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Optical Imaging in
Projection Microlithography

Alfred Kwok-Kit Wong

Tutorial Texts in Optical Engineering
Volume TT66

SPIE PRESS
Bellingham, Washington USA
Introduction to the Series

Since its conception in 1989, the Tutorial Texts series has grown to more than 60 titles covering many diverse fields of science and engineering. When the series was started, the goal of the series was to provide a way to make the material presented in SPIE short courses available to those who could not attend, and to provide a reference text for those who could. Many of the texts in this series are generated from notes that were presented during these short courses. But as stand-alone documents, short course notes do not generally serve the student or reader well. Short course notes typically are developed on the assumption that supporting material will be presented verbally to complement the notes, which are generally written in summary form to highlight key technical topics and therefore are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information accompanying the notes require the further explanation given during the instructor’s lecture. Thus, by adding the appropriate detail presented during the lecture, the course material can be read and used independently in a tutorial fashion.

What separates the books in this series from other technical monographs and textbooks is the way in which the material is presented. To keep in line with the tutorial nature of the series, many of the topics presented in these texts are followed by detailed examples that further explain the concepts presented. Many pictures and illustrations are included with each text and, where appropriate, tabular reference data are also included.

The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, and micromachining. When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the processes and technologies under discussion.

It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

Arthur R. Weeks, Jr., University of Central Florida
Tutorial Texts Series Editor
dedicated to
my grandmother

獻給 我的祖母
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Lithographers have pushed optical projection printing well beyond the imagined limits. Even microwave engineers, quantum physicists, and photonic scientists would not have expected the majority of integrated circuit chips in existence today to have feature sizes below the fundamental half-wavelength limit of waveguide modes, eigenstates, and stop bands. This has been accomplished by the introduction of innovations by many technologists. These innovations include off-axis illumination, phase-shifting masks, measurement of aberrations and flare, high-NA imaging, immersion, resist coatings, and photomask precompensation for optical and even process effects. Equally as important has been the ability to integrate these innovations as part of a complete system and simultaneously optimize the interplay of their key parameters.

Here for the first time is an integrated mathematical view of the physics and numerical modeling of projection printing that efficiently covers the full spectrum of the important concepts. This book is far broader than the material found in any optical text or reference book. Alfred Wong works from his firsthand involvement in semiconductor manufacturing and his interest in theoretical concepts. His writing is like the circuits he once designed in that it performs the desired function quickly, without wasted energy, space or glitches. Alfred Wong pulls together the diverse aspects in a common framework with a solid physical foundation. The framework is used to give intuitive explanations, models for quantitative characterization, tolerances for controlling variations and insight into simulation methodologies. The broad scope includes many second-order effects that dominate production and design for manufacturing strategies.

Specifically, the value of this book is that it systematically redevelops and extends in one notation the rather challenging and extensive set of theoretical concepts used in advanced projection printing systems and their numerical simulation. In a sense, it is all of those one-assumption-at-a-time steps and messy equations that there is never time nor space for in a conference paper. By starting from the basics of Maxwell’s equations, ray-tracing and diffraction, the important conceptual elements associated with them are nicely summarized. The extension of the formulation of imaging to the full optical system gives a particularly clear treatment of several advanced concepts. These include the relationship of the illumination spec-
trum to the spatial degree of coherence across the mask, the simplification of the formulation when the image only depends on differences in distances, and when the diffraction efficiency of the mask is independent of the angle of incidence.

Through a simplifying assumption about the mask spectrum, the formulation is extended to give both new and previously known equations for image modulation, cut-off limits, mask requirements, and unwanted side effects. Full formulations are made for the new high-NA challenges of polarization, vector imaging, resist materials and immersion. Both aberration effects on imaging and the advanced theoretical concepts for monitoring them are considered. The parallel treatment of the Abbe, the Hopkins, and the more advanced sum of coherent system approaches for image calculation clarifies their methodologies and advantages. The identification and parameterization of some eleven sources of variability in imaging is in itself a framework for characterizing exposure tools.

Readers with a good working knowledge of calculus can follow through the step by step development. A technologist may want to get the general idea of each concept and then skip ahead to the key characterization equations that result. Even the casual reader will gain a perspective on the key concepts and this will likely help facilitate dialog among technologists much in the way that the $k_1$ and $k_2$ parameters of Burn Lin have done.

This book is a tribute to the advanced concepts and innovation used in the field of projection printing over the last 30 years. Alfred Wong offers rigorous underpinning, clarity in systematic formulation, physical insight into emerging ideas, as well as a system level view of the parameter tolerances required in manufacturing. This book is very much the “Born and Wolf of Projection Printing” and Alfred is our seminal chanticleer for the concepts that support this practice.

ANDREW R. NEUREUTHER
Preface

Optical projection lithography will remain the predominant microlithography technology in the foreseeable future. With 193-nm radiation and an immersed numerical aperture of 1.38, the $k_1$ factor of a 45-nm feature is 0.32. Fabrication at such low $k_1$ factors requires both image enhancement and tight control of process fluctuations. A prerequisite to successful resolution improvement and variability control is an understanding of optical imaging fundamentals. This book aims to explicate the principles of image formation in projection microlithography, balancing intuitive understanding with mathematical rigor such that the readers can both distill the essence of the physics and form a firm foundation from which imaging techniques can be analyzed and developed.

Chapter 1 derives the properties of light that are relevant for analysis of image formulation in photolithography. From Maxwell’s equations we deduce that light is a transverse wave, with the electric and magnetic field vectors vibrating in a plane that is normal to its direction of propagation. When light interacts with objects whose physical dimensions are large compared with its wavelength, we can neglect the field vectors under many circumstances, and approximate Maxwell’s equations by laws formulated in the language of geometry. This topic of geometrical optics is treated in Chapter 2. To describe light transmission through apertures whose dimensions are comparable to or smaller than the wavelength, however, we need to resort to diffraction theory, a subject we discuss in Chapter 3.

Photomasks used in optical lithography require illumination by light sources that are physically extended. Despite incoherence between source points making up the extended source, vibrations at different object points are correlated due to diffraction of the illumination optics. Chapter 4 develops the concept of spatial coherence and the associated mutual intensity function that enable mathematical description of partially coherent imaging scenarios. The resulting equations are used in Chapter 5 to examine the theoretical and practical limits of the minimum dimension and the minimum half-pitch.

Based on the foundation of the first five chapters, we further our development to address topics that are becoming crucial as microlithographers push the limits of optical imaging. The use of high-numerical-aperture lenses necessitates consideration of the directional nature of light vibrations. Chapter 6 formulates the vector
theory of imaging that is applicable for immersion lithography in the presence of a stratified wafer stack. Simultaneous with increasing numerical aperture are stringent aberration requirements. The impact of lens aberrations is explored through diffraction theory in Chapter 7.

Our abilities to harness the power of affordable computers to predict images of object patterns, and to optimize the photomask and exposure configuration given a desired image are becoming indispensable. Chapter 8 discusses common numerical approaches for imaging simulation. Variability control is also integral for successful low-$k_1$ lithography, as both layout shapes and image tolerance are shrinking rapidly compared with $\lambda_0/NA$. Chapter 9 discusses significant causes of patterning nonuniformity arising from optical imaging, and techniques for their measurement.

I am thankful to many friends and colleagues during the course of this project. In the first place, I am grateful to Dr. Anthony Yen for encouraging me to write a text on this topic. I am indebted to Dr. Timothy Brunner, Dr. Gregg Gallatin, Professor Andrew Neureuther, Dr. Alan Rosenbluth, Dr. Frank Schellenberg, and Dr. Yen for their comments and their meticulous review of the manuscript. I am much beholden to my dissertation advisors, Professor Andrew Neureuther and Professor William Oldham, for introducing me to microlithography and for their lessons of wisdom. It is an honor to have the Foreword of this book written by Professor Neureuther.

I am obliged to Dr. Gallatin and Dr. Yen for their suggestions on development of the Rayleigh-Sommerfeld diffraction formula in §3.5, and to Dr. Rosenbluth for his exposition of the obliquity factor in §4.2. I would also like to acknowledge Dr. Wilhelm Ulrich’s permission for reproduction of the illustration in Fig. 2.6. Publication of this book is the culmination of years of work by the SPIE Press staff, to whom I owe much thanks.

I have many fond memories in writing this text, as my wife Aida and I often agonize side by side on our respective writings. I hope the readers will also enjoy this book, and privilege me with suggestions for improvement.

ALFRED WONG KWOK-KIT
黄国杰
List of Symbols

SI units are used unless otherwise stated. Real quantities are generally denoted by small letters, complex quantities by capitals, and vector quantities are expressed in bold type. There may be exceptions where confusion is unlikely to arise.

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<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>e</td>
<td>electric field</td>
</tr>
<tr>
<td>d</td>
<td>electric displacement</td>
</tr>
<tr>
<td>h</td>
<td>magnetic field</td>
</tr>
<tr>
<td>b</td>
<td>magnetic induction</td>
</tr>
<tr>
<td>j</td>
<td>electric current density</td>
</tr>
<tr>
<td>E, D, H, B, J</td>
<td>field phasors</td>
</tr>
<tr>
<td>ρ_e</td>
<td>electric charge density</td>
</tr>
<tr>
<td>σ_c</td>
<td>electric conductivity</td>
</tr>
<tr>
<td>ε_e</td>
<td>permittivity</td>
</tr>
<tr>
<td>µ_m</td>
<td>magnetic permeability</td>
</tr>
<tr>
<td>n</td>
<td>refractive index; integer</td>
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<tr>
<td>κ</td>
<td>extinction coefficient</td>
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<tr>
<td>η</td>
<td>characteristic impedance</td>
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<tr>
<td>w_e</td>
<td>electric energy density</td>
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<tr>
<td>w_m</td>
<td>magnetic energy density</td>
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<tr>
<td>S</td>
<td>Poynting vector</td>
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<tr>
<td>u, v</td>
<td>scalar field components</td>
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<tr>
<td>U, V</td>
<td>field component phasors</td>
</tr>
<tr>
<td>ω</td>
<td>angular frequency</td>
</tr>
<tr>
<td>ν</td>
<td>(temporal) frequency</td>
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<tr>
<td>λ</td>
<td>wavelength</td>
</tr>
<tr>
<td>k</td>
<td>wave number</td>
</tr>
<tr>
<td>k</td>
<td>wave vector</td>
</tr>
<tr>
<td>c</td>
<td>speed of light</td>
</tr>
<tr>
<td>Δt_coh</td>
<td>coherence time</td>
</tr>
<tr>
<td>Δl_coh</td>
<td>coherence length</td>
</tr>
<tr>
<td>φ(r)</td>
<td>optical path</td>
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### Symbols

- $f$: focal length
- $M, M_{\text{lateral}}$: lateral magnification (positive quantity)
- $M_{\text{angular}}$: angular magnification
- $M_{\text{longitudinal}}$: longitudinal magnification
- $I$: intensity
- $\hat{H}(\hat{x}, \hat{y})$: optical system transfer function
- $\hat{\tilde{H}}(\hat{f}, \hat{g})$: coherent frequency transfer function
- $\hat{G}(\hat{f}, \hat{g})$: auto-correlation function of $\hat{H}(\hat{f}, \hat{g})$
- $\hat{E}(\hat{\rho})$: obliquity factor
- $\Gamma(P_1, P_2; \tau)$: mutual coherence function
- $\gamma(P_1, P_2; \tau)$: complex degree of coherence
- $\hat{J}(P_1, P_2)$: mutual intensity
- $\mu(P_1, P_2)$: complex degree of coherence
- $\hat{O}(\hat{x}, \hat{y})$: object function (field)
- $\hat{O}(\hat{f}, \hat{g})$: object spectrum
- $\tilde{TCC}(\hat{f}', \hat{g}'; \hat{f}'', \hat{g}'')$: transmission cross-coefficient
- $\hat{x}, \hat{y}$: normalized spatial coordinates
- $\hat{f}, \hat{g}$: normalized frequencies
- $\hat{\rho}$: $\hat{\rho} = \sqrt{f^2 + g^2}$
- $\hat{\rho}_\theta$: $\hat{\rho}_\theta = \hat{\rho} \sin \theta_{\text{obj}}$
- $\theta_{\text{obj}}$: semi-aperture angle at the image plane
- NA: numerical aperture
- $p$: pattern period (pitch)
- $p_{\text{min}}$: minimum resolvable pitch
- $h_{\text{min}}$: minimum resolvable half-pitch
- $k_{1\text{half-pitch}}$: normalized half-pitch of interest
- $k_1; d$: normalized dimension of interest
- $t_{\text{bg}}$: object background transmittance (field)
- $t_{fg}$: object foreground transmittance (field)
- $P$: degree of polarization; a point
- $\mu_{xx}, \mu_{yy}, \mu_{xy}, \mu_{yx}$: complex correlation factor
- $J$: coherency matrix
- $\rho_\perp, \rho_\parallel$: reflection coefficients (field)
- $\tau_\perp, \tau_\parallel$: transmission coefficients (field)
- $R$: reflectivity (intensity)
- $T$: transmissivity (intensity)
- $M$: characteristic matrix of stratified medium
Symbols

Φ  aberration function
ΔΦ rms  root-mean-square deviation of wavefront
Z j  jth Zernike polynomial
sinc(x)  sinc function: sinc(x) = sin(πx)/(πx)
J_n(x)  Bessel functions
circ(\hat{f}, \hat{g}, σ)  circle function
Q(x,y)  quadrant function
D_0  dose to clear positive resist or harden negative resist
D_{print}  dose supplied in exposure
I_{threshold}  intensity threshold
R. U.  Rayleigh unit of defocus
r  distance
\mathbf{r}  position vector
\mathbf{\hat{s}}  unit vector
\mathbf{\hat{n}}  unit surface normal
\mathbf{\hat{l}}  unit tangent
dl  differential curve element
dS  differential surface element
dV  differential volume element
C  curve
S  surface
V  volume
\nabla \times  curl
\nabla \cdot  divergence
\nabla  gradient
\nabla^2  Laplacian
Optical Imaging in Projection Microlithography