

Optical and EUV Lithography

A Modeling Perspective

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SPIE PRESS

Bellingham, Washington USA

Library of Congress Cataloguing-in-Publication Data

Names: Erdmann, Andreas, author.

Title: Optical and EUV lithography : a modeling perspective / Andreas Erdmann.

Description: Bellingham : SPIE—The International Society for Optical Engineering, 2021. | Includes bibliographical references and index.

Identifiers: LCCN 2020041503 (print) | LCCN 2020041504 (ebook) |

ISBN 9781510639010 (paperback) | ISBN 9781510639027 (pdf)

Subjects: LCSH: Photolithography. | Extreme ultraviolet lithography.

Classification: LCC TR940 .E73 2021 (print) | LCC TR940 (ebook) |

DDC 686.2/32—dc23

LC record available at <https://lcn.loc.gov/2020041503>

LC ebook record available at <https://lcn.loc.gov/2020041504>

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: books@spie.org

Web: <http://spie.org>

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Printed in the United States of America.

First Printing.

For updates to this book, visit <http://spie.org> and type “PM323” in the search field.

SPIE.

To Huixian, Laura, and Samuel.

Contents

<i>Preface</i>	<i>xiii</i>
<i>Abbreviations and Acronyms</i>	<i>xvii</i>
<i>Frequently Used Symbols</i>	<i>xxi</i>
1 Overview of Lithographic Processing	1
1.1 From Miniaturization in Microelectronics Towards Nanotechnology	1
1.2 Historical Development	3
1.3 Aerial Image Formation in Projection Scanners	6
1.4 Photoresist Processing	10
1.5 Process Characteristics	13
1.6 Summary	19
References	20
2 Image Formation in Projection Lithography	23
2.1 Projection Scanners	23
2.2 Theory of Image Formation	24
2.2.1 Fourier optical description	24
2.2.2 Oblique illumination and partially coherent imaging	30
2.2.3 Alternative image simulation methods	34
2.3 Abbe–Rayleigh Criteria and Consequences	35
2.3.1 Resolution limit and depth of focus	35
2.3.2 Consequences	40
2.4 Summary	44
References	45
3 Photoresists	47
3.1 Overview, General Reaction Schemes, and Phenomenological Description	48
3.1.1 Classification of photoresists	48
3.1.2 Diazonaphthoquinone (DNQ)-based photoresists	51
3.1.3 State-of-the-art positive-tone chemically amplified resists (CARs)	53
3.1.4 Phenomenological model	54
3.2 Photoresist Processing Steps and Modeling Approaches	57
3.2.1 Selected technical aspects	57

3.2.2	Exposure	58
3.2.3	Post-exposure bake	62
3.2.3.1	Diazonaphthoquinone (DNQ) resists	62
3.2.3.2	Chemically amplified resists (CARs)	64
3.2.4	Chemical development	66
3.3	General Remarks on Modeling Approaches and Compact Resist Models	70
3.4	Negative- versus Positive-Tone Materials and Processes	75
3.5	Summary	79
	References	80
4	Optical Resolution Enhancements	87
4.1	Off-Axis Illumination	87
4.1.1	Optimum off-axis illumination for line-space patterns	89
4.1.2	Off-axis illumination for arrays of contact holes	90
4.1.3	From conventional and parametric source shapes to free-form illumination	92
4.2	Optical Proximity Correction	94
4.2.1	Compensation of the iso-dense bias	95
4.2.2	Compensation of line-end shortening	97
4.2.3	From rule-based to model-based OPC and inverse lithography	98
4.2.4	OPC models and process flows	101
4.3	Phase Shift Masks	103
4.3.1	Strong phase shift masks: Alternating PSMs	103
4.3.2	Attenuated or weak PSMs	110
4.4	Pupil Filters	113
4.5	Source and Mask Optimization	115
4.6	Multiple-Exposure Techniques	120
4.7	Summary	122
	References	123
5	Material-Driven Resolution Enhancements	129
5.1	The Resolution Limit Revisited	129
5.2	Nonlinear Double-Exposure	133
5.2.1	Two-photon absorption materials	133
5.2.2	Optical threshold materials	134
5.2.3	Reversible contrast enhancement materials	135
5.3	Double and Multiple Patterning	137
5.3.1	Litho-etch-litho-etch (LELE)	137
5.3.2	Litho-freeze-litho-etch (LFLE)	138
5.3.3	Self-aligned double patterning (SADP)	139
5.3.4	Dual-tone development (DTD)	140
5.3.5	Selection of options for double and multiple patterning	141

5.4	Directed Self-Assembly (DSA)	142
5.5	Thin-Film-Imaging Technologies	148
5.6	Summary	149
	References	150
6	Lithography with Extreme-Ultraviolet Light	157
6.1	Light Sources	159
6.2	Optical Material Properties in the EUV and Multilayer Coatings	161
6.3	Masks	164
6.4	Exposure Tools and Image Formation	169
6.5	Resists	173
6.6	Mask Defects	175
6.7	Optical Resolution Limits of EUV Lithography	179
6.7.1	Beyond EUV (BEUV) lithography at 6.x nm wavelength	180
6.7.2	Towards high-NA lithography	180
6.7.3	Towards smaller k_1 : Optical resolution enhancements for EUV lithography	184
6.8	Summary	185
	References	186
7	Optical Lithography Beyond Projection Imaging	197
7.1	Optical Lithography without a Projection Lens: Contact and Proximity Lithography	198
7.1.1	Image formation and resolution limit	198
7.1.2	Technical realization	201
7.1.3	Advanced mask aligner lithography	204
7.2	Optical Lithography without a Mask	209
7.2.1	Interference lithography	209
7.2.2	Laser direct write lithography (LDWL)	213
7.3	Optical Lithography without a Diffraction Limit	218
7.3.1	Near-field lithography	219
7.3.2	Employing optical nonlinearities	223
7.4	Optical Lithography in Three Dimensions	228
7.4.1	Grayscale lithography	229
7.4.2	3D interference lithography	231
7.4.3	Stereolithography and 3D microprinting	232
7.5	A Few Remarks on Lithography without Light	236
7.6	Summary	237
	References	237
8	Lithographic Projection Systems: Advanced Topics	251
8.1	Wave Aberrations in Real Projection Systems	251
8.1.1	Zernike representation of wave aberrations	252

8.1.2	Wavefront tilt	256
8.1.3	Power aberration	257
8.1.4	Astigmatism	257
8.1.5	Coma	258
8.1.6	Spherical aberration	262
8.1.7	Trefoil aberration	263
8.1.8	Concluding remarks on Zernike-type wave aberrations	263
8.2	Flare	265
8.2.1	Constant flare model	266
8.2.2	Modeling of flare with power spectral densities	267
8.3	Polarization Effects in High-NA Projection Lithography	270
8.3.1	Mask polarization effects	270
8.3.2	Polarization effects in image formation	271
8.3.3	Polarization effects resulting from the resist and wafer stack interfaces	273
8.3.4	Polarization effects in the projector and the vector model for image formation	276
8.3.5	Polarized illumination	279
8.4	Other Imaging Effects in Projection Scanners	280
8.5	Summary	281
	References	281
9	Mask and Wafer Topography Effects in Lithography	285
9.1	Methods for Rigorous Electromagnetic Field Simulation	287
9.1.1	Finite-difference time-domain (FDTD) method	289
9.1.2	Waveguide method	292
9.2	Mask Topography Effects	295
9.2.1	Mask diffraction analysis	296
9.2.2	Oblique incidence effects	299
9.2.3	Mask-induced imaging effects	300
9.2.4	Mask topography effects in EUV lithography and mitigation strategies	305
9.2.5	Variations of 3D mask models	310
9.3	Wafer Topography Effects	312
9.3.1	BARC deposition strategies	313
9.3.2	Resist footing close to poly-lines	315
9.3.3	Linewidth variation in double patterning	316
9.4	Summary	317
	References	317
10	Stochastic Effects in Advanced Lithography	325
10.1	Random Variables and Processes	325
10.2	Phenomena	328

10.3 Modeling Approaches	332
10.4 Dependencies and Consequences	334
10.5 Summary	337
References	337
<i>Index</i>	343

Preface

State-of-the-art semiconductor lithography combines the most advanced optical systems of our world with cleverly designed and highly optimized photochemical materials and processes to fabricate micro- and nanostructures that enable our modern information society. The unique combination of applied optics, chemistry, and material science provides an ideal playground for scientists and engineers with an interest in applied natural sciences and technology. For many years the development of lithographic patterning techniques was almost exclusively scaling driven and focused on the improvement of resolution to support Gordon Moore's vision of cramming more components onto integrated circuits. Although this scaling has still not reached its ultimate limits, it gets increasingly difficult and expensive to generate even more and smaller patterns on semiconductor chips with the required uniformity and without defects. Future lithographic techniques for emerging novel applications will have to emphasize different requirements, including three-dimensional (3D) shape control, integration of novel (functional) materials, patterning over non-planar surfaces, flexible adaptation of the target patterns to the final application, etc. The knowledge and experience of semiconductor lithographers, which were gained during more than 50 years of technology development, provide an important key to the development of novel micro- and nanotechnology-driven applications.

The material for this book was compiled over many years of giving lectures on Optical Lithography: Technology, Physical Effects, and Modeling at the Friedrich-Alexander-University Erlangen-Nuremberg and in preparation for dedicated courses on special aspects of lithography in companies and as side events of conferences. The book is intended to help interested students with backgrounds in physics, optics, computational engineering, mathematics, chemistry, material science, nanotechnology, and other areas to get started in the fascinating field of lithographic techniques for nanofabrication. It should also help senior engineers and managers to widen their view on alternative methods and applications.

It is not the intention of this book to provide a complete description of all aspects of lithographic patterning techniques. Instead, the book focuses on the explanation of the fundamental principles of image and pattern formation.

These fundamental principles are demonstrated by simple, hopefully easy to understand, examples. The pros and cons of certain approaches and technology options are discussed. Extensive lists of references direct the reader to articles and books for further reading on special topics. To limit both the volume of this book and the time needed to write it, several important aspects of lithographic patterning technologies are not or are only rarely addressed in this book: Metrology and process control becomes increasingly important for high-volume lithographic fabrication. Advanced DUV and EUV projection lithographies require flexible fabrication, inspection, tuning, and repair of high-quality masks. Modern semiconductor fabrication involves a close interaction between the designers of electronic circuits and lithography process technology experts to provide a lithography-friendly design. Finally, there are many non-optical lithography techniques. These aspects are covered in several other books and review articles.

There are already several excellent books on semiconductor lithography. Why do we need another book on this topic? Most importantly, because lithography is one of the most dynamic fields of technology. It evolves due to the integration of new ideas and technologies with very different backgrounds. Research and development for modern lithography is highly multidisciplinary. The precise fabrication and characterization of nanopatterns requires an in-depth understanding of all involved physical and chemical effects. This book tries to support such understanding from a modeling-driven perspective, but without relying on heavy mathematics. The contents of this book reflects my special interest and background in applied optics, diffractive optics, rigorous modeling, and optimization of the interaction of light with micro- and nanostructures. Consequently, mask- and wafer-topography effects and related light-scattering effects are more extensively discussed than in other books on lithography. Finally, this book aims to bridge the gap between highly specialized engineers in semiconductor fabrication and scientists and other engineers exploring novel applications of lithographic patterning techniques for alternative applications.

Optical (projection) lithography combines the imaging of a mask or template onto a photosensitive material (photoresist) with the processing of the photoresist to transfer the optical image into a 3D pattern. The first chapter of the book provides an introduction to aerial image formation and photoresist processing. Typical metrics for the quantitative evaluation of images, of photoresist profiles, and of lithographic process variations are explained. Analysis of these metrics helps one to understand the impact of image and process enhancements that are discussed in the following parts of the book.

Chapter 2 describes the image formation by superposition of diffracted light that is transmitted through the opening (numerical aperture) of a projection lens and focused onto the photoresist. The resolution limit of

projection systems is governed by the Abbe–Rayleigh equation. The fundamentals of photoresist chemistry and processing are explained in Chapter 3. The next two chapters provide an overview of resolution enhancements that are employed to print smaller features with a given wavelength and numerical aperture of the optical system. Optical resolution enhancements include off-axis illumination (OAI), optical proximity correction (OPC), phase shift mask (PSM), and source mask optimization (SMO). Multiple patterning and directed self-assembly (DSA) employ special materials and processing techniques to fabricate smaller features. Extreme-ultraviolet (EUV) lithography with a wavelength of 13.5 nm extends optical projection lithography into the spectral range of soft x-rays. There are no materials that transmit light at these small wavelengths. As explained in Chapter 6, EUV lithography has to employ reflective optics and mask, but also novel light sources and photoresist materials. Chapter 7 provides an overview of alternative optical lithography methods, including approaches to 3D lithography.

The remaining chapters of the book are dedicated to the description of important physical and chemical effects in advanced optical and EUV lithography. Chapter 8 discusses the impact of wave aberrations, polarization effects, and randomly scattered light on the intensity distribution inside the photoresist. Mask- and wafer-topography effects, which are caused by the scattering of light from small features on the mask and on the wafer, are described in Chapter 9. The last chapter of the book is devoted to stochastic effects that are responsible for non-smooth photoresist profiles with a line edge roughness (LER) on the order of a few nanometers and for the occurrence of fatal patterning defects such as microbridging and the incomplete opening of contact holes.

The order of the chapters follows the sequence of my lecture at the Friedrich-Alexander University Erlangen-Nuremberg. It is intended to provide an interesting mixture of theoretical background and application of optics and chemistry, and a description of various technology options. Chapters 1–5 describe the general background of optics and photoresist chemistry and should be read in this sequence. The reading order of Chapters 6–10 can be adapted to the special interests of the reader. Chapter 7 provides a general overview of alternative (optical) lithography methods that are more interesting for various applications of micro- and nanofabrication beyond nanoelectronics. People with exclusive interest in lithography for (advanced) semiconductor fabrication can skip this chapter.

Joint research work and fruitful discussions with many colleagues and project partners provided invaluable input for the material in this book. I am most grateful for suggestions from experts on special sections of this book, particularly the following: Antony Yen from ASML, Hans-Jürgen Stock from Synopsys, John Sturtevant from Mentor Graphics, Marcus Müller from the

University of Göttingen, Michael Mundt from Zeiss SMT, Uzodinma Okoroanyanwu from Enx Labs, and Raluca Tiron from CEA-Leti.

Many thanks to all present and former members and students of the Fraunhofer IISB Computational Lithography and Optics group, especially to Peter Evanschitzky, Zelalem Belete, Hazem Mesilhy, Sean D'Silva, Abdalaziz Awad, Tim Fühner, Alexandre Vial, Balint Meliorisz, Bernd Tollkühn, Christian Motzek, Daniela Matiut, David Reibold, Dongbo Xu, Feng Shao, Guiseppe Citarella, Przemislaw Michalak, Shijie Liu, Temitope Onanuga, Thomas Graf, Thomas Schnattinger, Viviana Agudelo Moreno, and Zhabis Rahimi. All of these people contributed to our Fraunhofer IISB Development and Research LiTHOgraphy simulator Dr.LiTHO, which was used to generate most of the figures in this book. Many useful remarks and tips from members of the Fraunhofer Lithography group and from students of my lithography lecture at the Erlangen University helped me to improve the material for this book.

Special thanks to Dara Burrows and Tim Lamkins from SPIE Press for their many useful tips and editorial assistance.

Andreas Erdmann
Erlangen, December 2020

Abbreviations and Acronyms

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AFM	atomic force microscopy
AIMS™	Aerial Image Measurement System (Zeiss)
AltPSM	alternating PSM
AMOL	absorbance modulation optical lithography
AttPSM	attenuated PSM
BARC	bottom antireflective coating
CAR	chemically amplified resist
CD	critical dimension
CEL	contrast enhancement layer
CPL	chromeless phase shift lithography
CPU	central processing unit
CQuad	cross-polarized quadrupole with poles along x and y
CRAO	chief ray angle at object
CVD	chemical vapor deposition
DMD	digital mirror display
DNQ	diazonaphthoquinone
DOE	diffractive optical element
DoF	depth of focus
DoP	degree of polarization
DPP	discharge-produced plasma
DSA	directed self-assembly
DTD	dual-tone development
DUV	deep-ultraviolet
EMF	electromagnetic field
EPE	edge placement error
EUV	extreme-ultraviolet
FDTD	finite-difference time-domain
FEM	finite-element methods
FIT	finite-integral techniques

FLEX	focus-latitude enhancement exposure
FMM	Fourier modal method
FWHM	full width at half maximum
HEBS	high-energy-beam-sensitive (glass)
HMDS	hexamethyldisilazane
HSQ	hydrogen silesquioxane
IDEAL	innovative double exposure by advanced lithography
ILT	inverse lithography technology
ISTP	intermediate-state two-photon (materials)
LCD	liquid crystal display
LDWL	laser direct-write lithography
LDWP	laser direct-write material processing
LED	light-emitting diode
LELE	litho-etch-litho-etch
LER	line edge roughness
LFLE	litho-freeze-litho-etch
LPP	laser-produced plasma
LW	linewidth
LWR	linewidth roughness
MEEF	mask error enhancement factor
MEMS	micro-electro-mechanical system
Mo/Si	molybdenum silicon multilayer for EUV mask blanks
MoSi	molybdenum silicon alloy for DUV mask absorbers
NA	numerical aperture
NILS	normalized image log slope
NTD	negative-tone development
OAI	off-axis illumination
OMOG	opaque MoSi on glass
OOB	out-of-band (radiation)
OPC	optical proximity correction
OPD	optical path difference
ORMOCER	organically modified ceramic microresist
PAC	photoactive component
PAG	photoacid generator
PEB	post-exposure bake
PS- <i>b</i> -PMMA	polystyrene-block-poly(methyl methacrylate)
PSD	power spectral density
PSM	phase shift mask
PTD	positive-tone development
PV	process variation
RCEL	reversible contrast enhancement layer
RCWA	rigorous coupled-wave analysis
RMS	root mean square (error)

SADP	self-aligned double patterning
SEM	scanning electron microscope
SMO	source mask optimization
SOCS	sum of coherent systems
SPP	surface plasmon polariton
STED	stimulated emission depletion
TARC	top antireflective coating
TCC	transmission cross coefficient
TE	transverse electric
THR	threshold
THRS	threshold-to-size
TIS	total integrated scatter
TM	transverse magnetic
TPA	two-photon absorption
TPP	two-photon polymerization
TSI	top-surface imaging
UV	ultraviolet
VTRM	variable-threshold resist model

Frequently Used Symbols

A_{Dill}	photoresist bleachable absorption
B_{Dill}	photoresist unbleachable absorption
C_{Dill}	photoresist exposure sensitivity
D	exposure dose
I	intensity
P	pupil function
T	temperature
Z_i	Zernike coefficients
$[A]$	photoacid concentration
$[M]$	concentration of dissolution inhibitor or deprotected sides
$[Q]$	quencher concentration
α	absorption coefficient
ϵ	(relative) electric permittivity
ϵ_0	vacuum electric permittivity
η	diffraction efficiency
γ	photoresist contrast
κ_{1-5}	kinetic reaction coefficients
λ	wavelength
$\mathfrak{F}$	Fourier transform
μ_0	vacuum magnetic permeability
∇	nabla-operator
ϕ	phase (of light)
ρ	diffusion length
σ	spatial coherence factor
σ_{LER}	line edge roughness
τ	amplitude transmission
θ	diffraction or opening angle
$\tilde{D}$	diffusion coefficient
$\tilde{k}$	magnitude of wave vector
$\vec{E}$	electric field vector
$\vec{H}$	magnetic field vector

$\vec{k}$	wave vector
$\tilde{T}$	intensity transmission
c	vacuum velocity of light
d	(photoresist) thickness
$f_{x/y}$	spatial frequencies
h	Planck constant
k	extinction coefficient
$k_{1,2}$	technology factor in first/second Abbe–Rayleigh criterion
n	refractive index
p	pitch or period
t	time
$x/y/z$	spatial coordinates