry, School of Physical Sciences at Amrita Vishwa Vidyapeetham, Amritapuri, Kollam, India. Her research interests include polymer micro and nanocomposites, polymer blends, graphene-based composites, rubber nanocomposites, 2D materials for energy storage and EMI shielding, biocomposites, electrospun fiber composites, shape memory composites, and epoxy nanocomposites.

Dr. Jitha S. Jayan is a Postdoc Fellow in the Department of Chemistry, School of Physical Sciences, Amrita Vishwa Vidyapeetham, Amritapuri, Kollam, India. She has worked as a Research Associate at Tata Steel Ltd. for the initiative India Innovation Center for Graphene (IICG). Her research interests include nanomaterial synthesis and functionalization, polymer synthesis and processing, polymer nanocomposites, block copolymers, biopolymers, graphene and its derivatives, 2D materials, hydrogels, sensing, energy storage, and anticorrosion.

Dr. A.S. Sethulekshmi presently serves as a C2F Postdoctoral Fellow in the Department of Chemical Technology at Chulalongkorn University, Bangkok, Thailand. Her research interests span a wide range of areas including natural rubber nanocomposites, 2D materials, green nanocomposites, green synthesis of nanomaterials, and textile coating.

This page intentionally left blank

Electrical properties of graphene

4

Kardelen Altan Ertaş, and Hülya Silah
Department of Chemistry, Faculty of Science, Bilecik Seyh Edebali University, Bilecik, Türkiye

4.1 Introduction

The term "graphene" was first introduced by Boehm in 1986. The history of graphene extends back to the 1940s when Schafhaeutl utilized nitric and sulfuric acids to intercalate and exfoliate graphite [1,2]. Graphene, a form of elemental carbon, has garnered significant attention nowadays because of its inimitable features. It comprises a single layer of carbon atoms arranged in a honeycomb-like model. The first successful production of graphene was achieved by a team led by Konstantin Novoselov and Andre Geim in 2004. However, they informed Hanns Peter Boehm and other scientists who conducted experiments comparing graphene with thin graphite flakes for this discovery. Consequently, Hanns Peter Boehm became the first scientist to utilize the term "graphene" in 1986 [3,4]. Graphene has three main derivatives: graphane, graphene oxide, and fluorographene. Fig. 4.1 displays these alongside other derivatives, like graphite, fullerenes, and carbon nanotubes. These derivatives differ significantly owing to unique characteristics. Derivatives of graphene have distinct properties due to variations in structure and chemical composition [3]. Graphene has various stacking configurations, including monolayer (SLG), few-layer (FLG), and multilayer graphene (MLG). SLG consists of a single sheet of carbon atoms in a hexagonal lattice, with each atom forming sp^2 covalent bonds with its neighbors. The 2D arrangement of graphene serves as the elemental unit for numerous carbon allotropes, comprising zero-dimensional (0D) fullerenes, one-dimensional (1D) carbon nanotubes, and three-dimensional (3D) graphite. Graphene is also lightweight, structurally robust, extremely tough, and has significant electrical and thermal conductivity, among other advantageous qualities. Among nanomaterials, it is acknowledged to be the strongest and thinnest substance. Excellent electrical and thermal conductivity, great electron mobility, and significant mechanical strength are only a few of graphene's many diverse qualities [5]. This makes SLG incredibly thin, at just one atom thick [6]. Graphene has become a significant carbon nanomaterial, initially identified through the groundbreaking research conducted by Konstantin Novoselov and Andre Geim in 2004. They successfully isolated graphene by exfoliating graphite using adhesive tape [7].

Approximately 40 years ago, the research on graphene gained substantial importance when it was proposed that graphene serves as a condensed matter analog of quantum electrodynamics, encompassing two spatial dimensions and one temporal dimension [8]. Graphene is referred to as "the simplest complex material" and has

Graphene: Synthesis, Properties, Technology, and Applications. DOI: https://doi.org/10.1016/B978-0-443-26627-0.00010-5