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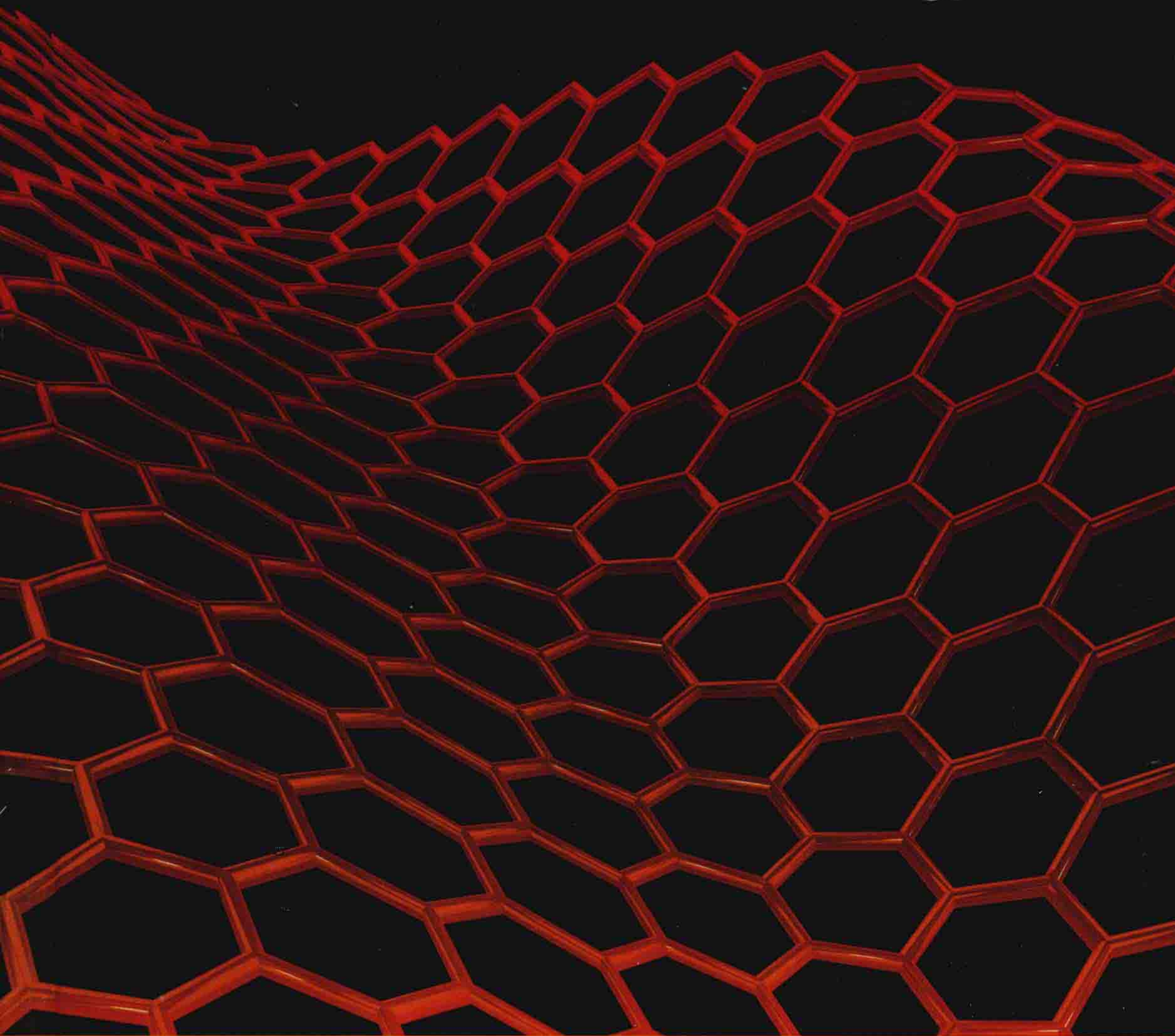
Graphene-Based Materials

Science and Technology



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Preface

An atom-thin form of carbon called graphene has been continuously studied since its discovery due to its versatile properties, such as exceptional electronics, half-integer quantum hall effect, ballistic electron transport, optoelectronic properties, and high crystal quality. Further, graphene offers truly unique opportunities because, unlike most semiconductor systems, its two-dimensional (2D) electronic states are not buried deep under the surface, and it can be easily accessed directly by tunneling or by other local probes. Until now, graphene has been considered the strongest and thinnest material known. Tremendous advancements have been made for the application of graphene in nanoelectronics. Moreover, graphene has been used in biological systems for the detection of DNA, RNA, proteins, and nucleic acids. In addition, graphene-based nanodevices are available for the detection of bacteria and pathogens. Presently, graphene holds the key to everything from small computers to high-storage batteries and capacitors. Graphene's properties are attractive to physicists, materials scientists, and electrical engineers for several reasons, not least of which is that it might be possible to build circuits that are smaller and faster than what can be built in silicon. Due to all the properties exhibited by graphene, A. K. Geim and K. S. Novoselov, the inventors of graphene, were awarded a Nobel Prize in 2010. In this book, we analyze the recent advancements in graphene research, such as synthesis, properties, and important applications in several fields.

Chapter 1 gives a brief introduction regarding the history of graphene and its important properties. Chapter 2 discusses the different methods of graphene synthesis available in the literature. Chapter 3 gives a brief overview of a few important characterization techniques that distinguish graphene from its allotropes. The application of graphene in gas sensors is presented in detail in Chapter 4. In Chapter 5, the application of graphene in biosensors and energy storage is discussed in detail. Chapter 6 presents the important photonic device and optoelectronic device applications of graphene-based materials.

We would like to thank Professor Shyam Mohapatra, distinguished professor and director, Nanomedicine Research Center, College of Medicine, University of South Florida, Tampa, for his valuable suggestions and comments during the preparation of this book.

Dr. Alwarappan would also like to thank Chen-Zhong Li, Kaufmann professor, Department of Biomedical Engineering, Florida International University, Miami, with whom he started his graphene-based electrochemical biosensor research. Since 2009, Dr. Alwarappan has been supported by Dr. Li in his graphene-related work.

We would like to extend thanks to the technical staff at the Nanotechnology Research and Education Center and Nanomedicine Research Center, University of South Florida, Tampa, for their support in our graphene research for the last two years.

We extend thanks to the publishers who granted us permission to reproduce the artwork and experimental figures published in their journals.

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Finally, Dr. Alwarappan would like to thank his wife and family for their support and encouragement throughout the preparation of this book.

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Dr. Subbiah Alwarappan received his BSc (chemistry, 1999) from Alagappa Government Arts College, Karaikudi, Tamilnadu, India, and MSc (chemistry, 2001) from Presidency College, Chennai, Tamilnadu, India. Later, he was awarded an International Postgraduate Research Scholarship fellowship to pursue his PhD (in electroanalytical chemistry, 2006) at Macquarie University, Sydney, Australia. During his PhD studies, he worked toward the design of miniaturized pyrolyzed carbon electrodes for the *in vivo* detection of important neurotransmitters. Later, he worked as a postdoctoral researcher at the University of Iowa, Iowa City, for one year. In November 2007, he moved to Florida International University, Miami, and spent two years there as a postdoctoral research associate (November 2007 to November 2009). He accepted a position at the Nanomaterials Research and Education Center, University of South Florida, Tampa, and worked there for a year as a senior postdoctoral researcher (November 2009 to December 2010). He was then a joint research faculty member at the College of Medicine and Nanotechnology Research and Education Center at the University of South Florida, Tampa (January 2011 to January 2013). During this period, his research interests included synthesis and characterization of novel carbon-based materials such as graphene, carbon nanotubes for high-performance biosensing, immunosensing, environmental toxin detection, and modeling of various processes occurring at an electrode's interface. Dr. Alwarappan has published more than 26 peer-reviewed research articles in the electroanalytical research area, especially on graphene-based electrochemical sensors. He also authored three book chapters and has delivered more than 20 presentations at conferences, symposia, and invited talks. His articles have been cited more than 500 times. He has been the invited reviewer for more than 30 peer-reviewed journals published by the Royal Society of Chemistry (RSC), American Chemical Society (ACS), and Elsevier. He is also serving as a reviewer for several prestigious funding agencies.

Dr. Ashok Kumar is a professor in the Department of Mechanical Engineering at the University of South Florida, Tampa. His research is focused toward the development of nanotechnology-based novel materials for multifunctional applications. His other interests include K–12 educational outreach, gender and science education, and nanotechnology industrial outreach. He has published 2 textbooks; edited 7 books of proceedings; and 12 book chapters, including 200 peer-reviewed articles. His excellence as a researcher has been recognized with a number of honors, including the ASM Fellow (2007), AAAS Fellow (2010), ASM-IIM Visiting Lecture Award (2007), Theodore and Venette Askounes Ashford Distinguished Scholar Award (2006), USF Outstanding Faculty Research Achievement Award (2004), USF President Faculty Excellence Award (2003), NSF (National Science Foundation) Faculty Early Career Development Award (2000), National Research Council Twining Fellowship Award (1997), and NSF and DOE (Department of Energy) EPSCoR Young Investigator Awards (1996–1997). He also received the Professor Honorario award from the Universidad del Norte, Barranquilla, Colombia (2009) and an outstanding faculty award in 2013 from the University of South Florida.

Contents

Chapter 1

Graphene: An Introduction

1.1 Graphene: History and Background

The possibility of graphene's existence or that of a two-dimensional (2D) allotrope of carbon has been theoretically studied for 60 years. Often, the term *graphene* was used to describe the properties of carbon allotropes [1–3]. However, after four decades it has been realized that graphene also provides an excellent condensed matter analogue of (2 + 1)-dimensional quantum electrodynamics [4–7], thereby exposing graphene to a thriving theoretical "toy" model [7]. Graphene was expected to be unstable due to the formation of curved structures such as soot, fullerenes, and nanotubes. Further, graphene was believed not to exist in its free state. Unexpectedly, in 2004, the prediction of graphene's existence became true when freestanding graphene was discovered by Geim and Novoselov [8,9]. Moreover, the follow-up experiments demonstrated that its charge carriers were indeed massless Dirac fermions [10,11]. As a result of this phenomenon, graphene is indeed the material of choice for numerous researchers. Geim and Novoselov shared the 2010 Nobel Prize in Physics for the discovery of graphene [12–14].

Graphene is considered the flat single layer of carbon atoms that are tightly packed into a honeycomb-like crystalline lattice in a 2D fashion [8–11]. Further, graphene is often known as the "mother" or the basic building unit of all other carbon allotropes. For instance, graphene can be wrapped up to a zero-dimensional (0D) fullerene, rolled to resemble one-dimensional (1D) carbon nanotubes, or stacked to a three-dimensional (3D) graphite (see Figure 1.1) [8–11]. To understand 2D graphene in detail, we briefly describe the 2D crystals [7]. A single atomic plane of graphene is

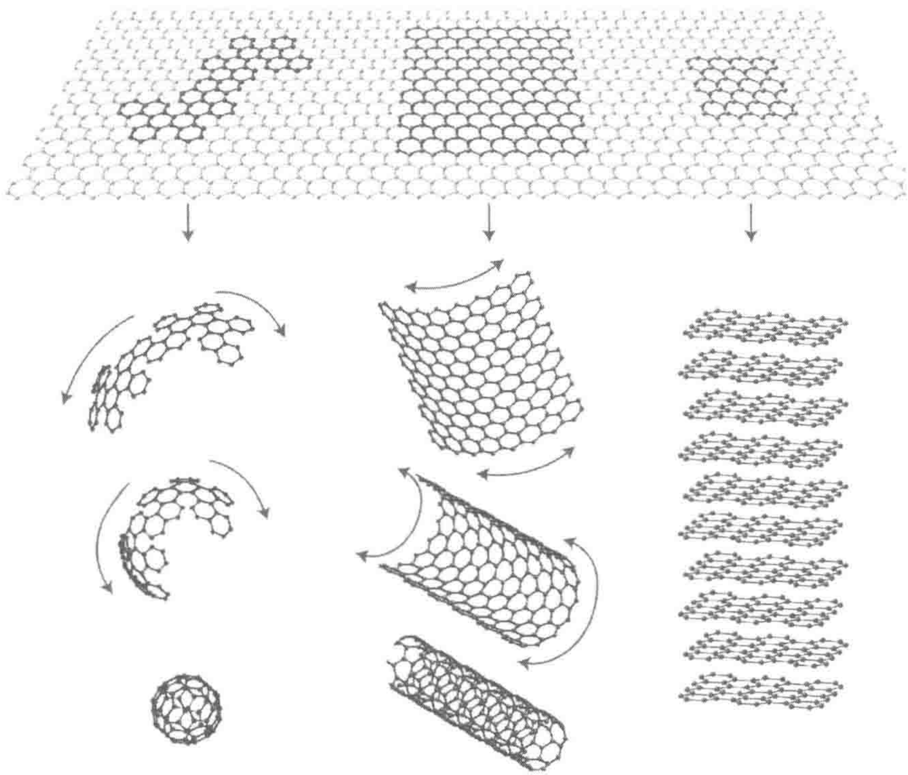

Figure 1.1 Scheme showing graphene can be wrapped to 0D fullerenes, wrapped to form 1D carbon nanotubes (CNTs), or stacked to form 3D graphite. (Reproduced with permission from A.K. Geim, K.S. Novoselov, *Nat. Mater.* 6, 183–191, 2007.)