Contents

1. Introduction 1
1.1 Types of Electron Microscopes 1
1.1.1 Electron Microscopes for the Direct Imaging of Surfaces of Bulk Specimens 1
1.1.2 Instruments Using Electron Microprobes 3
1.1.3 Transmission Electron Microscopes 5
1.2 Electron-Specimen Interactions and Their Applications . . 8
1.2.1 Elastic Scattering 8
1.2.2 Electron Diffraction 9
1.2.3 Inelastic Scattering and X-Ray Emission 10
1.3 Special Applications of Transmission Electron Microscopy . 11
1.3.1 High-Resolution Electron Microscopy 11
1.3.2 Analytical Electron Microscopy 14
1.3.3 High-Voltage Electron Microscopy 15

2. Particle Optics of Electrons 19
2.1 Acceleration and Deflection of Electrons 19
2.1.1 Relativistic Mechanics of Electron Acceleration . . . 19
2.1.2 Electron Trajectories in Homogeneous Magnetic Fields 22
2.1.3 Small-Angle Deflections in Electric and Magnetic Fields 24
2.2 Electron Lenses 26
2.2.1 Electron Trajectories in a Magnetic Field of Rotational Symmetry 26
2.2.2 Optics of an Electron Lens with a Bell-Shaped Field . 28
2.2.3 Special Electron Lenses 33
2.3 Lens Aberrations 37
2.3.1 Classification of Lens Aberrations 37
2.3.2 Spherical Aberration 37
2.3.3 Astigmatism and Field Curvature 39
2.3.4 Distortion and Coma 41
2.3.5 Anisotropic Aberrations 43
2.3.6 Chromatic Aberration 44
2.3.7 Corrections of Lens Aberrations 45

3. Wave Optics of Electrons 50
3.1 Electron Waves and Phase Shifts 50
3.1.1 de Broglie Waves 50
3.1.2 Probability Density and Wave Packets 55
3.1.3 Electron-Optical Refractive Index and the Schrödinger Equation 56
3.1.4 Electron Interferometry and Coherence 59
3.1.5 Phase Shift by Magnetic Fields 62
3.2 Fresnel and Fraunhofer Diffraction 63
3.2.1 Huygens Principle and Fresnel Diffraction 63
3.2.2 Fresnel Fringes 67
3.2.3 Fraunhofer Diffraction 70
3.2.4 Mathematics of Fourier Transforms 72
3.3 Wave-Optical Formulation of Imaging 79
3.3.1 Wave Aberration of an Electron Lens 79
3.3.2 Wave-Optical Theory of Imaging 83

4. Elements of a Transmission Electron Microscope 86
4.1 Electron Guns 86
4.1.1 Physics of Electron Emission 86
4.1.2 Energy Spread and Gun Brightness 89
4.1.3 Thermionic Electron Guns 92
4.1.4 Field-Emission Guns 97
4.2 The Illumination System of a TEM 99
4.2.1 Two-Lens Condenser System 99
4.2.2 Electron-Probe Formation 102
4.2.3 Illumination with an Objective Pre-Field Lens 106
4.3 Specimens 108
4.3.1 Useful Specimen Thickness 108
4.3.2 Specimen Mounting 109
4.3.3 Specimen Manipulation 110
4.4 The Imaging System of a TEM 112
4.4.1 Objective-Lens System 112
4.4.2 Imaging Modes of a TEM 114
4.4.3 Magnification and Calibration 117
4.4.4 Depth of Image and Depth of Focus 119
4.5 Scanning Transmission Electron Microscopy (STEM) 120
4.5.1 Scanning Transmission Mode of TEM 120
4.5.2 Field-Emission STEM 122
4.5.3 Theorem of Reciprocity 123
4.6 Image Recording and Electron Detection 125
4.6.1 Fluorescent Screens 125
4.6.2 Photographic Emulsions 126
4.6.3 Image Intensification 131

4.6.4 Faraday Cages 132
4.6.5 Semiconductor Detectors 133
4.6.6 Scintillation Detectors 133

5. Electron-Specimen Interactions 135
5.1 Elastic Scattering 135
5.1.1 Cross-Section and Mean Free Path 135
5.1.2 Energy Transfer in an Electron-Nucleus Collision . . 138
5.1.3 Elastic Differential Cross-Section for Small-Angle Scattering 140
5.1.4 Differential Cross-Section for Large-Angle Scattering 148
5.1.5 Total Elastic Cross-Section 150
5.2 Inelastic Scattering 151
5.2.1 Electron-Specimen Interactions with Energy Loss . . 151
5.2.2 Inelastic Scattering at a Single Atom 153
5.2.3 Energy Losses in Solids 156
5.2.4 Energy Losses Caused by Inner-Shell Ionisation . . . 165
5.3 Multiple-Scattering Effects 168
5.3.1 Angular Distribution of Scattered Electrons 168
5.3.2 Energy Distribution of Transmitted Electrons 170
5.3.3 Electron-Probe Broadening by Multiple Scattering . 172
5.3.4 Electron Diffusion, Backscattering and Secondary-Electron Emission 176
5.4 X-Ray and Auger-Electron Emission 178
5.4.1 X-Ray Continuum 178
5.4.2 Characteristic X-Ray and Auger-Electron Emission . 180

6. Scattering and Phase Contrast for Amorphous Specimens 185
6.1 Scattering Contrast 186
6.1.1 Transmission in the Bright-Field Mode 186
6.1.2 Dark-Field Mode 192
6.1.3 Examples of Scattering Contrast 193
6.1.4 Scattering Contrast in the STEM Mode 196
6.1.5 Measurement of Mass-Thickness and Total Mass . . 198
6.2 Phase Contrast 199
6.2.1 The Origin of Phase Contrast 199
6.2.2 Defocusing Phase Contrast of Supporting Films . . . 200
6.2.3 Examples of Phase Contrast of Small Particles and Lamellar Systems 203
6.2.4 Theoretical Methods for Calculating Phase Contrast 204
6.3 Imaging of Single Atoms 205
6.3.1 Imaging of a Point Source 205
6.3.2 Imaging of Single Atoms in TEM 208

6.3.3 Complex Scattering Amplitudes and Scattering Contrast 212
6.3.4 Dependence of Phase Contrast on Electron Energy 213
6.3.5 Imaging of Single Atoms in the STEM Mode 214
6.4 Contrast-Transfer Function (CTF) 217
6.4.1 CTF for Amplitude and Phase Specimens 217
6.4.2 Influence of Energy Spread and Illumination Aperture 219
6.4.3 CTF for Tilted-Beam and Hollow-Cone Illumination 222
6.4.4 Contrast Transfer in STEM 225
6.4.5 Improvement of CTF Inside the Microscope 227
6.4.6 Control and Measurement of the CTF by Optical Diffraction 228
6.5 Electron Holography and Image Processing 232
6.5.1 Fresnel and Fraunhofer In-Line Holography 232
6.5.2 Single-Sideband Holography 235
6.5.3 Off-Axis Holography 236
6.5.4 Optical Filtering and Image Processing 239
6.5.5 Digital Image Processing 242
6.5.6 Three-Dimensional Reconstruction 248
6.6 Lorentz Microscopy 249
6.6.1 Lorentz Microscopy and Fresnel Diffraction 249
6.6.2 Imaging Modes of Lorentz Microscopy 251
6.6.3 Imaging of Electrostatic Specimen Fields 257

7. Kinematical and Dynamical Theory of Electron Diffraction 259
7.1 Fundamentals of Crystallography 259
7.1.1 Bravais Lattice and Lattice Planes 259
7.1.2 The Reciprocal Lattice 265
7.1.3 Calculation of Lattice-Plane Spacings 268
7.1.4 Construction of Laue Zones 269
7.2 Kinematical Theory of Electron Diffraction 271
7.2.1 Bragg Condition and Ewald Sphere 271
7.2.2 Structure and Lattice Amplitude 272
7.2.3 Column Approximation 277
7.3 Dynamical Theory of Electron Diffraction 279
7.3.1 Limitations of the Kinematical Theory 279
7.3.2 Formulation of the Dynamical Theory as a System of Differential Equations 280
7.3.3 Formulation of the Dynamical Theory as an Eigenvalue Problem 281
7.3.4 Discussion of the Two-Beam Case 285
7.4 Dynamical Theory Considering Absorption 291
7.4.1 Inelastic-Scattering Processes in Crystals 291
7.4.2 Absorption of the Bloch-Wave Field 295

7.4.3 Dynamical *n*-Beam Theory 300
7.4.4 The Bethe Dynamical Potential and the Critical-Voltage Phenomenon 302
7.5 Intensity Distributions in Diffraction Patterns 306
7.5.1 Diffraction at Amorphous Specimens 306
7.5.2 Intensity of Debye-Scherrer Rings 307
7.5.3 Influence of Thermal Diffuse Scattering 309
7.5.4 Kikuchi Lines and Bands 311

8. Diffraction Contrast and Crystal-Structure Imaging 315
8.1 Diffraction Contrast of Crystals Free of Defects 315
8.1.1 Edge and Bend Contours 315
8.1.2 Dark-Field Imaging 318
8.1.3 The STEM Mode and Multi-Beam Imaging 319
8.1.4 Transmission by Crystalline Specimens 322
8.1.5 Imaging of Atomic Surface Steps 324
8.2 Crystal-Structure Imaging 327
8.2.1 Lattice-Plane Fringes 327
8.2.2 Crystal-Structure Imaging 330
8.2.3 Moiré Fringes 333
8.3 Calculation of Diffraction Contrast of Lattice Defects 336
8.3.1 Kinematical Theory and the Howie-Whelan Equations 336
8.3.2 Matrix-Multiplication Method 338
8.3.3 Bloch-Wave Method 340
8.4 Planar Lattice Faults 341
8.4.1 Kinematical Theory of Stacking-Fault Contrast . . . 341
8.4.2 Dynamical Theory of Stacking-Fault Contrast 343
8.4.3 Antiphase and Other Boundaries 346
8.5 Dislocations 349
8.5.1 Kinematical Theory of Dislocation Contrast 349
8.5.2 Dynamical Effects in Dislocation Images 354
8.5.3 Weak-Beam Imaging 355
8.5.4 Determination of the Burgers Vector 358
8.6 Lattice Defects of Small Dimensions 360
8.6.1 Coherent and Incoherent Precipitates 360
8.6.2 Defect Clusters 363

9. Analytical Electron Microscopy 365
9.1 X-Ray Microanalysis in a TEM 366
9.1.1 Wavelength-Dispersive Spectrometry 366
9.1.2 Energy-Dispersive Spectrometer 367
9.1.3 X-Ray Emission from Thin and Bulk Specimens . . . 372
9.1.4 Standardless Methods for Thin Specimens 375
9.1.5 Counting Statistics and Sensitivity 377

9.2 Energy-Loss Spectroscopy and Energy-Selecting Microscopy 378
9.2.1 Electron Spectrometers and Filters 378
9.2.2 The Recording and Analysis of Energy-Loss Spectra 384
9.2.3 Information from Low-Energy Losses 386
9.2.4 Elemental Analysis by Inner-Shell Ionisations 387
9.2.5 Energy-Selecting Microscopy 391
9.3 Electron-Diffraction Modes 393
9.3.1 Selected-Area Electron Diffraction (SAED) 393
9.3.2 Electron Diffraction Using a Rocking Beam 395
9.3.3 Electron Diffraction Using an Electron Probe 397
9.3.4 Further Diffraction Modes in TEM 401
9.4 Applications of Electron Diffraction 404
9.4.1 Lattice-Plane Spacings 404
9.4.2 Texture Diagrams 406
9.4.3 Crystal Structure 407
9.4.4 Crystal Orientation 409
9.4.5 Examples of Extra Spots and Streaks 411
9.4.6 Convergent Beam and High-Order Laue Zone (HOLZ) Diffraction Patterns 415
9.5 Further Analytical Modes 418
9.5.1 Cathodoluminescence 418
9.5.2 Electron-Beam-Induced Current (EBIC) 419

10. Specimen Damage by Electron Irradiation 421
10.1 Specimen Heating 421
10.1.1 Methods of Measuring Specimen Temperature . . . 421
10.1.2 Generation of Heat by Electron Irradiation 423
10.1.3 Calculation of Specimen Temperature 425
10.2 Radiation Damage of Organic Specimens 429
10.2.1 Elementary Damage Processes in Organic Specimens 429
10.2.2 Quantitative Methods of Measuring Damage Effects 433
10.2.3 Methods of Reducing the Radiation Damage Rate . 439
10.2.4 Radiation Damage and High Resolution 442
10.3 Radiation Damage of Inorganic Specimens 444
10.3.1 Damage by Electron Excitation 444
10.3.2 Radiation Damage by Knock-On Collisions 445
10.4 Contamination 447
10.4.1 Origin and Sources of Contamination 447
10.4.2 Methods for Decreasing Contamination 448
10.4.3 Dependence of Contamination on Irradiation Conditions 450

References 455

Subject Index 511