SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION

This self-contained, comprehensive book describes the fundamental properties of soft x-rays and extreme ultraviolet (EUV) radiation and discusses their applications in a wide variety of fields, including EUV lithography for semiconductor chip manufacture and soft x-ray biomicroscopy.

The author begins by presenting the relevant basic principles such as radiation and scattering, wave propagation, diffraction, and coherence. He then goes on to examine a broad range of phenomena and applications. Each chapter begins with a simple summary of key results and concepts, followed by an introduction with little or no mathematics so as to be accessible to the widest possible audience. This is followed by a detailed mathematical development of the theoretical structure of the subject in question. The topics covered include EUV lithography, biomicroscopy, spectromicroscopy, EUV astronomy, synchrotron radiation, and soft x-ray lasers.

The author also provides a great deal of useful reference material such as electron binding energies, characteristic emission lines, and photoabsorption cross-sections. The book will be of great interest to graduate students and researchers in engineering, physics, chemistry, and the life sciences. It will also appeal to practicing engineers involved in semiconductor fabrication and materials science.

David Attwood is the Director of the Center for X-Ray Optics at the Lawrence Berkeley National Laboratory. He is also a Professor in Residence in both the Department of Electrical Engineering and Computer Science and the Graduate Group in Applied Science and Technology at the University of California, Berkeley. He is a Fellow of the Optical Society of America and has published over 100 scientific articles.

SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION

Principles and Applications

DAVID ATTWOOD

UNIVERSITY OF CALIFORNIA, BERKELEY
AND
LAWRENCE BERKELEY
NATIONAL LABORATORY

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521652148

First published 1999
This digitally printed first paperback version (with amendments) 2007

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Attwood. David T.
Soft x-rays and extreme ultraviolet radiation : principles and applications / David Attwood.
p. cm.
Includes bibliographical references.
ISBN 0-521-65214-6 (hbk.)
1. Grenz rays. 2. Ultraviolet radiation. I. Title.
QC482.G68A88 1999
539.7′222 – dc21 99-21078
CIP

ISBN-13 978-0-521-65214-8 hardback
ISBN-10 0-521-65214-6 hardback

ISBN-13 978-0-521-02997-1 paperback
ISBN-10 0-521-02997-X paperback

The colour figures referred to in this publication have been replaced with black and white images for this digital reprinting. At the time of going to press the original images were available in colour for download from http://www.cambridge.org/9780521029971

To Professors Stanley Goldstein
and Nathan Marcuvitz

Contents

Preface

This book is intended to provide an introduction to the physics and applications of soft x-rays and extreme ultraviolet (EUV) radiation. These short wavelengths are located within the electromagnetic spectrum between the ultraviolet, which we commonly associate with sunburn, and harder x-rays, which we often associate with medical and dental imaging. The soft x-ray/EUV region of the spectrum has been slow to develop because of the myriad atomic resonances and concomitant short absorption lengths in all materials, typically of order one micrometer or less. This spectral region, however, offers great opportunities for both science and technology. Here the wavelengths are considerably shorter than visible or ultraviolet radiation, thus permitting one to see smaller features in microscopy, and to write finer patterns in lithography. Furthermore, optical techniques such as high spatial resolution lenses and high reflectivity mirrors have been developed that enable these applications to a degree not possible at still shorter wavelengths. Photon energies in the soft x-ray/EUV spectral region are well matched to primary resonances of essentially all elements. While this leads to very short absorption lengths, typically one micrometer or less, it provides a very accurate means for elemental and chemical speciation, which is essential, for instance, in the surface and environmental sciences. Interestingly, water is relatively transparent in the spectral region below the oxygen absorption edge, providing a natural contrast mechanism for imaging carbon-containing material in the spectral window extending from 284 to 543 eV. This provides interesting new opportunities for both the life and the environmental sciences.

Exploitation of this region of the spectrum is relatively recent. Indeed the names and spectral limits of soft x-rays and extreme ultraviolet radiation are not yet uniformly accepted. We have chosen here to follow the lead of astronomers, the lithography community, and much of the synchrotron and plasma physics communities in taking extreme ultraviolet as extending from photon energies of about 30 eV to 250 eV (wavelengths from about 40 nm to 5 nm) and soft x-rays as extending from about 250 eV (just below the carbon K edge) to several thousand eV (wavelengths from 5 nm to about 0.3 nm). The overlaps with ultraviolet radiation on the low photon energy side and with x-rays on the high photon energy side of the spectrum are not well defined. For comparison, green light has a photon energy in the vicinity of 2.3 eV and a wavelength of 530 nm. Recent developments involve advances in both science and technology, moving forward in a symbiotic relationship. Of particular importance is the development of nanofabrication techniques by the electronics industry. These provide well-defined structures with feature sizes similar to the wavelengths of interest here. The development of thin film multilayer coating capabilities by the materials science community has also been of great importance.

This book is intended for use by graduate students and researchers from physics, chemistry, engineering, and the life sciences. It is an outgrowth of classes I have taught during the past 14 years at the University of California at Berkeley. Typically the students in these classes were from the Ph.D. programs in Applied Science and Technology, Electrical Engineering and Computer Science, Physics, Chemistry, Materials Science, Nuclear Engineering, and Bioengineering. In some cases there were undergraduate students. This diversity of academic backgrounds has led to a text well suited for interdisciplinary pursuits. The text is intended to be comprehensive, covering basic knowledge of electromagnetic theory, sources, optics, and applications. It is designed to bring readers from these backgrounds to a common understanding with reviews of relevant atomic physics and electromagnetic theory in the first chapters. The remaining chapters develop understanding of multilayer coated optics with applications to materials science and EUV astronomy; synchrotron and undulator radiation; laser-produced plasmas; EUV and soft-x-ray lasers; coherence at short wavelengths; zone plate lenses and other diffractive structures with applications to biomicroscopy, materials microscopy and inspection of nanostructure patterns; and, finally, a chapter on the application of EUV and soft x-ray lithography to future high-volume production of sub-100 nm feature size electronic devices.

While the book is comprehensive in nature, it is meant to be accessible to the widest possible audience. Each chapter begins with a short summary of the important points in the material, illustrations that capture the main subject matter, and a few selected equations to whet the academic appetite. Most chapters have introductory sections designed for readers new to the field that include heuristic arguments and illustrations meant to clarify basic concepts. Each chapter also contains a mathematical development of equations for graduate students and specialists with particular interest in the chapter subject matter. To follow these mathematical developments, an undergraduate training in vector calculus and Fourier transforms is required. Descriptions of current applications in the physical and life sciences are incorporated. While there is a rigorous mathematical development, it is possible to absorb important concepts in the introductory material and then skip directly to the applications. Homework problems, which may be found at the website http://www.coe.berkeley.edu/AST/sxreuv, are designed to strengthen understanding of the material, to familiarize the reader with units and magnitudes, and to illustrate application of various formulas to current applications.

Over 600 references are provided to serve as an entry point to current research and applications. To facilitate use as a reference work many of the more important equations are boxed. In some cases the equations are repeated in numerical form, with common units, for more convenient use in a handbook fashion. Reference appendicies include tables of electron binding energies, characteristic emission lines, tables and graphs of real and imaginary scattering factors for many elements, graphs of calculated photo-absorption cross-sections, updated physical constants, and a convenient list of vector and mathematical relations. The International System of Units (SI) is also summarized, with lists of derived units and conversion factors commonly used in this field.

Berkeley, California
June 1999

Acknowledgments

It is my pleasure to acknowledge the sustained efforts, over several years, of Rudolf (Bob) Barton and Linda Geniesse. Bob typed and edited several versions of the text, carefully setting all the equations and showing great patience as I constantly revised the text and references. Linda, my wife, was responsible for all of the figures and created all of the original artwork, which I believe will benefit readers. She too showed patience far beyond reasonable expectations as we fine-tuned the artwork many times over for maximum clarity.

This book is a direct descendant of notes used at UC Berkeley in classes taught in thirteen of the past fourteen years. As such its content, method of presentation, and level of detail have been greatly influenced by Cal students. Their probing questions, discussions in class, occasional puzzled looks, contributions to homeworks, critical advice, and suggestions at semesters end have affected every paragraph of this book. I greatly appreciate their contributions. In particular I wish to acknowledge specific contributions by Kostas Adam, Junwei Bao, H. Raul Beguiristain, Kevin Bowers, Matt Brukman, Chang Chang, Gregory Denbeaux (Duke University), Eric DeVries, Daniel Finkenthal, Andrea Franke, Qian Fu, Ernie Glover, Kenneth Goldberg, Susanna Gordon, Joseph Heanue, Ronald Haff (UC Davis), John Heck, W.R. (Tony) Huff, Nasif Iskander, Ishtak Karim, Chih-wei Lai, Luke Lee, Sang Hun Lee, Yanwei Liu, Martin Magnuson (Uppsala University), Edward Moler, Vladimir Nikitin, Khanh Nguyen, Tai Nguyen, Tom Pistor, Nen-Wen Pu, Richard Schenker, Robert Socha, Regina Soufli, Alan Sullivan, Edita Tejnil, Akira Villar, Max Wei, Yan Wu, and Andrew Zenk.

The book has also benefited substantially from colleagues near and far. In preparing lectures I have sought advice and clarification from members of the Center for X-Ray Optics at Lawrence Berkeley National Laboratory. James Underwood provided original material and helpful insights on many occasions, Eric Gullikson modified many tables and graphs for use in the text, and Kwang-Je Kim, now at Argonne National Laboratory and the University of Chicago, patiently tutored me on the subject of synchrotron radiation. Werner Meyer-Ilse, Stanley Mrowka, Erik Anderson, Jeffrey Bokor (also of UC Berkeley), Patrick Naulleau, and Kenneth Goldberg each made contributions in their areas of expertise. Several of them also read particular chapters of the text and provided critical feedback. Michael Lieberman of UC Berkeley also read several early chapters and provided feedback. Portions of Chapters 2 and 6 follow lectures by Nathan Marcuvitz, then at New York University.

From a greater distance many other colleagues helped to improve the text by reading specific chapters and suggesting a wide range of improvements, corrections, and additions. For this I am grateful to Ingolf Lindau (Stanford and Lund Universities), Bernd Crasemann (University of Oregon), Joseph Nordgren (Uppsala University), David Windt (Lucent

Technologies), Claude Montcalm (LLNL), Eric Ziegler (ESRF), Alexandre Vinogradov (Lebedev Physical Institute), Albert Hofmann (CERN), R. Paul Drake (University of Michigan), R. Kauffman (LLNL), Andrei Shikanov (Lebedev Physical Institute), Luiz DaSilva (LLNL), Syzmon Suckewer (Princeton University), Jorge Rocca (Colorado State University), Emil Wolf (University of Rochester), Günter Schmahl (Göttingen University), Janos Kirz (SUNY, Stony Brook), Alexei Popov (Instit. Terr. Magn. Iono. Rad. Prop., Troitsk), Franco Cerrina (University of Wisconsin), Donald Sweeney (LLNL), Richard Stulen (Sandia), Hiroo Kinoshita (Himeji University), Victor Pol (Motorola), David Williamson (SVGL), and Frits Zernike.

Finally I am grateful to those who contributed to the atmosphere of support for research and teaching in Berkeley. These include Louis Ianiello, Iran Thomas, William Oosterhuis, and Jerry Smith at the Department of Energy's Office of Basic Energy Sciences; Howard Schlossberg at the Air Force Office of Scientific Research, who supported student research activities in our group over many years; David Patterson, who heads DARPA's Advanced Lithography Program; and the Intel, Motorola, and Advanced Micro Devices Corporations. A special note of gratitude goes to John Carruthers of Intel for his continual support of these activities and of this book in particular. Daniel Chemla is warmly acknowledged for his support and encouragement, without which it would not have been possible to maintain a vibrant research group while teaching, advising, and writing a lengthy text.

Berkeley, California
June 1999