

# Advances in Scanning Probe Microscopy Research

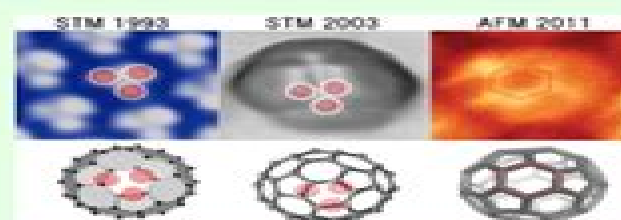
Tomihiko Hashizume<sup>†</sup>

Center for Exploratory Research, Hitachi, Ltd., 2520 Atsukawa, Hitoyama, Saitama 350-0895, Japan  
<sup>†</sup> Corresponding author: tomihiko.hashizume.gbh@hitachi.com

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In this review, advances in scanning probe microscopy (SPM) from the last two decades are presented. Progress in analyzing  $C_{60}$  molecules is described as an example of molecular imaging quality improvement for each decade. Innovations and progress in SPM imaging techniques are then outlined, especially atomic force microscopy operating in ultrahigh vacuum (UHV) or in aqueous environments, and the widely spread low-temperature and/or high-performance UHV scanning tunneling microscopy.

**Keywords:** Scanning probe microscopy; Surface property; Vacuum; Atmospheric; Aqueous



## I. INTRODUCTION

This study provides an overview of the last 20 years of scanning probe microscopy (SPM). It particularly focuses on the remarkable advances in ultrahigh vacuum (UHV) and aqueous atomic force microscopy (AFM), as well as on research using the widely spread UHV scanning tunneling microscopy (STM). There has also been progression of other technologies and expansion of research in SPM, which are mentioned in the Future Outlook section. All these research projects have or will lead to important technological innovations.

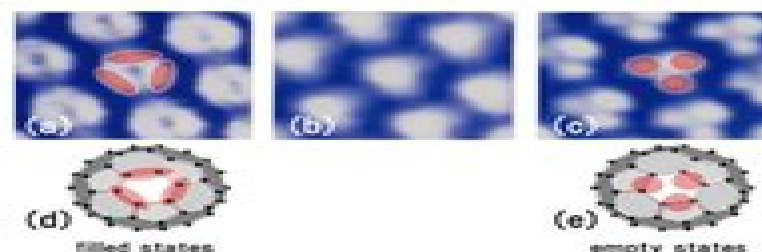
## II. ADVANCES in $C_{60}$ MOLECULE IMAGING

$C_{60}$  was first reported in 1985 by Kroto, Smalley, Curl *et al.* [1, 2], and since then, large-scale synthesis and purification methods have been developed. There has been extensive research on higher fullerenes, endohedral metallofullerenes, and fullerene derivatives [3].

### A. Density of states mapping of $C_{60}$ molecules

STM maps the density of electronic states near the Fermi level on the sample surface, and information on the unoccupied/occupied electronic states of the sample is obtained by the positive/negative sample voltage respect to the probe.

Initially, STM images of the fullerene molecules appeared to show uniform electronic states, and striated internal structure was also observed [4]. However, the highly symmetrical internal structure of  $C_{60}$  was observed in  $Cu(111)-4\times 4-C_{60}$  monolayer phases at room temperature, and it was reported [5] that this internal structure mapped the electronic state of  $C_{60}$  molecules, combining first-principle calculations and STM (Figure 1). This report was the first to confirm that the



**Figure 1:** STM images of  $C_{60}$  molecules in a  $Cu(111)-4\times 4-C_{60}$  monolayer phase with sample bias voltages of (a)  $-2.0$  V, (b)  $-0.10$  V, and (c)  $2.0$  V [5]. (d, e) Ball-and-stick models of a  $C_{60}$  molecule. Marked areas in (a, d) and (c, e) correspond to filled ( $\pi$ ) and empty ( $\pi^*$ ) electronic density states of  $C=C$  double bonds, respectively.

# Advances In Scanning Probe Microscopy

**I. Meisel, C. S. Kniep, S. Spiegel, K.  
Grieve**



## **Advances In Scanning Probe Microscopy:**

*Advances in Scanning Probe Microscopy* T. Sakurai, Y. Watanabe, 2012-12-06 There have been many books published on scanning tunneling microscopy STM atomic force microscopy AFM and related subjects since Dr Cerd Binnig and Dr Heinrich Rohrer invented STM in 1982 and AFM in 1986 at IBM Research Center in Zurich Switzerland These two techniques STM and AFM now form the core of what has come to be called the scanning probe microscopy SPM family SPM is not just the most powerful microscope for scientists to image atoms on surfaces but is also becoming an indispensable tool for manipulating atoms and molecules to construct man made materials and devices Its impact has been felt in various fields from surface physics and chemistry to nano mechanics nano electronics and medical science Its influence will surely extend further as the years go by beyond the reach of our present imagination and new research applications will continue to emerge This book therefore is not intended to be a comprehensive review or textbook on SPM Its aim is to cover only a selected part of the active re search fields of SPM and related topics in which I have been directly involved over the years These include the basic principles of STM and AFM and their applications to fullerene film growth SiC surface reconstructions MBE molecular beam epitaxy growth of CaAs atomic scale manipulation of Si surfaces and meso scopic work function

**Advances in Scanning Probe Microscopy for Imaging Functionality on the Nanoscale** Stephen Jesse, 2013

**Advances in Scanning Probe Microscopy** T. Mueller, 2014

*Scanning Probe Microscopy* Ernst Meyer, Hans Josef Hug, Roland Bennewitz, 2013-03-14 Two decades after its invention scanning probe microscopy has become a widely used method in laboratories as diverse as industrial magnetic stor age development or structural biology Consequently the community of users ranges from biologists and medical researchers to physicists and engineers all of them exploiting the unrivalled resolution and profiting from the relative simplicity of the experimental implementation In recent years the authors have taught numerous courses on scanning probe microscopy normally in combination with hands on student experi ments The audiences ranged from physics freshmen to biology post docs and even high school teachers We found it of particular importance to cover not only the physical principles behind scanning probe microscopy but also ques tions of instrumental designs basic features of the different imaging modes and recurring artifacts With this book our intention is to provide a gen eral textbook for all types of classes that address scanning probe microscopy Third year undergraduates and beyond should be able to use it for self study or as textbook to accompany a course on probe microscopy Furthermore it will be valuable as reference book in any scanning probe microscopy labora tory

**Scanning Probe Microscopy for Energy Research** Dawn A. Bonnell, Sergei V. Kalinin, 2013 Efficiency and life time of solar cells energy and power density of the batteries and costs of the fuel cells alike cannot be improved unless the complex electronic optoelectronic and ionic mechanisms underpinning operation of these materials and devices are understood on the nanometer level of individual defects Only by probing these phenomena locally can we hope to link materials structure and

functionality thus opening pathway for predictive modeling and synthesis While structures of these materials are now accessible on length scales from macroscopic to atomic their functionality has remained Terra Incognitae In this volume we provide a summary of recent advances in scanning probe microscopy studies of local functionality of energy materials and devices ranging from photovoltaics to batteries fuel cells and energy harvesting systems Recently emergent SPM modes and combined SPM electron microscopy approaches are also discussed Contributions by internationally renowned leaders in the field describe the frontiers in this important field

**Advances in Ultrafast Scanning Probe Microscopy**, 1994 We review the development of the ultrafast scanning tunneling microscope Experimental results on the tunneling gap response to a short voltage pulse excitation are presented

*Scanning Probe Microscopy* Nikodem Tomczak, Kuan Eng Johnson Goh, 2010-12-13 Scanning Probe Microscopy SPM is the enabling tool for nano bio technology which has opened new vistas in many interdisciplinary research areas Concomitant with the developments in SPM instrumentation and techniques are new and previously unthought of opportunities in materials nanofabrication and characterisation In particular the developments in addressing and manipulating matter at the level of single atoms or molecules and studies of biological materials e.g live cells or cell membranes result in new and exciting discoveries The rising importance of SPM demands a concise treatment in the form of a book which is accessible to interdisciplinary practitioners This book highlights recent advances in the field of SPM with sufficient depth and breadth to provide an intellectually stimulating overview of the current state of the art The book is based on a set of carefully selected original works from renowned contributors on topics that range from atom technology scanning tunneling spectroscopy of self assembled nanostructures SPM probe fabrication scanning force microscopy applications in biology and materials science down to the single molecule level novel scanning probe techniques and nanolithography The variety of topics underlines the strong interdisciplinary character of SPM related research and the combined expertise of the contributors gives us a unique opportunity to discuss possible future trends in SPM related research This makes the book not merely a collection of already published material but an enlightening insight into cutting edge research and global SPM research trends

[Scanning Probe Microscopy For Energy Research: Materials, Devices, And Applications](#) Dawn Bonnell, Sergei V Kalinin, 2013-03-26 Efficiency and life time of solar cells energy and power density of the batteries and costs of the fuel cells alike cannot be improved unless the complex electronic optoelectronic and ionic mechanisms underpinning operation of these materials and devices are understood on the nanometer level of individual defects Only by probing these phenomena locally can we hope to link materials structure and functionality thus opening pathway for predictive modeling and synthesis While structures of these materials are now accessible on length scales from macroscopic to atomic their functionality has remained Terra Incognitae In this volume we provide a summary of recent advances in scanning probe microscopy studies of local functionality of energy materials and devices ranging from photovoltaics to batteries fuel cells and energy harvesting systems Recently emergent SPM modes and combined SPM

electron microscopy approaches are also discussed Contributions by internationally renowned leaders in the field describe the frontiers in this important field

**Advances in High-resolution Probes for Scanning Probe Microscopy** Marc A. Unger, California Institute of Technology, Division of Chemistry and Chemical Engineering, 1999

**Scanning Probe Microscopy of Functional Materials** Sergei V. Kalinin, Alexei Gruverman, 2010-12-13 The goal of this book is to provide a general overview of the rapidly developing field of novel scanning probe microscopy SPM techniques for characterization of a wide range of functional materials including complex oxides biopolymers and semiconductors Many recent advances in condensed matter physics and materials science including transport mechanisms in carbon nanostructures and the role of disorder on high temperature superconductivity would have been impossible without SPM The unique aspect of SPM is its potential for imaging functional properties of materials as opposed to structural characterization by electron microscopy Examples include electrical transport and magnetic optical and electromechanical properties By bringing together critical reviews by leading researchers on the application of SPM to the nanoscale characterization of functional materials properties this book provides insight into fundamental and technological advances and future trends in key areas of nanoscience and nanotechnology

**Advances in Scanning Probe Microscopy of Polymers** I. Meisel, C. S. Kniep, S. Spiegel, K. Grieve, 2001-08-15 The symposium Recent Advances in Scanning Probe Microscopy of Polymers held during the 220th American Chemical Society National Meeting in Washington DC in August 2000 focused on the latest advances in applications of SPM techniques for the study of polymeric and organic materials The main topics consisted of SPM imaging of polymer morphology and microstructure microtribological properties of polymers micromechanical probing of polymers microthermal imaging studies of ultrathin and molecular organic and polymeric films modeling of tip surface interactions chemical compositional analysis of heterogeneous materials and SPM applications to industrial polymers This volume of Macromolecular Symposia will be a valuable guide in the field of contemporary SPM studies of polymeric materials

Scanning Probe Microscopy: Characterization, Nanofabrication and Device Application of Functional Materials Paula M. Vilarinho, Yossi Rosenwaks, Angus Kingon, 2006-06-15 As the characteristic dimensions of electronic devices continue to shrink the ability to characterize their electronic properties at the nanometer scale has come to be of outstanding importance In this sense Scanning Probe Microscopy SPM is becoming an indispensable tool playing a key role in nanoscience and nanotechnology SPM is opening new opportunities to measure semiconductor electronic properties with unprecedented spatial resolution SPM is being successfully applied for nanoscale characterization of ferroelectric thin films In the area of functional molecular materials it is being used as a probe to contact molecular structures in order to characterize their electrical properties as a manipulator to assemble nanoparticles and nanotubes into simple devices and as a tool to pattern molecular nanostructures This book provides in depth information on new and emerging applications of SPM to the field of materials science namely in the areas of characterisation device application and nanofabrication of functional materials

Starting with the general properties of functional materials the authors present an updated overview of the fundamentals of Scanning Probe Techniques and the application of SPM techniques to the characterization of specified functional materials such as piezoelectric and ferroelectric and to the fabrication of some nano electronic devices Its uniqueness is in the combination of the fundamental nanoscale research with the progress in fabrication of realistic nanodevices By bringing together the contribution of leading researchers from the materials science and SPM communities relevant information is conveyed that allows researchers to learn more about the actual developments in SPM applied to functional materials This book will contribute to the continuous education and development in the field of nanotechnology

**Advances and Applications in Scanning Probe Microscopy** Kong Gay Loh,1994     Roadmap of Scanning Probe Microscopy Seizo Morita,2006-10-26 Scanning tunneling microscopy has achieved remarkable progress and become the key technology for surface science This book predicts the future development for all of scanning probe microscopy SPM Such forecasts may help to determine the course ultimately taken and may accelerate research and development on nanotechnology and nanoscience as well as all in SPM related fields in the future

**Exploring Scanning Probe Microscopy with MATHEMATICA** Dror Sarid,2007-04-09 This new and completely updated edition features not only an accompanying CD ROM but also a new applications section reflecting the many breakthroughs in the field over the last few years It provides a complete set of computational models that describe the physical phenomena associated with scanning tunneling microscopy atomic force microscopy and related technologies The result is both a solid professional reference and an advanced level text beginning with the basics and moving on to the latest techniques experiments and theory In the section devoted to atomic force microscopy the author describes the mechanical properties of cantilevers atomic force microscope tip sample interactions and cantilever vibration characteristics This is followed by an in depth treatment of theoretical and practical aspects of tunneling phenomena including metal insulator metal tunneling and Fowler Nordheim field emission The final section features applications dealing with among others Kelvin and Raman probe microscopy The self contained presentation spares researchers valuable time spent hunting through the technical literature for the theoretical results required to understand the models presented The Mathematica code for all the examples is included in the CD ROM affording the freedom to change the values and parameters of specific problems as desired or even modify the programs themselves to suit various modeling needs

*Quantitative Data Processing in Scanning Probe Microscopy* Petr Klapetek,2012-12-31 Accurate measurement at the nano scale nanometrology is a critical tool for advanced nanotechnology applications where exact quantities and engineering precision are beyond the capabilities of traditional measuring techniques and instruments Scanning Probe Microscopy SPM builds up a picture of a specimen by scanning with a physical probe unrestrained by the wavelength of light or electrons the resolution obtainable with this technique can resolve atoms SPM instruments include the Atomic Force Microscope AFM and Scanning Tunneling Microscope STM Despite tremendous advances in Scanning Probe Microscopy

SPM over the last twenty years its potential as a quantitative measurement tool have not been fully realized due to challenges such as the complexity of tip sample interaction In this book Petr Klapetek uses the latest research to unlock SPM as a toolkit for nanometrology in fields as diverse as nanotechnology surface physics materials engineering thin film optics and life sciences Klapetek s considerable experience of Quantitive Data Processing using software tools enables him to not only explain the microscopy techniques but also to demystify the analysis and interpretation of the data collected In addition to the essential principles and theory of SPM metrology Klapetek provides readers with a number of worked examples to demonstrate typical ways of solving problems in SPM analysis Source data for the examples as well as most of the described open source software tools are available on a companion website Unlocks the use of Scanning Probe Microscopy SPM for nanometrology applications in engineering physics life science and earth science settings Provides practical guidance regarding areas of difficulty such as tip sample interaction and calibration making metrology applications achievable Gives guidance on data collection and interpretation including the use of software based modeling using applications that are mostly freely available

Scanning Probe Microscopy and Spectroscopy Dawn Bonnell,2000-12-05 A practical introduction to basic theory and contemporary applications across a wide range of research disciplines Over the past two decades scanning probe microscopies and spectroscopies have gained acceptance as indispensable characterization tools for an array of disciplines This book provides novices and experienced researchers with a highly accessible treatment of basic theory alongside detailed examples of current applications of both scanning tunneling and force microscopies and spectroscopies Like its popular predecessor Scanning Probe Microscopy and Spectroscopy Second Edition features contributions from distinguished scientists working in a wide range of specialties at university commercial and government research labs around the world Chapters have been edited for clarity conciseness and uniformity of presentation to provide professionals with a concise working reference to scanning probe microscopic and spectroscopic principles techniques and practices This Second Edition has been substantially revised and expanded to reflect important advances and new applications In addition to numerous examples the Second Edition features expanded coverage of electrostatic and magnetic force microscopies near field optical microscopies and new applications of buried interfaces in nanomechanics electrochemistry and biology Scanning Probe Microscopy and Spectroscopy Second Edition is an indispensable working resource for surface scientists microscopists and spectroscopists in materials science chemistry engineering biochemistry physics and the life sciences It is also an unparalleled reference text for advanced undergraduates and graduate students in those fields

**Scanning Probe Microscopy** Nikodem Tomczak,Kuan Eng Johnson Goh,2011 Scanning Probe Microscopy SPM is the enabling tool for nano bio technology which has opened new vistas in many interdisciplinary research areas Concomitant with the developments in SPM instrumentation and techniques are new and previously unthought of opportunities in materials nanofabrication and characterisation In particular the developments in addressing and manipulating matter at the level of single atoms or

molecules and studies of biological materials e.g. live cells or cell membranes result in new and exciting discoveries. The rising importance of SPM demands a concise treatment in the form of a book which is accessible to interdisciplinary practitioners. This book highlights recent advances in the field of SPM with sufficient depth and breadth to provide an intellectually stimulating overview of the current state of the art. The book is based on a set of carefully selected original works from renowned contributors on topics that range from atom technology scanning tunneling spectroscopy of self-assembled nanostructures SPM probe fabrication scanning force microscopy applications in biology and materials science down to the single molecule level novel scanning probe techniques and nanolithography. The variety of topics underlines the strong interdisciplinary character of SPM related research and the combined expertise of the contributors gives us a unique opportunity to discuss possible future trends in SPM related research. This makes the book not merely a collection of already published material but an enlightening insight into cutting edge research and global SPM research trends.

Atomic Force Microscopy/Scanning Tunneling Microscopy 3 Samuel H. Cohen, Marcia L. Lightbody, 2013-05-22 The Foundation for Advances in Medicine and Science FAMS the organizers of SCANNING 98 sponsored its third annual Atomic Force Microscopy Scanning Tunneling Microscopy Symposium at the Omni Inner Harbor Hotel in Baltimore Maryland from May 9 to 12 1998. This book represents the compilation of papers that were presented at the AFM STM Symposium as well as a few that were presented at SCANNING 96 and SCANNING 97 meetings that took place in Monterey California. The purpose of the symposium was to provide an interface between scientists and engineers representatives of industry government and academia all of whom have a common interest in probe microscopies. The meetings offered an ideal forum where ideas could easily be exchanged and where individuals from diverse fields who are on the cutting edge of probe microscopy research could communicate with one another. Experts in probe microscopy from around the world representing a wide range of disciplines including physics biotechnology nanotechnology chemistry material science etc were invited to participate. The format of the meeting was structured so as to encourage communication among these individuals. During the first day sessions papers were presented on general topics such as application of scanning probe microscopy in materials science STM and scanning tunneling spectroscopy of organic materials fractal analysis in AFM and nanomanipulation. Other papers presented included unexpected ordering of a molecule synthesis of peptides and oligonucleotides and analysis of lunar soils from Apollo 11.

**Scanning Probe Microscopy of Functional Materials** Sergei V. Kalinin, Alexei Gruverman, 2010-12-10. The goal of this book is to provide a general overview of the rapidly developing field of novel scanning probe microscopy SPM techniques for characterization of a wide range of functional materials including complex oxides biopolymers and semiconductors. Many recent advances in condensed matter physics and materials science including transport mechanisms in carbon nanostructures and the role of disorder on high temperature superconductivity would have been impossible without SPM. The unique aspect of SPM is its potential for imaging functional properties of materials as opposed to structural

characterization by electron microscopy Examples include electrical transport and magnetic optical and electromechanical properties By bringing together critical reviews by leading researchers on the application of SPM to to the nanoscale characterization of functional materials properties this book provides insight into fundamental and technological advances and future trends in key areas of nanoscience and nanotechnology

## **Advances In Scanning Probe Microscopy** Book Review: Unveiling the Power of Words

In a global driven by information and connectivity, the power of words has be much more evident than ever. They have the capacity to inspire, provoke, and ignite change. Such is the essence of the book **Advances In Scanning Probe Microscopy**, a literary masterpiece that delves deep in to the significance of words and their affect our lives. Published by a renowned author, this captivating work takes readers on a transformative journey, unraveling the secrets and potential behind every word. In this review, we will explore the book is key themes, examine its writing style, and analyze its overall effect on readers.

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