

Contents

I ■ Basics

1 ■ The Transmission Electron Microscope

Chapter Preview	3
1.1. Why Use Electrons?	5
1.1 .A. An Extremely Brief History	5
1.1 .B Microscopy and the Concept of Resolution	6
1.1 .C Interaction of Electrons with Matter	7
1.1.D.Depth of Field	8
1.1 .E. Diffraction	9
1.2. Limitations of the TEM	9
1.2.A. Sampling	9
1.2.B Interpreting Transmission Images	10
1.2.C Electron Beam Damage and Safety	10
1.2.D. Specimen Preparation	11
1.3. Different Kinds of TEMs 	11
1.4. Some Fundamental Properties of Electrons	11
1.5. Microscopy on the Internet/World Wide Web ...	13
1.5.A. Microscopy and Microanalysis-Related WWW Sites	14
1.5.B. Microscopy and Microanalysis Software	14
Chapter Summary	16
References	16

2 ■ Scattering and Diffraction

Chapter Preview	19
2.1. Why Are We Interested in Electron Scattering?	21
2.2. Terminology of Scattering	22
2.3. The Characteristics of Electron Scattering	23
2.4. The Interaction Cross Section	24
2.5. The Mean Free Path	25
2.6. The Differential Cross Section	25

2.7. Other Factors Affecting Scattering	26
2.8. Comparison to X-ray Diffraction	26
2.9. Fraunhofer and Fresnel Diffraction	27
2.10. Diffraction of Light from Slits	27
2.11. Coherent Interference	28
2.12. A Word about Angles	30
2.13. Electron Diffraction Patterns	30
Chapter Summary	31
References	33

3 ■ Elastic Scattering

Chapter Preview	35
3.1. Particles and Waves	37
3.2. Mechanisms of Elastic Scattering	37
3.3. Scatter from Isolated Atoms	38
3.4. The Rutherford Cross Section	39
3.5. Modifications to the Rutherford Cross Section	39
3.6. Coherency of the Rutherford-Scattered Electrons	40
3.7. The Atomic Scattering Factor	41
3.8. The Origin of $f(\theta)$	42
3.9. The Structure Factor $F(\theta)$	43
3.10. Simple Diffraction Concepts	44
3.10.A. Interference of Electron Waves	44
3.10.B. Diffraction Equations	45
Chapter Summary	46
References	47

4 ■ Inelastic Scattering and Beam Damage

Chapter Preview	49
4.1. Which Inelastic Processes Occur in the TEM? ...	51
4.2. X-ray Emission	51
4.2.A. Characteristic X-rays	52
4.2.B. Bremsstrahlung X-rays	56

4.3. Secondary Electron Emission	57	6.3. Electron Lenses	91
4.3.A. Slow Secondary Electrons	57	6.3.A. Polepieces and Coils	91
4.3.B. Fast Secondary Electrons	58	6.3.B. Different Kinds of Lenses	92
4.3.C. Auger Electrons	58	6.3.C. Electron Ray Paths through Magnetic Fields	93
4.4. Electron-Hole Pairs and Cathodoluminescence (CL)	59	6.3.D. Image Rotation and the Eucentric Plane	95
4.5. Plasmons and Phonons	60	6.3.E. Deflecting the Beam	95
4.6. Beam Damage	61	6.4. Apertures and Diaphragms	95
4.6.A. Electron Dose	62	6.5. Real Lenses and Their Problems	97
4.6.B. Specimen Heating	62	6.5.A. Spherical Aberration	97
4.6.C. Beam Damage in Polymers	62	6.5.B. Chromatic Aberration	98
4.6.D. Beam Damage in Covalent and Ionic Crystals	63	6.5.C. Astigmatism	98
4.6.E. Beam Damage in Metals	63	6.6. The Resolution of the Electron Lens (and Ultimately of the TEM)	99
4.6.F. Sputtering	65	6.6.A. Theoretical Resolution	99
Chapter Summary	65	6.6.B. Spherical Aberration-Limited Resolution (The Practical Resolution) ...	100
References	65	6.6.C. Confusion in the Definitions of Resolution	101
5 ■ Electron Sources		6.7. Depth of Focus and Depth of Field	102
Chapter Preview	67	Chapter Summary	103
5.1. The Physics of Different Electron Sources	69	References	104
5.1.A. Thermionic Emission	69	7 ■ How to “See” Electrons	
5.1.B. Field Emission	70	Chapter Preview	105
5.2. The Characteristics of the Electron Beam	70	7.1. Electron Detection and Display	107
5.2.A. Brightness	70	7.2. Viewing Screens	108
5.2.B. Temporal Coherency and Energy Spread	71	7.3. Electron Detectors	108
5.2.C. Spatial Coherency and Source Size	72	7.3.A. Semiconductor Detectors	108
5.2.D. Stability	72	7.3.B. Scintillator-Photomultiplier Detectors ...	110
5.3. Electron Guns	72	7.3.C. TV Cameras and Charge-Coupled Devices	111
5.3.A. Thermionic Guns	72	7.3.D. Faraday Cup	112
5.3.B. Field-Emission Guns (FEGs)	76	7.4. Which Detector Do We Use for Which Signal?	112
5.4. Comparison of Guns	77	7.5. Image Recording	114
5.5. Measuring Your Gun Characteristics	78	7.5.A. Photographic Emulsions	114
5.5.A. Beam Current	78	7.5.B. Other Image Recording Methods	114
5.5.B. Convergence Angle	78	7.6. Comparison of Scanning Images and Static TEM Images	115
5.5.C. Calculating the Beam Diameter	79	Chapter Summary	115
5.5.D. Measuring the Beam Diameter	79	References	115
5.5.E. Energy Spread	82	8 ■ Pumps and Holders	
5.5.F. Spatial Coherency	82	Chapter Preview	117
5.6. What kV Should You Use?	82	8.1. Vacuums	119
Chapter Summary	82	8.2. Roughing Pumps	119
References	83	8.3. High/Ultra-High Vacuum Pumps	120
6 ■ Lenses, Apertures, and Resolution		8.3.A. Diffusion Pumps	120
Chapter Preview	85	8.3.B. Turbomolecular Pumps	120
6.1. Why Learn about Lenses?!	87	8.3.C. Ion Pumps	121
6.2. Light Optics and Electron Optics	87	8.3.D. Cryogenic (Adsorption) Pumps	121
6.2.A. How to Draw a Ray Diagram	88		
6.2.B. The Principal Optical Elements	89		
6.2.C. The Lens Equation	90		
6.2.D. Magnification, Demagnification, and Focus	90		

8.4. The Whole System	122
8.5. Leak Detection	123
8.6. Contamination: Hydrocarbons and Water Vapor	123
8.7. Specimen Holders and Stages	124
8.8. Side-Entry Holders	124
8.9. Top-Entry Holders	125
8.10. Different Types of Holders	125
Chapter Summary	128
References	129

9 ■ The Instrument

Chapter Preview	131
9.1. The Illumination System	133
9.1.A. TEM Operation Using a Parallel Beam . . .	133
9.1.B. Convergent-Beam (S)TEM Mode	133
9.1.C. Translating and Tilting the Beam	135
9.1.D. Alignment	136
9.1.E. Condenser Lens Defects	137
9.1.F. Calibration	138
9.2. The Objective Lens and Stage	139
9.3. Forming Diffraction Patterns and Images:	
The TEM Imaging System	140
9.3.A. Selected-Area Diffraction	140
9.3.B. Bright-Field and Dark-Field Imaging . . .	142
9.3.C. Centered DF Operation	143
9.4. Forming Diffraction Patterns and Images:	
The STEM Imaging System	144
9.4.A. Bright-Field STEM Images	144
9.4.B. Dark-Field STEM Images	145
9.4.C. Annular DF Images	145
9.4.D. Magnification in STEM	146
9.5. Alignment and Stigmation	147
9.5.A. Lens Rotation Centers	147
9.5.B. Correction of Astigmatism in the Imaging Lenses	147
9.6. Calibration of the Imaging System	148
9.6.A. Magnification Calibration	148
9.6.B. Camera-Length Calibration	150
9.6.C. Rotation of the Image Relative to the Diffraction Pattern	151
9.6.D. Analysis of TEM Images and Diffraction Patterns	151
9.7. Other Calibrations	151
Chapter Summary	153
References	153

10 ■ Specimen Preparation

Chapter Preview	155
10.1. Safety	157
10.2. Self-Supporting Disk or Use a Grid?	158
10.3. Preparing a Self-Supporting Disk for Final Thinning	159

10.3.A. Creation of a Thin Slice from the Bulk Sample	159
10.3.B. Cutting the Disk	159
10.3.C. Prethinning the Disk	160
10.4. Final Thinning of the Disk	161
10.4.A. Electropolishing	161
10.4.B. Ion Milling	162
10.5. Cross-Section Specimens	165
10.6. Specimens on Grids/Washers	166
10.6.A. Electropolishing-The Window Method for Metals and Alloys	166
10.6.B. Ultramicrotomy	167
10.6.C. Grinding and Crushing	167
10.6.D. Replication and Extraction	168
10.6.E. Cleaving	168
10.6.F. The 90° Wedge	169
10.6.G. Lithography	169
10.6.H. Preferential Chemical Etching	169
10.7. Storing Specimens	170
Chapter Summary	170
References	172

II ■ Diffraction

11 Diffraction Patterns

Chapter Preview	177
11.1. Why Use Diffraction in the TEM?	179
11.2. The TEM, Diffraction Cameras, and the TV . . .	179
11.3. Scattering from a Plane of Atoms	181
11.4. Scattering from a Crystal	182
11.5. Meaning of n in Bragg's Law	184
11.6. A Pictorial Introduction to Dynamical Effects	185
11.7. Use of Indices in Diffraction Patterns	185
11.8. Practical Aspects of Diffraction-Pattern Formation	185
11.9. More on Selected-Area Diffraction Patterns . .	186
Chapter Summary	189
References	189

12 ■ Thinking in Reciprocal Space

Chapter Preview	191
12.1. Why Introduce Another Lattice?	193
12.2. Mathematical Definition of the Reciprocal Lattice	193
12.3. The Vector \mathbf{g}	194
12.4. The Laue Equations and Their Relation to Bragg's Law	195
12.5. The Ewald Sphere of Reflection	196
12.6. The Excitation Error	197
12.7. Thin-Foil Effect and the Effect of Accelerating Voltage	199

Chapter Summary	200	16.3. Some Important Structures: bcc, fcc, and hcp	241
References	200	16.4. Extending fcc and hcp to Include a Basis ...	242
13 ■ Diffracted Beams		16.5. Applying the bcc and fcc Analysis to Simple Cubic	243
Chapter Preview	201	16.6. Extending hcp to Ti_3Al	244
13.1. Why Calculate Intensities?	203	16.7. Superlattice Reflections and Imaging	244
13.2. The Approach	203	16.8. Diffraction from Long-Period Superlattices	246
13.3. The Amplitude of a Diffracted Beam	204	16.9. Forbidden Reflections	247
13.4. The Characteristic Length ξ_g	205	16.10. Using the International Tables	247
13.5. The Howie–Whelan Equations	206	Chapter Summary	249
13.6. Reformulating the Howie–Whelan Equations	207	References	249
13.7. Solving the Howie–Whelan Equations	207	17 ■ Diffraction from Small Volumes	
13.8. The Importance of $\gamma^{(1)}$ and $\gamma^{(2)}$	208	Chapter Preview	251
13.9. The Total Wave Amplitude	209	17.1. Introduction	253
13.10. The Effective Excitation Error	210	17.1.A. The Summation Approach	253
13.11. The Column Approximation	210	17.1.B. The Integration Approach	254
13.12. The Approximations and Simplifications ...	211	17.2. The Thin-Foil Effect	255
13.13. The Coupled Harmonic Oscillator Analog ...	212	17.3. Diffraction from Wedge-Shaped Specimens ...	256
Chapter Summary	212	17.4. Diffraction from Planar Defects	256
References	213	17.5. Diffraction from Particles	258
14 ■ Bloch Waves		17.6. Diffraction from Dislocations, Individually and Collectively	259
Chapter Preview	215	17.7. Diffraction and the Dispersion Surface	261
14.1. Wave Equation in TEM	217	Chapter Summary	262
14.2. The Crystal	217	References	263
14.3. Bloch Functions	219	18 ■ Indexing Diffraction Patterns	
14.4. Schrödinger's Equation for Bloch Waves ...	219	Chapter Preview	265
14.5. The Plane-Wave Amplitudes	221	18.1. Choosing Your Technique	267
14.6. Absorption of Bloch Waves	223	18.2. Experimental Techniques	267
Chapter Summary	223	18.3. The Stereographic Projection ...	269
References	224	18.4. Indexing Single-Crystal Diffraction Patterns	271
15 Dispersion Surfaces		18.5. Ring Patterns from Polycrystalline Materials	273
Chapter Preview	225	18.6. Ring Patterns from Amorphous Materials	274
15.1. Introduction	227	18.7. Double Diffraction	278
15.2. The Dispersion Diagram when $U_g = 0$	228	18.8. Orientation of the Specimen	280
15.3. The Dispersion Diagram when $U_g \neq 0$	228	18.9. Orientation Relationships	280
15.4. Relating Dispersion Surfaces and Diffraction Patterns	229	18.10. Computer Analysis	285
15.5. The Relation between U_g , ξ_g , and s_g	232	Chapter Summary	286
15.6. The Amplitudes of Bloch Waves	233	References	286
15.7. Extending to More Beams	234	19 Kikuchi Diffraction	
15.8. Dispersion Surfaces and Defects	235	Chapter Preview	289
Chapter Summary	235	19.1. The Origin of Kikuchi Lines	291
References	236	19.2. Kikuchi Lines and Bragg Scattering	291
16 ■ Diffraction from Crystals		19.3. Constructing Kikuchi Maps	293
Chapter Preview	237		
16.1. Review of Diffraction from a Primitive Lattice	239		
16.2. Structure Factors: The Idea	240		

19.4. Crystal Orientation and Kikuchi Maps	295
19.5. Setting the Value of s_{\parallel}	296
19.6. Intensities	297
Chapter Summary	298
References	298

20 ■ Obtaining CBED Patterns

Chapter Preview	301
20.1. Why Use a Convergent Beam?	303
20.2. Obtaining CBED Patterns	304
20.2.A. Comparing SAD and CBED	304
20.2.B. CBED in TEM	305
20.2.C. Choosing the C2 Aperture	305
20.2.D. Choosing the Camera Length	306
20.2.E. Focusing Your Pattern	306
20.2.F. Choice of Beam Size	307
20.2.G. Effect of Specimen Thickness	308
20.2.H. Final Adjustment	308
20.2.I. CBED in STEM Mode	308
20.3. Zero-Order and Higher-Order Laue-Zone Diffraction	309
20.3.A. ZOLZ Patterns	309
20.3.B. HOLZ Patterns	309
20.3.C. Indexing HOLZ Patterns	311
20.4. Kikuchi Lines in CBED Patterns	314
20.5. HOLZ Lines	315
20.5.A. The Relationship between HOLZ Lines and Kikuchi Lines	315
20.5.B. Acquiring HOLZ Lines	315
20.5.C. Indexing HOLZ Lines	317
Chapter Summary	318
References	318

21 ■ Using Convergent-Beam Techniques

Chapter Preview	319
21.1. Thickness Determination	321
21.2. Unit-Cell Determination	323
21.2.A. Experimental Considerations	323
21.2.B. The Importance of the HOLZ-Ring Radius	323
21.2.C. Determining the Lattice Centering	325
21.3. Symmetry Determination	326
21.3.A. Introduction to Symmetry Concepts	326
21.3.A.1. Friedel's Law	738
21.3.C. Looking for Symmetry in Your Patterns	328
21.3.D. Point-Group Determination	330
21.3.E. Space-Group Determination	332
21.4. Lattice Parameter, Strain, and Composition Analysis	338
21.5. Determination of Enantiomorphism	341
21.6. Convergent-Beam Imaging	341

21.7. Scanning-Beam Diffraction	341
21.8. Other Methods of Microdiffraction	343
Chapter Summary	344
References	345

III Imaging

22 Imaging in the TEM

Chapter Preview	349
22.1. What Is Contrast?	351
22.2. Principles of Image Contrast	351
22.2.A. Images and Diffraction Patterns	351
22.2.B. Use of the Objective Aperture or the STEM Detector: BF and DF Images	351
22.3. Mass-Thickness Contrast	353
22.3.A. Mechanism of Mass-Thickness Contrast	353
22.3.B. TEM Images	354
22.3.C. STEM Images	355
22.3.D. Specimens Which Show Mass-Thickness Contrast	357
22.3.E. Quantitative Mass-Thickness Contrast	357
22.4. Z Contrast	358
22.5. TEM Diffraction Contrast	361
22.5.A. Two-Beam Conditions	361
22.5.B. Setting the Deviation Parameter, s	361
22.5.C. Setting Up a Two-Beam CDF Image	361
22.5.D. Relationship between the Image and the Diffraction Pattern	363
22.6. STEM Diffraction Contrast	364
Chapter Summary	366
References	366

23 Thickness and Bending Effects

Chapter Preview	367
23.1. The Fundamental Ideas	369
23.2. Thickness Fringes	369
23.3. Thickness Fringes and the Diffraction Pattern	371
23.4. Bend Contours (Annoying Artifact, Useful Tool, and Valuable Insight)	372
23.5. ZAPs and Real-Space Crystallography	373
23.6. Hillocks, Dents, or Saddles	374
23.7. Absorption Effects	374
23.8. Computer Simulation of Thickness Fringes	375
23.9. Thickness-Fringe/Bend-Contour Interactions	375

23.10. Other Effects of Bending	376	26 ■ Weak-Beam Dark-Field Microscopy	
Chapter Summary	377	Chapter Preview	42 1
References	378	26.1. Intensity in WBDF Images	423
24 Planar Defects		26.2. Setting s_g Using the Kikuchi Pattern	423
Chapter Preview	379	26.3. How to Do WBDF	425
24.1. Translations and Rotations	38 1	26.4. Thickness Fringes in Weak-Beam Images ...	426
24.2. Why Do Translations Produce Contrast? ...	382	26.5. Imaging Strain Fields	427
24.3. The Scattering Matrix	383	26.6. Predicting Dislocation Peak Positions	428
24.4. Using the Scattering Matrix	384	26.7. Phasor Diagrams	430
24.5. Stacking Faults in fcc Materials	385	26.8. Weak-Beam Images of Dissociated	
24.5.A. Why fcc Materials?	386	Dislocations	432
24.5.B. Some Rules	386	26.9. Other Thoughts	436
24.5.C. Intensity Calculations	387	26.9.A. Thinking of Weak-Beam	
24.5.D. Overlapping Faults	388	Diffraction as a Coupled Pendulum ...	436
24.6. Other Translations: π and δ Fringes 	389	26.9.B. Bloch Waves	436
24.7. Phase Boundaries	391	26.9.C. If Other Reflections Are Present	437
24.8. Rotation Boundaries	39 1	26.9.D. The Future	437
24.9. Diffraction Patterns		Chapter Summary	438
and Dispersion Surfaces	391	References	438
24.10. Bloch Waves and BF/DF Image Pairs	393	27 ■ Phase-Contrast Images	
24.11. Computer Modeling	394	Chapter Preview	439
24.12. The Generalized Cross Section	395	27.1. Introduction	44 1
24.13. Quantitative Imaging	396	27.2. The Origin of Lattice Fringes	44 1
24.13.A. Theoretical Basis and		27.3. Some Practical Aspects of Lattice Fringes ...	442
Parameters	396	27.3.A. If $s=0$	442
24.13.B. Apparent Extinction Distance	397	27.3.B. If $s \neq 0$	442
24.13.C. Avoiding the Column		27.4. On-Axis Lattice-Fringe Imaging	442
Approximation	397	27.5. Moire Patterns	444
24.13.D. The User Interface	398	27.5.A. Translational Moire Fringes	445
Chapter Summary	398	27.5.B. Rotational Moire Fringes	445
References	398	27.5.C. General Moire Fringes	445
25 ■ Strain Fields		27.6. Experimental Observations of Moire	
Chapter Preview	401	Fringes	445
25.1. Why Image Strain Fields?	403	27.6.A. Translational Moiré Patterns	446
25.2. Howie-Whelan Equations	403	27.6.B. Rotational Moire Fringes	447
25.3. Contrast from a Single Dislocation	405	27.6.C. Dislocations and Moire Fringes	447
25.4. Displacement Fields and Ewald's Sphere ...	408	27.6.D. Complex Moire Fringes	448
25.5. Dislocation Nodes and Networks	409	27.7. Fresnel Contrast	450
25.6. Dislocation Loops and Dipoles	409	27.7.A. The Fresnel Biprism	450
25.7. Dislocation Pairs, Arrays, and Tangles	411	27.7.B. Magnetic-Domain Walls	45 1
25.8. Surface Effects	412	27.8. Fresnel Contrast from Voids or Gas Bubbles ...	45 1
25.9. Dislocations and Interfaces	413	27.9. Fresnel Contrast from Lattice Defects	452
25.10. Volume Defects and Particles	417	27.9.A. Grain Boundaries	453
25.11. Simulating Images	418	27.9.B. End-On Dislocations	453
25.11 .A. The Defect Geometry	418	Chapter Summary	455
25.11 .B. Crystal Defects and Calculating		References	455
the Displacement Field	418	28 ■ High-Resolution TEM	
25.11 .C. The Parameters	419	Chapter Preview	457
Chapter Summary	419	28.1. The Role of an Optical System	459
References	420	28.2. The Radio Analogy	459

28.3. The Specimen	461	30.5.D. Kernels	507
28.4. Applying the WPOA to the TEM	462	30.6. Applications	507
28.5. The Transfer Function	462	30.6.A. Beam-Sensitive Materials	507
28.6. More on $\chi(\mathbf{u})$, $\sin \chi(\mathbf{u})$, and $\cos \chi(\mathbf{u})$	463	30.6.B. Periodic Images	508
28.7. Scherzer Defocus	465	30.6.C Correcting Drift	508
28.8. Envelope Damping Functions	466	30.6.D. Reconstructing the Phase	508
28.9. Imaging Using Passbands	467	30.6.E. Diffraction Patterns	508
28.10. Experimental Considerations	468	30.6.F Tilted-Beam Series	510
28.11. The Future for HRTEM	469	30.7. Automated Alignment	511
28.12. The TEM as a Linear System	470	30.8. Quantitative Methods of Image Analysis	5 1 2
28.13. FEGTEMs and the Information Limit	470	30.9. Pattern Recognition in HRTEM	5 1 3
28.14. Some Difficulties in Using an FEG	473	30.10. Parameterizing the Image Using QUANTITEM	514
28.15. Selectively Imaging Sublattices	475	30.10.A The Example of a Specimen with Uniform Composition	514
28.16. Interfaces and Surfaces	476	30.10.B Calibrating the Path of R	516
28.17. Incommensurate Structures	478	30.10.C. Noise Analysis	516
28.18. Quasicrystals	479	30.11. Quantitative Chemical Lattice Imaging	518
28.19. Single Atoms	480	30.12. Methods of Measuring Fit	518
Chapter Summary	481	30.13. Quantitative Comparison of Simulated and Experimental HRTEM Images	521
References	481	30.14. A Fourier Technique for Quantitative Analysis	523
29 ■ Image Simulation		30.15. Real or Reciprocal Space?	523
Chapter Preview	483	30.16. The Optical Bench	5 2 4
29.1. Simulating Images	485	Chapter Summary	526
29.2. The Multislice Method	485	References	526
29.3. The Reciprocal-Space Approach	485	31 ■ Other Imaging Techniques	
29.4. The FFT Approach	487	Chapter Preview	529
29.5. The Real-Space Approach	488	3 1.1. Stereo Microscopy	531
29.6. Bloch Waves and HRTEM Simulation	488	31.2.2 /2D Microscopy	532
29.7. The Ewald Sphere Is Curved	489	3 1.3. Magnetic Specimens	534
29.8. Choosing the Thickness of the Slice	490	3 1.3.A The Magnetic Correction	534
29.9. Beam Converge	490	3 1.3.B Lorentz Microscopy	535
29.10. Modeling the Structure	491	3 1.4. Chemically Sensitive Images	538
29.11. Surface Grooves and Simulating Fresnel Contrast	492	3 1.5. Imaging with Diffusely Scattered Electrons	538
29.12. Calculating Images of Defects	493	3 1.6. Surface Imaging	540
29.13. Simulating Quasicrystals	494	3 1.6.A Reflection Electron Microscopy	540
29.14. Bonding in Crystals	496	3 1.6.B. Topographic Contrast	540
Chapter Summary	497	3 1.7. High-Order BF Imaging	541
References	497	3 1.8. Secondary-Electron Imaging	541
30 Quantifying and Processing HRTEM Images		3 1.9. Backscattered-Electron Imaging	542
Chapter Preview	499	3 1.10. Charge-Collection Microscopy and Cathodoluminescence	543
30.1. What Is Image Processing?	501	3 1.11. Electron Holography	543
30.2. Processing and Quantifying Images	501	3 1.12. <i>In situ</i> TEM: Dynamic Experiments	546
30.3. A Cautionary Note	502	3 1.13. Other Variations Possible in a STEM	547
30.4. Image Input	502	Chapter Summary	548
30.5. Processing Techniques	502	References	548
30.5.A. Fourier Filtering and Reconstruction	502		
30.5.B. Analyzing Diffractograms	504		
30.5.C. Averaging Images and Other Techniques	506		

IV Spectrometry

32 X-ray Spectrometry

Chapter Preview	553
32.1. X-ray Analysis: Why Bother?	555
32.2. Basic Operational Mode	555
32.3. The Energy-Dispersive Spectrometer	558
32.4. Semiconductor Detectors	559
32.4.A. How Does XEDS Work?	559
32.4.B. Different Kinds of Windows	560
32.4.C. Intrinsic Germanium Detectors	562
32.5. Pulse Processing and Dead Time	563
32.6. Resolution of the Detector	564
32.7. What You Should Know about Your XEDS	565
32.7.A. Detector Variables	565
32.7.B. Processing Variables	566
32.7.C. Artifacts Common to XEDS Systems	5 6 8
32.8. Wavelength-Dispersive Spectrometers	570
Chapter Summary	571
References	572

33 ■ The XEDS-TEM Interface

Chapter Preview	573
33.1. The Requirements	575
33.2. The Collimator	575
33.2.A. Collection Angle	575
33.2.B. Take-Off Angle	576
33.2.C. Orientation of the Detector to the Specimen	577
33.3. Protecting the Detector from Intense Radiation	578
33.4. System X-rays and Spurious X-rays	578
33.4.A. Pre-Specimen Effects	578
33.4.B. Post-Specimen Scatter	580
33.4.C. Coherent Bremsstrahlung	583
33.5. Peak-to-Background Ratio	583
Chapter Summary	584
References	585

34 Qualitative X-ray Analysis

Chapter Preview	587
34.1. Microscope Variables	589
34.2. Acquiring a Spectrum	589
34.3. Peak Identification	590
34.4. Peak Visibility	593
Chapter Summary	595
References	595

35 ■ Quantitative X-ray Microanalysis

Chapter Preview	597
35.1. Historical Perspective	599
35.2. The Cliff-Lorimer Ratio Technique	600

35.3. Practical Steps for Quantitative Microanalysis	600
35.3.A. Background Subtraction	601
35.3.B. Peak Integration	603
35.4. Determining k Factors	605
35.4.A. Experimental Determination of k_{AB}	605
35.4.B. Errors in Quantification	606
35.4.C. Calculating k_{AB}	609
35.5. Absorption Correction	612
35.6. Extrapolation Techniques for Absorption Correction	614
35.7. The Fluorescence Correction	615
35.8. ALCHEMI	616
35.9. Examples: Profiles and Maps	617
Chapter Summary	619
References	619

36 ■ Spatial Resolution and Minimum Detectability

Chapter Preview	621
36.1. Why Is Spatial Resolution Important?	623
36.2. Definition of Spatial Resolution	623
36.3. Beam Spreading	624
36.4. The Spatial Resolution Equation	625
36.5. Measurement of Spatial Resolution	626
36.6. Thickness Measurement	628
36.6.A. TEM Methods	628
36.6.B. Contamination-Spot Separation Method	629
36.6.C. X-ray Spectrometry Methods	630
36.6.D. Electron Energy-Loss Spectrometry Methods	631
36.6.E. Convergent-Beam Diffraction Method	631
36.7. Minimum Detectability	631
36.7.A. Experimental Factors Affecting the MMF	632
36.7.B. Statistical Criterion for the MMF	632
36.7.C. Comparison with Other Definitions	633
36.7.D. Minimum Detectable Mass	634
Chapter Summary	634
References	634

37 ■ Electron Energy-Loss Spectrometers

Chapter Preview	637
37.1. Why Do Electron Energy-Loss Spectrometry?	639
37.2. The Magnetic Prism: A Spectrometer and a Lens	640
37.2.A. Focusing the Spectrometer	641
37.2.B. Calibrating the Spectrometer	642
37.3. Acquiring a Spectrum	642
37.3.A. Serial Collection	642

37.3.B. Parallel Collection	644	39.4.C. Edge Integration	676
37.3.C. Spectrometer Dispersion	645	39.4.D. The Zero-Loss Integral	676
37.3.D. Spectrometer Resolution	645	39.4.E. The Partial Ionization Cross Section	676
37.3.E. Point-Spread Function	646	39.5. Measuring Thickness from the Energy-Loss Spectrum	678
37.4. Image and Diffraction Modes	646	39.6. Deconvolution	680
37.4.A. Spectrometer Collection Angle	647	39.7. Correction for Convergence of the Incident Beam	682
37.4.B. Spatial Selection	649	39.8. The Effect of the Specimen Orientation	682
37.5. What You Need to Know about Your PEELS	6 4 9	39.9. Spatial Resolution	682
37.6. Imaging Spectrometers	6 5 0	39.10. Detectability Limits	683
Chapter Summary	6 5 1	Chapter Summary	684
Reference\	6 5 1	References	684
38 The Energy-Loss Spectrum		40 Everything Else in the Spectrum	
Chapter Preview	653	Chapter Preview	687
3X. I. A Few Basic Concepts	655	40.1. Fine Structure in the Ionization Edge\	689
3X.2. The Zero-Loss Peak	656	40.1.A\ ELNES	689
3X.3. The Low-Loss Spectrum	656	40.1.B. EXELFS	694
38.3.A\ Plasmons	656	40.2. The Low-Loss Spectrum	696
38.3.B\ Inter- and Intra-Band Transitions	658	40.2.A\ Plasmon Losses	696
3X.4. The High-Loss Spectrum	658	40.2.B\ Dielectric-Constant Determination	697
38.4.A\ Inner-Shell Ionization\	658	40.2.C\ Band-Gap and Inter-Band Transitions	698
3X.4.B. Ionization-Edge Characteristics	662	40.2.D. Angle-Resolved EELS	698
3X.5. Artifacts in the Spectrum	664	40.3. Energy-Filtered and Spectrum Imaging	699
Chapter Summary	665	40.3.A\ STEM Digital Imaging	700
References	666	40.3.B. TEM Analog Imaging	700
39 ■ Microanalysis with Ionization-Loss Electrons		Chapter Summary	703
Chapter Preview	6 6 7	References	703
39.1\ Choice of Operating Parameters	6 6 9	Index	705
39.2. What Should Your Spectrum Look Like?	6 7 0	Acknowledgements for Figures	717
39.3. Qualitative Microanalysis	671		
39.4. Quantitative Microanalysis	6 7 2		
39.4.A. Derivation of the Equations for Quantification	6 7 3		
39.4.B. Background Subtraction	674		