Frontiers of Science and Technology for the 21st Century

Handbook of Nanophase and Nanostructured Materials — Characterization

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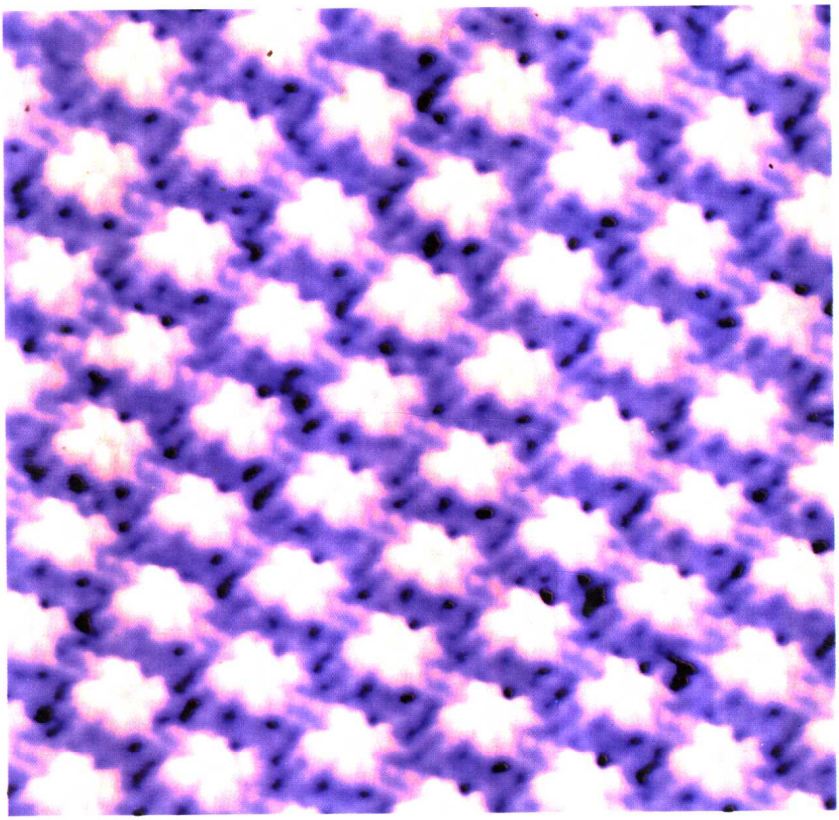

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Handbook of Nanophase and Nanostructured Materials—Characterization

纳米相和纳米结构材料
——结构和性能表征
手　册

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内 容 简 介

纳米相和纳米结构材料是纳米科学和纳米技术的基础。纳米相和纳米结构材料手册是一套综述纳米学科在材料合成、结构和性能表征、理论模拟、实际应用和发展前沿的书籍。本书是这套丛书的第二本。书中内容详细阐述分析表征纳米材料的方法和技术。主要围绕表征技术在分析纳米材料原子结构和物理化学性能中的原理、数据分析过程和具体应用,并介绍了各种方法的最新进展和参考文献。

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STM image of self-assembled CuPcOC8 on HOPG surface [Courtesy Dr. Chunli Bai and Dr. Chen Wang (Institute of Chemistry, CAS, Beijing)].

21 世纪科技前沿丛书

Frontiers of Science and Technology for the 21st Century

FOREWORD

Over the next several years, Tsinghua University Press will publish a series of books addressing progress in basic sciences and innovations in technology. We have made no attempt to pursue a comprehensive coverage of all disciplines of science and technology. Rather, topics for this series were selected with an emphasis on the currently active forefront of science and technology that will be contemporary in the next century. Most books in this series will deal with subjects of cross disciplines and newly emerging fields. Each book will be completed by individual authors or in a collaborative effort managed by an editor(s), and will be self-consistent, with contents systematically focused on review of the most recent advances and description of current progresses in the field. Sufficient introduction and references will be provided for readers with varying backgrounds. We have realize clearly the challenge of encompassing the diverse subjects of science and technology in one series. However, we hope that, through intensive collaboration between the authors and editors, high standards in editorial quality and scientific merit will be maintained for the entire series.

The international collaboration on this series has been coordinated by the Association of Chinese Scientists and Engineers-USA(ACSE). In the science community, authors voluntarily publish their results and discoveries in the full conviction that science should serve human society. The editors and authors of this series share this academic tradition, and many of them are fulfilling a spiritual commitment as well. For our editors and authors who were graduated from universities in China and further educated abroad in science and engineering, this is an opportunity to dedicate their work to

the international education community and to commemorate the historical open-door movement that began in China two decades ago. When the human society enters the information age, there is no geographic boundary for science. The Editorial committee hopes that this series will promote further international collaboration in scientific research and education at the dawn of the new century.

The Editorial Committee
1999. 6

《21 世纪科技前沿》

丛书序言

由清华大学出版社出版的这套丛书是基础科学和应用科学领域内的专门著作。除了可作为研究生教材外，也可作为科研和工程技术人员的参考书。在丛书的题材选择中，着重考虑目前比较活跃而且具有发展前景的新兴学科。因此，这套丛书大都涉及交叉和新兴学科的内容。编写的方式大多由主编策划并组织本学科有影响的专家共同执笔完成，从而使每一本书的系统性和各章节内容的连贯性得到了充分的兼顾。丛书涵盖学科的最新学术进展，兼顾到基本理论和新技术、新方法的介绍，并引入必要的导论和充分的参考文献以适应具有不同学术背景的读者。编撰一套容纳多学科的科技丛书是一项浩繁的工作，我们希望通过主编和作者的集体努力和精诚协作，使整套丛书的学术水准能够保持在较高的水平上。

编辑《21 世纪科技前沿》丛书是由"旅美中国科学家工程师协会"发起的一项国际科技界的合作。传递信息，加强交流，促进新世纪的科技繁荣是编著者们参与此项工作的共同信念。此外，这套丛书还具有特别的纪念意义。20 年前，历史的进程使成千上万的中国学生、学者有机会走出国门，到世界各地学习和从事科学研究。今天，活跃在世界科技前沿领域的中华学子们没有忘记振兴祖国科技教育事业的责任和推动国际学术交流与合作的义务。正是基于这一共同的心愿，大家积极参与这套系列丛书的撰写、组稿和编辑工作。为此，我们愿以这套丛书来纪念中国改革开放 20 周年。

编委会

1999. 6

Preface I

Materials are the base and forerunner of modern civilization. The progress of society usually takes the widely used material as a milestone in history, for examples the Stone Age, the Pottery Age, the Bronze Age, etc. modern civilization is symbolized by the application of steel and different metals in the 19th century. The present information age is based on the discovery and wide application of semiconducting materials, and it is sometimes called the Silicon Age.

Materials used by mankind were obtained from nature in ancient times, and then followed by artificial synthesis, and most important materials used at present are prepared artificially. The process of preparation may be macroscopic, microscopic or even atomic. Material made with atomic accuracy is called nanomaterial or nanostructured material. Nanomaterials usually show unique properties through nanoscale size confinement, predominance of interfacial phenomena and the quantum effect. Therefore, by reducing the dimension of a structure to nanosize, many inconceivable properties will appear and may lead to different applications.

In February 2000, a proposal , the "National Nanotechnology Initiative Leading to the Next Industrial Revolution," was published. This was produced by agencies of the U. S. government under the auspices of the National Science and Technology Council. They considered that nanotechnology could have a profound impact on the economy and society in the early 21st century, which might be comparable to that of information or biological technology. Hence, they suggested that materials science and technology should be given top priority.

Based on the government's concern, it can be predicted that an upsurge of R & D on nanotechnology will soon come, and *Nanophase and Nanostructured Materials*, edited by Z. L. Wang, Y. Liu and Z. Zhang, is just in time. This book is a complete and up-to-date treatise dealing with

nanostructured materials. It starts from materials synthesis and preparation with different methods, followed by characterization of a nanostructure and properties with different types of sophisticated instruments and novel experimental methods. About half of the book concentrate on materials systems and applications, which is considered a major part of the exploration of nanoscience and technology. Several chapters deal with information technology of the next generation, such as materials related to computer, storage and display. Several chapters are deal with superhard and superhigh strength materials, which are vital for future space and transportation technology . Biomaterials and biotechnology are hot topics for the next century, and several chapters focus on this aspect too.

The second feature of this book is that most authors are young scientists from different countries; United States, China, Japan and Singapore. They are active on the frontier of the field of nanoscience and technology and their works are stimulating and suggestive.

In all, nanoscience and technology is a rapidly growing field. I believe that the book will give a general survey for newcomers and a better understanding of the whole field to those who are working in specific areas.

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Chang Xu Shi
August, 2000

Preface Ⅱ

Nanoscale science and technology are experiencing a rapid development, and they are likely to have profound impact on every field of research in the first decade of the 21st century. The technologies for real-space atomic-scale imaging, atomic and molecular manipulation and nano-fabrication have been developed since the discovery of the Scanning Tunneling Microscope by G. Binning and H. Rohrer, who were awarded the Nobel Prize in physics in 1986. This invention has played a key role in promoting the development of nanoscale science and technology. The governments and enterprises of developed countries, such as the United States, Japan, Germany, United Kingdom, France, etc., are investing a lot of funds for nanotechnology research.

Nanoscale science and technology link many fields. The former chief editor of *Nature*, John Maddox, said: "The idea that physics has almost been worked out as a field for interesting investigations is widely current but mistaken. There is as much left to do as has been done." There are large quantities of unknown phenomena in the fields of mesoscopic physics, nanochemistry and nanobiology. Nanochemistry and nanoelectronics should be related to mesoscopic physics. Nanochemistry, for example, will face to the systems with limited atoms, molecules and ultrafine particles(i.e., clusters), and is related to chemical synthesis, self-assembled systems, self-organization growth, and so on.

Small microbes with life phenomenon belong to nanoscale. The diameter of a DNA molecule is less than 3 nm, and the diameter of a protein molecule is about a few nanometers. Therefore, nanobiology and nanomedicine have many virgin fields that remain to be explored. A scientist said: "When some matter can be designed and manufactured in biomolecular scales, the prospects will be wonderful. This is the excitement of nanoscience and nanotechnology."

Due to the development of integrated circuits, microelectronics should

advance into nanoelectronics and further, to molecular electronics: But the new materials, device design and manipulation, and manufacturing are the key challenges that have to be conquered step-by-step. Nanophase and nanostructured materials are fundamental to nanoscale science and technology.

The four volumes edited by Zhong Lin Wang, Yi Liu and Ze Zhang are very timely. There are 40 chapters in these volumes. Each chapter was written by specialists. These books will serve as excellent textbooks and references for researchers and graduate students in the field. This is the first set of the books published domestically in the field, and they will be very useful in promoting the development of nanoscience and nanotechnology in China as well as in the world.

Dr. Zhong Lin Wang, the main editor of these volumes, is a young professor at Georgia Institute of Technology, who has published over 200 scientific papers. He is famous for his work on "nanobalance". Dr. Wang is also a visiting professor at the Center for Nanoscale Science and Technology, Peking University. It is a privilege for me to write a preface for these volumes. I am confident that their publication will be a great success.

Center for Nanoscale Science and Technology
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Member of Chinese Academy of Sciences

Quan De Wu
August, 2000

Forward

Advances in science and technology in the 21st century are likely to focus on four directions: information science, life science, environmental science and nanotechnology. Wireless telecommunication, super-fast computers, and advanced computing technology have impacted everyone's daily life. The information highway has revolutionalized international communication and business operation. Life science is expected to have many breakthroughs in fields such as genetic engineering, biomedical sciences, disease prevention, control and curing. Preservation of natural resources and the environment is a challenge to human civilization and social progress because we only have one earth. Nanotechnology is based on the smallest unit of matter to engineering new materials and devices atombyatom, aiming at achieving superior properties and performance through atomic-scale architecture.

Advanced materials and advanced manufacturing will be the basis of the technological revolution. Take microelectronics as an example. Silicon technology is nearlly reaching its limit and the device size is in the sub-micro range; the era of nanoelectronics is arriving. As a result of reduced device sizes, many interesting quantum mechanical phenomena become dominant. A totally new and different approach is needed in device fabrication and system assembly. Therefore, nanophase and nanostructured materials, as a field of advanced materials, are the basis of nanoscience and nanotechnology. Research in nanoscience and nanotechnology faces four main challenges:

- Synthesis of structurally controlled nanomaterials, with well defined atomic-scale structure, high purity and large yield;
- Characterization of the structures and properties, especially the properties of individual nanostructures;
- Device fabrication, nanomanipulation and inter-device interconnection;
- System integration and large-scale manufacturing.

Research in nanomaterials is a multidisciplinary effort that involves physicists, chemists, materials scientists, electrical engineers, biological and, possibly, medical scientists. A rapid development in the field requires a book that covers the forefront research in a wide range, including materials synthesis, structure and property characterizations, theoretical modeling and applications. After editing these four volumes, we are convinced that nanomaterials will be the basis of nanotechnology. These books are about the synthesis, characterization and applications of nanophase and nanostructured

materials, which are referred to as nanomaterials. By nanophase materials we mean dispersive nanoparticles. Nanostructured materials are solid materials made of nanocrystallites. Nanomaterials are attractive because of their unique and superior electrical, mechanical and chemical properties, where the size of the grains approaches a few to a few hundreds of nanometers. Many of the outstanding properties are strongly enhanced when the size of the object is smaller than the electron mean-free-path length. There is no clear cut size smaller than that for which the materials are called nanomaterials, but a common understanding is that nanomaterials must exhibit some unique size-dependent properties that are minimal or vanish for large bulk crystals.

The contents of the volumes are classified into three parts. The first part emphasizes the synthesis of nanocrystal materials, aiming at describing the principles and approaches of the synthesis techniques, processing controls and the outcoming quality of the nanomaterials using chemical and physical techniques. The second part emphasizes the techniques used for characterizing nanomaterials, aiming at describing the physical mechanism, data interpretation and detailed applications for characterizing nanophase materials to understand the morphology, surface and the atomic level microstructures of nanophase materials and their associated properties. The final part focuses on the systems of different nanomaterials. The objective is to show their characteristics, unique properties and applications.

These volumes are intended as textbooks which not only reflect the state-of-the-art and give a sound review of the literature, but delineate the underlying concepts and bearing of this interdisciplinary field. The book is aimed at being a handbook which is the standard reference in the field for years to come. Our goal is to provide a comprehensive and complete introduction about nanomaterials to graduate students and researchers, whose background can be in chemistry, physics, materials science, chemical engineering, electrical engineering or even biomedical science.

We express our gratitude and appreciation to all of the authors for their hard work and contributions.

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前　言

21 世纪科学和技术的发展主要是围绕四大领域：信息科学、生命科学、环境科学和纳米技术。无线电通信，超快巨型计算机和先进的计算技术等给每个人的生活带来了巨大的变化。信息高速公路正在对国际通信和商业运作带来革命性的变更。生命科学期待在基因工程、生物医学、疾病预防、控制和治疗等领域取得突破性进展。自然资源和自然环境的保护是当务之急，因为人类只有一个地球。纳米技术是基于物质结构的最基本单元进行一个原子接一个原子的设计和制造新材料，其目的是通过原子级的操纵来实现超级性能和效益。

先进材料和先进制造业是技术革命的基础。以微电子技术为例，硅芯片技术的发展快要接近经典物理的极限，元件的尺寸已达到了亚微米级之小，紧接着就要达到纳米级了。随着元件尺寸的不断小型化，量子效应将起主导作用，因此元件的制造和集成将需要一崭新的且完全不同的工艺和程序。作为先进材料的一员，纳米相和纳米结构材料是纳米科学和纳米技术的基础，这方面的研究将面临四大挑战：

——合成原子级结构可控，高纯度和高产量的纳米材料；

——纳米材料结构的表征，特别是单个纳米结构的表征；

——器件合成，纳米级操纵和器件间的互联；

——体系集成和大规模生产。

纳米材料的研究是一跨学科跨领域并由物理学家、化学家、材料学家，电机工程师、生物学家和医学家等共同参与的研究。这方面的研究发展飞速，急需一套综述该学科在材料合成、结构和性能表征、理论模拟、实际应用和发展前沿的书籍。通过编辑这四本书籍，我们坚信纳米材料是纳米技术的基础。这些书是关于纳米相材料和纳米结构材料（统称为纳米材料）的合成、表征和应用。纳米相材料是指分散的纳米颗粒，而纳米结构材料则是由纳米晶粒所组成的固态物质。纳米材料之所以这么重要是由于尺寸减小而导致的独特而超常的电学，力学，光学和化学性能。当微粒尺寸在一维、二维或三维小于电子传输自由程时，它们的许多性能出现巨大的变化和增强。关于材料颗粒尺

寸究竟要小于多少才可被定义为纳米材料一般不存在一严格的界限，但是一个基本条件是当颗粒小于该尺寸时一些超常的或增强的性能必须呈现出来，否则尺寸再小也不算纳米材料。

这四卷书的内容可以分为三部分。第一部分（卷一）强调纳米材料的合成，主要目的是详细介绍常用的化学和物理纳米合成方法的原理和基本程序。第二部分（卷二）详细阐述分析和表征纳米材料的方法和技术，主要围绕表征技术在分析纳米材料原子结构和物理化学性能中的原理、数据分析过程和具体应用。第三部分（卷三和卷四）集中介绍和阐述纳米材料在各个领域中的应用。

这四卷书是互相关联但又可以分开的。它们不但可以作为纳米材料方面的教科书，同时也是系统介绍该领域内最新进展和文献综述的参考书。我们是把这些书籍作为纳米材料方面手册性资料来编辑的，目的是把该领域作一全面性的介绍和综述。它们适合于化学、物理、材料、化工、电机和生物医学等方面研究开发人员及高等院校的师生。

参加本系列书籍写作的作者主要来自于美国、中国和新加坡，他们都是在纳米材料和相关领域研究中卓有成效的世界级专家。我们衷心感谢他们为本套书的写作所付出的辛勤劳动和贡献。

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