Selected Papers on
Resolution Enhancement Techniques in Optical Lithography

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Contents

xv Preface
   F.M. Schellenberg

Section One
Resolution and Lithography

1 Section Introduction

3 On the diffraction of an object-glass with circular aperture
   George Biddell Airy (Transactions of the Cambridge Philosophical Society 1835)

12 Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung
   [Contributions to the theory of the microscope and the nature of microscopic vision]
   E. Abbe (Archiv für Mikroskopische Anatomie [Archive for Microscopic Anatomy] 1873)

18 English translation of previous paper
   (Translated by H.E. Fripp, 1874, and edited/revised by W. Maurer and F.M. Schellenberg)

25 Investigations in optics, with special reference to the spectroscope, §§ 1–6
   Lord Rayleigh (The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 1879)

43 Investigations in optics, with special reference to the spectroscope, § 7
   Lord Rayleigh (The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 1880)
On the theory of optical images, with special reference to the microscope
Lord Rayleigh (The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 1896)

On the diffraction theory of microscopic vision
Albert B. Porter (The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 1906)

On spectroscopic resolving power

The concept of degree of coherence and its application to optical problems
F. Zernike (Physica 1938)

The influence of the condenser on microscopic resolution
H.H. Hopkins, P.M. Barham (Proceedings of the Physical Society Section B 1950)

The concept of partial coherence in optics
H.H. Hopkins (Proceedings of the Royal Society of London Series A 1951)

On the diffraction theory of optical images
H.H. Hopkins (Proceedings of the Royal Society of London Series A 1953)

Two-point resolution with partially coherent light
Diana Nyyssonen Grimes, Brian J. Thompson (Journal of the Optical Society of America 1967)

Image of a periodic complex object in an optical system under partially coherent illumination

Partially coherent imaging in two dimensions and the theoretical limits of projection printing in microfabrication
Burn Jeng Lin (IEEE Transactions on Electron Devices 1980)

Where is the lost resolution?
Burn J. Lin (in Optical Microlithography V, H.L. Stover, editor, 1986)

Identifying and monitoring effects of lens aberrations in projection printing

Section Two

Moore's Law

Cramming more components onto integrated circuits
Gordon E. Moore (Electronics 1965)

Progress in digital integrated electronics

Lithography and the future of Moore's Law
Gordon E. Moore (in Optical/Microlithography VIII, T.A. Brunner, editor, 1995)

National lithography roadmap: wafer requirements in the year 2000
Section Three
Optical Process/Proximity Correction (OPC)

Section Introduction

Techniques of microphotography: precision photography at extreme reductions
(Eastman Kodak Industrial Data Book 1963)

Reduction of errors of microphotographic reproductions by optimal corrections of original masks
Bahaa E.A. Saleh, Soheil I. Sayegh (Optical Engineering 1981)

Image construction through diffraction-limited high-contrast imaging systems: an iterative approach
Karen M. Nashold, Bahaa E.A. Saleh (Journal of the Optical Society of America A 1985)

Image construction: optimum amplitude and phase masks in photolithography
Bahaa E.A. Saleh, Karen M. Nashold (Applied Optics 1985)

Proximity effects and influences of nonuniform illumination in projection lithography

A study of projected optical images for typical IC mask patterns illuminated by partially coherent light

A critical examination of submicron optical lithography using simulated projection images

Proximity effects in submicron lithography
Paul Chien, Mung Chen (in Optical Microlithography VI, H.L. Stover, editor, 1987)

[Photo-projection image distortion correction for a 1-μm pattern process]
Tetsuo Ito, Masaya Tanuma, Yasuo Morooka, Kazuya Kadota
(Transactions of the Institute of Electronics, Information and Communication Engineers (IEICE) 1985)

Photo-projection image distortion correction for a 1-μm pattern process
[an English translation of the previous paper]
Tetsuo Ito, Masaya Tanuma, Yasuo Morooka, Kazuya Kadota
(Electronics and Communications in Japan Part II: Electronics 1986)

Use of a single size square serif for variable print bias compensation in microlithography: method, design, and practice

Lithographic process having improved image quality
Burn J. Lin, Anne M. Moruzzi, Alan E. Rosenbluth
(U.S. Patent No. 4,902,899; filed June 1, 1987, issued February 20, 1990)

Variable proximity corrections for submicron optical lithographic masks
Y. Nissan-Cohen, P. Frank, E.W. Balch, B. Thompson, K. Polasko, D.M. Brown
(1987 Symposium on VLSI Technology, Digest of Technical Papers)

A method for correction of proximity effect in optical projection lithography
Nader Shamma, Frederik Sporon-Fiedler, Edward Lin
(Proceedings of the KTI Microlithography Seminar Interface '91)

Mask for photolithography
Jang F. Chen, James A. Matthews
Section Four

Phase-Shifting Masks (PSM)

Section Introduction

Verfahren zur Herstellung einer Phasenmaske mit Amplitudenstruktur
[Process for the production of a phase mask with amplitude structure]
Hartmut Hänsel, Wulf Polack (German Democratic Republic Patent No. 126,361; filed April 30, 1976, issued July 13, 1977)

English translation of previous patent
(Translated by Interlingua, edited by F. M. Schellenberg and H. Hänsel)

Some partially coherent images
Douglas Goodman (Optical Sciences Center Newsletter 1978)

Spatial period division exposing
Dale C. Flanders, Henry I. Smith (U.S. Patent No. 4,360,586; filed April 14, 1980, issued November 23, 1982)

English translation of previous patent
(Translated by Interlingua, edited by F. M. Schellenberg)

Improving resolution in photolithography with a phase-shifting mask
Marc D. Levenson, N.S. Viswanathan, Robert A. Simpson
(IEEE Transactions on Electron Devices 1982)

The phase-shifting mask II: imaging simulations and submicrometer resist exposures

Optical imaging with phase shift masks

ホトマスク[Photomask]

English translation of previous patent
(Translated by Interlingua, edited by F. M. Schellenberg)

ホトマスク[Photomask]

English translation of previous patent
(Translated by Japanese Technical Translators, edited by F. M. Schellenberg)

ホトマスク [Photomask]
English translation of previous patent
(Translated by Interlingua, edited by F. M. Schellenberg)

Element forming method
Hiroshi Fukuda, Tsuneo Terasawa, Norio Hasegawa, Toshikiko Tanaka, Taku Oshima
(Translated by F. M. Schellenberg, edited by F. M. Schellenberg)

Sub-μm lithography using the phase shift method (1)
Tsuneo Terasawa, Toshiie Kurosaki, Norio Hasegawa
(49th Applied Physics Society Scientific Conference, Conference Abstracts)

Sub-μm lithography using the phase shift method (2)
N. Hasegawa, T. Terasawa, T. Yamamoto, T. Tanaka, T. Kurosaki
(49th Applied Physics Society Scientific Conference, Conference Abstracts)

Use of a pi-phase shifting x-ray mask to increase the intensity slope at feature edges
Y.-C. Ku, Erik H. Anderson, Mark L. Schattenburg, Henry I. Smith
(Journal of Vacuum Science and Technology B 1988)

Lithography mask with a π-phase shifting attenuator
Henry I. Smith, Erik H. Anderson, Mark L. Schattenburg

Imaging characteristics of multi-phase-shifting and halftone phase-shifting masks
Tsuneo Terasawa, Norio Hasegawa, Hiroshi Fukuda, Souichi Katagiri

New phase shifting mask with self-aligned phase shifters for a quarter micron photolithography
Akihiro Nitayama, Takashi Sato, Kohji Hashimoto, Fumiaki Shigemitsu, Makoto Nakase

Chromeless phase-shifted masks: a new approach to phase-shifting masks
Kenny K.H. Toh, Giang Dao, Rajeev Singh, Henry Gaw

Fabrication of grooved glass substrates by phase mask lithography
Phillip J. Brock, Marc D. Levenson, James M. Zavislan, James R. Lyerla, John C. Cheng, Carl V. Podlogar
(International Electron Devices Meeting 1990 Technical Digest)

0.2 μm or less i-line lithography by phase-shifting-mask technology
Hideyuki Jinbo, Yoshio Yamashita
(International Electron Devices Meeting 1990 Technical Digest)

Improvement of phase-shifter edge line mask method

Transparent phase shifting mask with multistage phase shifter and comb-shaped shifter
Hisashi Watanabe, Yoshihiro Todokoro, Yoshihiko Hirai, Morio Inoue
(International Electron Devices Meeting 1990 Technical Digest)
64Mの位相シフト採用は不可避
Adoption of phase shift at 64M is unavoidable. For 0.3μm lithography, a combination with I-line is the final decision
Kazuyoshi Takayama (日経マイクロデバイス [Nikkei Microdevices] 1990)

English translation of previous paper
(Translated by F. M. Schellenberg)

64Mの位相シフト採用は不可避
Adoption of phase shift at 64M is unavoidable. Different reticle structures are clarified by calculation and experiment
Hiroshi Fukuda, Norio Hasegawa, Akira Imai, Shinji Okazaki
(日経マイクロデバイス [Nikkei Microdevices] 1990)

English translation of previous paper
(Translated by F. M. Schellenberg)

Conjugate twin-shifter for the new phase shift method to high resolution lithography
H. Ohtsuka, K. Abe, T. Onodera, K. Kuwahara, T. Taguchi
(in Optical/Laser Microlithography IV, V. Pol, editor, 1991)

Optimization of real phase mask performance

Section Five
Off-Axis Illumination (OAI)

Images of periodic objects under partially coherent illumination

A concept for a high resolution optical lithographic system for producing one-half micron linewidths
George O. Reynolds (in Optical Microolithography V, H.L. Stover, editor, 1986)

Optimum stepper performance through image manipulation
Chris A. Mack (Proceedings of the KTI Microelectronics Seminar Interface '89)

Illuminator modification of an optical aligner
Delmer L. Fehrs, Howard B. Lovering, Robert T. Scruton
(Proceedings of the KTI Microelectronics Seminar Interface '89)

Improving projection lithography image illumination by using sources far from the optical axis
Satoru Asai, Isamu Hanyu, Kohki Hikosaka
(Journal of Vacuum Science and Technology B 1991)

Subhalf micron lithography system with phase-shifting effect
Miyoko Noguchi, Masato Muraki, Yuuichi Iwasaki, Akiyoshi Suzuki
(in Optical/Laser Microlithography V, J.D. Cuthbert, editor, 1992)

New imaging technique for 64M-DRAM
Naomasa Shiraishi, Shigeru Hirukawa, Yuichiro Takeuchi, Nobutaka Magome
(in Optical/Laser Microlithography V, J.D. Cuthbert, editor, 1992)

The effective light source optimization with the modified beam for the depth-of-focus enhancements

High performance optical lithography using a separated light source
Satoru Asai, Isamu Hanyu, Kohki Hikosaka
(Journal of Vacuum Science and Technology B 1992)
New effects of modified illumination in optical lithography

Photolithography system using a combination of modified illumination and phase shift mask

Investigation of single sideband optical lithography using oblique incidence illumination
Emi Tamechika, Seitaro Matsuo, Kazuhiro Komatsu, Yoshinobu Takeuchi, Yoshiaki Mimura, Katsuhiko Harada (Journal of Vacuum Science and Technology B 1992)

Resolution improvement using auxiliary pattern groups in oblique illumination lithography

Mask assisted off-axis illumination technique for random logic

Rim phase-shift mask combined with off-axis illumination: a path to 0.5λ/numerical aperture geometries
Timothy A. Brunner (Optical Engineering 1993)

Wavefront engineering for photolithography
Marc D. Levenson (Physics Today 1993)

Section Six
Computer-Aided Design (CAD)

Computer aided proximity effect correction system in photolithography

Investigating phase-shifting mask layout issues using a CAD toolkit

Phase-shifting mask design tool

Algorithm for phase-shift mask design with priority on shifter placement

Heuristic method for phase-conflict minimization in automatic phase-shift mask design

Computer aided design software for designing phase-shifting masks
Kazuko Ooi, Shige Hiro Hara, Kiyomi Koyama (Japanese Journal of Applied Physics 1993)

Method of designing phase-shifting masks utilizing a compactor

Application of alternating-type phase shift mask to polysilicon level for random logic circuits
Automated determination of CAD layout failures through focus: experiment and simulation

Automatic generation of phase shift mask layouts

Automated optical proximity correction—a rules-based approach

Fast sparse aerial image calculation for OPC

Section Seven
Other Resolution Enhancement Techniques

A new method for enhancing focus latitude in optical lithography: FLEX

Spatial filtering for depth of focus and resolution enhancement in optical lithography
Hiroshi Fukuda, Tsuneo Terasawa, Shinji Okazaki (Journal of Vacuum Science and Technology B 1991)

Resolution enhancement by oblique illumination optical lithography using a transmittance-adjusted pupil filter

Projection photolithography-liftoff techniques for production of 0.2-μm metal patterns

Optical projection lithography using lenses with numerical apertures greater than unity

1/8 μm optical lithography

Resolution limit for optical lithography using polarized light illumination

Multiple-exposure interferometric lithography

Performance of resolution enhancement technique using both multiple exposure and nonlinear resist

Author Index

Subject Index