

# CARBON NANOTECHNOLOGY

RECENT DEVELOPMENTS IN CHEMISTRY,  
PHYSICS, MATERIALS SCIENCE AND  
DEVICE APPLICATIONS



LIMING DAI  
EDITOR

# **Carbon Nanotechnology**

**Recent Developments in Chemistry, Physics,  
Materials Science and Device Applications**

Edited by

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## FOREWORD

The world of nanotechnology has opened up a vast array of novel fundamental and applied frontiers in materials science and engineering. Nanotechnology is the control of matter at the nanometer-length scale and the exploitation of the novel properties and phenomena developed at that scale in the creation of practical materials, devices, and systems. Nanoscale materials and processes, especially biologically based ones, have always been around us, but it has only been in recent years that we have had the tools to identify these materials, to study and characterize them, and to manipulate in a controlled process. The relatively recent discoveries of buckminsterfullerene  $C_{60}$  and the carbon nanotube have created a whirlwind of exploration of both natural and man-made carbon nanomaterials and related nanotechnology.

For nearly 40 years, micron-size carbon fibers have been used for their high strength and stiffness and lightweight to reinforce polymeric materials for a variety of applications, ranging from tennis racquets to aircraft parts. Today, nanoscale carbon materials are being actively pursued for a large variety of applications such as household appliances, recreational sporting goods, biomedical devices, electronics, telecommunications, automobiles, aircraft, and space vehicles. In particular, it is envisioned that future aircraft and space vehicles will have a structure based on a material with a high strength-to-weight ratio, that is designed to withstand flight, launch, and landing loads, and also perform additional functions. The structure will incorporate various built-in miniaturized smart systems, including sensors, actuators, electronic and photonic devices. These smart systems will help to distribute loads and heat, sense environmental and load conditions, determine the state of health of the vehicle, provide electrical and magnetic fields for changing material properties, serve as a source of power, and offer sites for receiving, storing, processing, and transmitting information. However, today's conventional materials and designs cannot provide the desired multifunctionality. Because of their unusually high mechanical strength, high resilience, low density, excellent thermal and electronic properties, and tailorability, carbon nanotubes could provide multifunctional, super-strong, and light-weight composite structures for aircraft/aerospace and many other applications.

Recently, the nanoscale design and engineering of multifunctional materials and devices based on carbon nanotube composites have moved from a few empirical examples to a thriving, science-based activity. However, there are many challenges to overcome before carbon nanotechnology reaches its full potential. For instance, high-quality carbon nanotubes of a reproducible, uniform structure are not yet available in large quantities. Large quantities are essential to allow engineers to design, process, and test *structure*. If the price of carbon nanotubes remains as high as it is today, any large-scale application of carbon nanotubes will be unrealistic. Therefore, issues such as controlled syntheses of high-quality carbon nanotubes, new methods for functionalization of nanomaterials, and novel nanodevice design and integration are currently being actively investigated. The field of carbon

nanotechnology is expanding at a tremendous rate. With a comprehensive coverage of the recent development in the field, *Carbon Nanotechnology: Recent Developments in Chemistry, Physics, Materials Science and Device Applications*, edited by Liming Dai, is a timely and important addition to the currently available resources. It bridges the gap between the fundamental science of carbon nanomaterials and the development of practical devices through a broad treatment of key fields of work. Materials science and engineering, as well as device construction and application, are covered, with a large number of updated references and world-renowned experts' remarks. This book will be useful to both researchers who actively work with carbon nanomaterials and those merely curious about the possibilities that carbon nanomaterials offer. It can also be used both as a textbook and a critical reference by professionals and students in the disciplines of materials science, chemistry, physics, biology, and engineering.

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## PREFACE

Nanotechnology is no longer merely a topic of social conversation, but is beginning to affect the lives of everyone. Although nanotechnology, in general, covers many nanomaterials and processes, this book will focus on advances in carbon nanomaterials. Carbon has long been known to exist in three forms: amorphous carbon, graphite, and diamond. However, the Nobel Prize-winning discovery in 1985 of buckminsterfullerene  $C_{60}$ , which is a pure carbon molecule with a soccer ball-like structure consisting of 12 pentagons and 20 hexagons facing symmetrically, has created an entirely new branch of carbon chemistry. The subsequent discovery of carbon nanotubes in 1991 opened up a new era in materials science and nanotechnology.

A decade later, carbon nanotechnology has evolved into a truly interdisciplinary field encompassing chemistry, physics, biology, materials science, and engineering. This is a field, in which a huge amount of literature has been rapidly generated with the number of publications continuing to increase each year. Therefore, it is very important to cover the most recent developments in this field in a timely manner. To systematically manage a field of such breadth, *Carbon Nanotechnology* utilizes the expertise of many world-renowned experts and contributions from top researchers who have been actively working in the field. The reader will be exposed to a synopsis of the most cutting-edge research through comprehensive literature reviews in each chapter. This approach fosters an understanding of the scientific basis of carbon nanotechnology, and then extends this knowledge to the development, construction, and application of functional devices.

In order to cover a multidisciplinary field of such diversity, this book is divided into three major parts. The first part of the book, from Chapters 2 to 6, gives an overview of carbon nanomaterials. Then, Chapters 7 to 13 elucidate the basic science of nanocarbon chemistry and physics. The final part of the book, from Chapters 14 to 19, describes various device applications involving carbon nanomaterials. In addition, Chapter 1 gives a historical perspective of the field while Chapter 20 outlines some directions for the future development.

*Carbon Nanotechnology* is formatted to build off of a foundation of concepts fundamental to all fields of science. Therefore, it will be an essential reference for scientists, engineers, teachers, and students with backgrounds in physics, chemistry, biology, materials science, and engineering. While many self-explanatory illustrations could provide an overview understanding to those who are new to the field, the large number of updated references cited in each of the chapters should enable advanced readers to quickly review this challenging multidisciplinary field for the latest developments. Experienced academic and industrial professionals can use this book to broaden their knowledge of nanotechnology and/or to develop practical devices while graduate and senior undergraduate students can gain insight into a field of the future.

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# **INTRODUCTION**



## Chapter 1

# **From conventional technology to carbon nanotechnology: The fourth industrial revolution and the discoveries of C<sub>60</sub>, carbon nanotube and nanodiamond**

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### **1. THE INDUSTRIAL REVOLUTIONS THAT CHANGED THE WORLD**

Since the development of the two-cylinder steam engine by James Watt in the 1760s, human-kind has experienced three industrial revolutions [1]. The first industrial revolution, as represented by the appearance of Watt's steam engine, employed various machines to replace human labor. The second industrial revolution began at the end of the 19th century and was characterized by the discovery of the internal combustion engine and electric generator [2], which lead to the increased usage of electrical appliances, automobiles, and petroleum products. The construction of the first computer in the 1940s led to the third industrial revolution, which was followed by the rapid development of information technology [2].

Although many of these inventions and developments provide innumerable benefits, they also pose new and sometimes unforeseeable risks. For example, the appearance of internal combustion engineering led to the wide-spread availability of electric power for lighting, home appliances, industrial machines, automobiles, and aerocrafts. However, it also has contributed to the levels of air pollution and accelerated global warming. With the rapid increase in population, consumption of natural resources, environmental pollution, and information overflow, the turn of this century witnessed the birth of nanotechnology. The demand for miniaturized and multifunctional systems has been a driving force for the development of nanotechnology.

### **2. NANOTECHNOLOGY—THE FOURTH INDUSTRIAL REVOLUTION**

Owing to the intriguing size-dependent properties of nanophase materials [3], the recent development of nanoscience and nanotechnology has opened up novel fundamental and applied frontiers in materials science and engineering. The concept of nanotechnology was first introduced by Nobel laureate Richard Feynman [4] in 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech). In his classic lecture entitled: "There is a plenty room at the bottom", Feynman stated, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom". Later, Notio



Taniguchi from the Tokyo Science University first defined the nanotechnology as: (1) the creation of useful materials, devices, and systems through the control matter at the nanometer ( $10^{-9}$  m) length scale and (2) the exploitation of novel properties and phenomena developed at that scale [5]. The first scientific paper on nanotechnology was published in 1981 by Eric Drexler [6], a former student of Dr. Feynman at Caltech. Drexler's [7] idea of molecular manufacturing was followed by his book entitled: *Engines of Creation—The Coming Era of Nanotechnology* published in 1986. In this classic nanotechnology book, Drexler proposed the atom-stacking mechanism to produce machines smaller than a living cell and also presented some potential applications of nanotechnology. Although Drexler's publications have motivated researchers in the field of nanotechnology, the main breakthrough in nanotechnology occurred in 1981 when Binnig and Rohrer [8] at IBM Zurich invented the scanning tunneling microscope (STM)—the first instrument to generate real-space images of surfaces with atomic resolution. This discovery opened up the important new field of nanotechnology and was recognized by the 1986 Nobel Prize in Physics, along with the inventor of the electron microscope. Subsequently, Gerd Binnig, Christopher Gerber, and Calvin Quate of IBM devised the atomic force microscope (AFM) [9]. STM and AFM enabled not only the imaging of individual atoms, but also the manipulation of a single atom. Using STM, an IBM group precisely deposited 35 xenon atoms to spell out the name of IBM in April of 1990 [10]. Donald Eigler, the lead author on the *Nature* paper describing this work, saw clearly where all this is leading. Eigler [10] said, "For decades, the electronics industry has been facing the challenge of how to build smaller and smaller structures. For those of us who will now be using individual atoms as building blocks, the challenge will be how to build up structures atom by atom".

All matter is made up of atoms, with its properties depending strongly on how those atoms are arranged in space. If we could rearrange the atoms in coal, we could make diamond. If we could rearrange the atoms in sand (and add a few other trace elements), we could make computer chips. Consequently, nanotechnology, as defined to build materials and devices atom by atom, holds vast promise for innovation in virtually every industry and public sector, including health care, electronics, transportation, environment, and national security.

### 2.1. The bottom up vs. top down approaches

There are essentially two different approaches to creating very small structures or devices. As schematically illustrated in Fig. 1, individual atoms and/or molecules can be precisely placed where they are needed by scanning probe microscopy (e.g. AFM, STM, optical tweezers) or self-assembling [11]. This approach is designated as the "bottom up" because atomic or molecular building blocks are put together to create bigger objects. The second approach is called the "top down" approach, where macro-scale systems are converted into nanoscale ones by a series of sequential reduction operations to remove the unwanted portions away from the object that is wanted. The smallest features that can be created by the "top down" approach depend on the tools used and the system operator's experience and skills. In principle, there is no difference between the "top down" approach and the way a