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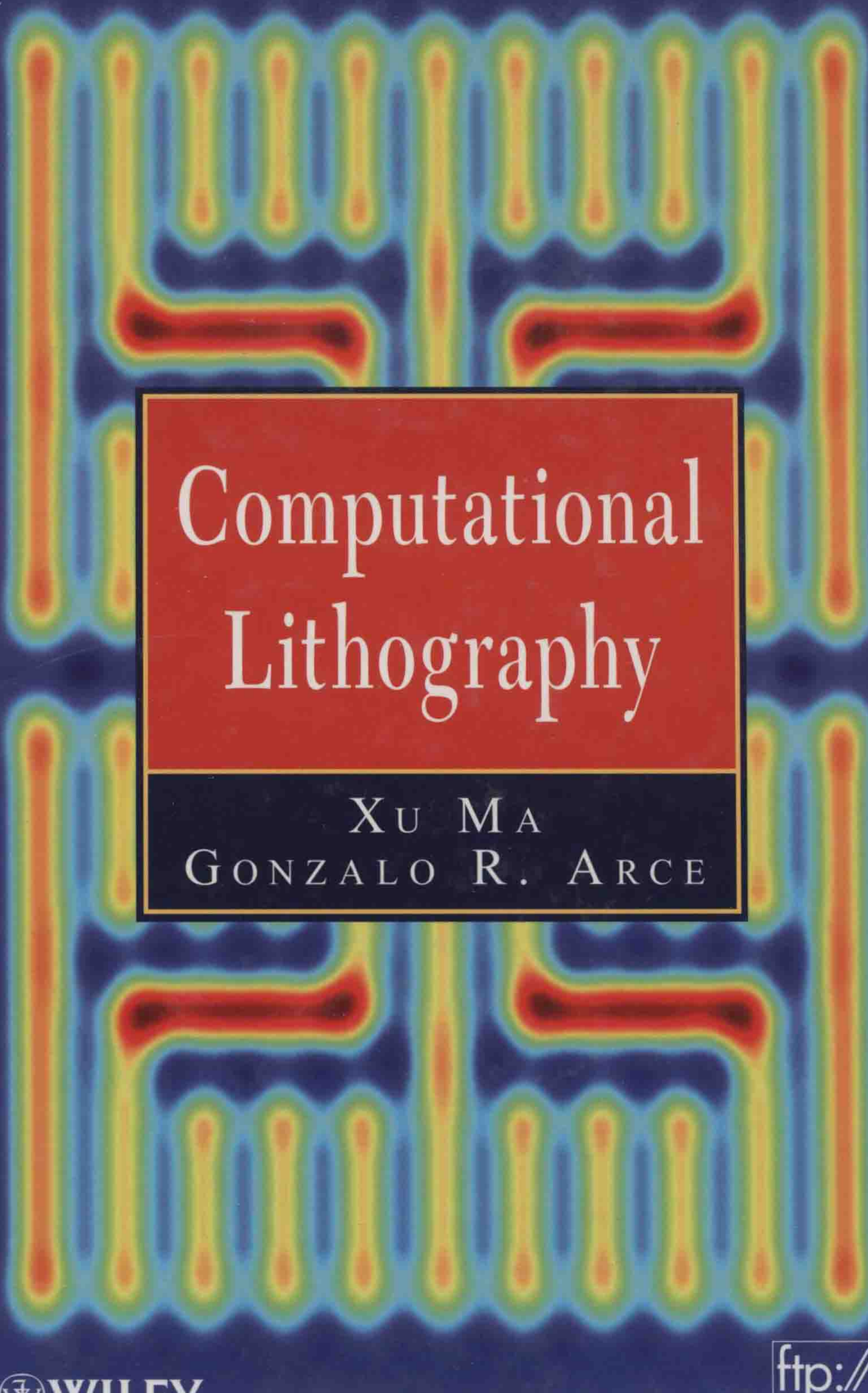

Computational Lithography

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XU MA AND GONZALO R. ARCE

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To Our Families

Preface

Moore's law and the integrated circuit industry have led the electronics industry to make technological advances that have transformed the society in many ways. Wireless communications, the Internet, and the astonishing new modalities in medical imaging have all been realized by the availability of the computational power inside IC processors. At this pace, if Moore's law continues to hold for the next couple of decades, the computational power of integrated circuits will play a key role in unveiling the secrets of the working mechanisms behind the living brain, it will also be the enabler in the advances of health informatics and of the solutions to other grand challenges singled out by the National Academy of Engineering. Maintaining this pace, however, requires a constant search by the semiconductor industry for new approaches to reduce the size of transistors. At the heart of Moore's law is optical lithography by which ICs are patterned, one layer at a time. By steadily reducing the wavelength of light in optical lithography, the IC industry has kept pace with the Moore's law. In the past two decades, the wavelength used in optical lithography has shrunk down to today's standard of 193 nm. This strategy, however, has become less certain as wavelengths shorter than 193 nm cannot be used without a major overhaul of the lithographic process, since shorter wavelengths are absorbed by the optical elements in lithography. While new lithography methods are under development, such as extreme ultraviolet (EUV) at the wavelength of 13 nm, the semiconductor industry is relying more on resolution enhancement techniques (RETs) that aim at coaxing light into resolving IC features that are smaller than its wavelength. RETs are becoming increasingly important since their implementation does not require significant changes in fabrication infrastructure.

The laws of optical wave propagation determine that the smallest resolvable features in optical lithography are proportional to the wavelength used and inversely proportional to the numerical aperture of the underlying optical system. Reducing the optical wavelength in optical lithography and exploring new methods to increase the numerical aperture are the two ways in which the semiconductor industry has made advances to keep up with the Moore's law. A third approach is that of reducing the proportionality constant k through resolution enhancement techniques. RETs manipulate the amplitude, phase, and direction of light propagation impinging on the lithographic mask to reduce the proportionality constant. In particular, optical proximity correction (OPC) modifies the wavefront amplitude, off-axis illumination (OAI) modifies the light wave direction of propagation, and phase-shifting masks manipulate the phase. OPC methods add assisting subresolution features on the mask pattern to correct the distortion of the optical projection systems. PSM methods modify both the amplitude and phase of the mask patterns. OAI methods exploit various illumination configurations to enhance the resolution. Used individually or in combination, RETs have proven effective in subwavelength lithography.

The literature on RET methods has been growing rapidly in journals and conference articles. Most of the methods used in RET exploit the rule-based principles developed and refined by practicing lithographers. Several excellent books on optical lithography have appeared in print recently. Wong provides a tutorial reference focusing on RET technology in optical lithography systems [92]. Wong subsequently extended this previous work and provided an integrated mathematical view of the physics and numerical modeling of optical projection lithography [93]. Levinson addressed and discussed an overall view of lithography, from the specific technical details to economical costs [36]. Mack captured the fundamental principles of the incredibly fast-changing field of semiconductor microlithography from the underlying scientific principles of optical lithography [49]. While the rule-based RET methods will continue to provide a valuable tool set for mask design in optical lithography, the new frontier for RETs will be on the development of tools and methods that capitalize from the ever rapid increase of computational power available for the RET design.

This book first aims at providing an adequate summary of the rule-based RET methodology as well as a basic understanding of optical lithography. It can thus serve as a tutorial for those who are new to the field. Different from the above-mentioned textbooks, this book is also the first to address the computational optimization approaches to RETs in optical lithography. Having vast computational resources at hand, computational lithography exploits the rich mathematical theory and practice of inverse problems, mathematical optimization, and computational imaging to develop optimization-based resolution enhancement techniques for optical lithography. The unique contribution of the book is thus a unified summary of the models and the optimization methods used in computational lithography. In particular, this book provides an in-depth and elaborate discussion on OPC, PSM, and OAI RET tools that use model-based mathematical optimization in their design. The book starts with an introduction of optical lithography systems, electric magnetic field principles, and fundamentals of optimization. Based on this preliminary knowledge, this book describes different types of optimization algorithms to implement RETs in detail. Most of the optimization algorithms developed in this book are based on the application of the OPC, PSM, and OAI approaches and their combinations. In addition, mathematical derivations of all the optimization frameworks are presented as appendices at the end of the book.

The Matlab's m-files for all the RET methods described in the book are provided at ftp://ftp.wiley.com/public/sci_tech_med/computational_lithography. All the optimization tools are made available at ftp://ftp.wiley.com/public/sci_tech_med/computational_lithography as Matlab's m-files. Readers may run and investigate the codes to understand the algorithms. Furthermore, these codes may be used by readers for their research and development activities in their academic or industrial organizations. The contents of this book are tailored for both entry-level and experienced readers.

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Acronyms

ACAA	Average Coherence Approximation Algorithm
BL	Boundary Layer
CD	Critical Dimension
CMTF	Critical Modulation Transfer Function
DCT	Discrete Cosine Transform
DEL	Double Exposure Lithography
DPL	Double Patterning Lithography
DUVL	Deep Ultraviolet Lithography
EBL	E-Beam Lithography
EUVL	Extreme Ultraviolet Lithography
FDTD	Finite-Difference Time-Domain Method
FFT	Fast Fourier Transform
IC	Integrated Circuit
ILT	Inverse Lithography Technique
ITRS	International Technology Roadmap for Semiconductors
MOS	Metal Oxide Silicon
MoSi	Molybdenum Silicide
MTF	Modulation Transfer Function
NA	Numerical Aperture
OAI	Off-Axis Illumination
OPC	Optical Proximity Correction
PAC	Photoactive Compound
PCI	Partially Coherent Illumination
PSF	Point Spread Function
PSM	Phase-Shifting Mask
RET	Resolution Enhancement Technique
SMO	Simultaneous Source and Mask Optimization
SNR	Signal-to-Noise Ratio
SOCS	Sum of Coherent System
SR1	Symmetric Rank One
SVD	Singular Value Decomposition
WG	Waveguide Method

Contents

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1

Introduction

1.1 OPTICAL LITHOGRAPHY

Complex circuitries of modern microelectronic devices are created by building and wiring millions of transistors together. At the heart of this technology is optical lithography. Optical lithography technology is similar in concept to printing, which was invented more than 3000 years ago [92]. In optical lithography systems, a mask is used as the template, on which the target circuit patterns are carved. A light-sensitive polymer (photoresist) coated on the semiconductor wafer is used as the recording medium, on which the circuit patterns are projected. Light is used as the writing material, which is transmitted through the mask, thus optically projecting the circuit patterns from the mask to the wafer. The lithography steps are typically repeated 20–30 times to make up a circuit, where each underprinting pattern must be aligned to the previously formed patterns. After a lengthy lithography process, a complex integrated circuit (IC) structure is built from the interconnection of basic transistors. Moore's law, first addressed by Intel cofounder G. E. Moore in 1965, describes a long-term trend in the history of computing hardware. Moore's law predicted that the critical dimension (CD) of the IC would shrink by 30% every 2 years. This trend has continued for almost half a century and is not expected to stop for another decade at least. As the dimension of IC reduces following Moore's law, optical lithography has become a critical driving force behind microelectronics technology. During the past few decades, our contemporary society has been transformed by the dramatic increases in electronic functionality and lithography technology. Two main factors of optical lithography attract the attention of scientists and engineers. First, since lithography is the cardinal part of the IC fabrication process, around 30% of the cost of IC manufacturing is attributed to the lithography steps. Second, the advance and ultimate performance of lithography determine further advances of the critical size reduction in IC and thus transistor speed and silicon area. Both of the above aspects drive optical lithography into one of the most challenging places in current IC manufacturing technology. Current commercial optical lithography systems are able to image features smaller than 100 nm (about one-thousandth the thickness of human hair) of the IC pattern. As the dimension of features printed on the wafer continuously

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shrinks, the diffraction and interference effects of the light become very pronounced resulting in distortion and blurring of the circuit patterns projected on the wafer. The resolution limit of the optical lithography system is related to the wavelength of light and the structure of the entire imaging system. Due to the resolution limits of optical lithography systems, the electronics industry has relied on *resolution enhancement techniques* (RETs) to compensate and minimize mask distortions as they are projected onto semiconductor wafers. There are three RET techniques: optical proximity correction (OPC), phase-shifting masks (PSMs), and off-axis illumination (OAI). OPC methods add assisting subresolution features on the mask pattern to correct the distortion of the optical projection systems. PSM methods modify both the amplitude and phase of the mask patterns. OAI methods exploit various illumination configurations to enhance the resolution.

1.1.1 Optical Lithography and Integrated Circuits

Optical lithography is at the heart of integrated circuit manufacturing. Generally, three stages are involved in the IC creation process: design, fabrication, and testing [92]. The flow chart of the IC creation process is illustrated in Fig. 1.1.

First, the IC products are defined and designed. In this stage, the abstract functional units such as amplifiers, inverters, adders, flip-flops, and multiplexers are translated into physically connected elements such as metal-oxide-silicon (MOS) transistors. Subsequently, the design results of the physically connected elements are exploited in the second stage of fabrication, where the desired circuit patterns are carved on the masks, which are to be replicated onto the wafers through an optical lithography process. After a series of development processes applied to the exposed wafer such as etching, adding impurities, and so on, the ICs are packaged and tested for functional

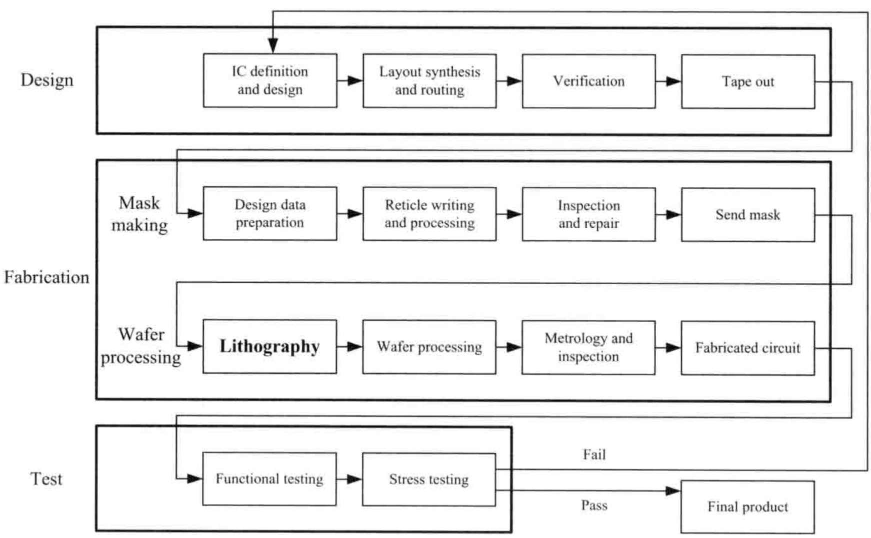

Figure 1.1 The flow chart of the IC creation process.

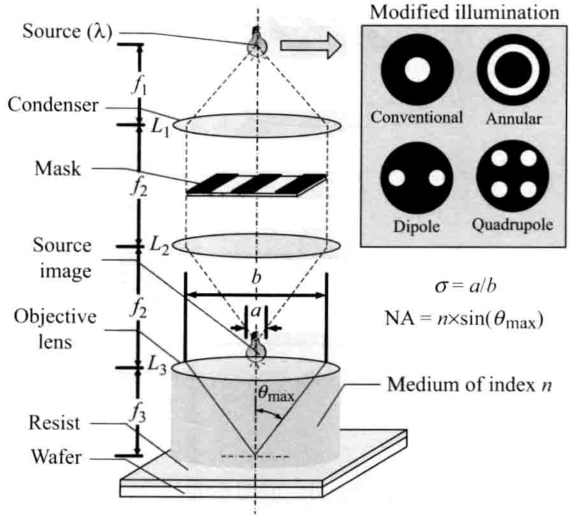

Figure 1.2 The scheme of a typical optical lithography system.

correctness and durability. During the entire IC creation process, optical lithography plays a significant role and is mainly responsible for the miniaturization of IC sizes.

Similar to printing, optical lithography uses light to print circuit patterns carried by the mask onto the wafer. The optical lithography system comprises four basic parts: an illumination system, a mask, an exposure system, and a wafer [92]. A typical optical lithography processing system is shown in Fig. 1.2. In Fig. 1.2, n is the diffraction index of the medium surrounding the lens. $\theta_{\max}$ is the maximum acceptable incident angle of the light exposed onto the wafer. The numerical aperture of the optical lithography system is defined as $\text{NA} = n \sin\theta_{\max}$. The partial coherence factor $\sigma = \frac{a}{b}$ is defined as the ratio between the size of the source image and that of the pupil. Partial coherence factor measures the physical extent of the illumination. Larger partial coherence factor represents larger illumination and lower degree of coherence of the light source [92].

In the optical lithography process, the output pattern sought on the wafer is carved on the mask. Light emitted from the illumination system is transmitted through the mask, where the electric field is modulated by the transparent clear quartz areas and opaque chrome areas on the mask. Subsequently, the modulated electric field propagates through the exposure system and is finally projected onto the light-sensitive photoresist layer coated on the wafer, which is then partially dissolved by the solvents. The details of the photoresist processes and characteristics are discussed in Section 1.3.

1.1.2 Brief History of Optical Lithography Systems

Early optical lithography systems used contact lithography methods, where the mask is pressed against the photoresist-coated wafer during the exposure [11]. Since neither

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