Contents

1	Inti	roduct	ion	1
	1.1	Trans	mission Electron Microscopy	1
		1.1.1	Conventional Transmission Electron Microscopy	1
		1.1.2	High-Resolution Electron Microscopy	3
		1.1.3	Analytical Electron Microscopy	5
		1.1.4	Energy-Filtering Electron Microscopy	7
		1.1.5	High-Voltage Electron Microscopy	7
		1.1.6	Dedicated Scanning Transmission Electron	
			Microscopy	9
	1.2	Alterr	native Types of Electron Microscopy	10
		1.2.1	Emission Electron Microscopy	10
		1.2.2	Reflection Electron Microscopy	11
		1.2.3	Mirror Electron Microscopy	11
		1.2.4	Scanning Electron Microscopy	12
		1.2.5	X-ray and Auger-Electron Microanalysis	14
		1.2.6	Scanning-Probe Microscopy	14
2	Par	ticle (Optics of Electrons	17
	2.1	Accele	eration and Deflection of Electrons	17
		2.1.1	Relativistic Mechanics of Electron Acceleration	17
		2.1.2	Deflection by Magnetic and Electric Fields	20
	2.2	Electr	ron Lenses	22
		2.2.1	Electron Trajectories in a Magnetic Lens Field	22
		2.2.2	Optics of an Electron Lens with a Bell-Shaped Field	25
		2.2.3	Special Electron Lenses	29
	2.3	Lens A	Aberrations	31
		2.3.1	Classification of Lens Aberrations	31
		2.3.2	Spherical Aberration	32
		2.3.3	Astigmatism and Field Curvature	34
		2.3.4	Distortion	36
		2.3.5	Coma	37

		2.3.6	Anisotropic Aberrations	
		2.3.7	Chromatic Aberration	
	2.4	Correc	ction of Aberrations and Microscope Alignment	
		2.4.1	Correction of Astigmatism	
		2.4.2	Correction of Spherical and Chromatic Aberrations	
		2.4.3	Microscope Alignment	. 43
3	Way		tics of Electrons	
	3.1	Electr	on Waves and Phase Shifts	
		3.1.1	De Broglie Waves	
		3.1.2	Probability Density and Wave Packets	. 49
		3.1.3	Electron-Optical Refractive Index	
			and the Schrödinger Equation	
		3.1.4	Electron Interferometry and Coherence	
	3.2		el and Fraunhofer Diffraction	
		3.2.1	Huygens' Principle and Fresnel Diffraction	
		3.2.2	Fresnel Fringes	
		3.2.3	Fraunhofer Diffraction	
		3.2.4	Mathematics of Fourier Transforms	
	3.3		Optical Formulation of Imaging	
		3.3.1	Wave Aberration of an Electron Lens	
		3.3.2	Wave-Optical Theory of Imaging	. 73
4	Elei		of a Transmission Electron Microscope	
	4.1		on Guns	
		4.1.1	Physics of Electron Emission	
		4.1.2	Energy Spread	
		4.1.3	Gun Brightness	
		4.1.4	Thermionic Electron Guns	
		4.1.5	Schottky Emission Guns	
		4.1.6	Field-Emission Guns	
	4.2		llumination System of a TEM	
		4.2.1	Condenser-Lens System	
		4.2.2	Electron-Probe Formation	
		4.2.3	Illumination with an Objective Prefield Lens	
	4.3	•	nens	
		4.3.1	Useful Specimen Thickness	
		4.3.2	1 8	
		4.3.3	Specimen Manipulation	
	4.4		maging System of a TEM	
		4.4.1	Objective Lens	
		4.4.2	Imaging Modes of a TEM	
				107
		4.4.3	Magnification and Calibration	
	4.5	4.4.4	Magnification and Calibration Depth of Image and Depth of Focus ing Transmission Electron Microscopy (STEM)	. 108

	4.5.1	Scanning Transmission Mode of TEM	109
	4.5.2	Dedicated STEM	
	4.5.3	Theorem of Reciprocity	
4.6	Electr	on Spectrometers and Imaging Energy Filters	
	4.6.1	Postcolumn Prism Spectrometer	
	4.6.2	Wien Filter	
	4.6.3	Imaging Energy Filter	
	4.6.4	Operating Modes with Energy Filtering	
4.7	Image	e Recording and Electron Detection	
	4.7.1	Fluorescent Screens	
	4.7.2	Photographic Emulsions	
	4.7.3	Imaging Plate	
	4.7.4	Detector Noise and Detection Quantum Efficiency	
	4.7.5	Low-Light-Level and Charge-Coupled-Device	
		(CCD) Cameras	134
	4.7.6	Semiconductor and Scintillation Detectors	
	4.7.7	Faraday Cages	
Ele	ctron–	Specimen Interactions	141
5.1	Elasti	c Scattering	
	5.1.1	Cross Section and Mean Free Path	141
	5.1.2	Energy Transfer in an Electron–Nucleus Collision	143
	5.1.3	Elastic Differential Cross Section for Small-Angle	
		Scattering	146
	5.1.4	Total Elastic Cross Section	152
5.2	Inelas	tic Scattering	153
	5.2.1	Electron–Specimen Interactions with Energy Loss	153
	5.2.2	Differential Cross Section for Single-Electron	
		Excitation	156
	5.2.3	Bethe Surface and Compton Scattering	158
	5.2.4	Approximation for the Total Inelastic Cross Section.	162
	5.2.5	Dielectric Theory and Plasmon Losses in Solids	163
	5.2.6	Surface-Plasmon Losses	171
5.3	Energ	y Losses by Inner-Shell Ionization	174
	5.3.1	Position and Shape of Ionization Edges	174
	5.3.2	Inner-Shell Ionization Cross Sections	177
	5.3.3	Energy-Loss Near-Edge Structure (ELNES)	179
	5.3.4	Extended Energy-Loss Fine Structure (EXELFS)	182
	5.3.5	Linear and Circular Dichroism	183
5.4	Multi	ple-Scattering Effects	184
	5.4.1	Angular Distribution of Scattered Electrons	184
	5.4.2	Energy Distribution of Transmitted Electrons	186
	5.4.3	Electron-Probe Broadening by Multiple Scattering	188
	5.4.4	Electron Diffusion, Backscattering,	
		and Secondary-Electron Emission	192

 $\mathbf{5}$

6	Scattering and Phase Contrast for Amorphous						
	Spe	Specimens					
	6.1	Scatte	ering Contrast				
		6.1.1	Transmission in the Bright-Field Mode				
		6.1.2	Dark-Field Mode				
		6.1.3	Examples of Scattering Contrast				
		6.1.4	Improvement of Scattering Contrast by Energy				
			Filtering				
		6.1.5	Scattering Contrast in the STEM Mode				
		6.1.6	Measurement of Mass Thickness and Total Mass 209				
	6.2	Phase	Contrast				
		6.2.1	The Origin of Phase Contrast				
		6.2.2	Defocusing Phase Contrast of Supporting Films 212				
		6.2.3	Examples of Phase Contrast				
		6.2.4	Theoretical Methods for Calculating Phase Contrast $\dots 216$				
		6.2.5	Imaging of a Scattering Point Object				
		6.2.6	Relation between Phase and Scattering Contrast220				
	6.3	-	ng of Single Atoms				
		6.3.1	Imaging of Single Atoms in TEM				
		6.3.2	Imaging of Single Atoms in the STEM Mode				
	6.4		ast-Transfer Function (CTF)228				
		6.4.1	The CTF for Amplitude and Phase Specimens				
		6.4.2	Influence of Energy Spread and Illumination				
			Aperture				
		6.4.3	The CTF for Tilted-Beam and Hollow-Cone				
			Illumination				
		6.4.4	Contrast Transfer in STEM				
		6.4.5	Phase Contrast by Inelastically Scattered Electrons 237				
		6.4.6	Improvement of the CTF Inside the Microscope				
		6.4.7	Control of the CTF by Optical or Digital Fourier				
	~ -		Transform				
	6.5		on Holography				
		6.5.1	Fresnel and Fraunhofer In-Line Holography				
		6.5.2	Single-Sideband Holography				
		6.5.3	Off-Axis Holography				
	0.0	6.5.4	Reconstruction of Off-Axis Holograms				
	6.6		Restoration and Specimen Reconstruction				
		6.6.1	General Aspects				
		6.6.2	Methods of Optical Analog Filtering				
		6.6.3	Digital Image Restoration				
		6.6.4	Alignment by Cross-Correlation				
	c =	6.6.5	Averaging of Periodic and Aperiodic Structures				
	6.7		-Dimensional Reconstruction				
		6.7.1	Stereometry				
		6.7.2	Electron Tomography				

	6.8	Loren 6.8.1 6.8.2 6.8.3	tz Microscopy Lorentz Microscopy and Fresnel Diffraction Imaging Modes of Lorentz Microscopy Imaging of Electrostatic Specimen Fields	262 264
7	The	eory o	f Electron Diffraction	273
	7.1	-	amentals of Crystallography	
		7.1.1	Bravais Lattice and Lattice Planes	274
		7.1.2	The Reciprocal Lattice	279
		7.1.3	Construction of Laue Zones	282
	7.2	Kiner	natical Theory of Electron Diffraction	283
		7.2.1	Bragg Condition and Ewald Sphere	283
		7.2.2	Structure Amplitude and Lattice Amplitude	285
		7.2.3	Column Approximation	289
	7.3	Dyna	mical Theory of Electron Diffraction	292
		7.3.1	Limitations of the Kinematical Theory	292
		7.3.2	Formulation of the Dynamical Theory as a System	
			of Differential Equations	293
		7.3.3	Formulation of the Dynamical Theory	
			as an Eigenvalue Problem	
		7.3.4	Discussion of the Two-Beam Case	
	7.4	Dyna	mical Theory Including Absorption	
		7.4.1	Inelastic-Scattering Processes in Crystals	
		7.4.2	Absorption of the Bloch-Wave Field	306
		7.4.3	Dynamical <i>n</i> -Beam Theory	311
		7.4.4	The Bethe Dynamical Potential and the Critical	
			Voltage Effect	
	7.5	Intens	sity Distribution in Diffraction Patterns	
		7.5.1	Diffraction at Amorphous Specimens	
		7.5.2	Intensity of Debye–Scherrer Rings	
		7.5.3	Influence of Thermal Diffuse Scattering	
		7.5.4	Kikuchi Lines and Bands	
		7.5.5	Electron Spectroscopic Diffraction	326
8	Ele	ctron-	Diffraction Modes and Applications	329
-	8.1		ron-Diffraction Modes	
		8.1.1		
			Electron Diffraction Using a Rocking Beam	
		8.1.3	Electron Diffraction Using a Stationary Electron	
			Probe	
		8.1.4	Electron Diffraction Using a Rocking Electron Probe.	
		8.1.5	Further Diffraction Modes in TEM	
	8.2		Uses of Diffraction Patterns with Bragg Reflections	
	.	8.2.1	Lattice-Plane Spacings	
		8.2.2	Texture Diagrams	

		8.2.3	Crystal Structure	345
		8.2.4	Crystal Orientation	347
		8.2.5	Examples of Extra Spots and Streaks	349
	8.3	Conve	ergent-Beam Electron Diffraction (CBED)	352
		8.3.1	Determination of Point and Space Groups	
		8.3.2	Determination of Foil Thickness	352
		8.3.3	Charge-Density Distributions	353
		8.3.4	High-Order Laue Zone (HOLZ) Patterns	354
		8.3.5	HOLZ Lines	355
		8.3.6	Large-Angle CBED	357
9	Ima	aging o	of Crystalline Specimens and Their Defects	359
	9.1	Diffra	ction Contrast of Crystals Free of Defects	
		9.1.1	Edge and Bend Contours	
		9.1.2	Dark-Field Imaging	362
		9.1.3	Moiré Fringes	
		9.1.4	The STEM Mode and Multibeam Imaging	367
		9.1.5	Energy Filtering of Diffraction Contrast	369
		9.1.6	Transmission of Crystalline Specimens	370
	9.2	Calcu	lation of Diffraction Contrast of Lattice Defects	373
		9.2.1	Kinematical Theory and the Howie–Whelan	
			Equations	
		9.2.2	Matrix-Multiplication Method	
		9.2.3	Bloch-Wave Method	
	9.3	Plana	r Lattice Faults	
		9.3.1	Kinematical Theory of Stacking-Fault Contrast	
		9.3.2	Dynamical Theory of Stacking-Fault Contrast	
		9.3.3	Antiphase and Other Boundaries	
	9.4		cations	
		9.4.1	Kinematical Theory of Dislocation Contrast	
		9.4.2	Dynamical Effects in Dislocation Images	
		9.4.3	Weak-Beam Imaging	
		9.4.4	Determination of the Burgers Vector	
	9.5	Lattic	ce Defects of Small Dimensions	
		9.5.1	Coherent and Incoherent Precipitates	396
		9.5.2	Defect Clusters	398
	9.6		Resolution Electron Microscopy (HREM) of Crystals .	
		9.6.1	Lattice-Plane Fringes	400
		9.6.2	General Aspects of Crystal-Structure Imaging	402
		9.6.3	Methods for Calculating Lattice-Image Contrast	405
		9.6.4	Simulation, Matching, and Reconstruction	
			of Crystal Images	
		9.6.5	Measurement of Atomic Displacements in HREM	409
		9.6.6	Crystal-Structure Imaging with a Scanning	
			Transmission Electron Microscope	411

	9.7	maging of Atomic Surface Steps and Structures0.7.1Imaging of Surface Steps in Transmission0.7.2Reflection Electron Microscopy0.7.3Surface-Profile Imaging	$\dots 412$ $\dots 416$
10	Elei	ental Analysis by X-ray and Electron Energy-Loss	
	Spe	roscopy	419
	10.1	K-ray and Auger-Electron Emission	
		0.1.1 X-ray Continuum	
		0.1.2 Characteristic X-ray and Auger-Electron Emission	421
	10.2	K-ray Microanalysis in a Transmission Electron Microscope	
		0.2.1 Wavelength-Dispersive Spectrometry	
		0.2.2 Energy-Dispersive Spectrometry (EDS)	427
		0.2.3 X-ray Emission from Bulk Specimens and ZAF \tilde{c}	
		Correction	
		0.2.4 X-ray Microanalysis of Thin Specimens	
	10.9	0.2.5 X-ray Microanalysis of Organic Specimens	
	10.5	Clectron Energy-Loss Spectroscopy	437
		0.3.2 Kramers-Kronig Relation	
		0.3.3 Background Fitting and Subtraction	
		0.3.4 Deconvolution	
		0.3.5 Elemental Analysis by Inner-Shell Ionizations	
	10.4	Clement-Distribution Images	
		0.4.1 Elemental Mapping by X-Rays	
		0.4.2 Element-Distribution Images Formed by Electron	
		Spectroscopic Imaging	448
		0.4.3 Three-Window Method	449
		0.4.4 White-Line Method	
		0.4.5 Correction of Scattering Contrast	
	10.5	imitations of Elemental Analysis	
		0.5.1 Specimen Thickness	
		0.5.2 Radiation Damage and Loss of Elements	
		0.5.3 Counting Statistics and Sensitivity	453
		0.5.4 Resolution and Detection Limits for Electron	450
		Spectroscopic Imaging	456
11	Spe	men Damage by Electron Irradiation	459
		pecimen Heating	
		1.1.1 Methods of Measuring Specimen Temperature	459
		1.1.2 Generation of Heat by Electron Irradiation	
		1.1.3 Calculation of Specimen Temperature	
	11.2	Radiation Damage of Organic Specimens	
		1.2.1 Elementary Damage Processes in Organic Specimens	
		1.2.2 Quantitative Methods of Measuring Damage Effects	470

XVI Contents

11.2.3 Methods of Reducing Radiation Damage
11.2.4 Radiation Damage and High Resolution
11.3 Radiation Damage of Inorganic Specimens
11.3.1 Damage by Electron Excitation
11.3.2 Radiation Damage by Knock-On Collisions
11.4 Contamination
11.4.1 Origin and Sources of Contamination
11.4.2 Methods for Decreasing Contamination
11.4.3 Dependence of Contamination on Irradiation
Conditions
References
Index