SCANNING ELECTRON MICROSCOPE OPTICS AND SPECTROMETERS

SCANNING ELECTRON MICROSCOPE OPTICS AND SPECTROMETERS

Anjam Khursheed

National University of Singapore, Singapore

World Scientific

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

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

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

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

British Library Cataloguing-in-Publication Data

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

SCANNING ELECTRON MICROSCOPE OPTICS AND SPECTROMETERS

Copyright © 2011 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN-13 978-981-283-667-0

ISBN-10 981-283-667-5

Printed in Singapore.

Dedication

I would like to dedicate this book to three people.

The first dedication goes to Alan Dinnis, who supervised my Ph.D between the years 1979 to 1983 at the University of Edinburgh in Scotland. It was Alan who first introduced me to the challenge of how best to combine electron energy spectrometers together with scanning electron microscopes, and much of the content in this book is the fruition of work we started together over 30 years ago.

The second dedication goes to my wife Francesca, thank you for your support, patience and understanding.

The third dedication goes to my three year old daughter Elettra, this just to wish you well, and thank you for being a part of my life.

Anjam Khursheed

This page is intentionally left blank

Preface

The subject matter of this book deals with the question of how to combine electron energy spectrometers with scanning electron microscopes (SEMs). For approximately three and half decades, starting from around 1968, this question attracted considerable research interest, fuelled primarily by the application of testing integrated circuit devices. After this period, due to changes in the way integrated circuits were manufactured, direct electron beam testing was no longer viable, and general interest in the subject dwindled. However, over the last 15 years or so, there is evidence of renewed interest. This is because, more applications, beyond the testing of integrated circuit devices are coming to light. Combining electron energy spectrometers with SEMs provides a way of obtaining depth information for multi-layer samples (Rao and Robinson, 1996), mapping the dopant concentration across p-n junctions (Kazemian *et al.*, 2006), monitoring negative charging of insulator samples (Belhaj *et al.*, 2008), and acquiring elemental identification on the nano-scale (Hoang and Khursheed, 2009).

Spectrometers are used in a wide range of different charged particle beam instruments, ranging from electron microscopes, mass analyzers and particle accelerators. Although this book focuses on their use in the SEM, ideas and methods are borrowed from their use elsewhere. There is in particular, a natural synergy with Scanning Auger Microscopy (SAM), which also combines a scanning focused electron beam with electron energy spectrometers. Both techniques share much in common. This book aims to present spectrometer developments in the context of the SEM to a wide audience of research scientists, with the intention of not

only improving SEM design, but also of enriching the design of other focused electron/ion beam instrumentation, as well as contributing to the design of spectrometers in general. The following pages are aimed at scientists, engineers and graduate students whose research area or study in some way involves the use of focused electron/ion beam instrumentation and/or charged particle spectrometers. It can be used both as an introduction to these subjects, as well as a guide to more advanced topics about SEM redesign.

The book is mainly a book of ideas. It emphasizes the concepts underlying design of SEMs and spectrometers, as opposed to providing practical engineering details. Wherever possible, spectrometers are discussed under one common framework, so that their relative strengths and weaknesses can be more readily appreciated. This will be done for the most part, through simulations and derivations carried out by the author himself. If not explicitly stated, the reader can assume that the programs used for simulation were written by the author. A detailed description of the numerical methods underlying the author's simulation programs can be found elsewhere (Khursheed, 1999).

Lastly, I would like to acknowledge help from various members of my research group. My postdoctoral fellow, Mans Osterberg, carefully proof-read most the manuscript and gave many detailed helpful suggestions. He carried out simulations of a quadruple-octupole aberration corrector and provided core information from which Chapter 4 (Aberration Correction) and Appendix 2 (Introduction to Multipoles) were written, a big thank you for all your help Mans. Help also came from my Ph.D student, Hung Hoang, who performed 3D simulations of a SE detector in a conventional SEM, and carried out simulations of various spectrometer designs, including the second version of my second-order focusing toroidal analyzer, a novel modified fountain analyzer design of his own, the cylindrical mirror analyzer, and the spherical deflector analyzer. He also carried out important experimental work. Particularly appreciated are the secondary electron/backscattered energy spectra from the second-order focusing toroidal analyzer prototype reported in Chapter 6. A Masters student, Saravanan

Musuwathi Kesavan, helped with the analytical derivations of field distribution expansions, paraxial ray equation, and on-axis aberration coefficients presented in Appendices 1.0–1.3. An undergraduate student Zhang Teng helped in the simulation of the parallel-plate/fountain and hemispherical analyzers, and my long standing research engineer, Karuppiah Nelliyan, provided many experimental SEM images.

This page is intentionally left blank

Contents

Preface	vii
1. Conventional SEM Design	1
1.1 Introduction to the SEM	2
1.2 Basic principles of electron optics	9
1.3 The electron gun	19
1.4 Lens aberrations and primary beam probe size	24
1.5 Deflection systems	36
1.6 Quadrupole stigmators	42
1.7 SEM output signals	48
1.8 The emission hemisphere and BSE collection	51
1.9 The scattered electron energy distribution	53
1.10 The SE collection efficiency	55
1.11 Specimen charging	59
1.12 Elastic BSE imaging	61
1.13 Selected SEM image examples	64
2. Spectrometer Design Principles	71
2.1 Figures of merit	72
2.2 The SAM and the SEM	76
2.3 The retarding field analyzer	78
2.4 Deflection field analyzers	83
2.4.1 The parallel plate analyzer	83
2.4.2 The cylindrical mirror analyzer	96
2.4.3 Electric sector analyzers	101
2.4.4 Magnetic deflector analyzers	113

2.4.5	Wien filters	124
2.4.6	Magnetic collimation and time of flight spectrometers	131
3.	In-lens Improvements	135
3.1	Magnetic immersion lenses	135
3.2	Magnetic semi-in-lens designs	143
3.3	Electric retarding field lenses	156
3.4	Mixed field in-lens designs	164
3.5	Selected in-lens image examples	176
4.	Sub-nanometer Probe Diameters	185
4.1	Monochromators and immersion objective lenses	185
4.2	Aberration correctors	198
4.3	The helium ion microscope	218
5.	Secondary Electron Spectrometers	223
5.1	Early deflection analyzers	223
5.2	Retarding field analyzers	226
5.3	Surface fields and signal-to-noise characteristics	237
5.4	Deflection/multi-channel analyzers	244
6.	Full Range Deflector Spectrometer Designs	263
6.1	First-order focusing toroidal analyzers	265
6.2	A second-order focusing toroidal analyzer design	270
6.3	A modified fountain analyzer design	281
7.	Full Range Parallel Energy Spectrometer Designs	287
7.1	The time-of-flight spectrometer	290
7.2	A Gaussian field magnetic sector	293
7.3	A round magnetic beam separator	301
8.	Spectroscopic SEM Proposals	319

Appendix 1.0 Field Expansions	327
Appendix 1.1 Derivation of the Paraxial Equation	337
Appendix 1.2 Spherical Aberration	349
Appendix 1.3 Chromatic Aberration	365
Appendix 2 Multipole Lenses	375
Bibliography	385
Index	399