# Optical and EUV Lithography

## A Modeling Perspective

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To Huixian, Laura, and Samuel.

# Contents

# 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

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*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-*b*-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

| | |
|---|---|
| $A_{\mathrm{Dill}}$ | photoresist bleachable absorption |
| $B_{\mathrm{Dill}}$ | photoresist unbleachable absorption |
| $C_{\mathrm{Dill}}$ | 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 |
| $\alpha$ | absorption coefficient |
| $\epsilon$ | (relative) electric permittivity |
| $\epsilon_0$ | vacuum electric permittivity |
| $\eta$ | diffraction efficiency |
| $\gamma$ | photoresist contrast |
| $\kappa_{1-5}$ | kinetic reaction coefficients |
| $\lambda$ | wavelength |
| $\mathfrak{F}$ | Fourier transform |
| $\mu_0$ | vacuum magnetic permeability |
| $\nabla$ | nabla-operator |
| $\phi$ | phase (of light) |
| $\rho$ | diffusion length |
| $\sigma$ | spatial coherence factor |
| $\sigma_{\mathrm{LER}}$ | line edge roughness |
| $\tau$ | amplitude transmission |
| $\theta$ | 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 |