RESOLUTION ENHANCEMENT TECHNIQUES

IN OPTICAL LITHOGRAPHY

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ALFRED KWOK-KIT WONG

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Introduction to the Series

The Tutorial Texts series was initiated in 1989 as a way to make the material presented in SPIE short courses available to those who couldn't attend and to provide a reference book for those who could. Typically, short course notes are developed with the thought in mind that supporting material will be presented verbally to complement the notes, which are generally written in summary form, highlight key technical topics, and are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information included with the notes require further explanation given in the instructor's lecture. As stand-alone documents, short course notes do not generally serve the student or reader well.

Many of the Tutorial Texts have thus started as short course notes subsequently expanded into books. The goal of the series is to provide readers with books that cover focused technical interest areas 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. Keeping in mind 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.

To date, the texts published in this series have encompassed a wide range of topics, from geometrical optics to optical detectors to image processing. 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 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.

During the past nine years, my predecessor, Donald C. O'Shea, has done an excellent job in building the Tutorial Texts series, which now numbers nearly forty books. It has expanded to include not only texts developed by short course instructors but also those written by other topic experts. It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include emerging as well as mature subjects in optics, photonics, and imaging.

Arthur R. Weeks, Jr.
Invivo Research Inc. and University of Central Florida

dedicated to
my mother
and
the memory of my father

Contents

Preface

The acceleration of integrated circuit miniaturization is challenging lithographers to push the limit of optical lithography by ever more precise engineering and innovations. As shrinkage of integrated circuit device dimension outpaces introduction of shorter-exposure wavelengths and higher-numerical-aperture lenses, resolution enhancement techniques are becoming essential in optical lithography. These enhancement techniques have been maturing over the last two decades, and their evolution has been reported in many journal articles and conference proceedings. This book attempts to summarize these numerous publications with discussion of both the theoretical and practical aspects of the commonly used techniques. It is hoped that this text can serve a few purposes: as a tutorial for those who are new to the field, as a reference for practicing lithographers, and as a participant in the discussion on the resolution limit of optical lithography.

This text originated from a one-day course that I teach with Dr. Lars Liebmann and Dr. Richard Ferguson. Focusing on practical issues, the course objective is to provide enough information such that students can form an opinion on the feasibility and impact of resolution enhancement techniques on technologies and processes of their interest. In writing this text, I have expanded the course materials by including more basic materials as well as providing more in-depth theoretical discussions and literature references on the topics treated. Although an understanding of optical lithography is useful, extensive knowledge in optical imaging is not essential for comprehension of the materials.

I am thankful to many friends and colleagues for their advice and help. In the first place, I am grateful to the initiator of our short course, Dr. Lars Liebmann, for insightful discussions and comments, especially on alternating phase-shifting masks and optical proximity correction. I have also learnt much from Dr. Richard Ferguson on the many practicalities concerning photolithography. I would also like to thank Dr. Timothy Brunner, Dr. Donis Flagello, Dr. Marc Levenson, Dr. Scott Mansfield, and Dr. Anthony Yen for critical reviews of the manuscript.

I am indebted to my graduate school advisors, Professor Andrew

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Finally I would like to thank my close friends and family for support throughout this project. In particular, Professor Chu Chong-Sun's dedication to physics has always been a source of inspiration. This text could not have been completed in a timely fashion without my wife, Professor Aida-Yuen Wong, whose all-rounded support enabled me to concentrate on this project.

Hong Kong ALFRED WONG KWOK-KIT
January 2001

List of symbols

λ	wavelength
NA	numerical aperture
θ	maximum diffracted angle captured by pupil ($\sin\theta = NA$)
k_1	measure of lithography aggressiveness
σ	partial coherence factor
x, y	spatial variables
$\hat{x}$, $\hat{y}$	normalized spatial variables ($\hat{x} = x\frac{NA}{\lambda}$, $x = \hat{x}\frac{\lambda}{NA}$)
r	$\sqrt{x^2 + y^2}$
f, g	spatial frequency variables
$\hat{f}$, $\hat{g}$	normalized spatial frequency variables ($\hat{f} = f\frac{\lambda}{NA}$, $f = \hat{f}\frac{NA}{\lambda}$)
f_s, g_s	spectrum shift due to angle of incident light
$I(x,y)$	image intensity at (x,y)
$\tilde{P}(f,g)$	pupil function
$\tilde{J}(f,g)$	mutual intensity (effective source function)
$O(x,y)$	object (mask) function
$\tilde{O}(f,g)$	mask spectrum
$O_x(x)$	one-dimensional mask function
$\tilde{O}_x(f,g)$	one-dimensional mask spectrum
M	demagnification of exposure system
d	pattern dimension ($\hat{d} = d\frac{NA}{\lambda} = k_1$)
d_{min}	minimum resolvable dimension
p	pattern spatial period ($\hat{p} = p\frac{NA}{\lambda}$, $p = \hat{p}\frac{\lambda}{NA}$)
p_{min}	pitch resolution limit
h	pattern half pitch ($h = p/2$, $\hat{h} = h\frac{NA}{\lambda}$, $h = \hat{h}\frac{\lambda}{NA}$)
h_{min}	half pitch resolution limit ($p_{\text{min}}/2$)
$\mu(\hat{r})$	complex degree of coherence
$\hat{R}_{\text{opt}}$	optical interaction range
Δ	design grid

Δ_{app}	apparent grid
d_{etch}	etch depth of alternating PSM
T	attenuated PSM background intensity transmission
t	attenuated PSM field transmission ($\sqrt{T}$)
I_{sidelobe}	side lobe intensity
$I_{\mathrm{threshold}}$	threshold intensity
E_0	dose to clear (dose to gel)
L_{diff}	photoresist diffusion length
γ	photoresist contrast
n, m	integer
$\mathbf{Z}$	the set of integers
$\mathbf{Z_0}^+$	zero and the set of positive integers
i	$\sqrt{-1}$
$\delta(x)$	Dirac delta function
$\mathbf{J_1}(x)$	Bessel function of the first kind and first order
$\mathrm{sinc}(z)$	sinc function ($\frac{\sin(\pi z)}{\pi z}$)
$\mathrm{circ}(\nu)$	circle function

List of abbreviations

ACLV	across-chip linewidth variation
ARC	antireflective coating
ASIC	application-specific integrated circuit
BIM	binary intensity mask
CAD	computer-aided design
CD	critical dimension ($\mathrm{CD}=k_1\frac{\lambda}{NA}$)
$\mathrm{CD}_{\mathrm{min}}$	minimum critical dimension
CMP	chemical mechanical polishing
COG	chromium-on-glass
CoO	cost of ownership
DOF	depth of focus
DRAM	dynamic random access memory
EL	exposure latitude
IC	integrated circuit
ILD	interlayer dielectric
LER	line edge roughness
MEF/MEEF	mask error (enhancement) factor
MOS	metal-oxide-silicon
MOSFET	metal-oxide-silicon field effect transistor
MTF	modulation transfer function
NILS	normalized image log slope
OAI	off-axis illumination
OPC	optical proximity correction
PSF	point spread function
PSM	phase-shifting mask
RET	resolution enhancement technique
RIE	reactive ion etch
R. U.	Rayleigh unit of depth of focus ($\frac{\lambda}{2NA^2}$)
SEM	scanning electron micrograph
TCC	transmission cross-coefficient
TW	total window
UDOF	usable depth of focus

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