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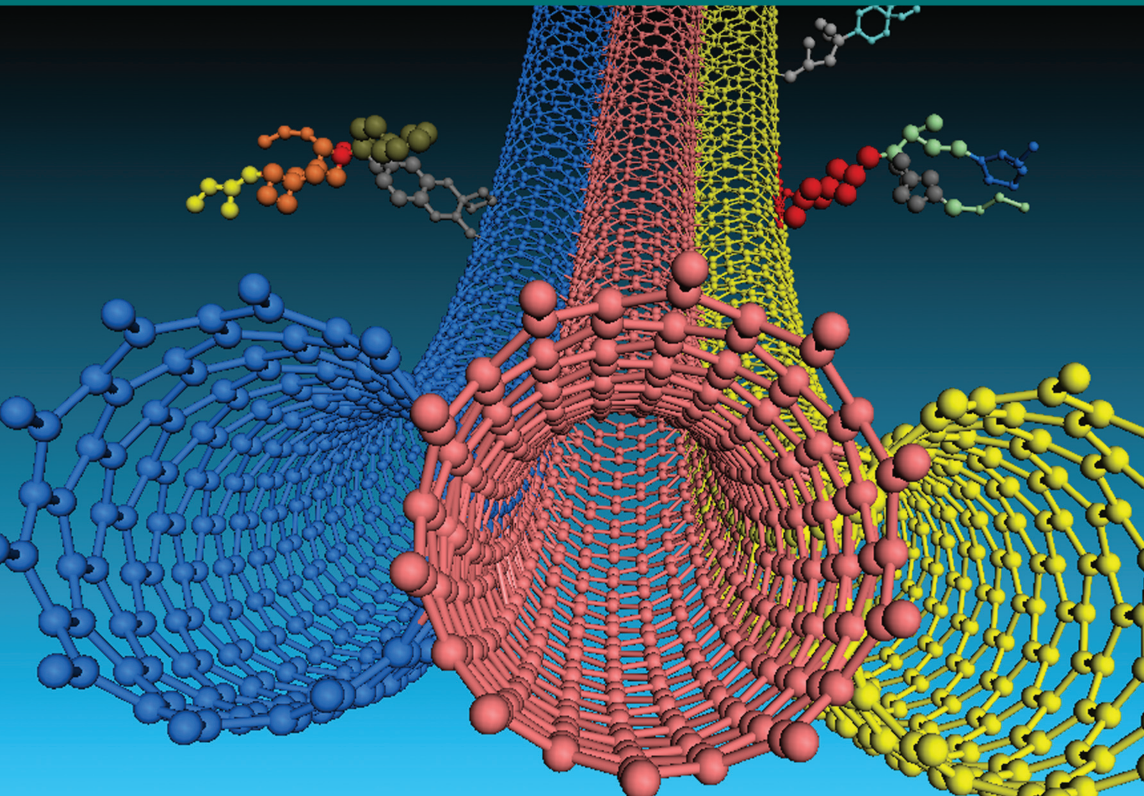
Carbon-Based Nanomaterials — Volume 1



Carbon Nanotubes and Their Applications

edited by
Qing Zhang

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Preface

Carbon nanotubes (CNTs) are a fantastic member of the carbon family. Their crystal structures are very close to graphite, belonging to sp^2-bonded carbon, rather than sp^3-hybridized carbon in diamond. Topologically, a single-wall CNT (SWCNT) can be constructed by rolling up a single layer of graphite or graphene along a certain direction into a tiny cylinder with a possible diameter from subnanometer to a few nanometers. Interestingly, the rolling-up direction and diameter or the chirality of an SWCNT determine its fundamental properties. Some SWCNTs have small energy bandgaps, showing semiconducting characteristics, whereas others do not have the bandgap and they are metallic ones. For CNTs with more than one cylindrical shell, the interactions between the shells must be taken into account. Indeed, different CNTs have different properties and application potentials. Until now, CNTs have not only attracted enormous research interest but also stimulated CNT-related applications and industrial development. This can be seen through the facts that more than 77,000 articles about CNTs have been published (ISI database, February 2012) and many CNT-relevant products are available on the market.

Extensive study of CNTs began in 1991 when very thin CNTs were observed by S. Iijima. Although tremendous progress has been made in understanding the fundamental properties of CNTs, optimizing CNT synthesis conditions and post-treatment processes, and exploring various potential applications, etc., are still very hot and active topics nowadays. The electrical and optical properties of SWCNTs are dominated by their chiralities. To obtain chirality-pure SWCNTs has been a dream for a long time. Precisely controlling CNT synthesis parameters and carefully selecting the catalysts used are confirmed to be the key factors that affect the chirality distribution of the grown CNTs. A large number of post-treatment processes have been reported to sort CNTs in terms of their semiconducting or metallic properties, their thickness and lengths, etc. The assembly of CNTs in desirable and controllable ways is another technical challenge. Many unique superior properties, say high electron mobility in electronic applications, high Young's modulus and yield strength in mechanic applications, etc., can be brought into play only when CNTs are uniformly oriented. Major advances in handling CNTs have been propelled by enormous interest in assembling CNTs. In contrast, when the orientation of CNTs is not a critical factor to be considered, CNT random network can be directly incorporated into the devices that could be printed on a soft substrate in a large scale at a low fabrication cost. SWCNTs can be regarded as a one-dimensional material that forms a perfect platform on which experimentalists could explore the mystery of physical puzzles observed only in a low-dimensional object. Super high sensitivity of CNTs, plus their high stability in most chemical environments and high compatibility to most biological materials, promotes CNTs to be utilized as the sensing elements in a wide variety of sensors for chemical and biological detections. Typically, CNT sensors are of much higher sensitivities than their counterparts made from other materials. However, how to improve the selectivity of CNT sensors is a big concern. CNT/polymers and CNT/metal composites have emerged as a class of new functional materials that are reinforced through embedded CNT network in favor of not only the composites' mechanical properties but also electrical properties. Besides, the study of CNTs and their composites in damping and viscoelastic properties is attracting more research attention. The investigation of these properties could lead to a feasible solution to dealing with the vibration damping in micro-/nanodevices. CNTs are not totally "black." Semiconducting CNTs are of direct bandgaps, and this greatly facilitates CNT-based optical and optoelectronic applications and opens the field of CNT nanophotonics.

This book collects 16 state-of-the-art chapters that cover the fundamental properties, relevant technologies and potential applications of CNTs. It gives an overview of the current status of the research and development activities of CNTs. It will be a valuable reference for scientists, researchers, engineers and students who wish to know more about CNTs. It will appeal to anyone involved in nanodevices, nanomaterials and nanofabrication.

Chapter 1 addresses the crystal structure and electronic band structure of SWCNTs. The density of states and singularities are presented to facilitate the discussion on the electronic and optical properties and basic phonon features of SWCNTs. Chapter 2 reviews various CNT synthesis techniques, especially chemical vapor deposition techniques, by which CNTs could grow at much lower temperatures compared with other commonly used methods. New approaches to efficiently growing high-quality CNTs at a large scale, macroscopically long CNTs, directed-grown CNTs, and chirality-pure CNTs are reviewed. The state-of-the-art synthetic assembly and post-synthetic assembly of CNTs are summarized in Chapter 3. It covers not only the assembly/alignment processes at a small scale for laboratory research purposes, but those for industrial production. Orientated CNTs are achievable in several post-synthetic treatments through electrical force, dielectrophoretic force, shear adhesion force, etc. Chapter 4 focuses on separating semiconducting CNTs from metallic ones. Several separation approaches with remarkably high capabilities are introduced in terms of the separation mechanisms and technical details. The electron transport properties and the electrical conductance of CNTs in response to electrical fields in the geometries of single-electron transistors, field-effect transistors, etc., are reviewed in Chapter 5. High carrier mobility is one of the key merits for CNT high frequency/speed electronic applications. The fabrication and high-frequency characterization of CNT field-effect transistors are summarized in Chapter 6. It has been demonstrated that tunneling field-effect transistors are capable of breaking through the smallest possible subthreshold swing for conventional metal–oxide–semiconductor field-effect transistors. In Chapter 7, the recent developments in CNT-based tunneling field-effect transistors are highlighted. High degree of CNT orientation may not be critical for some applications. A large category of CNT electronic devices are directly built on CNT random networks. Chapter 8 introduces several main techniques, including selective elimination or destruction of metallic CNTs and photolithography-assisted stripping to enhance the semiconducting behaviors of CNT networks. Metallic and multiwall CNTs have high electrical conductivities, and they also have extremely high aspect ratios. These make CNTs a very good material for electron field emitters. A comprehensive review on the recent development of CNT field emission technology for vacuum electronic applications in medical x-ray imaging and radiotherapy is presented in Chapter 9. There have been some arguments on ultrahigh temperature superconductivity of multiwall CNTs (MWCNTs). Chapter 10 presents several unusual magnetic experimental findings from Ni magnetic nanoparticles embedded in MWCNTs. The arguments on ultrahigh-temperature superconductivity of MWCNTs are revisited. The properties of CNTs are highly sensitive to the details how they interact with their surroundings. Based on these, a variety of CNT sensors have been developed. In Chapter 11, the electrocatalytic properties of CNTs and recent advances in CNT-based electrochemical biosensors are presented. In addition, CNT-based gas sensors and their sensing mechanisms are discussed in Chapter 12. Several measures to enhance the selectivity of CNT sensors are also highlighted. CNTs have excellent mechanical properties. The strength and weaknesses of applying CNTs and their composites to damping and viscoelastic applications are addressed in Chapter 13. Recent efforts have been devoted to spin and assemble CNTs into continuous lightweight and high-performance fibers. Various spinning methods, accompanied with different functionalities during spinning, are described in Chapter 14. The current status, future research focuses and challenges of several major CNT mechanical applications, including CNT nanomechanics and CNT actuators, are presented in Chapter 15. Finally, the origin of the optical nonlinearity of CNTs, the nonlinear effects, and potential CNT nonlinear applications are presented in Chapter 16.

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Qing Zhang
Singapore, February 2012

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