

Frontiers of Science and Technology for the 21st Century

21世纪科技前沿丛书

HANDBOOK OF MICROSCOPY FOR NANOTECHNOLOGY

Volume I: Optical Microscopy,
Scanning Probe Microscopy,
Ion Microscopy, and Nanofabrication

纳米技术中的显微学手册

第1卷：光学显微学、扫描探针显微学、
离子显微学和纳米制造

姚楠 主编
王中林



清华大学出版社

Frontiers of Science and Technology for the 21st Century

21世纪科技前沿丛书

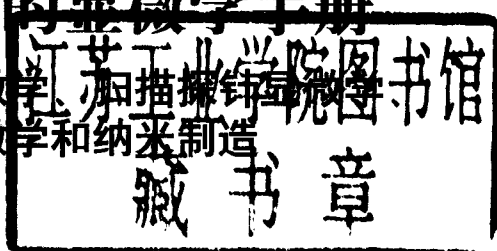
HANDBOOK OF MICROSCOPY FOR NANOTECHNOLOGY

Volume I: Optical Microscopy,
Scanning Probe Microscopy,
Ion Microscopy, and Nanofabrication

纳米技术中的显微学手册

第1卷：光学显微学、扫描探针显微学、
离子显微学和纳米制造

姚楠 主编
王中林



清华大学出版社

北京

内 容 简 介

现代显微学在纳米技术领域的研究和发展中起到“眼睛”和“手”的功能。迄今,人们仍在孜孜不倦地寻找纳米尺度上的“火眼金睛”。本手册的目的在于提供关于各种显微学的原理及其在该迅猛发展的领域内应用的综述参考书。本手册共有 22 个专题,每一专题都由不同研究领域的、处于世界前沿的科学家撰写。本书是第 1 卷,涵盖的范围包括共聚焦光学显微镜、扫描近场光学显微镜、各种扫描探针显微术、离子显微镜等,共有 10 个专题。本书力图使读者对所叙述的方法有一个概念上的理解,而不是只停留在对理论的堆砌上。在每一个专题里,都会叙述相关的实例及其应用并加以讨论,使读者对每种显微技术都能明了和理解;还会进一步展示各章之间的内在联系,表明每一种技术如何在综合性的、复杂的测试中各自扮演独特的角色,解决具体的问题。

版权所有,翻印必究。举报电话: 010-62782989 13501256678 13801310933

图书在版编目(CIP)数据

纳米技术中的显微学手册 第 1 卷: 光学显微学、扫描探针显微学、离子显微学和纳米制造 = Handbook of Microscopy for Nanotechnology Volume I: Optical Microscopy, Scanning Probe Microscopy, Ion Microscopy, and Nanofabrication/姚楠,王中林主编. —北京:清华大学出版社,2006.3

ISBN 7-302-11188-X

I. 纳… II. ①姚… ②王… III. 显微镜学—手册—英文 IV. TH742-62

中国版本图书馆 CIP 数据核字(2005)第 061255 号

出 版 者: 清华大学出版社

<http://www.tup.com.cn>

社 总 机: 010-62770175

地 址: 北京清华大学学研大厦

邮 编: 100084

客户服务: 010-62776969

组稿编辑: 张兆琪

文稿编辑: 韩燕丽

印 装 者: 北京华联印刷有限公司

发 行 者: 新华书店总店北京发行所

开 本: 153 × 235 印张: 22.25 彩插: 2 字数: 535 千字

版 次: 2006 年 3 月第 1 版 2006 年 3 月第 1 次印刷

书 号: ISBN 7-302-11188-X/TH · 168

印 数: 1 ~ 1500

定 价: 78.00 元

谨以此书献给我们的研究生导师 John M. Cowley 教授,以纪念他对科学和教育的杰出贡献。

21 世纪科技前沿丛书

Frontiers of Science and Technology for the 21st Century

主 编	刘国奎	美国阿冈国家实验室
Editor in Chief	G. K. Liu	Argonne National Laboratory, USA
编 委	陈忠孝	美国密歇根州立大学
	Z. X. Chen	Michigan State University, USA
	高 炜	美国科罗拉多州立大学
	W. Gao	Colorado State University, USA
	时东陆	美国辛辛那提大学
	D. Shi	University of Cincinnati, USA
	王中林	美国佐治亚理工学院
	Z. L. Wang	Georgia Institute of Technology, USA
	章效锋	美国劳伦斯伯克莱国家实验室
	X. F. Zhang	Lawrence Berkeley National Laboratory, USA

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 realized 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

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

《纳米技术中的显微学手册》

序

纳米技术的最新进展不断要求新的、有效的研究手段来迎接新世纪的挑战和机遇。在过去几年中,科学家们已经开始获得所必需的工具和知识来精确控制纳米尺度($1\text{nm} = 10^{-9}\text{m}$)上物质的结构,并能利用一个一个的原子来制作器件。这个被人们广泛称做纳米技术的、方兴未艾的领域,是以材料科学为基础的。在显微力学、电子技术、能量存储、磁性器件、分子水平上的构造等领域,纳米材料具有一系列令人眼花缭乱的性质并展现出一幅幅激动人心的美好前景。只有用一系列的现代显微分析技术,人们才能深入了解这些纳米材料和器件的“结构-组成-加工-性质”之间的内在联系。

如今,在这样一个多学科交叉的领域内编写这样一本手册显得尤为迫切。众所周知,三位纳米技术的主要开创者——扫描隧道显微镜的发明人 Heinrich Rohrer 和 Gerd Binnig 博士及世界上第一台电子显微镜的制造者 Ernst Ruska 教授由于他们在发展电子显微学方面做出的突出贡献分享了 1986 年诺贝尔物理奖。在纳米技术已经在全世界获得长足进展之际,这本手册想再次说明,显微技术的应用始终是科学发现的一个强大动力。而且,随着新技术的不断涌现,显微学作为推动纳米技术研究和发展的基本工具,显得比任何时候都更为重要。

现代显微学在纳米技术领域的发展和起到“眼睛”和“手”的功能。迄今,人们仍在孜孜不倦地寻找纳米尺度上的“火眼金睛”。本手册的目的在于提供关于各种显微学的原理及其在该迅猛发展的领域内应用的综述性参考书。本手册涵盖的范围包括共聚焦光学显微镜、扫描近场光学显微镜、各种扫描探针显微术、离子和电子显微镜、电子能量损失和 X 射线谱等。对于纳米技术领域内的研究人员和学生来说,这些都是极为重要的。在叙述这些专题时,本手册将提供广泛的应用实例,以激发读者进一步探索显微学的兴趣。本手册力图使读者对所叙述的方法有一个概念上的理解,而不是只停留在对理论的堆砌上。每一个专题都会叙述相关的实例及其应用并加以讨论,使读者对每种显微技术都能明了和理解。本手册还会进一步展示各章之间的内在联系,表明每一种技术如何在综合性的、复杂的测试中各自扮演独特的角色去解

决具体的问题。

本手册分上下两册,共有 22 个专题,每一专题都是由工作在不同研究领域的、处于世界前沿的科学家撰写。我们对这些作者致以衷心的感谢,正是他们的努力才使本手册得以顺利完成。向我们的研究生导师 John M. Cowley 教授表示最深的致意。他是一位卓越的科学家和教育家,是电子显微学、衍射和晶体学的先驱。更为重要的是,他是一个谦虚而和蔼的人,我们对他的指导深表感激。

姚 楠

王中林

2004 年 6 月

List of Contributors

Editors

- Nan Yao
Princeton University
Princeton Institute for the Science and Technology of Materials
70 Prospect Avenue, Princeton, New Jersey 08540 USA
E-mail: nyao@princeton. edu
http: // www. princeton. edu / nyao/
- Zhonglin Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta GA 30332-0245 USA
- Peter J. Lu
Harvard University
Department of Physics
Jefferson Laboratory
17 Oxford Street
Cambridge, MA 02138
Phone: (617)496 – 8915
Fax: (617)495 – 2875
E-mail: plu@fas. harvard. edu
- Alexandre Bouhelier
Center for Nanoscale Materials
Chemistry Division
Argonne National Laboratory, 9700 South Cass Avenue
Argonne, IL 60439 USA
E-mail: bouhelier@anl. gov
- Achim Hartschuh
Universität Siegen, Physikalische Chemie I
Adolf-Reichwein-Strasse 2
D-57068 Siegen, Germany
E-mail: hartschuh@chemie. uni-siegen. de
- Lukas Novotny
The Institute of Optics, University of Rochester
Wilmot Building, Rochester NY, 14627 USA
E-mail: novotny@optics. rochester. edu
- Jinfeng Jia
Institute of Physics
The Chinese Academy of Sciences
Beijing, 100080 China
E-mail: jfjia@aphy. iphy. ac. cn
- Weisheng Yang
Institute of Physics, the Chinese Academy of Sciences
Beijing, 100080 China
E-mail: wsyang@pku. edu. cn

Qikun Xue Institute of Physics, the Chinese Academy of Sciences
Beijing, 100080 P. R. China
E-mail: qkxue@aphy. iphy. ac. cn

Sergei N. Magonov Veeco Instruments
112 Robin Hill Rd. , Santa Barbara, CA 93117 USA
E-mail: smagonov@veeco. com

Natalya A. Yerina Veeco Instruments, 112 Robin Hill Rd. , Santa Barbara
CA 93117 USA
E-mail: NErina@veeco. com

Seunghun Hong Physics and NANO Systems Institute
Seoul National University, Seoul
151-747 Korea
E-mail: shong@phy. snu. ac. kr

Jiwoon Im Physics and NANO Systems Institute
Seoul National University
Seoul, 151-747 Korea
E-mail: jwim@phy. snu. ac. kr

Minbaek Lee Physics and Nano System Institute
Seoul National University, Seoul 151-747 Korea
E-mail: lmb100@snu. ac. kr

Narae Cho Physics and NANO Systems Institute
Seoul National University, Seoul, 151-747 Korea
E-mail: birdwings@phy. snu. ac. kr

Li Shi Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712 USA
Phone: (512)471-3109
Fax: (512)471-1045
E-mail: lishi@mail. utexas. edu

William A. Lamberti ExxonMobil Research & Engineering Company
Route 22 East
Annandale, New Jersey 08801
(908)730-2144
E-mail: william. a. lamberti@exxonmobil. com

M. K. Miller Metals and Ceramics Division
Oak Ridge National Laboratory P. O. Box 2008
Building 4500S, MS 6136
Oak Ridge, TN 37831-6136, USA
E-mail: millermk@ornl. gov

Zhiping (James) Zhou Microelectronics Research Center, Georgia Institute of
Technology
791 Atlantic Drive, Atlanta GA 30332-0269
Tel: 404-894-5172
Fax: 404-894-5028
E-mail: james. zhou@mirc. gatech. edu

Contents

List of Contributors	17
1 Confocal Scanning Optical Microscopy and Nanotechnology	1
1.1 Introduction	1
1.2 The Confocal Microscope	3
1.2.1 Principles of Confocal Microscopy	3
1.2.2 Instrumentation	4
1.2.3 Techniques for Improving Imaging of Nanoscale Materials	6
1.3 Applications to Nanotechnology	11
1.3.1 Three-Dimensional Systems	12
1.3.2 Two-Dimensional Systems	13
1.3.3 One-Dimensional Systems	14
1.3.4 Zero-Dimensional Systems	15
1.4 Summary and Future Perspectives	18
References	18
2 Scanning Near-Field Optical Microscopy in Nanosciences	25
2.1 Scanning Near-Field Optical Microscopy and Nanotechnology	25
2.2 Basic Concepts	26
2.3 Instrumentation	27
2.3.1 Probe Fabrication	28
2.3.2 Flexibility of Near-Field Measurements	33
2.4 Applications in Nanoscience	35
2.4.1 Fluorescence Microscopy	35
2.4.2 Raman Microscopy	39
2.4.3 Plasmonic and Photonic Nanostructures	42
2.4.4 Nanolithography	47
2.4.5 Semiconductors	50
2.5 Perspectives	52
References	53
3 Scanning Tunneling Microscopy	57
3.1 Basic Principles of Scanning Tunneling Microscopy	57
3.1.1 Electronic Tunneling	57
3.1.2 Scanning Tunneling Microscope	60

3.2	Surface Structure Determination by Scanning Tunneling Microscopy	61
3.2.1	Semiconductor Surfaces	62
3.2.2	Metal Surfaces	76
3.2.3	Insulator Surfaces	79
3.2.4	Nanotubes and Nanowires	81
3.2.5	Surface and Subsurface Dynamic Processes	83
3.3	Scanning Tunneling Spectroscopies	85
3.3.1	Scanning Tunneling Spectroscopy	85
3.3.2	Inelastic Tunneling Spectroscopy	87
3.3.3	Local Work Function Measurement	89
3.4	STM-Based Atomic Manipulation	95
3.4.1	Manipulation of Single atoms	95
3.4.2	STM Induced Chemical Reaction at Tip	98
3.5	Recent Developments	101
3.5.1	Spin-Polarized STM	103
3.5.2	Ultra-Low Temperature-STM	108
3.5.3	Dual-Tip STM	110
3.5.4	Variable Temperature Fast-Scanning STM	111
	References	113
4	Visualization of Nanostructures with Atomic Force Microscopy	119
4.1	Introductory Remarks	119
4.2	Basics of Atomic Force Microscopy	121
4.2.1	Main Principle and Components of Atomic Force Microscope	121
4.2.2	Operational Modes, Optimization of the Experiment and Image Resolution	128
4.2.3	Imaging in Various Environments and at Different Temperatures	135
4.3	Imaging of Macromolecules and Their Self-Assemblies	141
4.3.1	Visualization of Single Polymer Chains	141
4.3.2	Alkanes, Polyethylene and Fluoroalkanes	146
4.4	Studies of Heterogeneous Systems	154
4.4.1	Semicrystalline Polymers	154
4.4.2	Block Copolymers	155
4.4.3	Polymer Blends and Nanocomposites	158
4.5	Concluding Remarks	161
	References	162
5	Scanning Probe Microscopy for Nanoscale Manipulation and Patterning	165
5.1	Introduction	165
5.1.1	Nanoscale Toolbox for Nanotechnologists	165

5.1.2	Motivations	168
5.2	Nanoscale Pen Writing	170
5.2.1	Dip-Pen Nanolithography	170
5.2.2	Nanoscale Printing of Liquid Ink	174
5.3	Nanoscale Scratching	176
5.3.1	Nanoscale Indentation	176
5.3.2	Nanografting	178
5.3.3	Nanoscale Melting	179
5.4	Nanoscale Manipulation	180
5.4.1	Atomic and Molecular Manipulation	180
5.4.2	Manipulation of Nanostructures	181
5.4.3	Nanoscale Tweezers	183
5.5	Nanoscale Chemistry	184
5.5.1	Nanoscale Oxidation	184
5.5.2	Nanoscale Desorption of Self-Assembled Monolayers	186
5.5.3	Nanoscale Chemical Vapor Deposition	187
5.6	Nanoscale Light Exposure	187
5.7	Future Perspectives	188
	References	190
6	Scanning Thermal and Thermoelectric Microscopy	195
6.1	Introduction	195
6.2	Instrumentation of Scanning Thermal and Thermoelectric Microscopy	196
6.2.1	Instrumentation of Scanning Thermal Microscopy	196
6.2.2	Instrumentation of Scanning Thermoelectric Microscopy	201
6.3	Theory of Scanning Thermal and Thermoelectric Microscopy	203
6.3.1	Theory of Scanning Thermal Microscopy	203
6.3.2	Theory of Scanning Thermoelectric Microscopy	208
6.4	Applications of Scanning Thermal and Thermoelectric Microscopy in Nanotechnology	209
6.4.1	Thermal Imaging of Carbon Nanotube Electronics	209
6.4.2	Thermal Imaging of ULSI Devices and Interconnects	212
6.4.3	Shallow Junction Profiling	213
6.5	Summary and Future Aspects	217
	References	217
7	Imaging Secondary Ion Mass Spectrometry	219
7.1	Secondary Ion Mass Spectrometry and Nanotechnology	219
7.2	Introduction to Secondary Ion Mass Spectrometry	220
7.2.1	Overview	220

7.2.2	General SIMS Instruments	221
7.2.3	High Resolution Imaging SIMS Instruments	223
7.3	Experimental Issues in Imaging SIMS	224
7.4	Applications in Nanotechnology	227
7.4.1	Example—Precipitate Distributions in Metallurgy	227
7.4.2	Example—Heterogeneous Catalyst Studies	229
7.4.3	Example—Nanoscale Biological Structures	232
7.5	Summary and Future Perspectives	233
	References	233
8	Atom Probe Tomography	237
8.1	Atom Probe Tomography and Nanotechnology	237
8.2	Instrumentation of Atom Probe Tomography	237
8.2.1	Field Ion Microscope	238
8.2.2	Types of Atom Probe	240
8.2.3	Specimen Preparation	246
8.3	Basic Information	247
8.4	Data Interpretation and Visualization	248
8.4.1	Visualization Methods	249
8.4.2	Quantification Methods	251
8.5	Sample Analysis of Nanomaterials; Multilayer Films	254
8.6	Summary and Future Perspectives	256
	References	256
9	Focused Ion Beam System—a Multifunctional Tool for Nanotechnology	259
9.1	Introduction	259
9.2	Principles and Practice of the Focused Ion Beam System	262
9.2.1	Ion Beam Versus Electron Beam	265
9.2.2	Focused Ion Beam Microscope Versus Scanning Electron Microscope	266
9.2.3	Milling	268
9.2.4	Deposition	270
9.2.5	Implantation	272
9.2.6	Imaging	273
9.2.7	The Dual-Beam System	275
9.3	Application of Focused Ion Beam Instrumentation	277
9.3.1	Surface Structure Modification	278
9.3.2	Transmission Electron Microscopy Sample preparation for imaging and analysis	288
9.3.3	Sample Imaging—Defining the Third Dimension	291
9.3.4	Damage to the Sample Induced by the Focused Ion Beam	294
	References	295

10 Electron Beam Lithography 299

10.1 Electron Beam Lithography and Nanotechnology 299

10.2 Instrumentation of Electron Beam Lithography 301

10.2.1 Principle 301

10.2.2 Electron Optics 302

10.3 Electron-Solid Interactions 313

10.3.1 Electron Scattering in Solid 313

10.3.2 Proximity Effect 314

10.3.3 Electron Beam Resists 314

10.4 Pattern Transfer Process 318

10.4.1 Additive Processes 318

10.4.2 Subtractive Processes 320

10.5 Applications in Nanotechnology 322

10.5.1 Mask Making 322

10.5.2 Direct Writing 325

10.6 Summary and Future Perspectives 330

References 331

Index 335