Fundamentals of Atomic Force Microscopy

Part I: Foundations

Lessons from Nanoscience: A Lecture Note Series

ISSN: 2301-3354

Series Editors: Mark Lundstrom and Supriyo Datta
(Purdue University, USA)

"Lessons from Nanoscience" aims to present new viewpoints that help understand, integrate, and apply recent developments in nanoscience while also using them to re-think old and familiar subjects. Some of these viewpoints may not yet be in final form, but we hope this series will provide a forum for them to evolve and develop into the textbooks of tomorrow that train and guide our students and young researchers as they turn nanoscience into nanotechnology. To help communicate across disciplines, the series aims to be accessible to anyone with a bachelor's degree in science or engineering.

More information on the series as well as additional resources for each volume can be found at: http://nanohub.org/topics/LessonsfromNanoscience

---

Published:

Vol. 1 Lessons from Nanoelectronics: A New Perspective on Transport
by Supriyo Datta

Vol. 2 Near-Equilibrium Transport: Fundamentals and Applications
by Mark Lundstrom, Changwook Jeong and Raseong Kim

Vol. 3 Thermal Energy at the Nanoscale
by Timothy S Fisher

Vol. 4 Fundamentals of Atomic Force Microscopy, Part I: Foundations
by Ronald Reifenberger

Lessons from Nanoscience:
A Lecture Note Series

Vol. 4

Fundamentals of Atomic Force Microscopy

Part I: Foundations

Ronald Reifenberger

Purdue University, USA

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Lessons from Nanoscience: A Lecture Note Series — Vol. 4
FUNDAMENTALS OF ATOMIC FORCE MICROSCOPY
Part I: Foundations

ISBN 978-981-4630-34-4
ISBN 978-981-4630-35-1 (pbk)

In-house Editor: Song Yu

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore

Preface

Since dedicated courses are unlikely to spring up in university curricula to teach the fundamentals of Atomic Force Microscopy (AFM), it is useful to have a set of notes that interested students can work through in an independent, self-study mode at their own pace, without the benefit of a rigorous class schedule.

The lecture notes *Fundamentals of Atomic Force Microscopy, Part I: Foundations* were written to address this issue. The notes have slowly grown from three one-semester courses given at the graduate level at Purdue University in 2009, 2010, and an online NanoHUB-U course in 2012. In preparing and teaching these courses, I have all too often realized first-hand that students lack the background required to read the AFM literature critically. They often do not know the vocabulary, the core concepts, or the mathematics required to understand the fundamental principles underlying the operation of an AFM.

Why make an effort to work through these notes?

> First and foremost, an interdisciplinary background is required to meaningfully attack the truly challenging problems facing us today. The lecture notes attempt to fill many of the gaps in knowledge that traditional students (i.e., students who follow a traditional discipline-based course of study) often have when embarking on interdisciplinary studies.
>
> Secondly, the lecture notes are designed to be read in parallel with the two-part nanoHUB-U online course called *Fundamentals of AFM; Parts I and II* that was developed during the summer of 2012. The video lectures are freely available over the internet (see https://nanohub.org/courses/AFM1 and https://nanohub.org/courses/AFM2). While the notes are not

completely synchronized with the nanoHUB-U lectures, there is a sufficiently strong overlap that the interested student should benefit by following both the notes and lectures in parallel.

The pace of the online lectures is formidable and inevitably, typos and missing factors of π creep in. Most of these errors are corrected in the lecture notes and hopefully new errors have not reappeared during the process. If they have, I would be most happy if the reader takes the time to send me an email identifying the issue and listing the page or equation along with an explanation of the problem.

At the beginning of each chapter, I make an effort to identify why and how the chapter content is necessary for the intelligent use of an AFM. In each chapter, I develop topics that should be helpful to both acquire meaningful AFM data and to analyze it properly. I also attempt to identify the traditional academic disciplines that a four-year undergraduate might need to better appreciate the chapter content.

Lastly, my colleague Arvind Raman is preparing a set of lecture notes to cover Part II of the video lecture series, which focusses on dynamic AFM techniques and methods.

The notes are *not* intended to be exhaustive and they touch only on what I judge to be of fundamental interest. The AFM expert will not learn anything new since the notes are written with the beginning students in mind. I have attempted to provide specific references to the original literature whenever possible, but I have adopted the approach that in lecture notes, it is perhaps the ideas rather than the correct attribution that is most important.

R. Reifenberger
W. Lafayette, Indiana
April 3, 2014

. . . to the Student

There are many reasons why you are reading these lecture notes. Perhaps you have tried to perform an AFM experiment, you have obtained some results, but you don't know how to interpret the data. Or perhaps you are taking a short course on AFMs required by your plan of study. Or maybe you are just interested in learning more about the AFM technique in general. For whatever reason, we hope you will know more about how AFMs function after working through these notes.

The lecture notes are an outgrowth of previous semester-long courses offered at Purdue University in 2009, 2010 and 2012. The latest course in 2012 was incorporated into a nanoHUB-U set of online lectures that have been widely viewed on the web (see https://nanohub.org/courses/AFM1 and https://nanohub.org/courses/AFM2). Many of the students taking these online courses requested a set of written lecture notes. These lecture notes are a direct outgrowth of their requests.

While developing the *Fundamentals of AFM* lectures, I have come to appreciate a number of issues. First, the proper use of an AFM truly requires in-depth knowledge from many different traditional fields of study. Second, the ease that students integrate the many different topics discussed depends to some extent on their prior academic training. Third, there seems to be an overwhelming tendency for qualitative, hand-waving arguments to interpret experimental AFM results.

The lecture notes are organized with these issues in mind. Since not all students have the required background to understand the wide variety of topics discussed, I have attempted to summarize information relevant to AFM in one place. Since understanding tends to follow prior course work, I have provided both qualitative and quantitative background information

supported by mathematical derivations for the broader audience that may read these notes. While some may think a certain analysis is trivial, others may appreciate it because they happen to lack the necessary background that it discusses.

Finally, I include a number of worked-out examples to illustrate the ideas that have been developed. Only by attempting to calculate various quantities do you truly test your limits of understanding. To further this goal, I have made an attempt to standardize the notation found in the literature and use consistent symbols and formalism throughout the lecture notes. Homework problems are provided at the end of each chapter. References to the original literature are also provided as necessary.

Another feature of these lecture notes is the use of the free online AFM software VEDA developed by A. Raman and his students. Worked examples, which use the VEDA code to answer questions that cannot be solved analytically, are included. Knowing how to use VEDA will allow you to understand AFM data quantitatively and to devise better AFM experiments as you pursue your research interests.

Lastly, these notes have been prepared for students, not for AFM experts. There are already many reviews of AFM written by experts for experts. Unfortunately, the material contained in these reviews is often not readily accessible to the beginning student without a prior discussion of background material. For this reason, many of the discussions found in these lecture notes are intentionally pedagogic in-nature to better convey an understanding of the important fundamentals underlying scanning probe microscopy.

I would greatly appreciate knowing about my missteps, mistakes and oversights that I have made along the way. It's the only way an exposition of this material will improve.

R. Reifenberger
W. Lafayette, Indiana
May 3, 2014

Acknowledgments

While few who read this book will read this page, it is nonetheless important to thank those who have contributed to these lecture notes.

First and foremost are the ∼50 Purdue students who have satisfied MSc and PhD requirements working in my lab since I first became intrigued by Binnig's controllable tunnel gap in 1983. For ∼30 years we have designed, built and used scanning probe microscopes to investigate the amazing nanoscale properties of matter. These lecture notes are in no small part an attempt to answer the collective questions my students have asked me throughout the years.

The long term collaboration with Prof. Arturo Baro's *Laboratorio de Nuevas Microscopías* at the Universidad Autonoma de Madrid has contributed immensely to my understanding of scanning probe microscopy. The many discussions with Julio Gomez-Herrero as we walked through Madrid during the early days after the invention of the STM are especially noteworthy.

The decade long collaboration with my colleague from Purdue, Arvind Raman, has been instrumental in my understanding of cantilever dynamics and critical for the *Fundamentals of AFM* lectures that are now available on the web. His insistence on mathematical clarity and rigor has been a source of inspiration to an experimentalist who often relies on intuition, simple models and back of the envelope estimates for guidance on how best to proceed.

These notes have benefitted greatly from critical comments and suggestions by Maria Jose Cadena, Ryan Wagner and Scott Crittenden. Scott's yeoman-like attention to detail is especially notable for improving the content and presentation of the material found in these notes.

Lastly the life-long support of my wife Ellen cannot go without mention. Over the years, she has endured countless delayed meals, innumerable late-night trips back to the lab, and postponed many a weekend excursion with a grace and presence that few could understand much less realize. Perhaps now that these lecture notes are complete, I can accommodate her dream to spend a summer touring the Canadian Maritime Provinces.

R. Reifenberger
W. Lafayette, IN
May 25, 2014

Contents