

Contents

About the Authors	vii
Preface	xi
Foreword to First Edition	xiii
Foreword to Second Edition	xv
Acknowledgments	xix
List of Initials and Acronyms	xxi
List of Symbols	xxv
About the Companion Volume	xxxii
Figure Credits	xlix
PART 1 BASICS	1
1 The Transmission Electron Microscope	3
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

2	Scattering and Diffraction	23
	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
3	Elastic Scattering	39
	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
4	Inelastic Scattering and Beam Damage	53
	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

5	Electron Sources	73
	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
6	Lenses, Apertures, and Resolution	91
	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

7	How to ‘See’ Electrons	115
	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
8	Pumps and Holders	127
	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
9	The Instrument	141
	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
10	Specimen Preparation	173
	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
PART 2	DIFFRACTION	195
11	Diffraction in TEM	197
	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

12	Thinking in Reciprocal Space	211
	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
13	Diffracted Beams	221
	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
14	Bloch Waves	235
	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
15	Dispersion Surfaces	245
	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
16	Diffraction from Crystals	257
	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
17	Diffraction from Small Volumes	271
	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
18	Obtaining and Indexing Parallel-Beam Diffraction Patterns	283
	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
19	Kikuchi Diffraction	311
	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
20	Obtaining CBED Patterns	323
	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
21	Using Convergent-Beam Techniques	347
	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
PART 3	IMAGING	369
22	Amplitude Contrast	371
	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
23	Phase-Contrast Images	389
	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
24	Thickness and Bending Effects	407
	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

25	Planar Defects	419
	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: π and δ 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
26	Imaging Strain Fields	441
	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
27	Weak-Beam Dark-Field Microscopy	463
	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
28	High-Resolution TEM	483
	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
29	Other Imaging Techniques	511
	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
30	Image Simulation	533
	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
31	Processing and Quantifying Images	549
	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
PART 4	SPECTROMETRY	579
32	X-ray Spectrometry	581
	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
33	X-ray Spectra and Images	605
	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
34	Qualitative X-ray Analysis and Imaging	625
	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
35	Quantitative X-ray Analysis	639
	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
36	Spatial Resolution and Minimum Detection	663
	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
37	Electron Energy-Loss Spectrometers and Filters	679
	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
38	Low-Loss and No-Loss Spectra and Images	699
	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
39	High Energy-Loss Spectra and Images	715
	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
40	Fine Structure and Finer Details	741
	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
Index		I-1



<http://www.springer.com/978-0-387-76500-6>

Transmission Electron Microscopy

A Textbook for Materials Science

Williams, D.B.; Carter, C.B.

2009, LXII, 775 p., Hardcover

ISBN: 978-0-387-76500-6