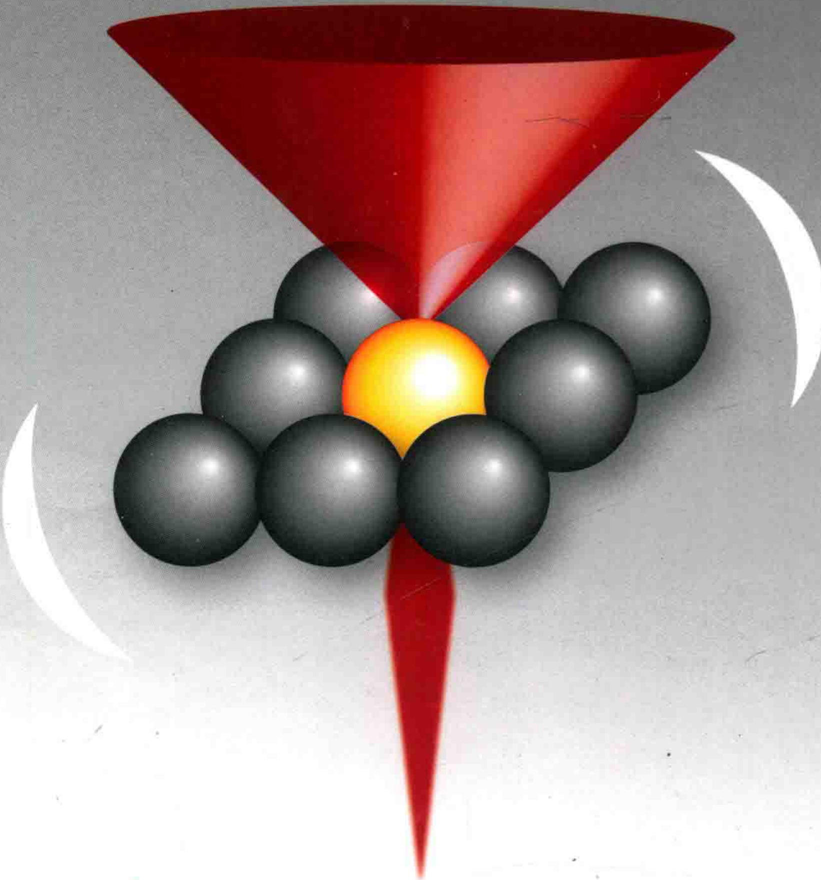

Aberration-Corrected Analytical Transmission Electron Microscopy

Editor **Rik Brydson**

WILEY

RMS

Aberration-Corrected Analytical Transmission Electron Microscopy

Edited by

Rik Brydson

Published in association with the Royal Microscopical Society

Series Editor: Susan Brooks

RMS

WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2011

Registered office
John Wiley & Sons Ltd., The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Aberration-corrected analytical transmission electron microscopy / edited by Rik Brydson ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-51851-9 (hardback)
1. Transmission electron microscopy. 2. Aberration. 3. Achromatism. I. Brydson, Rik.
QH212.T7A24 2011
502.8′25–dc23

2011019731

A catalogue record for this book is available from the British Library.

Print ISBN: 978-0470-518519 (H/B)
ePDF ISBN 978-1119-978855
oBook ISBN: 978-111-9978848
ePub ISBN: 978-1119-979906
Mobi ISBN: 978-1119-979913

Set in 10.5/13pt Sabon by Laserwords Private Limited, Chennai, India
Printed and bound in Malaysia by Vivar Printing Sdn Bhd

Aberration-Corrected Analytical Transmission Electron Microscopy

Current and future titles in the RMS-Wiley Imprint

Published

Principles and Practice of Variable Pressure/Environmental Scanning Electron Microscopy (VP-ESEM) – Debbie Stokes

Aberration-Corrected Analytical Electron Microscopy – Edited by Rik Brydson

Forthcoming

Understanding Practical Light Microscopy – Jeremy Sanderson

Atlas of Images and Spectra for Electron Microscopists – Edited by Ursel Bangert

Diagnostic Electron Microscopy – A Practical Guide to Tissue Preparation and Interpretation – Edited by John Stirling, Alan Curry & Brian Eyden

Practical Atomic Force Microscopy – Edited by Charles Clifford

Low Voltage Electron Microscopy – Principles and Applications – Edited by Natasha Erdman & David Bell

Focused Ion Beam Instrumentation: Techniques and Applications – Dudley Finch & Alexander Buxbaum

List of Contributors

Andrew Bleloch, School of Engineering, University of Liverpool, Liverpool, UK

Lawrence Michael Brown FRS, Robinson College, Cambridge and Cavendish Laboratory, Cambridge, UK

Rik Brydson, Leeds Electron Microscopy and Spectroscopy (LEMAS) Centre, Institute for Materials Research, SPEME, University of Leeds, Leeds, UK

Alan J. Craven, Department of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, UK

Peter J. Goodhew FREng, School of Engineering, University of Liverpool, Liverpool, UK

Sarah J. Haigh, Department of Materials, University of Oxford, Oxford, UK; University of Manchester, Materials Science Centre, Manchester, UK

Nicole Hondow, Leeds Electron Microscopy and Spectroscopy (LEMAS) Centre, Institute for Materials Research, SPEME, University of Leeds, Leeds, UK

Angus I. Kirkland, Department of Materials, University of Oxford, Oxford, UK

Peter D. Nellist, Department of Materials, Corpus Christi College, University of Oxford, Oxford, UK

Quentin Ramasse, SuperSTEM Facility, STFC Daresbury Laboratories, Daresbury, Cheshire, UK

Mervyn D. Shannon, SuperSTEM Facility, STFC Daresbury Laboratories, Daresbury, Cheshire, UK

Gordon J. Tatlock, School of Engineering, University of Liverpool, Liverpool, UK

All contributors helped in the preparation and editing of this book.

Preface

Electron Microscopy, very much the imaging tool of the 20th Century, has undergone a steep change in recent years due to the practical implementation of schemes which can diagnose and correct for the imperfections (aberrations) in both probe-forming and image-forming electron lenses. This book aims to review this exciting new area of 21st Century analytical science which can now allow true imaging and chemical analysis at the scale of single atoms.

The book is concerned with the theory, background and practical use of transmission electron microscopes with lens correctors which can mitigate for, and to some extent control the effects of spherical aberration inherent in round electromagnetic lenses. When fitted with probe correctors, such machines can achieve the formation of sub-Angstrom electron probes for the purposes of (scanned) imaging and also importantly chemical analysis of thin solid specimens at true atomic resolution. As a result, this book aims to concentrate on the subject primarily from the viewpoint of scanning transmission electron microscopy (STEM) which involves correcting focused electron probes, but it also includes a comparison with aberration correction in the conventional transmission electron microscope (CTEM) where the principal use of correctors is to correct aberrations in imaging lenses used with parallel beam illumination.

The book has arisen from the formation in 2001 of the world's first aberration corrected Scanning Transmission Electron Microscope Facility (SuperSTEM http://www.superstem.com) at Daresbury Laboratories in Cheshire in the UK. This originally involved a consortium of the Universities of Cambridge, Liverpool, Glasgow and Leeds, the Electron Microscopy and Analysis Group of the Institute of Physics and the Royal Microscopical Society and, very importantly, funded by the Engineering and Physical Sciences Research Council (EPSRC). Following its inception we have organised four postgraduate summer schools in 2004, 2006, 2008 and 2010. The current text has evolved from these Summer Schools and aims to be a (detailed) handbook which although introductory, has sections which go into some depth and contain pointers to seminal work in the (predominantly journal) literature in this area. We envisage that the text will be of benefit for postgraduate researchers who wish to understand the results from or wish to use directly these machines which are now key tools in nanomaterials research. The book complements the more detailed text edited by Peter Hawkes (*Aberration corrected Electron Microscopy*, Advances in Imaging and Electron Physics, Volume 153, 2008).

The form of the handbook is as follows:

In Chapters 1 and 2, Peter Goodhew and Gordon Tatlock introduce general concepts in transmission electron microscopy and electron optics. In Chapter 3 Mick Brown details the development of the concept of the scanning transmission electron microscope which arose from the pioneering vision of Albert Victor Crewe, who was notably born in Bradford in the West Riding of Yorkshire and was a graduate of Liverpool University. Probe forming lens aberrations and their diagnosis and correction are investigated further by Andrew Bleloch and Quentin Ramasse in Chapter 4. The theory of STEM imaging is outlined by Pete Nellist in Chapter 5, whilst the detailed instrumentation associated with STEM is given by Alan Craven in Chapter 6. Analytical spectroscopy in STEM and the implications of STEM probe correction are introduced in Chapter 7 by Rik Brydson and Nicole Hondow. Mervyn Shannon reviews some examples and applications of aberration corrected STEM in Chapter 8. Finally, in Chapter 9, Sarah Haigh and Angus Kirkland make comparisons with image correction in CTEM. All authors have very considerable experience in transmission electron microscopy and also aberration correction from either a practical or applied perspective and we have attempted to integrate the various separate chapters together so as to form a coherent text with a common nomenclature detailed in Appendix B. Although I have taken the nominal lead in editing the text, it has been a joint effort by all authors.

Tremendous thanks must go to all those associated with SuperSTEM over the years notably Meiken and Uwe Falke, Mhari Gass, Kasim Sader, Bernhard and Miroslava Schaffer, Budhika Mendis, Ian Godfrey, Peter Shields, Will Costello, Andy Calder, Quentin Ramasse, Michael Saharan, Dorothea Muecke-Herzberg, Marg Robinshaw, Ann Beckerlegge and Uschi Bangert. Dedicated SuperSTEM students have been invaluable

and have included Sarah Pan, Paul Robb, Peng Wang, Linshu Jiang, Dinesh Ram, Sunheel Motru and Gareth Vaughan.

The final statements concerning the book should belong to Charles Lutwidge Dodgson (aka Lewis Carroll) who was born at Daresbury Parsonage less than a mile from the SuperSTEM laboratory and who famously wrote, '*Through the* (aberration-corrected) *Looking Glass*' and '*Alice in Wonderland*'

'Begin at the beginning and go on till you come to the end: then stop.'

But.......

'I don't believe there's an atom of meaning in it.'

And........

'What is the use of a book, without pictures or conversations?'

Rik Brydson, Leeds 2011.

Contents

1

General Introduction to Transmission Electron Microscopy (TEM)

Peter Goodhew

School of Engineering, University of Liverpool, Liverpool, UK

1.1 WHAT TEM OFFERS

Transmission electron microscopy is used to reveal sub-micrometre, internal fine structure in solids. Materials scientists tend to call this *microstructure* while bioscientists usually prefer the term *ultrastructure*. The amount and scale of the information which can be extracted by TEM depends critically on four parameters; the resolving power of the microscope (usually smaller than 0.3 nm); the energy spread of the electron beam (often several eV); the thickness of the specimen (almost always significantly less than 1 μm), and; the composition and stability of the specimen. The first and second of these depend largely on the depth of your pocket – the more you spend, the better the microscope parameters. The third is usually determined by your experimental skill while the last depends on luck or your choice of experimental system. The slim book by Goodhew *et al*. (Goodhew, Humphreys and Beanland,

Aberration-Corrected Analytical Transmission Electron Microscopy, First Edition.
Edited by Rik Brydson.