X-ray Microscopy

Written by a pioneer in the field, this text provides a complete introduction to x-ray microscopy, providing all of the technical background required to use, understand, and even develop x-ray microscopes. Starting from the basics of x-ray physics and focusing optics, it goes on to cover imaging theory, tomography, chemical and elemental analysis, lensless imaging, computational methods, instrumentation, radiation damage, and cryomicroscopy, and includes a survey of recent scientific applications. Designed as a "one-stop" text, it provides a unified notation, and shows how computational methods in different areas are linked with one another. Including numerous derivations, and illustrated with dozens of examples throughout, this is an essential text for academics and practitioners across engineering, the physical sciences, and the life sciences who use x-ray microscopy to analyze their specimens, as well as those taking courses in x-ray microscopy.

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Advances in Microscopy and Microanalysis

Microscopic visualization techniques range from atomic imaging to visualization of living cells at near nanometer spatial resolution, and advances in the field are fueled by developments in computation, image detection devices, labeling, and sample preparation strategies. Microscopy has proven to be one of the most attractive and progressive research tools available to the scientific community, and remains at the forefront of research in many disciplines, from nanotechnology to live cell molecular imaging. This series reflects the diverse role of microscopy, defining it as any method of imaging objects of micrometer scale or less, and includes both introductory texts and highly technical and focused monographs for researchers and practitioners in materials and the life sciences

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Foreword

X-ray microscopy is an interdisciplinary topic, both in terms of its technical details and in terms of the scientific and engineering problems it is applied to. While there are a number of books that provide excellent coverage of certain aspects of x-ray physics, optics, and microscopy, it is my opinion that there has not been a single book that one can hand to someone new in the field of x-ray microscopy to give them an introduction to most of the key aspects they should know about. This book is an attempt to fill that need.

Are you a new PhD student entering a research group who will use x-ray microscopy for part of your research? If so, you have probably had at least a year or so of university physics during your studies. You are whom I have written the book for! At times I may push you a bit further in mathematics or physics than what you have learned thus far, but if you are in a PhD program you are a serious enough student so this should be OK. Besides, you can always skim over some of the more detailed points.

Are you an established researcher or engineer who is new to x-ray microscopy? This book is also for you! Your expertise might be with microscopes using other radiation, or on materials you hope to understand better using x-ray microscopy.

What I hope to do in this book is to give you a feel for the fundamental ideas that come into play in a variety of x-ray microscopy approaches and applications, and to do so with enough detail to allow you to go off and invent new approaches of your own. I look forward to seeing your contributions to x-ray microscopy!

What do I mean by x-ray microscopy? I have decided to focus on imaging at a spatial resolution of a few micrometers down to nanometers. This is not a book on medical radiology at 0.1 mm resolution as limited by acceptable radiation exposure, and it is not a book on crystallography. I consider X rays to be photons with an energy well above the plasmon resonance (20–50 eV for most solids) and in particular above about 100 eV, and I tend to concentrate on energies below 20 keV since at higher energies the fine structure that one hopes to see in a microscope has reduced contrast. While much useful research is done in an approach where X rays illuminate an area and magnetic or electrostatic lenses image the electrons that come off of the surface, these photoelectron emission microscopes (PEEM and its variations) are based on electron, not x-ray, optics so they are given only brief treatment in Section 6.5. However, I do discuss x-ray microscopy approaches where one uses the properties of x-ray scattering to recover images without the use of lenses in Chapter 10, and I also include the combination of x-ray microscopy with absorption and fluorescence-based spectroscopy in Chapter

9. I discuss three-dimensional imaging or tomography as a natural extension of two-dimensional microscopy in Chapter 8. Chapter 7 covers what I consider to be essential points on x-ray microscope instrumentation. X rays are ionizing radiation, so Chapter 11 is devoted to radiation damage as well as cryo microscopy methods that can help in minimizing damage. While Chapter 12 discusses applications of x-ray microscopy, these applications ultimately involve detailed knowledge in their respective scientific specialties, which may be undergoing rapid development. Therefore the coverage here is rather brief, while pointing out recent review papers when possible.

I expect that I have made many sins of commission, and of omission. Cambridge University Press has a web page www.cambridge.org/Jacobsen associated with this book (one can also reach this web page with `www.cambridge.org/9781107076570`). This web page will host errata, as well as online Appendices B and C.

This book was originally undertaken as a team effort with one of my favorite people in the world: Janos Kirz, who is one of the real pioneers in x-ray microscopy. However, the book has taken longer to complete than we had hoped, and Janos has rightfully been enjoying his retirement more completely as of late. His fingerprints are all over the earliest chapters, and he has provided valuable feedback on the entire tome. However, as the book has grown and developments in later chapters have motivated rewrites of earlier ones, all of the warts and blemishes in what remains have become my fault alone. Therefore at Janos' request he is no longer listed as a coauthor – which means, I guess, that you can't blame him for anything that's wrong or incomplete!

A number of other people have provided wonderful input. Some are listed as contributors to specific chapters, in which case I will not thank them again here. But people like Marc Allain, Elke Arenholz, Lahsen Assoufid, Anton Barty, Anna Bergamaschi, Sylvan Bohic, Anibal Boscoboinik, Virginie Chamard, Henry Chapman, Si Chen, Yong Chu, Marine Cotte, Björn De Samber, Peter Fischer, Manuel Guizar-Sicairos, Mirko Holler, Young Pyo Hong, Xiaojing Huang, Sarah Köster, Florian Meirer, Nino Miceli, Günter Schmahl (1936–2018), Xianbo Shi, Pierre Thibault, Stephen Urquhart, Ivan Vartanyants, Pablo Villanueva-Perez, Stefan Vogt, Michael Wojcik, Russell Woods, and Hanfei Yan have taken the time to read various sections of the book and give important critical comments and suggestions, or contributed figures. Several of my Northwestern University PhD students (Sajid Ali, Ming Du, and Saugat Kandel in particular) have given me great feedback on specific sections. Joshua Zachariah made early versions of several figures. Again, you can't blame any of the above for my mistakes, but you can thank them for reducing their number.

One can only undertake the project of writing a book like this with lots of support. The Advanced Photon Source at Argonne National Laboratory (a U.S. Department of Energy Office of Science user facility) has generously supported me in devoting considerable time to this effort, since x-ray microscopy is one of its widely used methods. My wife, Holly, has been patient with me in so many ways, and has helped keep me in balance as the project progressed by joining me on many activities, adventures, and travels that have kept me refreshed and enthusiastic!

Some income from this book is being directed to a student prize at the international conference series on x-ray microscopy.