

Contents

Preface

xv

1. Introduction to Semiconductor Lithography	1
1.1 Basics of IC Fabrication	2
1.1.1 Patterning	2
1.1.2 Etching	3
1.1.3 Ion Implantation	5
1.1.4 Process Integration	6
1.2 Moore's Law and the Semiconductor Industry	7
1.3 Lithography Processing	12
1.3.1 Substrate Preparation	14
1.3.2 Photoresist Coating	15
1.3.3 Post-Apply Bake	18
1.3.4 Alignment and Exposure	19
1.3.5 Post-exposure Bake	23
1.3.6 Development	24
1.3.7 Postbake	25
1.3.8 Measure and Inspect	25
1.3.9 Pattern Transfer	25
1.3.10 Strip	26
Problems	26
2. Aerial Image Formation – The Basics	29
2.1 Mathematical Description of Light	29
2.1.1 Maxwell's Equations and the Wave Equation	30
2.1.2 General Harmonic Fields and the Plane Wave in a Nonabsorbing Medium	32
2.1.3 Phasors and Wave Propagation in an Absorbing Medium	33
2.1.4 Intensity and the Poynting Vector	36
2.1.5 Intensity and Absorbed Electromagnetic Energy	37

2.2	Basic Imaging Theory	38
2.2.1	Diffraction	39
2.2.2	Fourier Transform Pairs	43
2.2.3	Imaging Lens	45
2.2.4	Forming an Image	47
2.2.5	Imaging Example: Dense Array of Lines and Spaces	48
2.2.6	Imaging Example: Isolated Space	50
2.2.7	The Point Spread Function	51
2.2.8	Reduction Imaging	53
2.3	Partial Coherence	56
2.3.1	Oblique Illumination	57
2.3.2	Partially Coherent Illumination	58
2.3.3	Hopkins Approach to Partial Coherence	62
2.3.4	Sum of Coherent Sources Approach	63
2.3.5	Off-Axis Illumination	65
2.3.6	Imaging Example: Dense Array of Lines and Spaces Under Annular Illumination	66
2.3.7	Köhler Illumination	66
2.3.8	Incoherent Illumination	69
2.4	Some Imaging Examples	70
	Problems	71
3.	Aerial Image Formation – The Details	75
3.1	Aberrations	75
3.1.1	The Causes of Aberrations	75
3.1.2	Describing Aberrations: the Zernike Polynomial	78
3.1.3	Aberration Example – Tilt	81
3.1.4	Aberration Example – Defocus, Spherical and Astigmatism	83
3.1.5	Aberration Example – Coma	84
3.1.6	Chromatic Aberrations	85
3.1.7	Strehl Ratio	90
3.2	Pupil Filters and Lens Apodization	90
3.3	Flare	91
3.3.1	Measuring Flare	92
3.3.2	Modeling Flare	94
3.4	Defocus	95
3.4.1	Defocus as an Aberration	95
3.4.2	Defocus Example: Dense Lines and Spaces and Three-Beam Imaging	98
3.4.3	Defocus Example: Dense Lines and Spaces and Two-Beam Imaging	100
3.4.4	Image Isofocal Point	102
3.4.5	Focus Averaging	103
3.4.6	Reticule Defocus	104
3.4.7	Rayleigh Depth of Focus	105

3.5	Imaging with Scanners Versus Steppers	106
3.6	Vector Nature of Light	108
3.6.1	Describing Polarization	111
3.6.2	Polarization Example: TE Versus TM Image of Lines and Spaces	113
3.6.3	Polarization Example: The Vector PSF	114
3.6.4	Polarization Aberrations and the Jones Pupil	114
3.7	Immersion Lithography	117
3.7.1	The Optical Invariant and Hyper-NA Lithography	118
3.7.2	Immersion Lithography and the Depth of Focus	120
3.8	Image Quality	121
3.8.1	Image CD	121
3.8.2	Image Placement Error (Distortion)	123
3.8.3	Normalized Image Log-Slope (NILS)	123
3.8.4	Focus Dependence of Image Quality	125
	Problems	126
4.	Imaging in Resist: Standing Waves and Swing Curves	129
4.1	Standing Waves	130
4.1.1	The Nature of Standing Waves	130
4.1.2	Standing Waves for Normally Incident Light in a Single Film	131
4.1.3	Standing Waves in a Multiple-Layer Film Stack	135
4.1.4	Oblique Incidence and the Vector Nature of Light	137
4.1.5	Broadband Illumination	141
4.2	Swing Curves	144
4.2.1	Reflectivity Swing Curve	144
4.2.2	Dose-to-Clear and CD Swing Curves	148
4.2.3	Swing Curves for Partially Coherent Illumination	149
4.2.4	Swing Ratio	151
4.2.5	Effective Absorption	154
4.3	Bottom Antireflection Coatings	156
4.3.1	BARC on an Absorbing Substrate	157
4.3.2	BARCs at High Numerical Apertures	160
4.3.3	BARC on a Transparent Substrate	164
4.3.4	BARC Performance	165
4.4	Top Antireflection Coatings	167
4.5	Contrast Enhancement Layer	170
4.6	Impact of the Phase of the Substrate Reflectance	170
4.7	Imaging in Resist	173
4.7.1	Image in Resist Contrast	173
4.7.2	Calculating the Image in Resist	177
4.7.3	Resist-Induced Spherical Aberrations	179
4.7.4	Standing Wave Amplitude Ratio	181

4.8	Defining Intensity	183
4.8.1	Intensity at Oblique Incidence	183
4.8.2	Refraction into an Absorbing Material	184
4.8.3	Intensity and Absorbed Energy	187
	Problems	188
5.	Conventional Resists: Exposure and Bake Chemistry	191
5.1	Exposure	191
5.1.1	Absorption	191
5.1.2	Exposure Kinetics	194
5.2	Post-Apply Bake	199
5.2.1	Sensitizer Decomposition	200
5.2.2	Solvent Diffusion and Evaporation	205
5.2.3	Solvent Effects in Lithography	209
5.3	Post-exposure Bake Diffusion	210
5.4	Detailed Bake Temperature Behavior	214
5.5	Measuring the <i>ABC</i> Parameters	217
	Problems	219
6.	Chemically Amplified Resists: Exposure and Bake Chemistry	223
6.1	Exposure Reaction	223
6.2	Chemical Amplification	224
6.2.1	Amplification Reaction	225
6.2.2	Diffusion	227
6.2.3	Acid Loss	230
6.2.4	Base Quencher	232
6.2.5	Reaction–Diffusion Systems	233
6.3	Measuring Chemically Amplified Resist Parameters	235
6.4	Stochastic Modeling of Resist Chemistry	237
6.4.1	Photon Shot Noise	237
6.4.2	Chemical Concentration	239
6.4.3	Some Mathematics of Binary Random Variables	241
6.4.4	Photon Absorption and Exposure	242
6.4.5	Acid Diffusion, Conventional Resist	246
6.4.6	Acid-Catalyzed Reaction–Diffusion	247
6.4.7	Reaction–Diffusion and Polymer Deblocking	251
6.4.8	Acid–Base Quenching	253
	Problems	254
7.	Photoresist Development	257
7.1	Kinetics of Development	257
7.1.1	A Simple Kinetic Development Model	258
7.1.2	Other Development Models	261
7.1.3	Molecular Weight Distributions and the Critical Ionization Model	264
7.1.4	Surface Inhibition	265

7.1.5	Extension to Negative Resists	267
7.1.6	Developer Temperature	267
7.1.7	Developer Normality	268
7.2	The Development Contrast	270
7.2.1	Defining Photoresist Contrast	270
7.2.2	Comparing Definitions of Contrast	274
7.2.3	The Practical Contrast	276
7.2.4	Relationship between γ and r_{\max}/r_{\min}	277
7.3	The Development Path	278
7.3.1	The Euler–Lagrange Equation	279
7.3.2	The Case of No z -Dependence	280
7.3.3	The Case of a Separable Development Rate Function	282
7.3.4	Resist Sidewall Angle	283
7.3.5	The Case of Constant Development Gradients	284
7.3.6	Segmented Development and the Lumped Parameter Model (LPM)	286
7.3.7	LPM Example – Gaussian Image	287
7.4	Measuring Development Rates	292
	Problems	293
8.	Lithographic Control in Semiconductor Manufacturing	297
8.1	Defining Lithographic Quality	297
8.2	Critical Dimension Control	299
8.2.1	Impact of CD Control	299
8.2.2	Improving CD Control	303
8.2.3	Sources of Focus and Dose Errors	305
8.2.4	Defining Critical Dimension	307
8.3	How to Characterize Critical Dimension Variations	309
8.3.1	Spatial Variations	309
8.3.2	Temporal Variations and Random Variations	311
8.3.3	Characterizing and Separating Sources of CD Variations	312
8.4	Overlay Control	314
8.4.1	Measuring and Expressing Overlay	315
8.4.2	Analysis and Modeling of Overlay Data	317
8.4.3	Improving Overlay Data Analysis	320
8.4.4	Using Overlay Data	323
8.4.5	Overlay Versus Pattern Placement Error	326
8.5	The Process Window	326
8.5.1	The Focus–Exposure Matrix	326
8.5.2	Defining the Process Window and DOF	332
8.5.3	The Isofocal Point	336
8.5.4	Overlapping Process Windows	338
8.5.5	Dose and Focus Control	339
8.6	H–V Bias	343
8.6.1	Astigmatism and H–V Bias	343
8.6.2	Source Shape Asymmetry	345

8.7	Mask Error Enhancement Factor (MEEF)	348
8.7.1	Linearity	348
8.7.2	Defining MEEF	349
8.7.3	Aerial Image MEEF	350
8.7.4	Contact Hole MEEF	352
8.7.5	Mask Errors as Effective Dose Errors	353
8.7.6	Resist Impact on MEEF	355
8.8	Line-End Shortening	356
8.8.1	Measuring LES	357
8.8.2	Characterizing LES Process Effects	359
8.9	Critical Shape and Edge Placement Errors	361
8.10	Pattern Collapse	362
	Problems	366
9.	Gradient-Based Lithographic Optimization: Using the Normalized Image Log-Slope	369
9.1	Lithography as Information Transfer	369
9.2	Aerial Image	370
9.3	Image in Resist	377
9.4	Exposure	378
9.5	Post-exposure Bake	381
9.5.1	Diffusion in Conventional Resists	381
9.5.2	Chemically Amplified Resists – Reaction Only	383
9.5.3	Chemically Amplified Resists – Reaction–Diffusion	384
9.5.4	Chemically Amplified Resists – Reaction–Diffusion with Quencher	391
9.6	Develop	393
9.6.1	Conventional Resist	397
9.6.2	Chemically Amplified Resist	399
9.7	Resist Profile Formation	400
9.7.1	The Case of a Separable Development Rate Function	400
9.7.2	Lumped Parameter Model	401
9.8	Line Edge Roughness	404
9.9	Summary	406
	Problems	408
10.	Resolution Enhancement Technologies	411
10.1	Resolution	412
10.1.1	Defining Resolution	413
10.1.2	Pitch Resolution	416
10.1.3	Natural Resolutions	418
10.1.4	Improving Resolution	418
10.2	Optical Proximity Correction (OPC)	419
10.2.1	Proximity Effects	419
10.2.2	Proximity Correction – Rule Based	422

10.2.3	Proximity Correction – Model Based	425
10.2.4	Subresolution Assist Features (SRAFs)	427
10.3	Off-Axis Illumination (OAI)	429
10.4	Phase-Shifting Masks (PSM)	434
10.4.1	Alternating PSM	435
10.4.2	Phase Conflicts	438
10.4.3	Phase and Intensity Imbalance	439
10.4.4	Attenuated PSM	441
10.4.5	Impact of Phase Errors	445
10.5	Natural Resolutions	450
10.5.1	Contact Holes and the Point Spread Function	450
10.5.2	The Coherent Line Spread Function (LSF)	452
10.5.3	The Isolated Phase Edge	453
	Problems	454
Appendix A.	Glossary of Microlithographic Terms	457
Appendix B.	Curl, Divergence, Gradient, Laplacian	491
Appendix C.	The Dirac Delta Function	495
Index		501

