Resolution Enhancement Techniques in Optical Lithography
Tutorial Texts Series

- Resolution Enhancement Techniques in Optical Lithography, Alfred Kwok-Kit Wong, Vol. TT47
- Copper Interconnect Technology, Christoph Steinbrüchel and Barry L. Chin, Vol. TT46
- Fundamentals of Contamination Control, Alan C. Tribble, Vol. TT44
- Evolutionary Computation: Principles and Practice for Signal Processing, David Fogel, Vol. TT43
- Infrared Optics and Zoom Lenses, Allen Mann, Vol. TT42
- Introduction to Adaptive Optics, Robert K. Tyson, Vol. TT41
- Fractal and Wavelet Image Compression Techniques, Stephen Welstead, Vol. TT40
- Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis, Valery Tuchin, Vol. TT38
- Design and Mounting of Prisms and Small Mirrors in Optical Instruments, Paul R. Yoder, Jr., Vol. TT32
- Basic Electro-Optics for Electrical Engineers, Glenn D. Boreman, Vol. TT31
- Optical Engineering Fundamentals, Bruce H. Walker, Vol. TT30
- Introduction to Radiometry, William L. Wolfe, Vol. TT29
- Lithography Process Control, Harry J. Levinson, Vol. TT28
- An Introduction to Interpretation of Graphic Images, Sergey Ablameyko, Vol. TT27
- Thermal Infrared Characterization of Ground Targets and Backgrounds, P. Jacobs, Vol. TT26
- Introduction to Imaging Spectrometers, William L. Wolfe, Vol. TT25
- Mounting Lenses in Optical Instruments, Paul R. Yoder, Jr., Vol. TT21
- Introduction to Wavefront Sensors, Joseph M. Geary, Vol. TT18
- Integration of Lasers and Fiber Optics into Robotic Systems, J. A. Marszalec, E. A. Marszalec, Vol. TT17
- Introduction to Optical Testing, Joseph M. Geary, Vol. TT15
- Diuzonaphthoquinone-based Resists, Ralph Dammel, Vol. TT11
- Infrared Window and Dome Materials, Daniel C. Harris, Vol. TT10
- An Introduction to Optics in Computers, Henri H. Arsenault, Yunlong Sheng, Vol. TT8
- Digital Image Compression Techniques, Majid Rabbani, Paul W. Jones, Vol. TT7
- Aberration Theory Made Simple, Virendra N. Mahajan, Vol. TT6
- An Introduction to Biological and Artificial Neural Networks for Pattern Recognition, Steven K. Rogers, Matthew Kabrisky, Vol. TT4
- Infrared Fiber Optics, Paul Klocok, George H. Sigel, Jr., Vol. TT2
- Spectrally Selective Surfaces for Heating and Cooling Applications, C. G. Granqvist, Vol. TT1
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** xiii

**List of symbols** xv

**List of abbreviations** xvii

1 Introduction 1

1.1 Brief history of printing and lithography 1

1.2 Optical lithography and integrated circuits 2

1.3 Basics of optical lithography 6

1.3.1 Illumination 6

1.3.2 Reticle 8

1.3.3 Exposure 13

1.3.4 Photoresist 18

1.3.5 Optical lithography system parameters 23

1.4 Requirements of microlithography 24

1.5 Nonoptical microlithography techniques 26

1.6 Current challenges of optical microlithography 27

1.7 Three parameters affecting resolution 28

1.8 Scope of discussion 30

2 Optical Imaging and Resolution 31

2.1 Coherent imaging 31

2.1.1 Principle 31

2.1.2 Resolution 34

2.2 Mask spectrum 39

2.2.1 Pitch dependence 42

2.2.2 Dependence on dimension 42

2.2.3 Two-dimensional patterns 44

2.3 Partially coherent imaging 45

2.4 Complex degree of coherence 55

2.5 Rayleigh’s resolution limit 58
## 2.6 Lithography resolution limit .................................. 59

### 2.7 Quantification of image quality ............................... 59
#### 2.7.1 Modulation transfer function .............................. 60
#### 2.7.2 Contrast ..................................................... 60
#### 2.7.3 Exposure latitude ............................................ 60
#### 2.7.4 Normalized image log slope ................................. 61
#### 2.7.5 Depth of focus .............................................. 62
#### 2.7.6 Exposure-defocus window ................................... 64
#### 2.7.7 Total window ............................................... 66
#### 2.7.8 Common window ............................................. 68
#### 2.7.9 Linewidth variability ......................................... 69

## 3 Modified Illumination .............................................. 71
### 3.1 Partial coherence factor ........................................ 71
#### 3.1.1 Large $\sigma$ .............................................. 71
#### 3.1.2 Small $\sigma$ ............................................... 79
#### 3.1.3 Medium $\sigma$ ............................................. 79
### 3.2 Off-axis illumination ........................................... 80
#### 3.2.1 Dipole .................................................... 80
#### 3.2.2 Quadrupole ............................................... 84
#### 3.2.3 Annular .................................................... 85
#### 3.2.4 Implementation issues ....................................... 87
### 3.3 General guidelines ............................................. 90

## 4 Optical Proximity Correction ....................................... 91
### 4.1 Image distortion ............................................... 91
### 4.2 Optical proximity correction approaches ......................... 92
#### 4.2.1 Catastrophic OPC ............................................ 93
#### 4.2.2 Linewidth variation minimization ............................ 94
#### 4.2.3 Line shortening ............................................. 100
#### 4.2.4 Corner rounding ............................................. 100
### 4.3 Numerical techniques ........................................... 101
#### 4.3.1 Rule-based ................................................ 102
#### 4.3.2 Model-based ............................................... 103
#### 4.3.3 Hybrid .................................................... 105
### 4.4 Implementation ................................................. 106
#### 4.4.1 Correction function derivation .............................. 106
#### 4.4.2 CAD system ................................................. 110
### 4.5 Discussion .................................................... 115
## 5 Alternating Phase-Shifting Mask

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Principle</td>
<td>117</td>
</tr>
<tr>
<td>5.2 Mask-making process</td>
<td>121</td>
</tr>
<tr>
<td>5.3 Issues</td>
<td>123</td>
</tr>
<tr>
<td>5.3.1 Intensity imbalance</td>
<td>123</td>
</tr>
<tr>
<td>5.3.2 Aberration sensitivity</td>
<td>126</td>
</tr>
<tr>
<td>5.3.3 Mask defect</td>
<td>128</td>
</tr>
<tr>
<td>5.4 Implementation</td>
<td>130</td>
</tr>
<tr>
<td>5.4.1 Dark-field application</td>
<td>131</td>
</tr>
<tr>
<td>5.4.2 Light-field application</td>
<td>133</td>
</tr>
<tr>
<td>5.5 Summary</td>
<td>138</td>
</tr>
</tbody>
</table>

## 6 Attenuated Phase-Shifting Mask

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Principle</td>
<td>139</td>
</tr>
<tr>
<td>6.2 Mask making</td>
<td>147</td>
</tr>
<tr>
<td>6.2.1 Thin film</td>
<td>147</td>
</tr>
<tr>
<td>6.2.2 Opaque border</td>
<td>148</td>
</tr>
<tr>
<td>6.3 Discussion</td>
<td>151</td>
</tr>
</tbody>
</table>

## 7 Selecting Appropriate RETs

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Critical levels</td>
<td>153</td>
</tr>
<tr>
<td>7.2 Methodology</td>
<td>154</td>
</tr>
<tr>
<td>7.2.1 Include applicable approaches</td>
<td>154</td>
</tr>
<tr>
<td>7.2.2 Select promising techniques</td>
<td>155</td>
</tr>
<tr>
<td>7.2.3 Experimental quantification</td>
<td>158</td>
</tr>
<tr>
<td>7.3 Optimization results</td>
<td>158</td>
</tr>
<tr>
<td>7.3.1 Storage</td>
<td>160</td>
</tr>
<tr>
<td>7.3.2 Isolation</td>
<td>163</td>
</tr>
<tr>
<td>7.3.3 Word line</td>
<td>164</td>
</tr>
<tr>
<td>7.3.4 Bit line contact</td>
<td>166</td>
</tr>
<tr>
<td>7.4 Summary and discussion</td>
<td>168</td>
</tr>
</tbody>
</table>

## 8 Second-Generation RETs

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Multiple exposure</td>
<td>171</td>
</tr>
<tr>
<td>8.1.1 Forming sharp corners</td>
<td>172</td>
</tr>
<tr>
<td>8.1.2 Assembling patterns</td>
<td>172</td>
</tr>
<tr>
<td>8.2 Pupil filtering</td>
<td>175</td>
</tr>
<tr>
<td>8.3 Advanced illumination scheme</td>
<td>176</td>
</tr>
<tr>
<td>8.3.1 Concurrent reticle-illumination optimization</td>
<td>176</td>
</tr>
<tr>
<td>8.3.2 Dark-field illumination</td>
<td>177</td>
</tr>
<tr>
<td>8.4 Compensating process</td>
<td>180</td>
</tr>
<tr>
<td>8.5 Mask and photoresist tone</td>
<td>180</td>
</tr>
</tbody>
</table>
Contents

Concluding Remarks 183

$k_1$ Conversion Charts 187

Bibliography 189

Index 209
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
Neureuther and Professor William Oldham, as well as many colleagues, who educated me and who contributed ideas to this text: Mr. Derek Chen, Dr. Ronald Dellaguardia, Dr. Tim Farrell, Mr. Carlos Fonseca, Dr. Michael Hibbs, Dr. Joseph Kirk, Ms. Antoinette Molless, Dr. Mark Neisser, Dr. Christopher Progler, Dr. Alan Rosenbluth, Dr. Donald Samuels, Mr. Alan Thomas, and Professor Michael Yeung.

Loan of an original photograph by Dr. Joseph Kirk (Fig. 3.19), and scanning electron micrographs by Dr. Chen Zheng (Fig. 6.8) and Dr. Ralf Schuster (Figs. 7.5, 7.8, and 7.12) are gratefully acknowledged. I would also like to acknowledge the permissions granted for reproduction of illustrations by Dr. Murrae Bowden (Fig. 1.6), Dr. Bob Leidy (Fig. 1.22), Dr. D. Cote (Fig. 2.1), Dr. Iba Junichiro (Fig. 3.20), Dr. Scott Mansfield (Fig. 4.8), Dr. Lars Liebmann (Fig. 6.12), Dr. Fukuda Hiroshi (Fig. 8.6), Dr. Alan Rosenbluth (Fig. 8.8), Dr. Obert Wood (Fig 8.9), and Dr. Toyoshima Toshiyuki (Fig. 8.10).

I would also like to thank my publisher, and in particular Mr. Rick Hermann. This book would not have been possible without his encouragement and support. The editorial support of the SPIE Press staff, as well as the assistance in \LaTeX printing by Vytas are also appreciated.

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
January 2001

ALFRED WONG KWOK-KIT
List of symbols

$\lambda$  
wavelength

$NA$  
numerical aperture

$\theta$  
maximum diffracted angle captured by pupil ($\sin \theta = NA$)

$k_1$  
measure of lithography aggressiveness

$\sigma$  
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 $(x,y)$

$\hat{P}(f,g)$  
pupil function

$\hat{J}(f,g)$  
mutual intensity (effective source function)

$O(x,y)$  
object (mask) function

$\hat{O}(f,g)$  
mask spectrum

$O_x(x)$  
one-dimensional mask function

$\hat{O}_x(f,g)$  
one-dimensional mask spectrum

$M$  
demagnification of exposure system

$d$  
pattern dimension ($\hat{d} = d \frac{NA}{\lambda} = k_1$)

$d_{\text{min}}$  
minimum resolvable dimension

$p$  
pattern spatial period ($\hat{p} = p \frac{NA}{\lambda}, p = \hat{p} \frac{\lambda}{NA}$)

$p_{\text{min}}$  
pitch resolution limit

$h$  
pattern half pitch ($\hat{h} = p/2, \hat{h} = h \frac{NA}{\lambda}, h = \hat{h} \frac{\lambda}{NA}$)

$h_{\text{min}}$  
half pitch resolution limit ($p_{\text{min}}/2$)

$\mu(\hat{r})$  
complex degree of coherence

$\hat{R}_{\text{opt}}$  
optical interaction range

$\Delta$  
design grid
Symbols

\[ \Delta_{\text{app}} \text{ apparent grid} \]

\[ d_{\text{etch}} \text{ etch depth of alternating PSM} \]

\[ T \text{ attenuated PSM background intensity transmission} \]

\[ t \text{ attenuated PSM field transmission } (\sqrt{T}) \]

\[ I_{\text{sidelobe}} \text{ side lobe intensity} \]

\[ I_{\text{threshold}} \text{ threshold intensity} \]

\[ E_0 \text{ dose to clear (dose to gel)} \]

\[ L_{\text{diff}} \text{ photoresist diffusion length} \]

\[ \gamma \text{ photoresist contrast} \]

\[ n, m \text{ integer} \]

\[ \mathbb{Z} \text{ the set of integers} \]

\[ \mathbb{Z}^+ \text{ zero and the set of positive integers} \]

\[ i \text{ } \sqrt{-1} \]

\[ \delta(x) \text{ Dirac delta function} \]

\[ J_1(x) \text{ Bessel function of the first kind and first order} \]

\[ \text{sinc}(z) \text{ sinc function } \left( \frac{\sin(\pi z)}{\pi z} \right) \]

\[ \text{circ}(\nu) \text{ circle function} \]
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 \((CD=k_1 \frac{\lambda}{NA})\)
CD\textsubscript{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
Resolution Enhancement Techniques in Optical Lithography