

# Transmission Electron Microscopy

A Textbook for Materials Science

# Transmission Electron Microscopy

## A Textbook for Materials Science

David B. Williams  
C. Barry Carter

 Springer

David B. Williams  
The University of Alabama in Huntsville  
Huntsville AL, USA  
david.williams@uah.edu

C. Barry Carter  
University of Connecticut  
Storrs, CT, USA  
cbcarter@enr.uconn.edu

ISBN 978-0-387-76500-6 hardcover  
ISBN 978-0-387-76502-0 softcover (This is a four-volume set. The volumes are not sold individually.)  
e-ISBN 978-0-387-76501-3

Library of Congress Control Number: 2008941103

© Springer Science+Business Media, LLC 1996, 2009

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

springer.com

*To our parents*

*Walter Dennis and Mary Isabel Carter  
and*

*Joseph Edward and Catherine Williams,  
who made everything possible.*

# About the Authors



David B. Williams

David B. Williams became the fifth President of the University of Alabama in Huntsville in July 2007. Before that he spent more than 30 years at Lehigh University where he was the Harold Chambers Senior Professor Emeritus of Materials Science and Engineering (MS&E). He obtained his BA (1970), MA (1974), PhD (1974) and ScD (2001) from Cambridge University, where he also earned four Blues in rugby and athletics. In 1976 he moved to Lehigh as Assistant Professor, becoming Associate Professor (1979) and Professor (1983). He directed the Electron Optical Laboratory (1980–1998) and led Lehigh’s Microscopy School for over 20 years. He was Chair of the MS&E Department from 1992 to 2000 and Vice Provost for Research from 2000 to 2006, and has held visiting-scientist positions at the University of New South Wales, the University of Sydney, Chalmers University (Gothenburg), Los Alamos National

Laboratory, the Max Planck Institut für Metallforschung (Stuttgart), the Office National d'Etudes et Recherches Aérospatiales (Paris) and Harbin Institute of Technology.

He has co-authored and edited 11 textbooks and conference proceedings, published more than 220 refereed journal papers and 200 abstracts/conference proceedings, and given 275 invited presentations at universities, conferences and research laboratories in 28 countries.

Among numerous awards, he has received the Burton Medal of the Electron Microscopy Society of America (1984), the Heinrich Medal of the US Microbeam Analysis Society (MAS) (1988), the MAS Presidential Science Award (1997) and was the first recipient of the Duncumb award for excellence in microanalysis (2007). From Lehigh, he received the Robinson Award (1979), the Libsch Award (1993) and was the Founders Day commencement speaker (1995). He has organized many national and international microscopy and analysis meetings including the 2nd International MAS conference (2000), and was co-chair of the scientific program for the 12th International Conference on Electron Microscopy (1990). He was an Editor of *Acta Materialia* (2001–2007) and the *Journal of Microscopy* (1989–1995) and was President of MAS (1991–1992) and the International Union of Microbeam Analysis Societies (1994–2000). He is a Fellow of The Minerals Metals and Materials Society (TMS), the American Society for Materials (ASM) International, The Institute of Materials (UK) (1985–1996) and the Royal Microscopical Society (UK).



C. Barry Carter

C. Barry Carter became the Head of the Department of Chemical, Materials & Biomolecular Engineering at the University of Connecticut in Storrs in July 2007. Before that he spent 12 years (1979–1991) on the Faculty at Cornell University in the Department of Materials Science and Engineering (MS&E) and 16 years as the 3 M

Heltzer Multidisciplinary Chair in the Department of Chemical Engineering and Materials Science (CEMS) at the University of Minnesota. He obtained his BA (1970), MA (1974) and ScD (2001) from Cambridge University, his MSc (1971) and DIC from Imperial College, London and his DPhil (1976) from Oxford University. After a postdoc in Oxford with his thesis advisor, Peter Hirsch, in 1977 he moved to Cornell initially as a postdoctoral fellow, becoming an Assistant Professor (1979), Associate Professor (1983) and Professor (1988) and directing the Electron Microscopy Facility (1987–1991). At Minnesota, he was the Founding Director of the High-Resolution Microscopy Center and then the Associate Director of the Center for Interfacial Engineering; he created the Characterization Facility as a unified facility including many forms of microscopy and diffraction in one physical location. He has held numerous visiting scientist positions: in the United States at the Sandia National Laboratories, Los Alamos National Laboratory and Xerox PARC; in Sweden at Chalmers University (Gothenburg); in Germany at the Max Planck Institut für Metallforschung (Stuttgart), the Forschungszentrum Jülich, Hannover University and IFW (Dresden); in France at ONERA (Chatillon); in the UK at Bristol University and at Cambridge University (Peterhouse); and in Japan at the ICYS at NIMS (Tsukuba).

He is the co-author of two textbooks (the other is *Ceramic Materials; Science & Engineering* with Grant Norton) and co-editor of six conference proceedings, and has published more than 275 refereed journal papers and more than 400 extended abstracts/conference proceedings. Since 1990 he has given more than 120 invited presentations at universities, conferences and research laboratories. Among numerous awards, he has received the Simon Guggenheim Award (1985–1986), the Berndt Matthias Scholar Award (1997/1998) and the Alexander von Humboldt Senior Award (1997). He organized the 16th International Symposium on the Reactivity of Solids (ISRS-16 in 2007). He was an Editor of the *Journal of Microscopy* (1995–1999) and of *Microscopy and Microanalysis* (2000–2004), and became (co-)Editor-in-Chief of the *Journal of Materials Science* in 2004. He was the 1997 President of MSA, and served on the Executive Board of the International Federation of Societies for Electron Microscopy (IFSEM; 1999–2002). He is now the General Secretary of the International Federation of Societies for Microscopy (IFSM; 2003–2010). He is a Fellow of the American Ceramics Society (1996) the Royal Microscopical Society (UK), the Materials Research Society (2009) and the Microscopy Society of America (2009).

# Preface

How is this book different from the many other TEM books? It has several unique features but what we think distinguishes it from all other such books is that it is truly a *textbook*. We wrote it to be read by, and taught to, senior undergraduates and starting graduate students, rather than studied in a research laboratory. We wrote it using the same style and sentence construction that we have used in countless classroom lectures, rather than how we have written our countless (and much-less read) formal scientific papers. In this respect particularly, we have been deliberate in *not* referencing the sources of every experimental fact or theoretical concept (although we do include some hints and clues in the chapters). However, at the end of each chapter we have included groups of references that should lead you to the best sources in the literature and help you go into more depth as you become more confident about what you are looking for. We are great believers in the value of history as the basis for understanding the present and so the history of the techniques and key historical references are threaded throughout the book. Just because a reference is dated in the previous century (or even the antepenultimate century) doesn't mean it isn't useful! Likewise, with the numerous figures drawn from across the fields of materials science and engineering and nanotechnology, we do not reference the source in each caption. But at the very end of the book each of our many generous colleagues whose work we have used is clearly acknowledged.

The book consists of 40 relatively small chapters (with a few notable Carter exceptions!). The contents of most of the chapters can be covered in a typical lecture of 50-75 minutes (especially if you talk as fast as Williams). Furthermore, each of the four softbound volumes is flexible enough to be usable at the TEM console so you can check what you are seeing against what you should be seeing. Most importantly perhaps, the softbound version is cheap enough for all serious students to buy. So we hope you won't have to try and work out the meaning of the many complex color diagrams from secondhand B&W copies that you acquired from a former student. We have deliberately used color where it is useful rather than simply for its own sake (since all electron signals are colorless anyhow). There are numerous boxes throughout the text, drawing your attention to key information (green), warnings about mistakes you might easily make (amber), and dangerous practices or common errors (red).

Our approach throughout this text is to answer two fundamental questions:

*Why* should we use a particular TEM technique?

*How* do we put the technique into practice?

In answering the first question we attempt to establish a sound theoretical basis where necessary although not always giving all the details. We use this knowledge to answer the second question by explaining operational details in a generic sense and showing many illustrative figures. In contrast, other TEM books tend to be either strongly theoretical or predominantly descriptive (often covering more than just TEM). We view our approach as a compromise between the two extremes, covering enough theory to be reasonably rigorous without incurring the wrath of electron physicists yet containing sufficient hands-on instructions and practical examples to be useful to the materials engineer/nanotechnologist who wants an answer to a

materials problem rather than just a set of glorious images, spectra, and diffraction patterns. We acknowledge that, in attempting to seek this compromise, we often gloss over the details of much of the physics and math behind the many techniques but contend that the content is usually approximately right (even if on occasions, it might be precisely incorrect!).

Since this text covers the whole field of TEM we incorporate, to varying degrees, *all* the capabilities of the various kinds of current TEMs and we attempt to create a coherent view of the many aspects of these instruments. For instance, rather than separating out the broad-beam techniques of a traditional TEM from the focused-beam techniques of an analytical TEM, we treat these two approaches as different sides of the same coin. There is no reason to regard ‘conventional’ bright-field imaging in a parallel-beam TEM as being more fundamental (although it is certainly a more-established technique) than annular dark-field imaging in a focused-beam STEM. Convergent beam, scanning beam, and selected-area diffraction are likewise integral parts of the whole of TEM diffraction.

However, in the decade and more since the first edition was published, there has been a significant increase in the number of TEM and related techniques, greater sophistication in the microscope’s experimental capabilities, astonishing improvements in computer control of the instrument, and new hardware designs and amazing developments in software to model the gigabytes of data generated by these almost-completely digital instruments. Much of this explosion of information has coincided with the worldwide drive to explore the nanoworld, and the still-ongoing effects of Moore’s law. It is not possible to include all of this new knowledge in the second edition without transforming the already doorstep sized text into something capable of halting a large projectile in its tracks. It is still essential that this second edition teaches you to understand the essence of the TEM before you attempt to master the latest advances. But we personally cannot hope to understand fully all the new techniques, especially as we both descend into more administrative positions in our professional lives. Therefore, we have prevailed on almost 20 of our close friends and colleagues to put together with us a companion text (TEM; a companion text, Williams and Carter (Eds.) Springer 2010) to which we will refer throughout this second edition. The companion text is just as it says—it’s a friend whose advice you should seek when the main text isn’t enough. The companion is not necessarily more advanced but is certainly more detailed in dealing with key recent developments as well as some more traditional aspects of TEM that have seen a resurgence of interest. We have taken our colleagues’ contributions and rewritten them in a similar conversational vein to this main text and we hope that this approach, combined with the in-depth cross-referencing between the two texts will guide you as you start down the rewarding path to becoming a transmission microscopist.

We each bring more than 35 years of teaching and research in all aspects of TEM. Our research into different materials includes metals, alloys, ceramics, semiconductors, glasses, composites, nano and other particles, atomic-level planar interfaces, and other crystal defects. (The lack of polymeric and biological materials in our own research is evident in their relative absence in this book.) We have contributed to the training of a generation of (we hope) skilled microscopists, several of whom have followed us as professors and researchers in the EM field. These students represent our legacy to our beloved research field and we are overtly proud of their accomplishments. But we also expect some combination of these (still relatively young) men and women to write the third edition. We know that they, like us, will find that writing such a text broadens their knowledge considerably and will also be the source of much joy, frustration, and enduring friendship. We hope you have as much fun reading this book as we had writing it, but we hope also that it takes you much less time. Lastly, we encourage you to send us any comments, both positive and negative. We can both be reached by e-mail: [david.williams@uah.edu](mailto:david.williams@uah.edu) and [cbcarter@enr.uconn.edu](mailto:cbcarter@enr.uconn.edu).

# Foreword to First Edition

Electron microscopy has revolutionized our understanding of materials by completing the *processing-structure-properties* links down to atomistic levels. It is now even possible to tailor the microstructure (and mesostructure) of materials to achieve specific sets of properties; the extraordinary abilities of modern transmission electron microscopy—TEM—instruments to provide almost all the structural, phase, and crystallographic data allow us to accomplish this feat. Therefore, it is obvious that any curriculum in modern materials education must include suitable courses in electron microscopy. It is also essential that suitable texts be available for the preparation of the students and researchers who must carry out electron microscopy properly and quantitatively.

The 40 chapters of this new text by Barry Carter and David Williams (like many of us, well schooled in microscopy at Cambridge and Oxford) do just that. If you want to learn about electron microscopy from specimen preparation (the ultimate limitation); or via the instrument; or how to use the TEM correctly to perform imaging, diffraction, and spectroscopy—it's all there! This, to my knowledge, is the only complete text now available that includes all the remarkable advances made in the field of TEM in the past 30 to 40 years. The timing for this book is just right and, personally, it is exciting to have been part of the development it covers—developments that have impacted so heavily on materials science.

In case there are people out there who still think TEM is just taking pretty pictures to fill up one's bibliography, please stop, pause, take a look at this book, and digest the extraordinary intellectual demands required of the microscopist in order to do the job properly: crystallography, diffraction, image contrast, inelastic scattering events, and spectroscopy. Remember, these used to be fields in themselves. Today, one has to understand the fundamentals of *all* these areas before one can hope to tackle significant problems in materials science. TEM is a technique of characterizing materials down to the atomic limits. It must be used with care and attention, in many cases involving teams of experts from different venues. The fundamentals are, of course, based in physics, so aspiring materials scientists would be well advised to have prior exposure to, for example, solid-state physics, crystallography, and crystal defects, as well as a basic understanding of materials science, for without the latter, how can a person see where TEM can (or may) be put to best use?

So much for the philosophy. This fine new book definitely fills a gap. It provides a sound basis for research workers and graduate students interested in exploring those aspects of structure, especially defects, that control properties. Even undergraduates are now expected (and rightly) to know the basis for electron microscopy, and this book, or appropriate parts of it, can also be utilized for undergraduate curricula in science and engineering.

The authors can be proud of an enormous task, very well done.

*G. Thomas*  
Berkeley, California

# Foreword to Second Edition

This book is an exciting entry into the world of atomic structure and characterization in materials science, with very practical instruction on how you can see it and measure it, using an electron microscope. You will learn an immense amount from it, and probably want to keep it for the rest of your life (particularly if the problems cost you some effort!).

Is nanoscience “the next industrial revolution”? Perhaps that will be some combination of energy, environmental and nanoscience. Whatever it is, the new methods which now allow control of materials synthesis at the atomic level will be a large part of it, from the manufacture of jet engine turbine-blades to that of catalysts, polymers, ceramics and semiconductors. As an exercise, work out how much reduction would result in the transatlantic airfare if aircraft turbine blade temperatures could be increased by 200°C. Now calculate the reduction in CO<sub>2</sub> emission, and increased efficiency (reduced coal use for the same amount of electricity) resulting from this temperature increase for a coal-fired electrical generating turbine. Perhaps you will be the person to invent these urgently needed things! The US Department of Energy’s Grand Challenge report on the web lists the remarkable advances in exotic nanomaterials useful for energy research, from separation media in fuel cells, to photovoltaics and nano-catalysts which might someday electrolyze water under sunlight alone. Beyond these functional and structural materials, we are now also starting to see for the first time the intentional fabrication of atomic structures in which atoms can be addressed individually, for example, as quantum computers based perhaps on quantum dots. ‘Quantum control’ has been demonstrated, and we have seen fluorescent nanodots which can be used to label proteins.

Increasingly, in order to find out exactly what new material we have made, and how perfect it is (and so to improve the synthesis), these new synthesis methods must be accompanied by atomic scale compositional and structural analysis. The transmission electron microscope (TEM) has emerged as the perfect tool for this purpose. It can now give us atomic-resolution images of materials and their defects, together with spectroscopic data and diffraction patterns from sub-nanometer regions. The field-emission electron gun it uses is still the brightest particle source in all of physics, so that electron microdiffraction produces the most intense signal from the smallest volume of matter in all of science. For the TEM electron beam probe, we have magnetic lenses (now aberration corrected) which are extremely difficult for our X-ray and neutron competitors to produce (even with much more limited performance) and, perhaps most important of all, our energy-loss spectroscopy provides unrivalled spatial resolution combined with parallel detection (not possible with X-ray absorption spectroscopy, where absorbed X-rays disappear, rather than losing some energy and continuing to the detector).

Much of the advance in synthesis is the legacy of half a century of research in the semiconductor industry, as we attempt to synthesize and fabricate with other materials what is now so easily done with silicon. Exotic oxides, for example, can now be laid down layer by layer to form artificial crystal structures with new, useful properties. But it is also a result of the spectacular advances in materials characterization, and our ability to see structures at the atomic level. Perhaps the best example of this is the discovery of the carbon nanotube, which was first identified by using an electron

microscope. Any curious and observant electron microscopist can now discover new nanostructures just because they look interesting at the atomic scale. The important point is that if this is done in an environmental microscope, he or she will know how to make them, since the thermodynamic conditions will be recorded when using such a ‘lab in a microscope’. There are efforts at materials discovery by just such combinatorial trial-and-error methods, which could perhaps be incorporated into our electron microscopes. This is needed because there are often just ‘too many possibilities’ in nature to explore in the computer — the number of possible structures rises very rapidly with the number of distinct types of atoms.

It was Richard Feynman who said that, “if, in some catastrophe, all scientific knowledge was lost, and only one sentence could be preserved, then the statement to be passed on, which contained the most information in the fewest words, would be that matter consists of atoms.” But confidence that matter consists of atoms developed surprisingly recently and as late as 1900 many (including Kelvin) were unconvinced, despite Avagadro’s work and Faraday’s on electrodeposition. Einstein’s Brownian motion paper of 1905 finally persuaded most, as did Rutherford’s experiments. Muller was first to see atoms (in his field-ion microscope in the early 1950s), and Albert Crewe two decades later in Chicago, with his invention of the field-emission gun for his scanning transmission electron microscope (STEM). The Greek Atomists first suggested that a stone, cut repeatedly, would eventually lead to an indivisible smallest fragment, and indeed Democritus believed that “nothing exists except vacuum and atoms. All else is opinion.” Marco Polo remarks on the use of spectacles by the Chinese, but it was van Leeuwenhoek (1632-1723) whose series of papers in *Phil. Trans.* brought the microworld to the general scientific community for the first time using his much improved optical microscope. Robert Hooke’s 1665 *Micrographica* sketches what he saw through his new compound microscope, including fascinating images of faceted crystallites, whose facet angles he explained with drawings of piles of cannon balls. Perhaps this was the first resurrection of the atomistic theory of matter since the Greeks. Zernike’s phase-plate in the 1930s brought phase contrast to previously invisible ultra-thin biological ‘phase objects’, and so is the forerunner for the corresponding theory in high-resolution electron microscopy.

The past fifty years has been a wonderfully exciting time for electron microscopists in materials science, with continuous rapid advances in all of its many modes and detectors. From the development of the theory of Bragg diffraction contrast and the column approximation, which enables us to understand TEM images of crystals and their defects, to the theory of high-resolution microscopy useful for atomic-scale imaging, and on into the theory of all the powerful analytic modes and associated detectors, such as X-rays, cathodoluminescence and energy-loss spectroscopy, we have seen steady advances. And we have always known that defect structure in most cases controls properties — the most common (first-order) phase transitions are initiated at special sites, and in the electronic oxides a whole zoo of charge-density excitations and defects waits to be fully understood by electron microscopy. The theory of phase-transformation toughening of ceramics, for example, is a wonderful story which combines TEM observations with theory, as does that of precipitate hardening in alloys, or the early stages of semiconductor-crystal growth. The study of diffuse scattering from defects as a function of temperature at phase transitions is in its infancy, yet we have a far stronger signal there than in competing X-ray methods. The mapping of strain-fields at the nanoscale in devices, by quantitative convergent-beam electron diffraction, was developed just in time to solve a problem listed on the Semiconductor Roadmap (the speed of your laptop depends on strain-induced mobility enhancement). In biology, where the quantification of TEM data is taken more seriously, we have seen three-dimensional image reconstructions of many large proteins, including the ribosome (the factory which makes proteins according to DNA instructions). Their work should be a model to the materials science community in the constant effort toward better quantification of data.

Like all the best textbooks, this one was distilled from lecture notes, debugged over many years and generations of students. The authors have extracted the heart from

many difficult theory papers and a huge literature, to explain to you in the simplest, clearest manner (with many examples) the most important concepts and practices of modern transmission electron microscopy. This is a great service to the field and to its teaching worldwide. Your love affair with atoms begins!

*J.C.H. Spence*  
Regent's Professor of Physics  
Arizona State University and Lawrence  
Berkeley National Laboratory

# Acknowledgments

We have spent over 20 years conceiving and writing this text and the preceding first edition and such an endeavor can't be accomplished in isolation. Our first acknowledgment must be to our respective wives and children: Margie, Matthew, Bryn, and Stephen and Bryony, Ben, Adam, and Emily. Our families have borne the brunt of our absences from home (and occasionally the brunt of our presence). Neither edition would have been possible without the encouragement, advice, and persistence of (and the fine wines served by) Amelia McNamara, our first editor at Plenum Press, then Kluwer, and Springer.

We have both been fortunate to work in our respective universities with many more talented colleagues, post-doctoral associates, and graduate students, all of whom have taught us much and contributed significantly to the examples in both editions. We would like to thank a few of these colleagues directly: Dave Ackland, Faisal Alamgir, Arzu Altay, Ian Anderson, Ilke Arslan, Joysurya Basu, Steve Baumann, Charlie Betz, John Bruley, Derrick Carpenter, Helen Chan, Steve Claves, Dov Cohen, Ray Coles, Vinayak Dravid, Alwyn Eades, Shelley Gillis, Jeff Farrer, Joe Goldstein, Pradyumna Gupta, Brian Hebert, Jason Hefflefinger, John Hunt, Yasuo Ito, Matt Johnson, Vicki Keast, Chris Kiely, Paul Kotula, Chunfei Li, Ron Liu, Charlie Lyman, Mike Mallamaci, Stuart McKernan, Joe Michael, Julia Nowak, Grant Norton, Adam Papworth, Chris Perrey, Sundar Ramamurthy, René Rasmussen, Ravi Ravishankar, Kathy Repa, Kathy Reuter, Al Romig, Jag Sankar, David A. Smith, Kamal Soni, Changmo Sung, Caroline Swanson, Ken Vecchio, Masashi Watanabe, Jonathan Winterstein, Janet Wood, and Mike Zemyan.

In addition, many other colleagues and friends in the field of microscopy and analysis have helped with the book (even if they weren't aware of it). These include Ron Anderson, Raghavan Ayer, Jim Bentley, Gracie Burke, Jeff Campbell, Graham Cliff, David Cockayne, Peter Doig, the late Chuck Fiori, Peter Goodhew, Brendan Griffin, Ron Gronsky, Peter Hawkes, Tom Huber, Gilles Hug, David Joy, Mike Kersker, Roar Kilaas, Sasha Krajnikov, the late Riccardo Levi-Setti, Gordon Lorimer, Harald Müllejjans, Dale Newbury, Mike O'Keefe, Peter Rez, Manfred Rühle, John-Henry Scott, John Steeds, Peter Swann, Gareth Thomas, Patrick Veysseyère, Peter Williams, Nestor Zaluzec, and Elmar Zeitler. Many of these (and other) colleagues provided the figures that we acknowledge individually at the end of the book.

We have received financial support for our microscopy studies through several different federal agencies; without this support none of the research that underpins the contents of this book would have been accomplished. In particular, DBW wishes to thank the National Science Foundation, Division of Materials Research for over 30 years of continuous funding, NASA, Division of Planetary Science (with Joe Goldstein) and The Department of Energy, Basic Energy Sciences (with Mike Notis and Himanshu Jain), Bettis Laboratories, Pittsburgh, and Sandia National Laboratories, Albuquerque. While this edition was finalized at the University of Alabama in Huntsville, both editions were written while DBW was in the Center for Advanced Materials and Nanotechnology at Lehigh University, which supports that outstanding electron microscopy laboratory. Portions of both editions were written while DBW was on sabbatical or during extended visits to various microscopy labs: Chalmers University, Göteborg, with Gordon Dunlop and Hans Nordén; The Max Planck

Institut für Metallforschung, Stuttgart, with Manfred Rühle; Los Alamos National Laboratory with Terry Mitchell; Dartmouth College, Thayer School of Engineering, with Erland Schulson; and the Electron Microscope Unit at Sydney University with Simon Ringer. CBC wishes to acknowledge the Department of Energy, Basic Energy Sciences, the National Science Foundation, Division of Materials Research, the Center for Interfacial Engineering at the University of Minnesota, The Materials Science Center at Cornell University, and the SHaRE program at Oak Ridge National Laboratories. The first edition was started while CBC was with the Department of Materials Science and Engineering at Cornell University. This edition was started at the Department of Chemical Engineering and Materials Science at the University of Minnesota where the first edition was finished and was finalized while CBC was at the University of Connecticut. The second edition was partly written while CBC was on Sabbatical Leave at Chalmers University with Eva Olssen (thanks also to Anders Tholen at Chalmers), at NIMS in Tsukuba with Yoshio Bando (thanks also to Dmitri Golberg and Kazuo Furuya at NIMS at Yuichi Ikuhara at the University of Tokyo) and at Cambridge University with Paul Midgley. CBC also thanks the Master and Fellows of Peterhouse for their hospitality during the latter period.

CBC would also like to thank the team at the Ernst Ruska Center for their repeated generous hospitality (special thanks to Knut Urban, Markus Lenzen, Andreas Thust, Martina Luysberg, Karsten Tillmann, Chunlin Jia and Lothar Houben)

Despite our common scientific beginnings as undergraduates in Christ's College Cambridge, we learned our trade under different microscopists: DBW with Jeff Edington in Cambridge and CBC with Sir Peter Hirsch and Mike Whelan in Oxford. Not surprisingly, the classic texts by these renowned microscopists are referred to throughout this book. They influenced our own views of TEM tremendously, contributing to the undoubted bias in our opinions, notation, and approach to the whole subject.

# List of Initials and Acronyms

---

The field of TEM is a rich source of initials and acronyms (these are words formed by the initials), behind which we hide both simple and esoteric concepts. While the generation of new initials and acronyms can be a source of original thinking (e.g., see ALCHEMI), it undoubtedly makes for easier communication in many cases and certainly reduces the length of voluminous textbooks. You have to master this strange language before being accepted into the community of microscopists, so we present a comprehensive listing that you should memorize.

ACF	absorption-correction factor	CB	coherent bremsstrahlung
ACT	automated crystallography for TEM	CBED	convergent-beam electron diffraction
A/D	analog to digital (converter)	CBIM	convergent beam imaging
ADF	annular dark field	CCD	charge-coupled device
AEM	analytical electron microscope/microscopy	CCF	cross-correlation function
AES	Auger electron spectrometer/spectroscopy	CCM	charge-collection microscopy
AFF	aberration-free focus	CDF	centered dark field
AFM	atomic force microscope/microscopy	CF	coherent Fresnel/Foucault
ALCHEMI	atom location by channeling-enhanced micro-analysis	CFE	cold field emission
ANL	Argonne National Laboratory	CL	cathodoluminescence
APB	anti-phase domain boundary	cps	counts per second
APFIM	atom-probe field ion microscope/microscopy	CRT	cathode-ray tube
APW	augmented plane wave	CS	crystallographic shear
ASW	augmented spherical wave	CSL	coincident-site lattice
ATW	atmospheric thin window	CVD	chemical vapor deposition
BF	bright field	DADF	displaced-aperture dark field
BFP	back-focal plane	DDF	diffuse dark field
BSE	backscattered electron	DF	dark field
BZB	Brillouin-zone boundary	DFT	density-functional theory
C1,2	condenser 1, 2, etc. lens	DOS	density of states
CASTEP	electronic-potential calculation software	DP	diffraction pattern
CAT	computerized axial tomography	DQE	detection quantum efficiency
		DSTEM	dedicated scanning transmission electron microscope/microscopy
		DTSA	desktop spectrum analyzer

EBIC electron beam-induced current/conductivity  
 EBSD electron-backscatter diffraction  
 EELS electron energy-loss spectrometer/  
 spectrometry  
 EFI energy-filtered imaging  
 EFTEM energy-filtered transmission electron  
 microscope  
 ELNES energy-loss near-edge structure  
 ELP<sup>TM</sup> energy-loss program (Gatan)  
 EMMA electron microscope microanalyzer  
 EMS electron microscopy image simulation  
 (E)MSA (Electron) Microscopy Society of America  
 EPMA electron-probe microanalyzer  
 ESCA electron spectroscopy for chemical analysis  
 ESI electron-spectroscopic imaging  
 EXAFS extended X-ray-absorption fine structure  
 EXELFS extended energy-loss fine structure  
  
 FEFF ab-initio multiple-scattering software  
 FEG field-emission gun  
 FET field-effect transistor  
 FFP front-focal plane  
 FFT fast Fourier transform  
 FIB focused ion beam  
 FLAPW full-potential linearized augmented  
 plane wave  
 FOLZ first-order Laue zone  
 FTP file-transfer protocol  
 FWHM full width at half maximum  
 FWTM full width at tenth maximum  
  
 GB grain boundary  
 GIF Gatan image filter<sup>TM</sup>  
 GIGO garbage in garbage out  
 GOS generalized oscillator strength  
  
 HAADF high-angle annular dark field  
 HOLZ higher-order Laue zone  
 HPGe high-purity germanium  
 HREELS high-resolution electron energy-loss  
 spectrometer/spectrometry  
 HRTEM high-resolution transmission electron  
 microscope/microscopy  
 HV high vacuum  
 HVEM high-voltage electron microscope/  
 microscopy  
  
 ICC incomplete charge collection  
 ICDD International Center for Diffraction Data  
 ID identification (of peaks in spectrum)  
 IDB inversion domain boundary  
 IEEE International Electronics and Electrical  
 Engineering  
 IG intrinsic Ge  
 IVEM intermediate-voltage electron microscope/  
 microscopy

K-M Kossel-Möllenstedt  
  
 LACBED large-angle convergent-beam electron  
 diffraction  
 LCAO linear combination of atomic orbitals  
 LCD liquid-crystal display  
 LDA local-density approximation  
 LEED low-energy electron diffraction  
 LKKR layered Korringa-Kohn-Rostoker  
  
 MAS Microbeam Analysis Society  
 MBE molecular-beam epitaxy  
 MC minimum contrast  
 MCA multichannel analyzer  
 MDM minimum detectable mass  
 MLS multiple least-squares  
 MMF minimum mass fraction  
 MO molecular orbital  
 MRS Materials Research Society  
 MS multiple scattering  
 MSA multivariate statistical analysis  
 MSDS material safety data sheets  
 MT muffin tin  
 MV megavolt  
  
 NCEMSS National Center for Electron Microscopy  
 simulation system  
 NIH National Institutes of Health  
 NIST National Institute of Standards and  
 Technology  
 NPL National Physical Laboratory  
  
 OIM orientation-imaging microscopy  
 OR orientation relationship  
  
 PARODI parallel recording of dark-field images  
 PB phase boundary  
 P/B peak-to-background ratio  
 PEELS parallel electron energy-loss spectrometer/  
 spectrometry  
 PIPS Precision Ion-Polishing System<sup>TM</sup>  
 PIXE proton-induced X-ray emission  
 PM photomultiplier  
 POA phase-object approximation  
 ppb/m parts per billion/million  
 PDA photo-diode array  
 PSF point-spread function  
 PTS position-tagged spectrometry  
  
 QHRTEM quantitative high-resolution transmission  
 electron microscopy  
  
 RB translation boundary (yes, it does!)  
 RDF radial distribution function  
 REM reflection electron microscope/microscopy  
 RHEED reflection high-energy electron diffraction

SACT small-angle cleaving technique  
 SAD(P) selected-area diffraction (pattern)  
 SCF self-consistent field  
 SDD silicon-drift detector  
 SE secondary electron  
 SEELS serial electron energy-loss spectrometer/  
 spectrometry  
 SEM scanning electron microscope/microscopy  
 SESAME sub-eV sub-Å microscope  
 SF stacking fault  
 SHRLI simulated high-resolution lattice images  
 SI spectrum imaging  
 SI Système Internationale  
 SIGMAK K-edge quantification software  
 SIGMAL L-edge quantification software  
 SIMS secondary-ion mass spectrometry  
 S/N signal-to-noise ratio  
 SOLZ second-order Laue zone  
 SRM standard reference material  
 STEM scanning transmission electron microscope/  
 microscopy  
 STM scanning tunneling microscope/microscopy  
  
 TB twin boundary  
 TEM transmission electron microscope/  
 microscopy  
 TFE thermal field emission  
 TMBA too many bloody acronyms  
  
 UHV ultrahigh vacuum  
 URL uniform resource locator  
 UTW ultra-thin window  
  
 V/F voltage to frequency (converter)  
 VLM visible-light microscope/microscopy  
 VUV vacuum ultra violet  
  
 WB weak beam  
 WBDF weak-beam dark field  
 WDS wavelength-dispersive spectrometer/spectrometry  
 WP whole pattern  
 WPOA weak-phase object approximation  
 WWW World Wide Web  
  
 XANES X-ray absorption near-edge structure  
 XEDS X-ray energy-dispersive spectrometer/  
 spectrometry  
 XPS X-ray photoelectron spectrometer/spectrometry  
 XRD/F X-ray diffraction/fluorescence  
  
 YAG yttrium-aluminum garnet  
 YBCO yttrium-barium-copper oxide  
 YSZ yttria-stabilized zirconia  
  
 ZAF atomic number/absorption/fluorescence correction  
 ZAP zone-axis pattern  
 ZLP zero-loss peak  
 ZOLZ zero-order Laue zone

# List of Symbols

We use a large number of symbols. Because we are constrained by the limits of our own and the Greek alphabets, we often use the same symbol for different terms, which can confuse the unwary. We have tried to be consistent where possible but undoubtedly we have not always succeeded. The following (not totally inclusive) list may help if you remain confused after reading the text.

$a$	interatomic spacing	<b>B</b>	beam direction
$a$	relative transition probability	<b>B</b>	magnetic field strength
$a$	width of diffraction disk	$B$	background intensity
$a_0$	Bohr radius	$B(\mathbf{u})$	aberration function
$a_0$	lattice parameter	$c$	centi
<b>a, b, c</b>	lattice vectors	$c$	velocity of light
<b>a*, b*, c*</b>	reciprocal-lattice vectors	$C$	composition
$A$	absorption-correction factor	$C$	contrast
$A$	active area of X-ray detector	$C$	coulomb
$A_0$	amplitude	$C_a$	astigmatism-aberration coefficient
$A$	amplitude of scattered beam	$C_c$	chromatic-aberration coefficient
$A$	amperes	$C_g$	<b>g</b> component of Bloch wave
$A$	atomic weight	$C_s$	spherical-aberration coefficient
$A$	Richardson's constant	$C_x$	fraction of X atoms on specific sites
$\text{\AA}$	Ångstrom	$C_0$	amplitude of direct beam
$\mathcal{A}$	Bloch wave amplitude	$C_\varepsilon$	combination of the elastic constants
$A(\mathbf{u})$	aperture function	$(C_s\lambda)^{1/2}$	scherzer
$A, B$	fitting parameters for energy-loss background subtraction	$(C_s\lambda^3)^{1/4}$	glaser
$b$	beam-broadening parameter	$c/o$	condenser /objective
$b$	separation of diffraction disks	$d$	beam (probe) diameter
$\mathbf{b}_e$	edge component of the Burgers vector	$d$	diameter of spectrometer entrance aperture
$\mathbf{b}_p$	Burgers vector of partial dislocation	$d$	interplanar spacing
$\mathbf{b}_T$	Burgers vector of total dislocation		

$d$	spacing of moire fringes	$E_D(\mathbf{u})$	envelope function for the detector
$d_c$	effective source size	$E_s(\mathbf{u})$	envelope function for the source
$d_d$	diffraction-limited beam diameter	$E_v(\mathbf{u})$	envelope function for specimen vibration
$d_{\text{eff}}$	effective entrance-aperture diameter at recording plane	$f$	focal length
$d_g$	Gaussian beam diameter	$f(\mathbf{r})$	strength of object at point $(x,y)$
$d_{hkl}$	$hkl$ interplanar spacing	$f(\theta)$	atomic-scattering factor
$d_i$	image distance	$f(\mathbf{k})$	atomic-scattering amplitude
$d_{\text{im}}$	smallest resolvable image distance	$f_x$	scattering factor for X-rays
$d_o$	object distance	$f_i(x)$	residual of least-squares fit
$d_{\text{ob}}$	smallest resolvable object distance	$F$	Fano factor
$d_s$	spherical-aberration limited beam diameter	$F$	fluorescence-correction factor
$d_t$	total beam diameter	$\mathbf{F}$	Lorentz force
$dz$	thickness of a diffracting slice	$F$	relativistic-correction factor
$d\sigma/d\Omega$	differential cross section of one atom	$F$	Fourier transform
$D$	aperture diameter	$F'$	Fourier transform of edge intensity
$D$	change in focus	$F_B$	fraction of alloying element B
$D$	dimension (as in 1D, 2D...)	$F_g$	special value of $F(\theta)$ when $\theta$ is the Bragg angle
$D$	distance from projector crossover to recording plane	$F(P)$	Fourier transform of plasmon intensity
$D$	electron dose	$F(\mathbf{u})$	Fourier transform of $f(\mathbf{r})$
$D_A$	distance from beam crossover to spectrometer entrance aperture	$F(0)$	Fourier transform of elastic intensity
$D_{\text{im}}$	depth of focus	$F(1)$	Fourier transform of single-scattering intensity
$D_{\text{ob}}$	depth of field	$F(\theta)$	structure factor
$D_1, D_2$	tie-line points on dispersion surfaces in presence of defect	$\mathbf{g}/\bar{g}$	diffraction vector (magnitude of $\pm \mathbf{K}$ at the Bragg angle)
$e$	charge on the electron	$\mathbf{g}_{hkl}$	diffraction vector for $hkl$ plane
$E$	energy	$g$	gram
$\mathbf{E}$	electric-field strength	$g(\mathbf{r})$	intensity of image at point $(x,y)$
$E$	Young's modulus	$G$	Bragg reflection
$E$	total energy	$G$	radius of a HOLZ ring
$\mathcal{E}$	energy loss	$G$	giga
$E_a$	spatial-coherence envelope	$G(\mathbf{u})$	Fourier transform of $g(\mathbf{r})$
$E_c$	chromatic-coherence envelope	$Gy$	gray (radiation unit)
$E_c$	critical ionization energy	$h$	Planck's constant
$E_d$	displacement energy	$h$	distance from specimen to the aperture
$E_F$	Fermi energy/level	$h(\mathbf{r})$	contrast-transfer function
$E_{h/l}$	high/low energy for background- subtraction window	$(hkl)$	Miller indices of a crystal plane
$E_{K/L/M}$	ionization energy for K/L/M-shell electron	$hkl$	indices of diffraction spots from $hkl$ plane
$E_{K/L/M}$	energy of K/L/M X-ray	$H$	spacing of the reciprocal-lattice planes parallel to beam
$\mathcal{E}_m$	average energy loss	$H(\mathbf{u})$	Fourier transform of $h(\mathbf{r})$
$E_P$	plasmon energy	$i$	beam current
$\mathcal{E}_P$	plasmon energy loss	$i$	imaginary number
$E_s$	sputtering-threshold energy	$i$	number of atoms in unit cell
$E_t$	threshold energy	$I$	intensity
$E_0$	beam energy	$I$	intrinsic line width of the XEDS detector
$E(\mathbf{u})$	envelope function	$i_e$	emission current
$E_c(\mathbf{u})$	envelope function for chromatic aberration		
$E_d(\mathbf{u})$	envelope function for specimen drift		

$i_f$	filament-heating current	$n$	number of scattered electrons
$I_g$	intensity in the diffracted beam	$n_0$	number of incident electrons
$I_{K/L/M}$	K/L/M-shell intensity above background	n	nano
$I(\mathbf{k})$	kinematical intensity	$n$	principal quantum number
$I(1)$	single-scattering intensity	$\mathbf{n}$	vector normal to the surface
$I_P$	intensity in the first plasmon peak	$n_s$	number of electrons in the ionized sub-shell
$I_T$	total transmitted intensity	$N$	$h + k + l$
$I_0$	intensity in the zero-loss peak	$N$	newton
$I_0$	intensity in the direct beam	$N$	noise
$I(t)$	low-loss spectrum intensity	$N$	number of counts in ionization edge
$J$	current density	$N$	number of atoms/unit area
$J$	joule	$N_V$	number of atoms/unit volume
$J$	sum of spin and angular quantum numbers	$N(E)$	number of bremsstrahlung photons of energy $E$
$k$	magnitude of the wave vector	$N_0$	Avogadro's number
$k$	Boltzmann's constant	$O$	direct beam
$k$	kilo	$p$	integer
$\mathbf{k}_I$	$\mathbf{k}$ -vector of the incident wave	$\mathbf{p}$	momentum
$\mathbf{k}_D$	$\mathbf{k}$ -vector of the diffracted wave	$p$	pico
$k_{AB}$	Cliff-Lorimer factor/sensitivity factor	$P$	probability of scattering
$K$	bulk modulus	$P$	peak intensity
$K$	Kelvin	$P$	FWHM of a randomized electronic-pulse generator
$K$	Kramers' constant	$\text{Pa}$	pascal
$K$	sensitivity factor	$P_{K/L/M}$	probability of K/L/M-shell ionization
$K/L/M$	inner-shell/characteristic X-ray/ionization edge	$P(z)$	scattering matrix for a slice of thickness $z$
$\mathbf{K}$	change in $\mathbf{k}$ due to diffraction	$q$	charge
$\mathbf{K}_B$	magnitude of $\mathbf{K}$ at the Bragg angle	$Q$	cross section
$K_0$	kernel	$r$	radius
$l$	angular quantum number	$r$	distance a wave propagates
$L$	camera length	$r$	distance between contamination spots
$L$	lattice spacing in beam direction	$r$	minimum resolvable distance/resolution
$L$	length of magnetic field	$r$	power term to fit background in EEL spectrum
$L_0$	length of magnetic field along optic axis	$r_M$	image-translation distance
$L$	path difference	$\mathbf{r}_n$	lattice vector
$L$	width of composition line-profile	$\mathbf{r}^*$	reciprocal-lattice vector
$m$	meters	$r_{ast}$	radius of astigmatism disk
$m$	milli	$r_{chr}$	radius of chromatic-aberration disk
$m$	mirror plane	$r_{sph}$	radius of spherical-aberration disk
$m$	number of focal increments	$r_{min}$	minimum disk radius
$m_0$	rest mass of the electron	$r_{th}$	theoretical disk radius
$M$	magnification	$\mathbf{r}'_n$	lattice vector in strained crystal
$M$	mega	$r_0$	maximum radius of DP in focal plane of spectrometer
$M_A$	angular magnification	$R$	ALCHEMI intensity ratio
$M_T$	transverse magnification	$R$	count rate
$M_1, M_2$	tie-line points on dispersion surfaces	$\mathbf{R}$	crystal-lattice vector
$n$	integer		
$n$	free-electron density		
$n$	number of counts		

$R$	distance on screen between diffraction spots	$w$	$s\xi_g$ (excitation error multiplied by extinction distance)
$R$	radius of curvature of EEL spectrometer	$w$	projected width of planar defect
$R$	resolution of XEDS detector	$w$	width
$R$	spatial resolution		
$R$	reduction in partial cross section with increasing $\alpha$	$x$	distance
		$\times$	times (magnification)
$R_{MAX}$	diameter of beam emerging from specimen	$x, y, z$	atom coordinates
$\mathbf{R}_n$	lattice-displacement vector	$X$	FWHM due to XEDS detector
$\mathbf{R}(\mathbf{r})$	displacement	$X$	rotation axis
		$y$	displacement at the specimen
$s$	excitation error/deviation parameter	$y$	number of counts in channel
$s$	second	$y$	parallax shift in the image
$s$	spin quantum number	$z$	distance within a specimen
$\mathbf{S}_R$	excitation error due to defect	$z$	distance along optic axis
$\mathbf{S}_z(\mathbf{s}_g)$	excitation error	$z$	specimen height
$s_{eff}$	effective excitation error	$Z$	atomic number/atomic-number correction factor
$S$	distance from specimen to detector		
$S$	signal		
$S$	standard deviation for $n$ measurements		
sr	steradians		
			<b>Greek symbols</b>
$\mathbf{t}$	shift vector between the ZOLZ and HOLZ	$\alpha$	phase shift due to defect
$t$	student ( $t$ ) distribution	$\alpha$	semi-angle of incidence/convergence
$t$	thickness	$\alpha$	X-ray take-off angle
$t'$	absorption path length	$\alpha_0$	beam divergence semi-angle at gun crossover
$t_0$	thickness at zero tilt	$\alpha_{opt}$	optimum convergence semi-angle
$T$	absolute temperature	$\beta$	brightness
$T$	tesla	$\beta$	ratio of electron velocity to light velocity
$T_c$	period of rotation	$\beta$	semi-angle of collection
$T(\mathbf{u})$	objective-lens transfer function	$\beta_{opt}$	optimum collection semi-angle
$T_{eff}(\mathbf{u})$	effective transfer function	$\gamma$	degree of spatial coherence
$\mathbf{u}$	reciprocal lattice vector	$\gamma$	phase of direct beam
$\mathbf{u}$	unit vector along the dislocation line	$\gamma$	relativistic-correction factor
		$\gamma$	specimen tilt angle
$\mathbf{u}^*$	vector normal to the ZOLZ	$\Delta$	change/difference
$U$	overvoltage	$\Delta$	width of energy window
$U_g$	Fourier component of the perfect-crystal potential	$\Delta d$	change in lattice parameter
$[UVW]$	indices of a crystal direction	$\Delta\phi$	phase difference
$UVW$	indices of beam direction	$\Delta\theta_i$	angle between Kossel–Möllenstedt fringes
		$\Delta_{AB}$	difference in mass-absorption coefficients
$v$	velocity	$\Delta E$	energy width /spread
$V$	accelerating voltage	$\Delta\mathcal{E}_P$	plasmon-line width/change in plasmon energy
$\mathcal{V}$	potential energy	$\Delta f$	maximum difference in focus
$V_c/V$	volume of the unit cell	$\Delta f$	defocus error due to chromatic aberration
$V_c$	inner potential of cavity	$\Delta f_{AFF}$	aberration-free (de)focus
$V_t$	projected potential through specimen thickness	$\Delta f_{MC}$	minimum contrast defocus
$V(\mathbf{r})$	crystal inner potential	$\Delta f_{opt}$	optimum defocus
		$\Delta$	change (in height)

$\Delta h$	relative depth in specimen	$\chi^2$	goodness of fit (between standard and experimental spectra)
$\Delta I$	change in intensity	$\chi(\mathbf{u})$	phase-distortion function
$\Delta p$	parallax shift	$\chi(\mathbf{k})$	momentum transfer
$\Delta V$	change in the inner potential		
$\Delta x$	path difference/image shift		
$\Delta x$	half-width of image of undissociated screw dislocation	$\kappa$	thermal conductivity
$\Delta x_{\text{res}}$	resolution at Scherzer defocus	$\xi_{\mathbf{g}}$	extinction distance for the diffracted beam
$\Delta f_{\text{sch}}$	Scherzer defocus	$\xi_{\mathbf{g}'}$	absorption parameter
		$\xi_0$	extinction distance for the direct beam
$\delta$	angle between XEDS detector normal and line from detector to specimen	$\xi_{\text{eff}}$	effective extinction distance ( $s \neq 0$ )
$\delta$	angle between beam and plane of defect	$\xi_{\mathbf{g}}^{\text{abs}}$	absorption-modified $\xi_{\mathbf{g}}$
$\delta$	diameter of disk image	$\lambda_{\text{c}}$	coherence length
$\delta$	diffuseness of interface	$\lambda$	mean-free path
$\delta$	precipitate/matrix misfit	$\lambda$	wavelength
$\delta$	small increment	$\lambda_{\text{K/L/M}}$	mean-free path for K/L/M-shell ionization
$\delta$	smallest resolvable distance (resolution)	$\lambda_{\text{p}}$	plasmon mean-free path
$\varepsilon$	deflection angle	$\lambda_{\text{R}}$	relativistic wavelength
$\varepsilon$	detector efficiency	$\lambda^{-1}$	radius of Ewald sphere
$\varepsilon$	energy to create an electron-hole pair		
$\varepsilon$	specimen-tilt angle	$\mu$	micro
$\varepsilon$	strain	$\mu$	refractive index
$\varepsilon_0$	permittivity of free space (dielectric constant)	$\mu/\rho$	mass-absorption coefficient
		$\mu^{(j)}(\mathbf{r})$	Bloch function
$\eta$	phase change		
$\eta$	angle between excess Kikuchi lines at $\mathbf{s} = 0$ and $\mathbf{s} > 0$	$\nu$	frequency
$\eta(\theta)$	phase of the atomic-scattering factor	$\nu$	Poisson's ratio
		$\psi$	amplitude of a wave
$\Phi$	phase shift accompanying scattering	$\psi$	the wave function
$\Phi$	work function	$\psi_{\text{sph}}$	amplitude of spherical wave
$\phi$	rotation angle between image and diffraction pattern	$\psi_{\text{tot}}$	total wave function
$\phi$	angle between Kikuchi line and diffraction spot	$\psi_0$	amplitude
$\phi$	angle between two Kikuchi-line pairs	$\rho$	angle between two directions
$\phi$	angle between two planes	$\rho$	density
$\phi$	angle between two plane normals	$\rho_{\text{c/s}}$	information limit due to chromatic/spherical aberration
$\phi$	angle of tilt between stereo images	$\rho(\mathbf{r})$	radial distribution function
$\phi$	phase of a wave	$\rho t$	mass thickness
$\phi^*$	complex conjugate of $\phi$	$\rho_i^2$	area of a pixel
$\phi_{\mathbf{g}}$	amplitude of the diffracted beam		
$\phi_0$	amplitude of the direct beam	$\sigma$	scattering cross section of one atom
$\phi_x$	angle of deflection of the beam	$\sigma$	standard deviation
$\phi(\rho t)$	depth distribution of X-ray production	$\sigma$	stress
		$\sigma_{\text{K/L/M}}$	ionization cross section for K/L/M-shell electron
$\chi$	wave vector outside the specimen	$\sigma_{\text{T}}$	total ionization cross section
$\chi_{\text{G}}$	wave vector terminating on the point G in reciprocal space	$\sigma_{\text{K/L/M}}(\beta\Delta)$	partial ionization cross section for K/L/M-shell electron
$\chi_{\text{O}}$	wave vector terminating on the point O in reciprocal space	$\theta$	scattering semi-angle

$\theta_B$	Bragg angle	$\omega_p$	plasmon frequency
$\theta_C$	cut-off semi-angle		
$\theta_E$	characteristic scattering semi-angle	$\Omega$	filter for energy loss
$\theta_0$	screening parameter	$\Omega$	solid angle of collection of XEDS
$\tau$	XEDS detector time constant	$\Omega$	volume of unit cell
$\tau$	dwel time		
$\tau$	analysis time	$\zeta$	zeta factor
$\omega$	fluorescence yield		
$\omega_c$	cyclotron frequency	$\otimes$	convolution (multiply and integrate)

# About the Companion Volume

As described in our Preface, the many years since the publication of the first edition have seen a significant increase in the number of TEM (and related) techniques and the sophistication of the microscope's experimental capabilities, as well as new hardware designs, astonishing improvements in computer control of the instrument and amazing developments in software to handle and model the gigabytes of data generated by these (now almost completely digital) instruments. Much of this explosion of information has coincided with the world-wide drive to explore the nanoworld, and the still-ongoing effects of Moore's law. It is not possible to include all of this new knowledge in a textbook, and the primary objective of the second edition is still to teach you to understand the essence of the TEM before you attempt to master the latest advances. We also personally cannot hope to comprehend fully all of the new techniques, especially as we both descend into more administrative positions in our professional lives.

Therefore, we have prevailed on almost 20 of our close friends and colleagues to put together with us a companion applications text (Carter and Williams, eds., Springer, 2010) to which we will refer throughout this second edition. The companion text is just as it says; it's a friend whose advice you should seek when the main text is not enough. The companion is not intended to be more advanced but it certainly provides much more detail on key recent developments and some more traditional aspects of TEM that have seen a resurgence of interest. We have taken our colleagues' contributions and worked with them to produce chapters that are in a similar conversational vein to this main text. While *Transmission Electron Microscopy, Second Edition*, is a completely stand-alone textbook, we think that you will find the cross-referencing between the two texts to be of great value as you continue along the rewarding path of becoming a transmission microscopist.

# Contents

<b>About the Authors</b> .....	<b>vii</b>
<b>Preface</b> .....	<b>xi</b>
<b>Foreword to First Edition</b> .....	<b>xiii</b>
<b>Foreword to Second Edition</b> .....	<b>xv</b>
<b>Acknowledgments</b> .....	<b>xix</b>
<b>List of Initials and Acronyms</b> .....	<b>xxi</b>
<b>List of Symbols</b> .....	<b>xxv</b>
<b>About the Companion Volume</b> .....	<b>xxxii</b>
<b>Figure Credits</b> .....	<b>xlix</b>
<b>PART 1 BASICS</b> .....	<b>1</b>
<b>1 The Transmission Electron Microscope</b> .....	<b>3</b>
Chapter Preview .....	3
1.1 What Materials Should We Study in the TEM? .....	3
1.2 Why Use Electrons? .....	4
1.2.A An Extremely Brief History .....	4
1.2.B Microscopy and the Concept of Resolution .....	5
1.2.C Interaction of Electrons with Matter .....	7
1.2.D Depth of Field and Depth of focus .....	8
1.2.E Diffraction .....	8
1.3 Limitations of the TEM .....	9
1.3.A Sampling .....	9
1.3.B Interpreting Transmission Images .....	9
1.3.C Electron Beam Damage and Safety .....	10
1.3.D Specimen Preparation .....	11
1.4 Different Kinds of TEMs .....	11
1.5 Some Fundamental Properties of Electrons .....	11
1.6 Microscopy on the Internet/World Wide Web .....	15
1.6.A Microscopy and Analysis-Related Web Sites .....	15
1.6.B Microscopy and Analysis Software .....	15
Chapter Summary .....	17

<b>2</b>	<b>Scattering and Diffraction</b> .....	<b>23</b>
	Chapter Preview .....	23
2.1	Why Are We Interested in Electron Scattering? .....	23
2.2	Terminology of Scattering and Diffraction .....	25
2.3	The Angle of Scattering .....	26
2.4	The Interaction Cross Section and Its Differential .....	27
	2.4.A Scattering from an Isolated Atom .....	27
	2.4.B Scattering from the Specimen .....	28
	2.4.C Some Numbers .....	28
2.5	The Mean Free Path .....	28
2.6	How We Use Scattering in the TEM .....	29
2.7	Comparison to X-ray Diffraction .....	30
2.8	Fraunhofer and Fresnel Diffraction .....	30
2.9	Diffraction of Light from Slits and Holes .....	31
2.10	Constructive Interference .....	33
2.11	A Word About Angles .....	34
2.12	Electron-Diffraction Patterns .....	34
	Chapter Summary .....	36
<b>3</b>	<b>Elastic Scattering</b> .....	<b>39</b>
	Chapter Preview .....	39
3.1	Particles and Waves .....	39
3.2	Mechanisms of Elastic Scattering .....	40
3.3	Elastic Scattering from Isolated Atoms .....	41
3.4	The Rutherford Cross Section .....	41
3.5	Modifications to the Rutherford Cross Section .....	42
3.6	Coherency of the Rutherford-Scattered Electrons .....	43
3.7	The Atomic-Scattering Factor .....	44
3.8	The Origin of $f(\theta)$ .....	45
3.9	The Structure Factor $F(\theta)$ .....	46
3.10	Simple Diffraction Concepts .....	47
	3.10.A Interference of Electron Waves; Creation of the Direct and Diffracted Beams .....	47
	3.10.B Diffraction Equations .....	48
	Chapter Summary .....	49
<b>4</b>	<b>Inelastic Scattering and Beam Damage</b> .....	<b>53</b>
	Chapter Preview .....	53
4.1	Which Inelastic Processes Occur in the TEM? .....	53
4.2	X-ray Emission .....	55
	4.2.A Characteristic X-rays .....	55
	4.2.B Bremsstrahlung X-rays .....	60
4.3	Secondary-Electron Emission .....	60
	4.3.A Secondary Electrons .....	60
	4.3.B Auger Electrons .....	61
4.4	Electron-Hole Pairs and Cathodoluminescence (CL) .....	62
4.5	Plasmons and Phonons .....	63
4.6	Beam Damage .....	64
	4.6.A Electron Dose .....	65
	4.6.B Specimen Heating .....	65
	4.6.C Beam Damage in Polymers .....	66
	4.6.D Beam Damage in Covalent and Ionic Crystals .....	66
	4.6.E Beam Damage in Metals .....	66
	4.6.F Sputtering .....	68
	Chapter Summary .....	68

<b>5</b>	<b>Electron Sources</b> .....	<b>73</b>
	Chapter Preview .....	73
5.1	The Physics of Different Electron Sources .....	73
	5.1.A Thermionic Emission .....	74
	5.1.B Field Emission .....	74
5.2	The Characteristics of the Electron Beam .....	75
	5.2.A Brightness .....	75
	5.2.B Temporal Coherency and Energy Spread .....	76
	5.2.C Spatial Coherency and Source Size .....	77
	5.2.D Stability .....	77
5.3	Electron Guns .....	77
	5.3.A Thermionic Guns .....	77
	5.3.B Field-Emission Guns (FEGs) .....	80
5.4	Comparison of Guns .....	81
5.5	Measuring Your Gun Characteristics .....	82
	5.5.A Beam Current .....	82
	5.5.B Convergence Angle .....	83
	5.5.C Calculating the Beam Diameter .....	83
	5.5.D Measuring the Beam Diameter .....	85
	5.5.E Energy Spread .....	85
	5.5.F Spatial Coherency .....	86
5.6	What kV should You Use? .....	86
	Chapter Summary .....	87
<b>6</b>	<b>Lenses, Apertures, and Resolution</b> .....	<b>91</b>
	Chapter Preview .....	91
6.1	Why Learn About Lenses? .....	91
6.2	Light Optics and Electron Optics .....	92
	6.2.A How to Draw a Ray Diagram .....	92
	6.2.B The Principal Optical Elements .....	94
	6.2.C The Lens Equation .....	94
	6.2.D Magnification, Demagnification, and Focus .....	95
6.3	Electron Lenses .....	96
	6.3.A Polepieces and Coils .....	96
	6.3.B Different Kinds of Lenses .....	97
	6.3.C Electron Ray Paths Through Magnetic Fields .....	99
	6.3.D Image Rotation and the Eucentric Plane .....	100
	6.3.E Deflecting the Beam .....	101
6.4	Apertures and Diaphragms .....	101
6.5	Real Lenses and their Problems .....	102
	6.5.A Spherical Aberration .....	103
	6.5.B Chromatic Aberration .....	104
	6.5.C Astigmatism .....	106
6.6	The Resolution of the Electron Lens (and Ultimately of the TEM) .....	106
	6.6.A Theoretical Resolution (Diffraction-Limited Resolution) .....	107
	6.6.B The Practical Resolution Due to Spherical Aberration .....	108
	6.6.C Specimen-Limited Resolution Due to Chromatic Aberration .....	109
	6.6.D Confusion in the Definitions of Resolution .....	109
6.7	Depth of Focus and Depth of Field .....	110
	Chapter Summary .....	111

<b>7</b>	<b>How to ‘See’ Electrons</b> . . . . .	<b>115</b>
	Chapter Preview . . . . .	115
7.1	Electron Detection and Display . . . . .	115
7.2	Viewing Screens . . . . .	116
7.3	Electron Detectors . . . . .	117
	7.3.A Semiconductor Detectors . . . . .	117
	7.3.B Scintillator-Photomultiplier Detectors/TV Cameras . . . . .	118
	7.3.C Charge-Coupled Device (CCD) Detectors . . . . .	120
	7.3.D Faraday Cup . . . . .	121
7.4	Which Detector Do We Use for which Signal? . . . . .	122
7.5	Image Recording . . . . .	122
	7.5.A Photographic Emulsions . . . . .	122
	7.5.B Other Image-Recording Methods . . . . .	124
7.6	Comparison of Scanning Images and Static Images . . . . .	124
	Chapter Summary . . . . .	125
<b>8</b>	<b>Pumps and Holders</b> . . . . .	<b>127</b>
	Chapter Preview . . . . .	127
8.1	The Vacuum . . . . .	127
8.2	Roughing Pumps . . . . .	128
8.3	High/Ultra High Vacuum Pumps . . . . .	129
	8.3.A Diffusion Pumps . . . . .	129
	8.3.B Turbomolecular Pumps . . . . .	129
	8.3.C Ion Pumps . . . . .	130
	8.3.D Cryogenic (Adsorption) Pumps . . . . .	130
8.4	The Whole System . . . . .	130
8.5	Leak Detection . . . . .	131
8.6	Contamination: Hydrocarbons and Water Vapor . . . . .	132
8.7	Specimen Holders and Stages . . . . .	132
8.8	Side-Entry Holders . . . . .	133
8.9	Top-entry Holders . . . . .	134
8.10	Tilt and Rotate Holders . . . . .	134
8.11	In-Situ Holders . . . . .	135
8.12	Plasma Cleaners . . . . .	138
	Chapter Summary . . . . .	138
<b>9</b>	<b>The Instrument</b> . . . . .	<b>141</b>
	Chapter Preview . . . . .	141
9.1	The Illumination System . . . . .	142
	9.1.A TEM Operation Using a Parallel Beam . . . . .	142
	9.1.B Convergent-Beam (S)TEM Mode . . . . .	143
	9.1.C The Condenser-Objective Lens . . . . .	145
	9.1.D Translating and Tilting the Beam . . . . .	147
	9.1.E Alignment of the C2 Aperture . . . . .	147
	9.1.F Condenser-Lens Defects . . . . .	148
	9.1.G Calibration . . . . .	149
9.2	The Objective Lens and Stage . . . . .	150
9.3	Forming DPs and Images: The TEM Imaging System . . . . .	152
	9.3.A Selected-Area Diffraction . . . . .	152
	9.3.B Bright-Field and Dark-Field Imaging . . . . .	155
	9.3.C Centered Dark-Field Operation . . . . .	155
	9.3.D Hollow-Cone Diffraction and Dark-Field Imaging . . . . .	157
9.4	Forming DPs and Images: The STEM Imaging System . . . . .	158

9.4.A	Bright-Field STEM Images .....	159
9.4.B	Dark-Field STEM Images .....	161
9.4.C	Annular Dark-Field Images .....	161
9.4.D	Magnification in STEM .....	161
9.5	Alignment and Stigmatism .....	161
9.5.A	Lens Rotation Centers .....	161
9.5.B	Correction of Astigmatism in the Imaging Lenses ..	162
9.6	Calibrating the Imaging System .....	164
9.6.A	Magnification Calibration .....	164
9.6.B	Camera-Length Calibration .....	165
9.6.C	Rotation of the Image Relative to the DP .....	167
9.6.D	Spatial Relationship Between Images and DPs ....	168
9.7	Other Calibrations .....	168
	Chapter Summary .....	169
<b>10</b>	<b>Specimen Preparation .....</b>	<b>173</b>
	Chapter Preview .....	173
10.1	Safety .....	173
10.2	Self-Supporting Disk or Use a Grid? .....	174
10.3	Preparing a Self-Supporting Disk for Final Thinning .....	175
10.3.A	Forming a Thin Slice from the Bulk Sample .....	176
10.3.B	Cutting the Disk .....	176
10.3.C	Prethinning the Disk .....	177
10.4	Final Thinning of the Disks .....	178
10.4.A	Electropolishing .....	178
10.4.B	Ion Milling .....	178
10.5	Cross-Section Specimens .....	182
10.6	Specimens on Grids/Washers .....	183
10.6.A	Electropolishing—The Window Method for Metals and Alloys .....	183
10.6.B	Ultramicrotomy .....	183
10.6.C	Grinding and Crushing .....	184
10.6.D	Replication and Extraction .....	184
10.6.E	Cleaving and the SACT .....	186
10.6.F	The 90° Wedge .....	186
10.6.G	Lithography .....	187
10.6.H	Preferential Chemical Etching .....	187
10.7	FIB .....	188
10.8	Storing Specimens .....	189
10.9	Some Rules .....	189
	Chapter Summary .....	191
<b>PART 2</b>	<b>DIFFRACTION .....</b>	<b>195</b>
<b>11</b>	<b>Diffraction in TEM .....</b>	<b>197</b>
	Chapter Preview .....	197
11.1	Why Use Diffraction in the TEM? .....	197
11.2	The TEM, Diffraction Cameras, and the TV .....	198
11.3	Scattering from a Plane of Atoms .....	199
11.4	Scattering from a Crystal .....	200
11.5	Meaning of <i>n</i> in Bragg's Law .....	202
11.6	A Pictorial Introduction to Dynamical Effects .....	203
11.7	Use of Indices in Diffraction Patterns .....	204
11.8	Practical Aspects of Diffraction-Pattern Formation .....	204
11.9	More on Selected-Area Diffraction Patterns .....	204
	Chapter Summary .....	208

<b>12</b>	<b>Thinking in Reciprocal Space</b> . . . . .	<b>211</b>
	Chapter Preview . . . . .	211
12.1	Why Introduce Another Lattice? . . . . .	211
12.2	Mathematical Definition of the Reciprocal Lattice . . . . .	212
12.3	The Vector $\mathbf{g}$ . . . . .	212
12.4	The Laue Equations and their Relation to Bragg's Law . . . . .	213
12.5	The Ewald Sphere of Reflection . . . . .	214
12.6	The Excitation Error . . . . .	216
12.7	Thin-Foil Effect and the Effect of Accelerating Voltage . . . . .	217
	Chapter Summary . . . . .	218
<b>13</b>	<b>Diffracted Beams</b> . . . . .	<b>221</b>
	Chapter Preview . . . . .	221
13.1	Why Calculate Intensities? . . . . .	221
13.2	The Approach . . . . .	222
13.3	The Amplitude of a Diffracted Beam . . . . .	223
13.4	The Characteristic Length $\xi_{\mathbf{g}}$ . . . . .	223
13.5	The Howie-Whelan Equations . . . . .	224
13.6	Reformulating the Howie-Whelan Equations . . . . .	225
13.7	Solving the Howie-Whelan Equations . . . . .	226
13.8	The Importance of $\gamma^{(1)}$ and $\gamma^{(2)}$ . . . . .	226
13.9	The Total Wave Amplitude . . . . .	227
13.10	The Effective Excitation Error . . . . .	228
13.11	The Column Approximation . . . . .	229
13.12	The Approximations and Simplifications . . . . .	230
13.13	The Coupled Harmonic Oscillator Analog . . . . .	231
	Chapter Summary . . . . .	231
<b>14</b>	<b>Bloch Waves</b> . . . . .	<b>235</b>
	Chapter Preview . . . . .	235
14.1	Wave Equation in TEM . . . . .	235
14.2	The Crystal . . . . .	236
14.3	Bloch Functions . . . . .	237
14.4	Schrödinger's Equation for Bloch Waves . . . . .	238
14.5	The Plane-Wave Amplitudes . . . . .	239
14.6	Absorption of Bloch Waves . . . . .	241
	Chapter Summary . . . . .	242
<b>15</b>	<b>Dispersion Surfaces</b> . . . . .	<b>245</b>
	Chapter Preview . . . . .	245
15.1	Introduction . . . . .	245
15.2	The Dispersion Diagram When $U_{\mathbf{g}} = 0$ . . . . .	246
15.3	The Dispersion Diagram When $U_{\mathbf{g}} \neq 0$ . . . . .	247
15.4	Relating Dispersion Surfaces and Diffraction Patterns . . . . .	247
15.5	The Relation Between $U_{\mathbf{g}}$ , $\xi_{\mathbf{g}}$ , and $s_{\mathbf{g}}$ . . . . .	250
15.6	The Amplitudes of Bloch Waves . . . . .	252
15.7	Extending to More Beams . . . . .	253
15.8	Dispersion Surfaces and Defects . . . . .	254
	Chapter Summary . . . . .	254
<b>16</b>	<b>Diffraction from Crystals</b> . . . . .	<b>257</b>
	Chapter Preview . . . . .	257
16.1	Review of Diffraction from a Primitive Lattice . . . . .	257
16.2	Structure Factors: The Idea . . . . .	258

16.3	Some Important Structures: BCC, FCC and HCP . . . . .	259
16.4	Extending fcc and hcp to Include a Basis . . . . .	261
16.5	Applying the bcc and fcc Analysis to Simple Cubic . . . . .	262
16.6	Extending hcp to TiAl . . . . .	262
16.7	Superlattice Reflections and Imaging . . . . .	262
16.8	Diffraction from Long-Period Superlattices . . . . .	264
16.9	Forbidden Reflections . . . . .	265
16.10	Using the International Tables . . . . .	265
	Chapter Summary . . . . .	267
<b>17</b>	<b>Diffraction from Small Volumes . . . . .</b>	<b>271</b>
	Chapter Preview . . . . .	271
17.1	Introduction . . . . .	271
	17.1.A The Summation Approach . . . . .	272
	17.1.B The Integration Approach . . . . .	273
17.2	The Thin-Foil Effect . . . . .	273
17.3	Diffraction from Wedge-Shaped Specimens . . . . .	274
17.4	Diffraction from Planar Defects . . . . .	275
17.5	Diffraction from Particles . . . . .	277
17.6	Diffraction from Dislocations, Individually and Collectively . . . . .	278
17.7	Diffraction and the Dispersion Surface . . . . .	279
	Chapter Summary . . . . .	281
<b>18</b>	<b>Obtaining and Indexing Parallel-Beam Diffraction Patterns . . . . .</b>	<b>283</b>
	Chapter Preview . . . . .	283
18.1	Choosing Your Technique . . . . .	284
18.2	Experimental SAD Techniques . . . . .	284
18.3	The Stereographic Projection . . . . .	286
18.4	Indexing Single-Crystal DPs . . . . .	287
18.5	Ring Patterns from Polycrystalline Materials . . . . .	290
18.6	Ring Patterns from Hollow-Cone Diffraction . . . . .	291
18.7	Ring Patterns from Amorphous Materials . . . . .	293
18.8	Precession Diffraction . . . . .	295
18.9	Double Diffraction . . . . .	296
18.10	Orientation of the Specimen . . . . .	298
18.11	Orientation Relationships . . . . .	302
18.12	Computer Analysis . . . . .	303
18.13	Automated Orientation Determination and Orientation Mapping . . . . .	305
	Chapter Summary . . . . .	305
<b>19</b>	<b>Kikuchi Diffraction . . . . .</b>	<b>311</b>
	Chapter Preview . . . . .	311
19.1	The Origin of Kikuchi Lines . . . . .	311
19.2	Kikuchi Lines and Bragg Scattering . . . . .	312
19.3	Constructing Kikuchi Maps . . . . .	313
19.4	Crystal Orientation and Kikuchi Maps . . . . .	317
19.5	Setting the Value of $S_g$ . . . . .	318
19.6	Intensities . . . . .	319
	Chapter Summary . . . . .	320
<b>20</b>	<b>Obtaining CBED Patterns . . . . .</b>	<b>323</b>
	Chapter Preview . . . . .	323
20.1	Why Use a Convergent Beam? . . . . .	323

20.2	Obtaining CBED Patterns . . . . .	324
20.2.A	Comparing SAD and CBED . . . . .	325
20.2.B	CBED in TEM Mode . . . . .	326
20.2.C	CBED in STEM Mode . . . . .	326
20.3	Experimental Variables . . . . .	327
20.3.A	Choosing the C2 Aperture . . . . .	327
20.3.B	Selecting the Camera Length . . . . .	328
20.3.C	Choice of Beam Size . . . . .	329
20.3.D	Effect of Specimen Thickness . . . . .	329
20.4	Focused and Defocused CBED Patterns . . . . .	329
20.4.A	Focusing a CBED Pattern . . . . .	330
20.4.B	Large-Angle (Defocused) CBED Patterns . . . . .	330
20.4.C	Final Adjustment . . . . .	332
20.5	Energy Filtering . . . . .	334
20.6	Zero-Order and High-Order Laue-Zone Diffraction . . . . .	335
20.6.A	ZOLZ Patterns . . . . .	335
20.6.B	HOLZ Patterns . . . . .	336
20.7	Kikuchi and Bragg Lines in CBED Patterns . . . . .	338
20.8	HOLZ Lines . . . . .	339
20.8.A	The Relationship Between HOLZ Lines and Kikuchi Lines . . . . .	339
20.8.B	Acquiring HOLZ Lines . . . . .	341
20.9	Hollow-Cone/Precession CBED . . . . .	342
	Chapter Summary . . . . .	343
<b>21</b>	<b>Using Convergent-Beam Techniques . . . . .</b>	<b>347</b>
	Chapter Preview . . . . .	347
21.1	Indexing CBED Patterns . . . . .	348
21.1.A	Indexing ZOLZ and HOLZ Patterns . . . . .	348
21.1.B	Indexing HOLZ Lines . . . . .	351
21.2	Thickness Determination . . . . .	352
21.3	Unit-Cell Determination . . . . .	354
21.3.A	Experimental Considerations . . . . .	354
21.3.B	The Importance of the HOLZ-Ring Radius . . . . .	355
21.3.C	Determining the Lattice Centering . . . . .	356
21.4	Basics of Symmetry Determination . . . . .	357
21.4.A	Reminder of Symmetry Concepts . . . . .	357
21.4.B	Friedel's Law . . . . .	358
21.4.C	Looking for Symmetry in Your Patterns . . . . .	358
21.5	Lattice-Strain Measurement . . . . .	361
21.6	Determination of Enantiomorphism . . . . .	363
21.7	Structure Factor and Charge-Density Determination . . . . .	364
21.8	Other Methods . . . . .	365
21.8.A	Scanning Methods . . . . .	365
21.8.B	Nanodiffraction . . . . .	366
	Chapter Summary . . . . .	366
<b>PART 3</b>	<b>IMAGING . . . . .</b>	<b>369</b>
<b>22</b>	<b>Amplitude Contrast . . . . .</b>	<b>371</b>
	Chapter Preview . . . . .	371
22.1	What Is Contrast? . . . . .	371
22.2	Amplitude contrast . . . . .	372
22.2.A	Images and Diffraction Patterns . . . . .	372
22.2.B	Use of the Objective Aperture or the STEM Detector: BF and DF Images . . . . .	372

22.3	Mass-Thickness Contrast . . . . .	373
22.3.A	Mechanism of Mass-Thickness Contrast . . . . .	373
22.3.B	TEM Images . . . . .	374
22.3.C	STEM Images . . . . .	376
22.3.D	Specimens Showing Mass-Thickness Contrast . . . . .	377
22.3.E	Quantitative Mass-Thickness Contrast . . . . .	378
22.4	Z-Contrast . . . . .	379
22.5	TEM Diffraction Contrast . . . . .	381
22.5.A	Two-Beam Conditions . . . . .	381
22.5.B	Setting the Deviation Parameter, $s$ . . . . .	382
22.5.C	Setting Up a Two-Beam CDF Image . . . . .	382
22.5.D	Relationship Between the Image and the Diffraction Pattern . . . . .	384
22.6	STEM Diffraction Contrast . . . . .	384
	Chapter Summary . . . . .	386
<b>23</b>	<b>Phase-Contrast Images . . . . .</b>	<b>389</b>
	Chapter Preview . . . . .	389
23.1	Introduction . . . . .	389
23.2	The Origin of Lattice Fringes . . . . .	389
23.3	Some Practical Aspects of Lattice Fringes . . . . .	390
23.3.A	If $s = 0$ . . . . .	390
23.3.B	If $s \neq 0$ . . . . .	390
23.4	On-Axis Lattice-Fringe Imaging . . . . .	391
23.5	Moiré Patterns . . . . .	392
23.5.A	Translational Moiré Fringes . . . . .	393
23.5.B	Rotational Moiré Fringes . . . . .	393
23.5.C	General Moiré Fringes . . . . .	393
23.6	Experimental Observations of Moiré Fringes . . . . .	393
23.6.A	Translational Moiré Patterns . . . . .	394
23.6.B	Rotational Moiré Patterns . . . . .	394
23.6.C	Dislocations and Moiré Fringes . . . . .	394
23.6.D	Complex Moiré Fringes . . . . .	396
23.7	Fresnel Contrast . . . . .	397
23.7.A	The Fresnel Biprism . . . . .	397
23.7.B	Magnetic-Domain Walls . . . . .	398
23.8	Fresnel Contrast from Voids or Gas Bubbles . . . . .	399
23.9	Fresnel Contrast from Lattice Defects . . . . .	400
23.9.A	Grain Boundaries . . . . .	402
23.9.B	End-On Dislocations . . . . .	402
	Chapter Summary . . . . .	402
<b>24</b>	<b>Thickness and Bending Effects . . . . .</b>	<b>407</b>
	Chapter Preview . . . . .	407
24.1	The Fundamental Ideas . . . . .	407
24.2	Thickness Fringes . . . . .	408
24.3	Thickness Fringes and the DP . . . . .	410
24.4	Bend Contours (Annoying Artifact, Useful Tool, Invaluable Insight) . . . . .	411
24.5	ZAPs and Real-Space Crystallography . . . . .	412
24.6	Hillocks, Dents, or Saddles . . . . .	413
24.7	Absorption Effects . . . . .	413
24.8	Computer Simulation of Thickness Fringes . . . . .	414
24.9	Thickness-Fringe/Bend-Contour Interactions . . . . .	414
24.10	Other Effects of Bending . . . . .	415
	Chapter Summary . . . . .	416

<b>25</b>	<b>Planar Defects</b> . . . . .	<b>419</b>
	Chapter Preview . . . . .	419
25.1	Translations and Rotations . . . . .	419
25.2	Why Do Translations Produce Contrast? . . . . .	421
25.3	The Scattering Matrix . . . . .	422
25.4	Using the Scattering Matrix . . . . .	423
25.5	Stacking Faults in fcc Materials . . . . .	424
	25.5.A Why fcc Materials? . . . . .	424
	25.5.B Some Rules . . . . .	425
	25.5.C Intensity Calculations . . . . .	426
	25.5.D Overlapping Faults . . . . .	426
25.6	Other Translations: $\pi$ and $\delta$ Fringes . . . . .	427
25.7	Phase Boundaries . . . . .	429
25.8	Rotation Boundaries . . . . .	430
25.9	Diffraction Patterns and Dispersion Surfaces . . . . .	430
25.10	Bloch Waves and BF/DF Image Pairs . . . . .	431
25.11	Computer Modeling . . . . .	432
25.12	The Generalized Cross Section . . . . .	433
25.13	Quantitative Imaging . . . . .	434
	25.13.A Theoretical Basis and Parameters . . . . .	434
	25.13.B Apparent Extinction Distance . . . . .	435
	25.13.C Avoiding the Column Approximation . . . . .	435
	25.13.D The User Interface . . . . .	436
	Chapter Summary . . . . .	436
<b>26</b>	<b>Imaging Strain Fields</b> . . . . .	<b>441</b>
	Chapter Preview . . . . .	441
26.1	Why Image Strain Fields? . . . . .	441
26.2	Howie-Whelan Equations . . . . .	442
26.3	Contrast from a Single Dislocation . . . . .	444
26.4	Displacement Fields and Ewald's Sphere . . . . .	447
26.5	Dislocation Nodes and Networks . . . . .	448
26.6	Dislocation Loops and Dipoles . . . . .	448
26.7	Dislocation Pairs, Arrays, and Tangles . . . . .	450
26.8	Surface Effects . . . . .	451
26.9	Dislocations and Interfaces . . . . .	452
26.10	Volume Defects and Particles . . . . .	456
26.11	Simulating Images . . . . .	457
	26.11.A The Defect Geometry . . . . .	457
	26.11.B Crystal Defects and Calculating the Displacement Field . . . . .	458
	26.11.C The Parameters . . . . .	458
	Chapter Summary . . . . .	459
<b>27</b>	<b>Weak-Beam Dark-Field Microscopy</b> . . . . .	<b>463</b>
	Chapter Preview . . . . .	463
27.1	Intensity in WBDF Images . . . . .	463
27.2	Setting $S_g$ Using the Kikuchi Pattern . . . . .	464
27.3	How to Do WBDF . . . . .	466
27.4	Thickness Fringes in Weak-Beam Images . . . . .	467
27.5	Imaging Strain Fields . . . . .	468
27.6	Predicting Dislocation Peak Positions . . . . .	469
27.7	Phasor Diagrams . . . . .	470
27.8	Weak-Beam Images of Dissociated Dislocations . . . . .	473
27.9	Other Thoughts . . . . .	477

27.9.A	Thinking of Weak-Beam Diffraction as a Coupled Pendulum	477
27.9.B	Bloch Waves	478
27.9.C	If Other Reflections are Present	478
27.9.D	The Future Is Now	478
	Chapter Summary	479
<b>28</b>	<b>High-Resolution TEM</b>	<b>483</b>
	Chapter Preview	483
28.1	The Role of an Optical System	483
28.2	The Radio Analogy	484
28.3	The Specimen	485
28.4	Applying the WPOA to the TEM	487
28.5	The Transfer Function	487
28.6	More on $\chi(u)$ , $\sin \chi(u)$ , and $\cos \chi(u)$	488
28.7	Scherzer Defocus	490
28.8	Envelope Damping Functions	491
28.9	Imaging Using Passbands	492
28.10	Experimental Considerations	493
28.11	The Future for HRTEM	494
28.12	The TEM as a Linear System	494
28.13	FEG TEMs and the Information Limit	495
28.14	Some Difficulties in Using an FEG	498
28.15	Selectively Imaging Sublattices	500
28.16	Interfaces and Surfaces	502
28.17	Incommensurate Structures	503
28.18	Quasicrystals	504
28.19	Single Atoms	505
	Chapter Summary	506
<b>29</b>	<b>Other Imaging Techniques</b>	<b>511</b>
	Chapter Preview	511
29.1	Stereo Microscopy and Tomography	511
29.2	$2\frac{1}{2}$ D Microscopy	512
29.3	Magnetic Specimens	514
	29.3.A The Magnetic Correction	514
	29.3.B Lorentz Microscopy	515
29.4	Chemically Sensitive Images	517
29.5	Imaging with Diffusely Scattered Electrons	517
29.6	Surface Imaging	519
	29.6.A Reflection Electron Microscopy	519
	29.6.B Topographic Contrast	521
29.7	High-Order BF Imaging	521
29.8	Secondary-Electron Imaging	522
29.9	Backscattered-Electron Imaging	523
29.10	Charge-Collection Microscopy and Cathodoluminescence	523
29.11	Electron Holography	524
29.12	In Situ TEM: Dynamic Experiments	526
29.13	Fluctuation Microscopy	528
29.14	Other Variations Possible in a STEM	528
	Chapter Summary	529
<b>30</b>	<b>Image Simulation</b>	<b>533</b>
	Chapter Preview	533
30.1	Simulating images	533
30.2	The Multislice Method	533

30.3	The Reciprocal-Space Approach .....	534
30.4	The FFT Approach.....	536
30.5	The Real-Space approach .....	536
30.6	Bloch Waves and HRTEM Simulation .....	536
30.7	The Ewald Sphere Is Curved .....	537
30.8	Choosing the Thickness of the Slice .....	537
30.9	Beam Convergence .....	538
30.10	Modeling the Structure .....	540
30.11	Surface Grooves and Simulating Fresnel Contrast.....	540
30.12	Calculating Images of Defects .....	542
30.13	Simulating Quasicrystals .....	543
30.14	Bonding in Crystals.....	544
30.15	Simulating Z-Contrast .....	545
30.16	Software for Phase-Contrast HRTEM .....	545
	Chapter Summary .....	545
<b>31</b>	<b>Processing and Quantifying Images .....</b>	<b>549</b>
	Chapter Preview .....	549
31.1	What Is Image Processing? .....	549
31.2	Processing and Quantifying Images .....	550
31.3	A Cautionary Note .....	550
31.4	Image Input.....	550
31.5	Processing Techniques .....	551
	31.5.A Fourier Filtering and Reconstruction .....	551
	31.5.B Analyzing Diffractograms .....	552
	31.5.C Averaging Images and Other Techniques .....	554
	31.5.D Kernels .....	556
31.6	Applications .....	556
	31.6.A Beam-Sensitive Materials .....	556
	31.6.B Periodic Images .....	557
	31.6.C Correcting Drift .....	557
	31.6.D Reconstructing the Phase .....	557
	31.6.E Diffraction Patterns .....	558
	31.6.F Tilted-Beam Series .....	559
31.7	Automated Alignment .....	560
31.8	Quantitative Methods of Image Analysis .....	561
31.9	Pattern Recognition in HRTEM .....	562
31.10	Parameterizing the Image Using QUANTITEM .....	563
	31.10.A The Example of a Specimen with Uniform Composition .....	563
	31.10.B Calibrating the Path of R.....	565
	31.10.C Noise Analysis .....	565
31.11	Quantitative Chemical Lattice Imaging .....	567
31.12	Methods of Measuring Fit .....	568
31.13	Quantitative Comparison of Simulated and Experimental HRTEM Images .....	570
31.14	A Fourier Technique for Quantitative Analysis .....	571
31.15	Real or Reciprocal Space? .....	572
31.16	Software .....	573
31.17	The Optical Bench—A Little History .....	573
	Chapter Summary .....	575
<b>PART 4</b>	<b>SPECTROMETRY .....</b>	<b>579</b>
<b>32</b>	<b>X-ray Spectrometry .....</b>	<b>581</b>
	Chapter Preview .....	581

32.1	X-ray Analysis: Why Bother? .....	581
32.2	Basic Operational Mode .....	584
32.3	The Energy-Dispersive Spectrometer .....	584
32.4	Semiconductor Detectors .....	585
32.4.A	How Does an XEDS Work? .....	585
32.4.B	Cool Detectors .....	586
32.4.C	Different Kinds of Windows .....	586
32.4.D	Intrinsic-Germanium Detectors .....	587
32.4.E	Silicon-Drift Detectors .....	588
32.5	Detectors with High-Energy Resolution .....	589
32.6	Wavelength-Dispersive Spectrometers .....	589
32.6.A	Crystal WDS .....	589
32.6.B	CCD-Based WDS .....	590
32.6.C	Bolometers/Microcalorimeters .....	590
32.7	Turning X-rays into Spectra .....	591
32.8	Energy Resolution .....	593
32.9	What You Should Know about Your XEDS .....	594
32.9.A	Detector Characteristics .....	594
32.9.B	Processing Variables .....	596
32.10	The XEDS-AEM Interface .....	598
32.10.A	Collection Angle .....	598
32.10.B	Take-Off Angle .....	599
32.10.C	Orientation of the Detector to the Specimen .....	599
32.11	Protecting the Detector from Intense Radiation .....	600
	Chapter Summary .....	601
<b>33</b>	<b>X-ray Spectra and Images .....</b>	<b>605</b>
	Chapter Preview .....	605
33.1	The Ideal Spectrum .....	605
33.1.A	The Characteristic Peaks .....	605
33.1.B	The Continuum Bremsstrahlung Background ..	606
33.2	Artifacts Common to Si(Li) XEDS Systems .....	606
33.3	The Real Spectrum .....	608
33.3.A	Pre-Specimen Effects .....	608
33.3.B	Post-Specimen Scatter .....	611
33.3.C	Coherent Bremsstrahlung .....	613
33.4	Measuring the Quality of the XEDS-AEM Interface .....	614
33.4.A	Peak-to-Background Ratio .....	614
33.4.B	Efficiency of the XEDS System .....	614
33.5	Acquiring X-ray Spectra .....	615
33.5.A	Spot Mode .....	615
33.5.B	Spectrum-Line Profiles .....	616
33.6	Acquiring X-ray Images .....	616
33.6.A	Analog Dot Mapping .....	617
33.6.B	Digital Mapping .....	618
33.6.C	Spectrum Imaging (SI) .....	619
33.6.D	Position-Tagged Spectrometry (PTS) .....	620
	Chapter Summary .....	620
<b>34</b>	<b>Qualitative X-ray Analysis and Imaging .....</b>	<b>625</b>
	Chapter Preview .....	625
34.1	Microscope and Specimen Variables .....	625
34.2	Basic Acquisition Requirements: Counts, Counts, and More Caffeine .....	626

34.3	Peak Identification . . . . .	627
34.4	Peak Deconvolution . . . . .	630
34.5	Peak Visibility . . . . .	632
34.6	Common Errors . . . . .	634
34.7	Qualitative X-ray Imaging: Principles and Practice . . . . .	634
	Chapter Summary . . . . .	636
<b>35</b>	<b>Quantitative X-ray Analysis . . . . .</b>	<b>639</b>
	Chapter Preview . . . . .	639
35.1	Historical Perspective . . . . .	639
35.2	The Cliff-Lorimer Ratio Technique . . . . .	640
35.3	Practical Steps for Quantification . . . . .	641
	35.3.A Background Subtraction . . . . .	641
	35.3.B Peak Integration . . . . .	644
35.4	Determining $k$ -Factors . . . . .	646
	35.4.A Experimental Determination of $k_{AB}$ . . . . .	646
	35.4.B Errors in Quantification: The Statistics . . . . .	647
	35.4.C Calculating $k_{AB}$ . . . . .	648
35.5	The Zeta-Factor Method . . . . .	652
35.6	Absorption Correction . . . . .	654
35.7	The Zeta-Factor Absorption Correction . . . . .	656
35.8	The Fluorescence Correction . . . . .	656
35.9	ALCHEMI . . . . .	657
35.10	Quantitative X-ray Mapping . . . . .	658
	Chapter Summary . . . . .	660
<b>36</b>	<b>Spatial Resolution and Minimum Detection . . . . .</b>	<b>663</b>
	Chapter Preview . . . . .	663
36.1	Why Is Spatial Resolution Important? . . . . .	663
36.2	Definition and Measurement of Spatial Resolution . . . . .	664
	36.2.A Beam Spreading . . . . .	665
	36.2.B The Spatial-Resolution Equation . . . . .	666
	36.2.C Measurement of Spatial Resolution . . . . .	667
36.3	Thickness Measurement . . . . .	668
	36.3.A TEM Methods . . . . .	669
	36.3.B Contamination-Spot Separation Method . . . . .	670
	36.3.C Convergent-Beam Diffraction Method . . . . .	671
	36.3.D Electron Energy-Loss Spectrometry Methods . . . . .	671
	36.3.E X-ray Spectrometry Method . . . . .	671
36.4	Minimum Detection . . . . .	672
	36.4.A Experimental Factors Affecting the MMF . . . . .	673
	36.4.B Statistical Criterion for the MMF . . . . .	673
	36.4.C Comparison with Other Definitions . . . . .	674
	36.4.D Minimum-Detectable Mass . . . . .	674
	Chapter Summary . . . . .	675
<b>37</b>	<b>Electron Energy-Loss Spectrometers and Filters . . . . .</b>	<b>679</b>
	Chapter Preview . . . . .	679
37.1	Why Do EELS? . . . . .	679
	37.1.A Pros and Cons of Inelastic Scattering . . . . .	679
	37.1.B The Energy-Loss Spectrum . . . . .	680
37.2	EELS Instrumentation . . . . .	681
37.3	The Magnetic Prism: A Spectrometer and a Lens . . . . .	681
	37.3.A Focusing the Spectrometer . . . . .	682
	37.3.B Spectrometer Dispersion . . . . .	683

	37.3.C Spectrometer Resolution . . . . .	683
	37.3.D Calibrating the Spectrometer . . . . .	684
37.4	Acquiring a Spectrum . . . . .	684
	37.4.A Image and Diffraction Modes . . . . .	685
	37.4.B Spectrometer-Collection Angle . . . . .	685
	37.4.C Spatial Selection . . . . .	688
37.5	Problems with PEELS . . . . .	688
	37.5.A Point-Spread Function . . . . .	688
	37.5.B PEELS Artifacts . . . . .	689
37.6	Imaging Filters . . . . .	690
	37.6.A The Omega Filter . . . . .	691
	37.6.B The GIF . . . . .	692
37.7	Monochromators . . . . .	693
37.8	Using Your Spectrometer and Filter . . . . .	694
	Chapter Summary . . . . .	696
<b>38</b>	<b>Low-Loss and No-Loss Spectra and Images . . . . .</b>	<b>699</b>
	Chapter Preview . . . . .	699
38.1	A Few Basic Concepts . . . . .	699
38.2	The Zero-Loss Peak (ZLP) . . . . .	701
	38.2.A Why the ZLP Really Isn't . . . . .	701
	38.2.B Removing the Tail of the ZLP . . . . .	701
	38.2.C Zero-Loss Images and Diffraction Patterns . . . . .	702
38.3	The Low-Loss Spectrum . . . . .	703
	38.3.A Chemical Fingerprinting . . . . .	704
	38.3.B Dielectric-Constant Determination . . . . .	705
	38.3.C Plasmons . . . . .	705
	38.3.D Plasmon-Loss Analysis . . . . .	707
	38.3.E Single-Electron Excitations . . . . .	709
	38.3.F The Band Gap . . . . .	709
38.4	Modeling The Low-Loss Spectrum . . . . .	710
	Chapter Summary . . . . .	711
<b>39</b>	<b>High Energy-Loss Spectra and Images . . . . .</b>	<b>715</b>
	Chapter Preview . . . . .	715
39.1	The High-Loss Spectrum . . . . .	715
	39.1.A Inner-Shell Ionization . . . . .	715
	39.1.B Ionization-Edge Characteristics . . . . .	717
39.2	Acquiring a High-Loss Spectrum . . . . .	721
39.3	Qualitative Analysis . . . . .	723
39.4	Quantitative Analysis . . . . .	723
	39.4.A Derivation of the Equations for Quantification . . . . .	724
	39.4.B Background Subtraction . . . . .	726
	39.4.C Edge Integration . . . . .	728
	39.4.D The Partial Ionization Cross Section . . . . .	728
39.5	Measuring Thickness from the Core-Loss Spectrum . . . . .	730
39.6	Deconvolution . . . . .	731
39.7	Correction for Convergence of the Incident Beam . . . . .	733
39.8	The Effect of the Specimen Orientation . . . . .	733
39.9	EFTEM Imaging with Ionization Edges . . . . .	733
	39.9.A Qualitative Imaging . . . . .	734
	39.9.B Quantitative Imaging . . . . .	734
39.10	Spatial Resolution: Atomic-Column EELS . . . . .	735

39.11	Detection Limits .....	736
	Chapter Summary .....	737
<b>40</b>	<b>Fine Structure and Finer Details .....</b>	<b>741</b>
	Chapter Preview .....	741
40.1	Why Does Fine Structure Occur? .....	741
40.2	ELNES Physics .....	742
	40.2.A Principles .....	742
	40.2.B White Lines .....	744
	40.2.C Quantum Aspects .....	744
40.3	Applications of ELNES .....	745
40.4	ELNES Fingerprinting .....	746
40.5	ELNES Calculations .....	747
	40.5.A The Potential Choice .....	748
	40.5.B Core-Holes and Excitons .....	749
	40.5.C Comparison of ELNES Calculations and Experiments .....	750
40.6	Chemical Shifts in the Edge Onset .....	750
40.7	EXELFS .....	751
	40.7.A RDF via EXELFS .....	752
	40.7.B RDF via Energy-Filtered Diffraction .....	753
	40.7.C A Final Thought Experiment .....	753
40.8	Angle-Resolved EELS .....	755
40.9	EELS Tomography .....	755
	Chapter Summary .....	757
<b>Index</b> .....		<b>I-1</b>

# Figure Credits

TEM is a visual science, and any TEM text is heavily dependent on figures, halftones, and (more recently) full color images to transmit its message. We have been fortunate to work with many colleagues over the years who have generously given us fine examples of the art and science of TEM; we would like to acknowledge them here. We have also used our own work, and the work of others, whose permission has been sought as listed below.

## Chapter 1

Figure 1.1: From Ruska, E (1980) *The Early History of the Electron Microscope*, Fig. 6 reproduced by permission of S. Herzel Verlag GmbH & Co.

Figure 1.2B,C: Specimen courtesy of Y Ikuhara and T Yamamoto, University of Tokyo, reproduced by permission of JEOL Ltd.

Figure 1.4: Courtesy of M Watanabe.

Figure 1.6: Courtesy of KS Vecchio.

Figure 1.7: Courtesy of T Hayes, from Hayes, T (1980) in O Johari Ed. SEM-1980 1 1, Fig. 8 reproduced by permission of Scanning Microscopy International.

Figure 1.9A: Courtesy of M Kersker, reproduced by permission of JEOL USA Inc.

Figure 1.9B: Courtesy of E Essers, reproduced by permission of Carl Zeiss SMT.

Figure 1.9C: Courtesy of K Jarausch, reproduced by permission of Hitachi High Technologies.

Figure 1.9D: Courtesy of M Kersker, reproduced by permission of JEOL USA Inc.

Figure 1.9E: Courtesy of OL Krivanek, reproduced by permission of NION Inc.

Figure 1.9F: Courtesy of JS Fahy, reproduced by permission of FEI Co.

## Chapter 2

Figure 2.4: Courtesy of J Bruley and VJ Keast.

Figure 2.11: Modified from Hecht, E (1988) *Optics*, Fig. 10.21 Addison-Wesley.

Figure 2.13A,D: Courtesy of KS Vecchio.

Figure 2.13C: Courtesy of DW Ackland.

## Chapter 3

Figure 3.3: Courtesy of DE Newbury, modified from Newbury, DE (1986) in DC Joy *et al.* Eds. *Principles of Analytical Electron Microscopy* p 6, Fig. 2 original reproduced by permission of Plenum Press.

Figure 3.4: Courtesy of DE Newbury, modified from data in Newbury, DE (1986) in DC Joy *et al.* Eds. *Principles of Analytical Electron Microscopy* p 8, Table II reproduced by permission of Plenum Press.

## Chapter 4

Figure 4.1: Courtesy of DE Newbury, modified from Newbury, DE (1986) in DC Joy *et al.* Eds. *Principles of Analytical Electron Microscopy* p 20, Fig. 4 original reproduced by permission of Plenum Press.

Figure 4.3: Modified from Woldseth, R (1973) *X-ray Energy Spectrometry*, Fig. 3 original reproduced by permission of Kevex Instruments.

Figure 4.4: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.3 reproduced by permission of Philips Electron Optics.

Figure 4.11: Courtesy of LW Hobbs, modified from Hobbs, LW (1979) in JJ Hren *et al.* Eds. *Introduction to Analytical Electron Microscopy*, Fig. 17.2 original reproduced by permission of Plenum Press.

Figure 4.12: Courtesy of LW Hobbs, modified from Hobbs, LW (1979) in JJ Hren *et al.* Eds. *Introduction to Analytical Electron Microscopy*, Fig. 17.4 original reproduced by permission of Plenum Press.

Table 4.1: Courtesy of JI Goldstein, from Goldstein, JI *et al.* (1992) *Scanning Electron Microscopy and X-ray Microanalysis*, 2nd Edition, Table 3.11 reproduced by permission of Plenum Press.

Table 4.2: Data obtained from National Physical Laboratory, Teddington, UK, web site. [http://www.kayelaby.npl.co.uk/atomic\\_and\\_nuclear\\_physics/4\\_2/4\\_2\\_1.html](http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_2/4_2_1.html)

Table 4.3: Courtesy of NJ Zaluzec and JF Mansfield, from Zaluzec, NJ and Mansfield, JF (1987) in K Rajan Ed. *Intermediate Voltage Electron Microscopy and Its Application to Materials Science* p 29, Table 1 reproduced by permission of Philips Electron Optics.

## Chapter 5

- Figure 5.1: Modified from Hall, CE (1966) *Introduction to Electron Microscopy*, Fig. 7.8 McGraw-Hill.
- Figure 5.4B: Courtesy of JI Goldstein, modified from Goldstein, JI *et al.* (1992) *Scanning Electron Microscopy and X-ray Microanalysis*, 2nd Edition, Fig. 2.7 original reproduced by permission of Plenum Press.
- Figure 5.5: Courtesy of DW Ackland.
- Figure 5.6A: Modified from Crewe, AV *et al.* (1969) *Rev. Sci. Instrum.* **40** 241, Fig. 2.
- Figure 5.6B: Courtesy of DW Ackland.
- Figure 5.7: Courtesy of M Watanabe, modified from Watanabe, M and Williams, DB (2006) *J. Microsc.* **221** 89, Fig. 14.
- Figure 5.10: Courtesy of JR Michael, modified from Michael, JR and Williams, DB (1987) *J. Microsc.* **147** 289, Fig. 3 original reproduced by permission of the Royal Microscopical Society.
- Figure 5.11: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 2.12B Philips Electron Optics.
- Figure 5.12: Courtesy of JR Michael, from Michael, JR and Williams, DB (1987) *J. Microsc.* **147** 289, Fig. 2 original reproduced by permission of the Royal Microscopical Society.
- Figure 5.13A: Courtesy of DW Ackland.
- Figure 5.13B: Reproduced by permission of NSA Hitachi Scientific Instruments Ltd.

## Chapter 6

- Figure 6.7: Courtesy of DW Ackland.
- Figure 6.8A: Reproduced by permission of Philips Electronic Instruments Inc.
- Figure 6.8B: Reproduced by permission of Kratos Ltd.
- Figure 6.8C: From Mulvey, T (1974) *Electron Microscopy-1974* 17, Fig. 1 reproduced by permission of the Australian Academy of Science.
- Figure 6.8D: From Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition, Fig. 2.12 reproduced by permission of Springer Verlag.
- Figure 6.9: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition, Fig. 2.3 Springer Verlag.
- Figure 6.10B: Courtesy of AO Benscoter.
- Figure 6.11: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition, Fig. 2.13 Springer Verlag.
- Figure 6.12A: Courtesy of OL Krivanek, reproduced by permission of NION Inc.
- Figure 6.12A: Courtesy of M Haider, reproduced by permission of CEOS GmbH.

Figure 6.15: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition, Fig. 4.23 Springer Verlag.

## Chapter 7

- Figure 7.1: Modified from Stephen, J *et al.* (1975) *J. Phys. E* **8** 607, Fig. 2.
- Figure 7.5: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 1.2 Philips Electron Optics.
- Figure 7.6: Modified from Berger, SD *et al.* (1985) *Electron Microscopy and Analysis* p 137, Fig. 1 original by permission of The Institute of Physics Publishing.

## Chapter 8

- Figure 8.1: Courtesy of WC Bigelow, modified from Bigelow, WC (1994) *Vacuum Methods in Electron Microscopy*, Fig. 4.1 original by permission of Portland Press Ltd.
- Figure 8.2: Courtesy of WC Bigelow, modified from Bigelow, WC (1994) *Vacuum Methods in Electron Microscopy*, Fig. 5.1 original by permission of Portland Press Ltd.
- Figure 8.3: Reproduced by permission of Leybold Vacuum Products Inc.
- Figure 8.4: Courtesy of WC Bigelow, modified from Bigelow, WC (1994) *Vacuum Methods in Electron Microscopy*, Fig. 7.1 original by permission of Portland Press Ltd.
- Figure 8.6: Reproduced by permission of Gatan Inc.
- Figure 8.7: Modified from Valdrè, U and Goringe, MJ (1971) in U Valdrè Ed. *Electron Microscopy in Materials Science* p 217, Fig. 6 original by permission of Academic Press Inc.
- Figure 8.8: Courtesy of NSA Hitachi Scientific Instruments Ltd.
- Figure 8.9A,B: Reproduced by permission of Gatan Inc.
- Figure 8.10A: Reproduced by permission of Gatan Inc.
- Figure 8.11: Reproduced by permission of Gatan Inc.
- Figure 8.12: Modified from Komatsu, M *et al.* (1994) *J. Amer. Ceram. Soc.* **77** 839, Fig. 1 original by permission of The American Ceramic Society.
- Figure 8.13: Original by permission of NSA Hitachi Scientific Instruments Ltd.
- Figure 8.14A: Courtesy PE Fischione, reproduced by permission of EA Fischione Instruments Inc.
- Figure 8.14B: Courtesy PE Fischione, reproduced by permission of EA Fischione Instruments Inc.
- Figure 8.15A,B: Courtesy NJ Zaluzec.

## Chapter 9

- Figure 9.5: Courtesy of J Rodenburg, modified from original diagram on web site.
- Figure 9.6: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition, Fig. 4.14 Springer Verlag.
- Figure 9.10B: Courtesy of M Watanabe, modified from Watanabe, M *et al.* (2006) *Microsc. Microanal.* **12** 515, Fig. 6
- Figure 9.15: Courtesy of R Ristau.
- Figure 9.17: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 1.7 original reproduced by permission of Philips Electron Optics.
- Figure 9.19B-D: Courtesy of DW Ackland.
- Figure 9.20: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 1.5 original reproduced by permission of Philips Electron Optics.
- Figure 9.21: Courtesy of S Ramamurthy.
- Figure 9.22: Courtesy of DW Ackland.
- Figure 9.24: Courtesy of DW Ackland.
- Figure 9.25: Courtesy of DW Ackland.
- Figure 9.26: Courtesy of S Ramamurthy.
- Table 9.1: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Table 2.4 reproduced by permission of Philips Electron Optics.
- Table 9.2: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Table 2.2 reproduced by permission of Philips Electron Optics.

## Chapter 10

- Figure 10.1: Modified from Médard, L *et al.* (1949) *Rev. Met.* **46** 549, Fig. 5.
- Figure 10.3: Reproduced by permission of SPI Inc.
- Figure 10.4: Reproduced by permission of South Bay Technology.
- Figure 10.5A: Reproduced by permission of Electron Microscopy Sciences.
- Figure 10.5B: Reproduced by permission of VCR Inc.
- Figure 10.8A: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Fig. 9 original reproduced by permission of Philips Electron Optics.
- Fig. 10.8B: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Fig. 7 original reproduced by permission of Philips Electron Optics.

- Figure 10.9A: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Fig. 12 original reproduced by permission of Philips Electron Optics.
- Figure 10.9B: Courtesy PE Fischione, reproduced by permission of EA Fischione Instruments Inc.
- Figure 10.10: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Fig. 11 Philips Electron Optics.
- Figure 10.11: Courtesy of R Alani, reproduced by permission of Gatan Inc.
- Figure 10.12: Courtesy of AG Cullis, from Cullis, AG *et al.* (1985) *Ultramicrosc.* **17** 203, Figs. 1A, 3 reproduced by permission of Elsevier Science BV.
- Figure 10.13: Modified from van Hellemont, J *et al.* (1988) in J Bravman *et al.* Eds. *Specimen Preparation for Transmission Electron Microscopy of Materials Mater. Res. Soc. Symp. Proc.* **115** 247, Fig. 1 original by permission of MRS.
- Figure 10.16A,B: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Figs. 20, 21 original reproduced by permission of Philips Electron Optics.
- Figure 10.17A: Modified from Thompson-Russell, KC and Edington, JW (1977) *Electron Microscope Specimen Preparation Techniques in Materials Science*, Fig. 25 original reproduced by permission of Philips Electron Optics.
- Figure 10.17B: Courtesy of M Aindow.
- Figure 10.19A-F: Courtesy of SD Walck.
- Figure 10.20: Modified from Hetherington, CJD (1988) in J Bravman *et al.* Eds. *Specimen Preparation for Transmission Electron Microscopy of Materials Mater. Res. Soc. Symp. Proc.* **115** 143, Fig. 1 original reproduced by permission of MRS.
- Figure 10.21: Modified from Dobisz, EA *et al.* (1986) *J. Vac. Sci. Technol. B* **4** 850, Fig. 1 original reproduced by permission of MRS.
- Figure 10.22A,B: After Fernandez, A (1988) in J Bravman *et al.* Eds. *Specimen Preparation for Transmission Electron Microscopy of Materials. Mater. Res. Soc. Symp. Proc.* **115** 119, Fig. 1.
- Figure 10.22C,D: Courtesy of J Basu.
- Figure 10.23: Reproduced by permission of FEI Inc.
- Figure 10.24A-F: Courtesy of L Giannuzzi.
- Figure 10.25A,B: Thanks to JR Michael.
- Figure 10.26: Modified from Goodhew, PJ (1988) in J Bravman *et al.* Eds. *Specimen Preparation for Transmission Electron Microscopy of Materials, Mater. Res. Soc. Symp. Proc.* **115** 52.
- Table 10.1: Courtesy of T Malis.

## Chapter 11

Table 11.1: Modified from Hirsch, PB *et al.* (1977) *Electron Microscopy of Thin Crystals*, 2nd Edition p 19, Krieger, NY.

## Chapter 13

Table 13.2: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition Table 7.2 p 296 Springer Verlag.

## Chapter 14

Figure 14.2: Modified from Hashimoto, H *et al.* (1962) Proc. Roy. Soc. (London) **A269** 80, Fig. 2.

Table 14.2: Modified from Reimer, L (1993) *Transmission Electron Microscopy*, 3rd Edition Table 3.2 p 58, Springer Verlag.

## Chapter 16

Figure 16.5: Courtesy of ML Jenkins, from Jenkins, ML *et al.* (1976) Philos. Mag. **34** 1141, Fig. 2 reproduced by permission of Taylor and Francis.

Figure 16.6: Courtesy of BC De Cooman.

Figure 16.7: From Dodsworth, J *et al.* (1983) Adv. Ceram. **6** 102, Fig. 3 reproduced by permission of the American Ceramic Society.

Figure 16.8: Courtesy of BC De Cooman.

Figure 16.9: Courtesy of M Gajdardziska-Josifovska, from Gajdardziska-Josifovska M *et al.* (1995) Ultramicrosc. **58** 65, Fig. 1 reproduced by permission of Elsevier Science BV.

Figure 16.10: Courtesy of S McKernan.

Figure 16.11: Modified from Hahn, T (Ed.) *International Tables for Crystallography A* pp 538–539, No. 164 original by permission of The International Union of Crystallography.

Table 16.1: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Appendix 8 Van Nostrand Reinhold.

## Chapter 17

Figure 17.2: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 2.16 original reproduced by permission of Philips Electron Optics.

Figure 17.7: From Carter, CB *et al.* (1981) Philos. Mag. **A43** 441, Fig. 5C reproduced by permission of Taylor and Francis.

Figure 17.9: Modified from Hirsch, PB *et al.* (1977) *Electron Microscopy of Thin Crystals*, 2nd Edition, Fig. 4.11, Krieger.

Figure 17.10: From Driver, JH *et al.* (1972) Phil Mag. **26** 1227, Fig. 3 reproduced by permission of Taylor and Francis.

Figure 17.11A-C: From Lewis, MH and Billingham, J (1972) JEOL News 10e(l) 8, Fig. 3 reproduced by permission of JEOL USA Inc.

Figure 17.11D: Modified from Sauvage, M and Parthè, E (1972) Acta Cryst. **A28** 607, Fig. 2.

Figure 17.12: Modified from Carter, CB *et al.* (1981) Philos. Mag. **A43** 441, Fig. 5A,B.

Figure 17.13: Modified from Carter, CB *et al.* (1980) J. Electron Microsc. **63** 623, Fig. 8.

Figure 17.14: Modified from Carter, CB (1984) Philos. Mag. **A50** 133, Figs. 1–3.

## Chapter 18

Figure 18.2: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. A1.7 original reproduced by permission of Philips Electron Optics.

Figure 18.7: Courtesy of S Ramamurthy.

Figure 18.9: Courtesy of S McKernan.

Figure 18.10A,C: Courtesy of S McKernan.

Figure 18.10B,D: Modified from Vainshtein, BK *et al.* (1992) in JM Cowley Ed. *Electron Diffraction Techniques 1*, Fig. 6.13 original reproduced by permission of Oxford University Press.

Figure 18.10E: From Vainshtein, BK *et al.* (1992) in JM Cowley Ed. *Electron Diffraction Techniques 1*, Fig. 6.13 reproduced by permission of Oxford University Press.

Figure 18.11: Modified from James, RW (1965) in L Bragg Ed. *The Optical Principles of the Diffraction of X-rays The Crystalline State II*, Figs. 170, 184 Cornell University Press.

Figure 18.12: Courtesy of DJH Cockayne, modified from Sproul, A *et al.* (1986) Philos. Mag. **B54** 113, Fig. 1 original by permission of Taylor and Francis.

Figure 18.13: From Graczyk, JF and Chaudhari, P (1973) Phys. stat. sol. b **58** 163, Fig. 10A reproduced by permission of Akademie Verlag GmbH.

Figure 18.14: Courtesy of A Howie, from Howie, A (1988) in PR Buseck *et al.* Eds. *High-Resolution Transmission Microscopy and Associated Techniques* p 60, Fig. 14.12 reproduced by permission of Oxford University Press.

Figure 18.15: Courtesy of LD Marks and CS Own, modified from Own, CS and Marks, LD (2005) Rev. Sci. Instrum. **76** 033703, Fig. 1.

Figure 18.16: Courtesy of J-P Morniroli.

Figure 18.17: From Tietz, LA *et al.* (1995) *Ultramicrosc.* **60** 241, Figs. 2–4 reproduced by permission of Elsevier Science BV.

Figure 18.18: Modified from Tietz, LA *et al.* (1995) *Ultramicrosc.* **60** 241, Fig. 5 original by permission of Elsevier Science BV.

Figure 18.19: Modified from Andrews, KW *et al.* (1971) *Interpretation of Electron Diffraction Patterns*, 2nd Edition, Fig. 41 original reproduced by permission of Plenum Press.

Figure 18.20: Modified from Andrews, KW *et al.* (1971) *Interpretation of Electron Diffraction Patterns*, 2nd Edition, Fig. 41 original reproduced by permission of Plenum Press.

Figure 18.21: Modified from Andrews, KW *et al.* (1971) *Interpretation of Electron Diffraction Patterns*, 2nd Edition, Fig. 41 original reproduced by permission of Plenum Press.

Figure 18.22: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 2.20 original reproduced by permission of Philips Electron Optics.

Figure 18.24: Modified from Li, C and Williams, DB (2003) *Interface Science* **11** 461–472, Figs. 2A, 4. Courtesy of C Li.

## Chapter 19

Figure 19.6A: Courtesy of G. Thomas, modified from Levine, E *et al.* (1966) *J. Appl. Phys.* **37** 2141, Fig. 1A original reproduced by permission of the American Institute of Physics.

Figure 19.7: Modified from Okamoto, PR *et al.* (1967) *J. Appl. Phys.* **38** 289, Fig. 5.

Figure 19.8: Courtesy of S Ramamurthy.

Figure 19.9A: Courtesy of G. Thomas, modified from Thomas, G and Goringe, MJ (1979) *Transmission Electron Microscopy of Metals*, Fig. 2.30 John Wiley & Sons Inc.

Figure 19.9B: Modified from Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 2.27 Van Nostrand Reinhold.

Figure 19.11: Modified from Thomas, G and Goringe, MJ (1979) *Transmission Electron Microscopy of Metals*, Fig. 2.29 John Wiley & Sons Inc. Thanks to G Thomas.

## Chapter 20

Figure 20.2A: Courtesy of KS Vecchio, from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.5 reproduced by permission of Oxford University Press.

Figure 20.2B: Courtesy of KS Vecchio, from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.17

reproduced by permission of Oxford University Press,

Figure 20.3: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 6.6 Philips Electron Optics.

Figure 20.5: Courtesy of JF Mansfield, from Mansfield, JF (1984) *Convergent Beam Diffraction of Alloy Phases*, Fig. 5.3 reproduced by permission of Institute of Physics Publishing.

Figure 20.6: From Lyman, CE *et al.* Eds. (1990) *Scanning Electron Microscopy, X-ray Microanalysis and Analytical Electron Microscopy—A Laboratory Workbook*, Fig. A 27.2 reproduced by permission of Plenum Press.

Figure 20.7A,B: Courtesy of J-P Morniroli, from Morniroli, J-P (2002) *Large-Angle Convergent-Beam Electron Diffraction*, Figs. V.8, V.12B (Thanks to SF Paris).

Figure 20.8A: Courtesy of J-P Morniroli, modified from Morniroli, J-P (2002) *Large-Angle Convergent-Beam Electron Diffraction*, Fig. VI.I.

Figure 20.8B-D: Courtesy of J-P Morniroli, from Morniroli, J-P (2002) *Large-Angle Convergent-Beam Electron Diffraction*, Fig. VI.2A-C (Thanks to SF Paris).

Figure 20.9: Courtesy of KS Vecchio, from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.21 reproduced by permission of Oxford University Press.

Figure 20.10: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 20.11D: Courtesy of R Ayer.

Figure 20.12: Modified from Ayer, R (1989) *J. Electron Microscopy Tech.* **13** 3, Fig. 3.

Figure 20.13: Courtesy of WAT Clark from Heilman, P *et al.* (1983) *Acta Metall.* **31** 1293, Fig. 4 reproduced by permission of Elsevier Science BV.

Figure 20.14: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 6.9 original by permission of Philips Electron Optics.

Figure 20.15: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 6.16 original by permission of Philips Electron Optics.

Figure 20.16: Courtesy of CM Sung.

Figure 20.17: Courtesy of M Terauchi.

Figure 20.18: Courtesy of CS Own and LD Marks.

## Chapter 21

Figure 21.1: Courtesy of ZL Wang, after Wang, ZL *et al.* (2003) *Phys. Rev. Lett.* **91** 185502, Fig. 2.

Figure 21.2: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials*

*Science*, 2nd Edition, Fig. 6.13 original by permission of Philips Electron Optics.

Figure 21.3: Modified from Williams, DB 1987 *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 6.14 original by permission of Philips Electron Optics.

Figure 21.4: Courtesy of JM Zuo, simulation from WebEMAPS.

Figure 21.5: Courtesy of B Ralph, modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 6.18 original by permission of Philips Electron Optics.

Figure 21.6: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.29A reproduced by permission of Philips Electron Optics.

Figure 21.8: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.29B,C original by permission of Philips Electron Optics.

Figure 21.9: Courtesy of R Ayer, from Raghavan, M *et al.* (1984) *Metall. Trans.* **15A** 783, Fig. 6 reproduced by permission of ASM International.

Figure 21.10A: Courtesy of KS Vecchio, modified from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.23 original by permission of Oxford University Press.

Figure 21.10B: Courtesy of R Ayer, modified from Ayer, R (1989) *J. Electron Microsc. Tech.* **13** 3, Fig. 7 original by permission of John Wiley & Sons Inc.

Figure 21.12: Courtesy of KS Vecchio, modified from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.19 original by permission of Oxford University Press.

Figure 21.13: Courtesy of JM Zuo, modified from Kim, M *et al.* (2004) *Appl. Phys. Lett.* **84** 2181, Fig. 1.

Figure 21.14: Modified from Johnson, A (2007) *Acta Cryst.* **B63** 511, Fig.7 reproduced by permission of The International Union of Crystallography. Courtesy A Johnson.

Figure 21.15: Modified from Zuo, JM *et al.* (1999) *Nature* **401** 49, Fig. 3A reproduced by permission of Macmillan Magazines Ltd. Courtesy JCH Spence.

Figure 21.16: Courtesy of R McConville, from Williams, DB *et al.* Eds. (1992) *Images of Materials*, Fig. 6.33 reproduced by permission of Oxford University Press.

Figure 21.17: Courtesy of JM Cowley, from Liu, M and Cowley, JM (1994) *Ultramicrosc.* **53** 333, Figs. 1, 2 reproduced by permission of Elsevier Science BV.

Table 21.1: Data from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition p 79, reproduced by permission of Philips Electron Optics.

Table 21.2: Data from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*,

2nd Edition p 79, reproduced by permission of Philips Electron Optics.

## Chapter 22

Figure 22.5: Courtesy of KA Repa.

Figure 22.6: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 3.7D reproduced by permission of Philips Electron Optics.

Figure 22.7: Courtesy of KB Reuter.

Figure 22.8: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 3.7C reproduced by permission of Philips Electron Optics.

Figure 22.9A,B: Courtesy of HL Tsai, from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 1.19A, B reproduced by permission of Philips Electron Optics.

Figure 22.9C: Courtesy of K-R Peters.

Figure 22.10: Modified from Williams, DB (1983) in Krakow, W *et al.* (Eds.) *Electron Microscopy of Materials Mater. Res. Soc. Symp. Proc.* **31** 11, Fig. 3A,B.

Figure 22.11A,B: Courtesy of IM Watt, from Watt, I (1996) *The Principles and Practice of Electron Microscopy*, 2nd Edition, Fig. 5.5A,B reproduced by permission of Cambridge University Press.

Figure 22.12: Courtesy of MMJ Treacy, from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 5.26B reproduced by permission of Philips Electron Optics.

Figure 22.14: Courtesy of SJ Pennycook, from Pennycook, SJ *et al.* (1986) *J. Microsc.* **144** 229, Fig. 8 reproduced by permission of the Royal Microscopical Society.

Figure 22.15A,B: Courtesy of SJ Pennycook, from Lyman, CE (1992) *Microscopy: The Key Research Tool*, special publication of the EMSA Bulletin **22** 7, Fig. 7 reproduced by permission of MSA.

Figure 22.15C: Courtesy of SJ Pennycook, from Browning, ND *et al.* (1995) *Interface Science* **2** 397, Fig. 4D reproduced by permission of Kluwer.

Figure 22.16A: From Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 2.34 reproduced by permission of Philips Electron Optics.

Figure 22.17: Courtesy of D Cohen.

## Chapter 23

Figure 23.3A: From Izui, KJ *et al.* (1977) *J. Electron Microsc.* **26** 129, Fig. 1 reproduced by permission of the Japanese Society of Electron Microscopy.

Figure 23.3C: Courtesy of JCH Spence, from Spence, JCH *Experimental High-Resolution Electron Microscopy*, Fig. 5.15 reproduced by permission of Oxford University Press.

Figure 23.4B: Courtesy of JL Hutchison, from Hutchison, JL *et al.* (1991) in J Heydenreich and W Neumann Eds. *High-Resolution Electron Microscopy—Fundamentals and Applications* p 205, Fig. 3 reproduced by permission of Halle/Saale.

Figure 23.4C: Courtesy of S McKernan.

Figure 23.4D: From Carter, CB *et al.* (1989) *Philos. Mag.* **A63** 279, Fig. 3 reproduced by permission of Taylor and Francis.

Figure 23.8: From Tietz, LA *et al.* (1992) *Philos. Mag.* **A65** 439, Figs. 3A, 12A,C reproduced by permission of Taylor and Francis.

Figure 23.10: Courtesy of J Zhu.

Figure 23.12: Modified from Vincent, R (1969) *Philos. Mag.* **19** 1127, Fig. 4.

Figure 23.13: Modified from Norton, MG and Carter, CB (1995) *J. Mater. Sci.* **30**, Fig. 6.

Figure 23.14: Courtesy of U Dahmen, from Hetherington, CJD and Dahmen, U (1992) in PW Hawkes Ed. *Signal and Image Processing in Microscopy and Micro-analysis Scanning Microscopy Supplement 6* 405, Fig. 9 reproduced by permission of Scanning Microscopy International.

Figure 23.15: From Heidenreich, RD (1964) *Fundamentals of Transmission Electron Microscopy*, Figs. 5.4, 5.6 reproduced by permission of John Wiley & Sons Inc.

Figure 23.16A: Modified from Heidenreich, RD (1964) *Fundamentals of Transmission Electron Microscopy*, Fig. 11.2 original by permission of John Wiley & Sons Inc.

Figure 23.16B: From Boersch, H *et al.* (1962) *Z. Phys.* **167** 72, Fig. 4 reproduced by permission of Springer Verlag.

Figure 23.17: Courtesy of M Rühle.

Figure 23.18: Modified from Kouh, YM *et al.* (1986) *J. Mater. Sci.* **21** 2689, Fig. 9.

Figure 23.19: Courtesy of M Rühle, from Rühle, M and Sass, SL (1984) *Philos. Mag.* **A49** 759, Fig. 2 reproduced by permission of Taylor and Francis.

Figure 23.20B,E: From Carter, CB *et al.* (1986) *Philos. Mag.* **A55** 21, Fig. 11 reproduced by permission of Taylor and Francis.

## Chapter 24

Figure 24.1: Courtesy of S Ramamurthy.

Figure 24.2: Redrawn after Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 3.2A.

Figure 24.3B: Courtesy of D Cohen.

Figure 24.3C: Courtesy of S King when not busy founding Cricinfo.

Figure 24.5: Courtesy of D Susnitzky.

Figure 24.7: Redrawn after Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 3.3.

Figure 24.8: Redrawn after Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Figs. 3.4B,D. Images reproduced by permission of Philips Electron Optics.

Figure 24.9: Courtesy of S Ramamurthy.

Figure 24.10: From Hashimoto, H *et al.* (1962) *Proc. Roy. Soc. (London)* **A269** 80, Fig. 11 reproduced by permission of The Royal Society.

Figure 24.11A: Courtesy of NSA Hitachi Scientific Instruments Ltd.

Figure 24.11B,C: Courtesy of D Cohen.

Figure 24.12: From Edington, JW (1976) *Practical Electron Microscopy in Materials Science*, Fig. 3.3D reproduced by permission of Philips Electron Optics.

Figure 24.13B,C: From De Cooman, BC *et al.* (1987) in JD Dow and IK Schuller Eds. *Interfaces, Superlattices, and Thin Films*, *Mater. Res. Soc. Symp. Proc.* **77** 187, Fig. 1 reproduced by permission of MRS.

## Chapter 25

Figure 25.4A-D: Courtesy of D Cohen.

Figure 25.4E,F: Modified from Gevers, R *et al.* (1963) *Phys. stat. sol.* **3** 1563, Table 3.

Figure 25.5: From Föll, H *et al.* (1980) *Phys. stat. sol.* (a) **58** 393, Fig. 6A,C reproduced by permission of Akademie Verlag GmbH.

Figure 25.7A,B: From Lewis, MH (1966) *Philos. Mag.* **14** 1003, Fig. 9 reproduced by permission of Taylor and Francis.

Figure 25.7C,D: Courtesy of S Amelinckx, from Amelinckx, S and Van Landuyt, J (1978) in S Amelinckx *et al.* Eds. *Diffraction and Imaging Techniques in Material Science I* 107, Figs. 3, 18 North-Holland.

Figure 25.8: From Rasmussen, DR *et al.* (1991) *Phys. Rev. Lett.* **66** (20) 262, Fig. 2 reproduced by permission of The American Physical Society.

Figure 25.9: Courtesy of S Summerfelt.

Figure 25.13: Modified from Metherell, AJ (1975) in U Valdrè and E Ruedl Eds. *Electron Microscopy in Materials Science II* 397, Fig. 13 Commission of the European Communities.

Figure 25.14: From Hashimoto, H *et al.* (1962) *Proc. Roy. Soc. (London)* **A269** 80, Fig. 15 original by permission of The Royal Society.

Figure 25.16: Modified from Rasmussen, R *et al.* (1991) *Philos. Mag.* **63** 1299, Fig. 4.

## Chapter 26

Figure 26.2B: Modified from Amelinckx, S (1964) *Solid State Physics Suppl.* **6**, Fig. 76.

Figure 26.6A-C: Modified from Carter, CB (1980) *Phys. stat. sol.* (a) **62** 139, Fig. 4.

Figure 26.6F: From Van Landuyt, J *et al.* (1970) *Phys. stat. sol.* **41** 271, Fig. 1 reproduced by permission of Akademie Verlag GmbH.

Figure 26.6G-H: Courtesy of BC De Cooman.

Figure 26.7: Modified from Hirsch, PB *et al.* (1977) *Electron Microscopy of Thin Crystals*, 2nd Edition, Fig. 7.8 Krieger.

Figure 26.8: From Delavignette, P and Amelinckx, S (1962) *J. Nucl. Mater.* **5** 17, Fig. 7 reproduced by permission of Elsevier Science BV.

Figure 26.10: From Urban, K (1971) in S Koda Ed. *The World Through the Electron Microscope Metallurgy V 26*, reproduced by permission of JEOL USA Inc.

Figure 26.11: Courtesy of A Howie, from Howie, A and Whelan, MJ (1962) *Proc. Roy. Soc. (London)* **A267** 206, Fig. 14 reproduced by permission of The Royal Society.

Figure 26.12: Modified from M Wilkens (1978) in S Amelinckx *et al.* Eds. *Diffraction and Imaging Techniques in Material Science I* 185, Fig. 4 North-Holland.

Figure 26.14: From Dupouy, G and Perrier, F (1971) in S Koda Ed. *The World Through the Electron Microscope Metallurgy V 100*, reproduced by permission of JEOL USA Inc.

Figure 26.15A: From Modeer, B and Lagneborg, R (1971) in S Koda Ed. *The World Through the Electron Microscope Metallurgy V 44*, reproduced by permission of JEOL USA Inc.

Figure 26.15B: Courtesy of DA Hughes, from Hansen, N and Hughes, DA (1995) *Phys. stat. sol. (a)* **149** 155, Fig. 5 reproduced by permission of Akademie Verlag GmbH.

Figure 26.16A: From Siems, F *et al.* (1962) *Phys. stat. sol.* **2** 421, Fig. 5A reproduced by permission of Akademie Verlag GmbH.

Figure 26.16C: From Siems, F *et al.* (1962) *Phys. stat. sol.* **2** 421, Fig. 15A reproduced by permission of Akademie Verlag GmbH.

Figure 26.17A: Modified from Whelan, MJ (1958–1959) *J. Inst. Met.* **87** 392, Fig. 25A.

Figure 26.17B: Courtesy of K Ostyn.

Figure 26.18: From Takayanagi, L (1988) *Surface Science* **205** 637, Fig. 5 reproduced by permission of Elsevier Science BV.

Figure 26.19A: From Tunstall, WJ *et al.* (1964) *Philos. Mag.* **9** 99, Fig. 9 reproduced by permission of Taylor and Francis.

Figure 26.19B: From Amelinckx, S in PG Merli and VM Anti-sari Eds. *Electron Microscopy in Materials Science* p 128, Fig. 45 reproduced by permission of World Scientific.

Figure 26.20: Courtesy of W Skrotski.

Figure 26.21: Courtesy of W Skrotski.

Figure 26.22: From Carter, CB *et al.* (1986) *Philos. Mag.* **A55** 21, Fig. 2 reproduced by permission of Taylor and Francis.

Figure 26.23: From Carter, CB *et al.* (1981) *Philos. Mag.* **A43** 441, Fig. 3 reproduced by permission of Taylor and Francis.

Figure 26.24: Courtesy of K Ostyn.

Figure 26.25: Courtesy of L Tietz.

Figure 26.26A: Courtesy of LM Brown, from Ashby, MF and Brown, LM (1963) *Philos. Mag.* **8** 1083, Fig. 10 reproduced by permission of Taylor and Francis.

Figure 26.26B: Modified from Whelan, MJ (1978) in S Amelinckx *et al.* Eds. *Diffraction and Imaging Techniques in Material Science I* 43, Fig. 36 North-Holland.

Figure 26.26C: Courtesy of LM Brown, from Ashby, MF and Brown, LM (1963) *Philos. Mag.* **8** 1083, Fig. 12 reproduced by permission of Taylor and Francis.

Figure 26.27: From Rasmussen, DR and Carter, CB (1991) *J. Electron Microsc. Technique* **18** 429, Fig. 2 reproduced by permission of John Wiley & Sons Inc.

## Chapter 27

Figure 27.7: Courtesy of S King.

Figure 27.10: Courtesy of DJH Cockayne, from Cockayne, DJH (1972) *Z. Naturforschung* **27a** 452, Fig. 6 original by permission of Verlag der Zeitschrift für Naturforschung, Tübingen.

Figure 27.13: Modified from Carter, CB *et al.* (1986) *Philos. Mag.* **A55** 1, Fig. 9.

Figure 27.15: Modified from Föll, H *et al.* (1980) *Phys. stat. sol. (a)* **58** 393, Fig. 6B,C.

Figure 27.17: From Heidenreich, RD (1964) *Fundamentals of Transmission Electron Microscopy*, Fig. 9.20 reproduced by permission of John Wiley & Sons Inc.

Figure 27.18: Courtesy of DJH Cockayne, from Ray, ILF and Cockayne, DJH (1971) *Proc. Roy. Soc. (London)* **A325** 543, Fig. 10 reproduced by permission of The Royal Society.

Figure 27.23: Modified from Carter, CB (1979) *J. Phys. (A)* **54** (1) 395, Fig. 8A.

## Chapter 28

Figure 28.4: Courtesy of R Gronsky, from Gronsky, R (1992) in DB Williams *et al.* Eds. *Images of Materials*, Fig. 7.6 original by permission of Oxford University Press.

Figure 28.5: Courtesy of S McKernan.

Figure 28.6: Courtesy of S McKernan.

Figure 28.7: Modified from Cowley, JM (1988) in PR Buseck *et al.* Eds. *High-Resolution Electron Microscopy and Associated Techniques*, Fig. 1.9 Oxford University Press.

Figure 28.8: Courtesy of JCH Spence, from Spence, JCH (1988) *Experimental High-Resolution Electron*

- Microscopy*, 2nd Edition, Fig. 4.3 original by permission of Oxford University Press.
- Figure 28.10: From de Jong, AF and Van Dyck, D (1993) *Ultramicrosc.* **49** 66, Fig. 1 original by permission of Elsevier Science BV.
- Figure 28.11: Courtesy of MT Otten, from Otten, MT and Coene, WMJ (1993) *Ultramicrosc.* **48** 77, Fig. 8 reproduced by permission of Elsevier Science BV.
- Figure 28.12: Courtesy of MT Otten, from Otten, MT and Coene, WMJ (1993) *Ultramicrosc.* **48** 77, Fig. 11 reproduced by permission of Elsevier Science BV.
- Figure 28.13: Courtesy of MT Otten, from Otten, MT and Coene, WMJ (1993) *Ultramicrosc.* **8** 77, Fig. 10 reproduced by permission of Elsevier Science BV.
- Figure 28.14A,B: From Amelinckx, S *et al.* (1993) *Ultramicrosc.* **51** 90, Fig. 2 original by permission of Elsevier Science BV.
- Figure 28.15: From Amelinckx, S *et al.* (1993) *Ultramicrosc.* **51** 90, Fig. 3 reproduced by permission of Elsevier Science BV.
- Figure 28.16: From Rasmussen, DR *et al.* (1995) *J. Microsc.* **179** 77, Fig. 2C,D reproduced by permission of the Royal Microscopical Society.
- Figure 28.18A: Courtesy of S McKernan.
- Figure 28.18B: From Berger, A *et al.* (1994) *Ultramicrosc.* **55** 101, Fig. 4B reproduced by permission of Elsevier Science BV.
- Figure 28.18C: Courtesy of S Summerfelt.
- Figure 28.18D: Courtesy of S McKernan.
- Figure 28.19: Courtesy of DJ Smith.
- Figure 28.21A: From Van Landuyt, J *et al.* (1991) in J Heydenreich and W Neumann Eds. *High-Resolution Electron Microscopy—Fundamentals and Applications*, p 254, Fig. 6 reproduced by permission of Halle/Saale.
- Figure 28.21D: From Van Landuyt, J *et al.* (1991) in J Heydenreich and W Neumann Eds. *High-Resolution Electron Microscopy—Fundamentals and Applications*, p 254, Fig. 8 reproduced by permission of Halle/Saale.
- Figure 28.22: From Nissen, H-U and Beeli, C (1991) in J Heydenreich and W Neumann Eds. *High-Resolution Electron Microscopy—Fundamentals and Applications*, p 272, Fig. 4 reproduced by permission of Halle/Saale.
- Figure 28.23: From Nissen, H-U and Beeli, C (1991) in J Heydenreich and W Neumann Eds. *High-Resolution Electron Microscopy—Fundamentals and Applications*, p 272, Fig. 2 reproduced by permission of Halle/Saale.
- Figure 28.24: From Parsons, JR *et al.* (1973) *Philos. Mag.* **29** 1359, Fig. 2 reproduced by permission of Taylor and Francis.
- Table 28.1: Modified from de Jong, AF and Van Dyck, D (1993) *Ultramicrosc.* **49** 66, Table 1.
- ## Chapter 29
- Figure 29.2: Courtesy of R Sinclair, from Sinclair, R *et al.* (1981) *Met. Trans.* **12A**, 1503, Figs. 13, 14 reproduced by permission of ASM International.
- Figure 29.4A,B: From Marcinkowski, MJ and Poliak, RM (1963) *Philos. Mag.* **8**, 1023, Fig. 15a,b reproduced by permission of Taylor and Francis.
- Figure 29.4C,D: Courtesy of J Silcox, from Silcox, J (1963) *Philos. Mag.* **8**, 7, Fig. 7 reproduced by permission of Taylor and Francis.
- Figure 29.5: Courtesy of AJ Craven, from Buggy, TW *et al.* (1981) *Analytical Electron Microscopy-1981*, p 231, Fig. 5 reproduced by permission of San Francisco Press.
- Figure 29.6D,E: Courtesy of NSA Hitachi Scientific Instruments Ltd. and S McKernan.
- Figure 29.7: Courtesy of R Sinclair.
- Figure 29.8: From Kuesters, K-H *et al.* (1985) *J. Cryst. Growth* **71**, 514, Fig. 4 reproduced by permission of Elsevier Science BV.
- Figure 29.9: Courtesy of M. Mallamaci.
- Figure 29.10A: Modified from De Cooman, BC *et al.* (1985) *J. Electron Microsc. Tech.* **2**, 533, Fig. 1.
- Figure 29.10B: Courtesy of SM Zemyan.
- Figure 29.10C-E: Courtesy of BC De Cooman.
- Figure 29.12: Courtesy of G Thomas, from Bell, WL and Thomas, G (1972) in G Thomas *et al.* Eds. *Electron Microscopy and Structure of Materials*, p 53, Fig. 28 reproduced by permission of University of California Press.
- Figure 29.13: Courtesy of K-R Peters, from Peters, K-R (1984) in DF Kyser *et al.* Eds. *Electron Beam Interactions with Solids for Microscopy, Microanalysis and Lithography*, p 363, Fig. 1 original by permission of Scanning Microscopy International.
- Figure 29.14: Courtesy of R McConville, from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 3.11 reproduced by permission of Philips Electron Optics.
- Figure 29.15: Courtesy of Philips Electronic Instruments, from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 3.10 reproduced by permission of Philips Electron Optics.
- Figure 29.16: Courtesy of H Lichte, from Lichte, H (1992) *Scanning Microscopy*, p 433, Fig. 1 reproduced by permission of Scanning Microscopy International.
- Figure 29.17: Modified from Lichte, H (1992) *Ultramicrosc.* **47**, 223, Fig. 1.
- Figure 29.18: Modified from Tonomura, A. Courtesy of NSA Hitachi Scientific Instruments Ltd.

Figure 29.19A-C: From Tonomura, A (1992) *Adv. Phys.* 41, 59, Fig. 29 reproduced by permission of Taylor and Francis.

Figure 29.19D: From Tonomura, A (1987) *Rev. Mod. Phys.* 59, 639, Fig. 41 reproduced by permission of The American Physical Society.

Figure 29.20A: From Tonomura, A (1992) *Adv. Phys.* 41, 59, Fig. 38, reproduced by permission of Taylor and Francis.

Figure 29.20B: From Tonomura, A (1992) *Adv. Phys.* 41, 59, Fig. 42 reproduced by permission of Taylor and Francis.

Figure 29.20C: From Tonomura, A (1992) *Adv. Phys.* 41, 59, Fig. 44 reproduced by permission of Taylor and Francis.

Figure 29.21: Courtesy of R Sinclair, from Sinclair, R *et al.* (1994) *Ultramicrosc.* 56, 225, Fig. 5 reproduced by permission of Elsevier Science BV.

Figure 29.22: Courtesy of M Treacy.

## Chapter 30

Figure 30.2A,B: Courtesy of MA O’Keefe, from O’Keefe, MA and Kilaas, R (1988) in PW Hawkes *et al.* Eds. *Image and Signal Processing in Electron Microscopy, Scanning Microscopy Supplement 2* p 225, Fig. 1 original by permission of Scanning Microscopy International.

Figure 30.3: From Kambe, K (1982) *Ultramicrosc* 10 223, Fig. 1A-D reproduced by permission of Elsevier Science BV.

Figure 30.4: Courtesy of MA O’Keefe, from O’Keefe, MA and Kilaas, R (1988) in PW Hawkes *et al.* Eds. *Image and Signal Processing in Electron Microscopy Scanning Microscopy Supplement 2* p 225, Fig. 4 reproduced by permission of Scanning Microscopy International.

Figure 30.5: Modified from Rasmussen, DR and Carter, CB (1990) *Ultramicrosc.* 32 337, Figs. 1, 2.

Figure 30.8: From Beeli, C and Horiuchi, S (1994) *Philos. Mag.* B70 215, Fig. 6A-D reproduced by permission of Taylor and Francis.

Figure 30.9: From Beeli, C and Horiuchi, S (1994) *Philos. Mag.* B70 215, Fig. 7A-D reproduced by permission of Taylor and Francis.

Figure 30.10: From Beeli, C and Horiuchi, S (1994) *Philos. Mag.* B70 215, Fig. 8 reproduced by permission of Taylor and Francis.

Figure 30.11: From Jiang, J *et al.* (1995) *Phil. Mag. Lett.* 71 123, Fig. 4 reproduced by permission of Taylor and Francis.

## Chapter 31

Figure 31.1: Courtesy of J. Heffelfinger.

Figure 31.2: From Rasmussen, DR *et al.* (1995) *J. Microsc.* 179, 77, Fig. 1b original by permission of The Royal Microscopical Society.

Figure 31.3: From Rasmussen, DR *et al.* (1995) *J. Microsc.* 179, 77, Fig. 5 reproduced by permission of The Royal Microscopical Society.

Figure 31.4: Courtesy of OL Krivanek, from Krivanek, OL (1988) in PR Buseck *et al.* Eds. *High-Resolution Electron Microscopy and Associated Techniques*, Fig. 12.6 reproduced by permission of Oxford University Press.

Figure 31.5: Courtesy of OL Krivanek, Krivanek, OL (1988) in PR Buseck *et al.* Eds. *High-Resolution Electron Microscopy and Associated Techniques*, Fig. 12.7 reproduced by permission of Oxford University Press.

Figure 31.6A: Courtesy of JCH Spence, from Spence, JCH and Zuo, JM (1992) *Electron Microdiffraction*, Fig. A1.3 reproduced by permission of Plenum Press.

Figure 31.6B: Courtesy of OL Krivanek, from Krivanek, OL (1988) in PR Buseck *et al.* Eds. *High-Resolution Electron Microscopy and Associated Techniques*, Fig. 12.8 reproduced by permission of Oxford University Press.

Figure 31.7: Courtesy of S McKernan.

Figure 31.8: Courtesy of ZL Wang. Wwang, ZL *et al.* (2007) *MRS Bulletin*, 109–116. Reproduced by permission of MRS.

Figure 31.9: Courtesy of ZC Lin, from Lin, ZC (1993) Ph.D. dissertation, Fig. 4.15, University of Minnesota.

Figure 31.10: Courtesy of O Saxton, from Kirkland, AI (1992) in PW Hawkes Ed. *Signal and Image Processing in Microscopy and Microanalysis, Scanning Microscopy Supplement 6*, 139, Figs. 1–3 reproduced by permission of Scanning Microscopy International.

Figure 31.11: From Zou, XD and Hovmöller, S (1993) *Ultramicrosc.* 49, 147, Fig. 1 reproduced by permission of Elsevier Science BV.

Figure 31.12A: From Kirkland, AI *et al.* (1995) *Ultramicrosc.* 57, 355, Fig. 1 reproduced by permission of Elsevier Science BV.

Figure 31.12B; From Kirkland. AI *et al.* (1995) *Ultramicrosc.* 57, 355, Fig. 3 reproduced by permission of Elsevier Science BV.

Figure 31.13A-C: From Kirkland, AI *et al.* (1995) *Ultramicrosc.* 57, 355, Fig. 8 reproduced by permission of Elsevier Science BV.

Figure 31.14: Courtesy of OL Krivanek, from Krivanek, OL and Fan, GY (1992) in PW Hawkes (Ed.) *Signal and Image Processing in Microscopy and Microanalysis, Scanning Microscopy Supplement 6*, p 105, Fig. 4 reproduced by permission of Scanning Microscopy International.

Figure 31.15: Courtesy of OL Krivanek, Krivanek, OL and Fan, GY (1992) in PW Hawkes (Ed.) *Signal and Image Processing in Microscopy and Microanalysis*,

Scanning Microscopy Supplement 6, p 105, Fig. 5 reproduced by permission of Scanning Microscopy International.

- Figure 31.16: After U Dahmen, from Paciornik, S *et al.* (1996) *Ultramicrosc.* 62, 15, Fig. 1.
- Figure 31.17: Courtesy of U Dahmen, from Paciornik, S *et al.* (1996) *Ultramicrosc.* 62, 15, Fig. 5 reproduced by permission of Elsevier Science BV.
- Figure 31.18: Courtesy of A Ourmazd, from Kisielowski, C *et al.* (1995) *Ultramicrosc.* 58, 131, Figs. 2–4 reproduced by permission of Elsevier Science BV.
- Figure 31.19: Courtesy of A Ourmazd, from Kisielowski, C *et al.* (1995) *Ultramicrosc.* 58, 131, Figs. 8, 10, 12 reproduced by permission of Elsevier Science BV.
- Figure 31.20A,B: Data from Ourmazd, A *et al.* (1990) *Ultramicrosc.* 34, 237, Fig. 1.
- Figure 31.20C,D: From Ourmazd, A *et al.* (1990) *Ultramicrosc.* 34, 237, Figs. 2, 5 reproduced by permission of Elsevier Science BV. Courtesy of A Ourmazd.
- Figure 31.21A-F: From Kisielowski, C *et al.* (1995) *Ultramicrosc.* 34, 237, Fig. 15 reproduced by permission of Elsevier Science BV. Courtesy of A Ourmazd.
- Figure 31.22: Courtesy of U Dahmen, from Paciornik, S *et al.* (1996) *Ultramicroscopy*, in press, Fig. 2 reproduced by permission of Elsevier Science BV.
- Figure 31.23: From King, WE and Campbell, GH (1994) *Ultramicrosc.* 56, 46, Fig. 1 reproduced by permission of Elsevier Science BV.
- Figure 31.24: From King, WE and Campbell, GH (1994) *Ultramicrosc.* 56, 46, Fig. 6 reproduced by permission of Elsevier Science BV.
- Figure 31.25: Courtesy of M Rühle, from Möbus, G *et al.* (1993) *Ultramicrosc.* 49, 46, Fig. 6 reproduced by permission of Elsevier Science BV.
- Figure 31.26: From Thon, F (1970) in U Valdrè Ed. *Electron Microscopy in Materials Science*, p 571, Fig. 36 reproduced by permission of Academic Press.
- Figure 31.27: Courtesy of J Heffelfinger.

## Chapter 32

- Figure 32.1: Courtesy of JE Yehoda, from Messier, R and Yehoda, JE (1985) *J. Appl. Phys.* **58** 3739, Fig. 1 reproduced by permission of the American Institute of Physics.
- Figure 32.2: Courtesy of M Watanabe.
- Figure 32.3B,C: Courtesy of JH Scott.
- Figure 32.4A: Courtesy of JH Scott.
- Figure 32.4B: Courtesy of P Statham, reproduced by permission of Oxford Instruments.
- Figure 32.5: Courtesy of N Rowlands, reproduced by permission of Oxford Instruments.
- Figures 32.6,7: Courtesy of SM Zemyan.
- Figure 32.8A-C: Courtesy of JH Scott, modified from figure originally supplied by Photon Detector Technologies.

Figure 32.8D: Courtesy of DE Newbury.

Figure 32.9A-C: Courtesy of M Terauchi.

Figure 32.9D: Courtesy of D Wollman, SW Nam and DE Newbury.

Figure 32.11: Courtesy of SM Zemyan, modified from Zemyan, S and Williams, DB (1995) in DB Williams *et al.* Eds. *X-ray Spectrometry in Electron Beam Instruments*, Fig. 12.9 original by permission of Plenum Press.

Figure 32.12A: Courtesy of SM Zemyan, modified from Zemyan, SM and Williams, DB (1995) in DB Williams *et al.* Eds. *X-ray Spectrometry in Electron Beam Instruments*, Fig. 12.10 original by permission of Plenum Press.

Figure 32.12B: Courtesy of JH Scott, modified from diagram originally supplied by Photon Detector Technologies .

Figure 32.13: Courtesy of JJ Friel, modified from Mott, RB and Friel, JJ (1995) in DB Williams *et al.* Eds. *X-ray Spectrometry in Electron Beam Instruments*, Fig. 9.8 original reproduced by permission of Plenum Press.

Figure 32.14: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.5A original reproduced by permission of Philips Electron Optics.

Figure 32.15: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.30 original reproduced by permission of Philips Electron Optics.

## Chapter 33

Figure 33.1: Courtesy of SM Zemyan.

Figure 33.2: Courtesy of SM Zemyan.

Figure 33.3: Courtesy of DE Newbury, from Newbury, DE (1995) in DB Williams *et al.* Eds. *X-ray Spectrometry in Electron Beam Instruments*, Fig. 11.18 reproduced by permission of Plenum Press.

Figure 33.4: Courtesy of SM Zemyan.

Figure 33.5A,B: Courtesy of G Cliff, modified from Cliff, G and Kenway, PB (1982) *Microbeam Analysis-1982* p 107, Figs. 5, 4 original reproduced by permission of San Francisco Press.

Figure 33.6: Modified from Williams, DB and Goldstein, JI (1981) in KFJ Heinrich *et al.* Eds. *Energy-Dispersive X-ray Spectrometry* p 346, Fig. 7A NBS.

Figure 33.7: Courtesy of SM Zemyan.

Figure 33.8: Courtesy of SM Zemyan.

Figure 33.9A: Courtesy of SM Zemyan.

Figure 33.9B: Courtesy of KS Vecchio, modified from Vecchio, KS and Williams, DB (1987) *J. Microsc.* **147** 15, Fig. 1 original by permission of the Royal Microscopical Society.

Figure 33.10A: Courtesy of SM Zemyan.

Figure 33.10B: Courtesy of SM Zemyan, modified from Zemyan, SM and Williams, DB (1994) *J. Microsc.* **174** 1, Fig. 6.

Figure 33.10C: Courtesy of SM Zeyan, modified from Zeyan, SM and Williams, DB (1995) in DB Williams *et al.* Eds. *X-ray Spectrometry in Electron Beam Instruments*, Fig. 12.7.

Figure 33.11: Courtesy of M Watanabe.

Figure 33.12: Courtesy of M Watanabe.

Figure 33.13A-C: Courtesy of CE Lyman, from Lyman, CE (1992) in CE Lyman *et al.* Eds. *Compositional Imaging in the Electron Microscope: An Overview*, Microscopy: The Key Research Tool p 1, Fig. 2.

Figure 33.14A: Modified frontispiece image by Hunneyball, PD *et al.* (1981) in GW Lorimer *et al.* Eds. *Quantitative Microanalysis with High Spatial Resolution* The Institute of Metals, London.

Figure 33.14B,C: Courtesy of DT Carpenter.

Figure 33.15: Courtesy of M Watanabe.

## Chapter 34

Figure 34.1: Courtesy of M Watanabe.

Figure 34.2: Courtesy of SM Zeyan and M Watanabe.

Figure 34.3: Courtesy of SM Zeyan and M Watanabe.

Figure 34.4A-D: Courtesy M Watanabe, from Watanabe, M and Williams, DB (2003) *Microsc. Microanal.* **9** Suppl. 2 p 124, Figs. 1–4 reproduced by permission of the Microscopy Society of America.

Figures 34.5–7: Courtesy of SM Zeyan and M Watanabe.

Figure 34.8: Courtesy of CH Kiely. Full report given by Enache, DI *et al.* (2006) *Science* **311** 362.

## Chapter 35

Figures 35.1–4: Courtesy of SM Zeyan and M Watanabe.

Figure 35.5A: Modified from Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.20 original by permission of Philips Electron Optics.

Figure 35.5B,C: Courtesy of SM Zeyan.

Figure 35.6: Courtesy of SM Zeyan.

Figure 35.7: Modified from Wood, JE *et al.* (1984) *J. Microsc.* **133** 255, Fig. 2.8 original by permission of the Royal Microscopical Society.

Figure 35.8: Modified from Bender, BA *et al.* (1980) *J. Amer. Ceram. Soc.* **63** 149, Fig. 1 original by permission of the American Ceramic Society.

Figure 35.10B: Courtesy of JA Eades, from Christenson, KK and Eades, JA (1986) *Proc. 44th EMSA Meeting* p 622, Fig. 2 original by permission of the Electron Microscopy Society of America.

Figure 35.11A-C: Courtesy of M Watanabe and MG Burke.

Figure 35.11D: Courtesy of M Watanabe, modified from Watanabe, M *et al.* (2006) *Microsc. Microanal.*

**12** 515, Figs. 10, 11 reproduced by permission of the Microscopy Society of America.

Tables 35.1, 2: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Table 4.2A,B reproduced by permission of Philips Electron Optics.

Table 35.3A,B: From Wood, JE *et al.* (1984) *J. Microsc.* **133** 255, Tables 9, 11 reproduced by permission of the Royal Microscopical Society.

Table 35.4: Courtesy of M Watanabe.

## Chapter 36

Figure 36.1: Courtesy of M Watanabe.

Figure 36.2: Courtesy of M Watanabe.

Figure 36.3: Courtesy of JR Michael, modified from Williams, DB *et al.* (1992) *Ultramicrosc.* **47** 121, Fig. 1.

Figure 36.4: Courtesy of JR Michael, modified from Williams, DB *et al.* (1992) *Ultramicrosc.* **47** 121, Fig. 2 original by permission of Elsevier Science BV.

Figure 36.5A-C: Courtesy of M Watanabe, modified from Watanabe, M *et al.* (2006) *Microsc. Microanal.* **12** Suppl. 2, 1568, Figs. 2–4 reproduced by permission of the Microscopy Society of America.

Figure 36.8A,B: From Williams, DB (1987) *Practical Analytical Electron Microscopy in Materials Science*, 2nd Edition, Fig. 4.27 reproduced by permission of Philips Electron Optics.

Figure 36.9: After Williams, DB *et al.* (2002) *J. Electron Microscopy* **51** (Suppl), S113, Figure courtesy of M Watanabe.

Figure 36.10: Courtesy of CE Lyman, modified from Lyman, CE (1987) in J Kirschner *et al.* Eds. *Physical Aspects of Microscopic Characterization of Materials* p 123, Fig. 1, original reproduced by permission of Scanning Microscopy International.

Figure 36.11: Courtesy of M Watanabe, modified from Watanabe, M *et al.* (2006) *Microsc. Microanal.* **12** 515, Fig. 13; in turn modified from Lyman, CE (1987) in J Kirschner *et al.* Eds. *Physical Aspects of Microscopic Characterization of Materials* p 123, Fig. 7.

Figure 36.12: Courtesy of M Watanabe, modified from Watanabe, M *et al.* (2006) *Microsc. Microanal.* **12** 515, Fig. 5 reproduced by permission of the Microscopy Society of America.

Figure 36.13: Courtesy of M Watanabe.

## Chapter 37

Figure 37.1: Courtesy of J Bruley.

Figure 37.2A Courtesy of JA Hunt, original by permission of Gatan Inc.

Figure 37.2B,C: Courtesy of RF Egerton, modified from Egerton, RF (1996) *Electron Energy-Loss Spectroscopy in the Electron Microscope*, 2nd edition,

Fig. 2.2 original reproduced by permission of Plenum Press.

Figure 37.3: Courtesy of K Scudder, reproduced by permission of Gatan Inc.

Figure 37.4A: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 37.4B: Courtesy of M Watanabe.

Figure 37.5: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 37.9A: Courtesy of JA Hunt, modified from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 7 original by permission of the Venezuelan Society for Electron Microscopy.

Figure 37.9B,C: Courtesy of C Colliex.

Figure 37.10: Courtesy of JA Hunt, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 5 reproduced by permission of the Venezuelan Society for Electron Microscopy.

Figure 37.11: Courtesy of JA Hunt, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 4 reproduced by permission of the Venezuelan Society for Electron Microscopy.

Figure 37.12: Courtesy of J Bruley, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 6 reproduced by permission of the Venezuelan Society for Electron Microscopy.

Figure 37.13A: Courtesy of OL Krivanek, modified from Krivanek, OL *et al.* (1991) *Microsc. Microanal. Microstruct.* **2** 315, Fig. 8.

Figure 37.13B: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 37.14: Courtesy of M Watanabe.

Figure 37.15A,B: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 37.16A,B: Courtesy of F Hofer.

Figure 37.17A: Courtesy of V Dravid.

Figure 37.17B: Courtesy of C Colliex.

Figure 37.17C,D: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

## Chapter 38

Figure 38.1: Courtesy of J Bruley.

Figures 38.2–4: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 38.5A: Courtesy of J Bruley.

Figure 38.5B: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 38.6A,B: Courtesy of RH French, modified from van Benthem, K, Elsässer, C and French, RH (2001) *J. Appl. Phys.* **90** 6156, Figs.1, 7.

Figure 38.7A: Courtesy of J Bruley.

Figure 38.7B: Courtesy of JA Hunt, reproduced by permission of Gatan Inc.

Figure 38.8A,B: From Williams, DB and Edington, JW (1976) *Acta Metall.* **24** 323, Fig. 7 reproduced by permission of Elsevier Science BV.

Figure 38.8C: Courtesy of AJ Strutt.

Figure 38.9A: Courtesy of JA Hunt.

Figure 38.9B: Courtesy of M Libera, modified from Kim *et al.* (2006) *J. Am. Chem. Soc.* **128** 6570, Figs.1, 2.

Figure 38.10A,B: Courtesy of JA Hunt.

Figure 38.11: Courtesy of VJ Keast.

Table 38.1: Courtesy of RF Egerton, from Egerton, RF (1996) *Electron Energy-Loss Spectroscopy in the Electron Microscopy*, 2nd edition p 157, Table 3.2.

## Chapter 39

Figure 39.1: Courtesy of OL Krivanek, modified from Ahn, CC and Krivanek, OL (1983) *EELS Atlas* p iv, original by permission of Gatan Inc.

Figure 39.2: Courtesy of J Bruley, modified from Joy, DC (1986) in DC Joy *et al.* Eds. *Principles of Analytical Electron Microscopy* p 249, Fig. 8 Plenum Press.

Figure 39.3: Courtesy of J Bruley.

Figure 39.4: Courtesy of CE Lyman, modified from Lyman, CE (1987) in J Kirschner *et al.* Eds. *Physical Aspects of Microscopic Characterization of Materials* p 123, Fig. 2 original by permission of Scanning Microscopy International.

Figure 39.5: Courtesy of DC Joy, modified from Joy, DC (1979) in JJ Hren *et al.* Eds. *Introduction to Analytical Electron Microscopy* p 235, Fig. 7.6 original by permission of Plenum Press.

Figure 39.6: Courtesy of M Kundmann.

Figure 39.7: Courtesy of J Bruley.

Figure 39.8: Courtesy of K Sato and Y Ishiguro, modified from Sato, K and Ishiguro, Y (1996) *Materials Transactions*, **37** 643, Figs. 1, 7 Japan Institute of Metals.

Figure 39.9: Courtesy of J Bruley.

Figure 39.10: Courtesy of JA Hunt, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 14 original by permission of the Venezuelan Society for Electron Microscopy.

Figure 39.11: Courtesy of JA Hunt, from Williams, DB and Goldstein, JI (1992) *Microbeam Analysis* **1** 29, Fig. 11 reproduced by permission of VCH.

Figures 39.12,13: Courtesy of JA Hunt, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 17A,B reproduced by permission of the Venezuelan Society for Electron Microscopy.

Figure 39.14: Courtesy of RF Egerton, modified from Egerton, RF (1993) *Ultramicrosc.* **50** 13, Fig. 6.

Figure 39.15–18: Courtesy of J Bruley.

Figure 39.19A,B: Courtesy of JA Hunt, from Hunt, JA and Williams, DB (1994) *Acta Microsc.* **3** 1, Fig. 16

reproduced by permission of the Venezuelan Society for Electron Microscopy.

Figure 39.20: Courtesy of F Hofer.

Figure 39.21: Modified from Egerton, RF (1996) *Electron Energy-Loss Spectroscopy in the Electron Microscope*, 2nd edition, Fig. 1.11 original by permission of Plenum Press. Courtesy of RF Egerton.

Figure 39.22: Courtesy of M Varela.

Figure 39.23: Courtesy of M Varela.

## Chapter 40

Figure 40.4: Modified from Zaluzec, NJ (1982) *Ultramicrosc.* **9** 319, Fig. 3. Courtesy of NJ Zaluzec.

Figure 40.5B: Courtesy of J Bruley.

Figure 40.6: Courtesy of PE Batson, from Batson, PE (1993) *Nature* **366** 727, Fig. 1 reproduced by permission of Macmillan Journals Ltd.

Figures 40.7A,B: Courtesy of VJ Keast, modified from Keast, VJ *et al.* (1998) *Acta Mater.* **46** 481.

Figure 40.8. Courtesy of RF Brydson, modified from Garvie, LAJ *et al.* (1994) *Amer. Mineralogist* **79** 411, Fig. 4.

Figure 40.11: Courtesy of J Bruley and J Mayer.

Figure 40.12: Courtesy of J Bruley.

Figure 40.13 Modified from Alamgir, FM *et al.* (2000) *Microscopy and Microanalysis Suppl.* **2** 194. Courtesy FM Alamgir.

Figure 40.14 Modified from Botton, GA (2005) *J. Electr. Spect. Rel. Phen.* **143** 129, Fig. 5. Courtesy of GA Botton.

Figure 40.15: Courtesy of M Aronova and RD Leapman, modified from Leapman, RD and Aronova, MA (2006) in *Cellular Electron Microscopy* Ed. JR McIntosh.