Investigation into optical nanolithography employing wavefront engineering techniques and evanescent waves interference

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**Investigation into optical nanolithography
employing wavefront engineering techniques
and evanescent waves interference**

(On the Spine)

INVESTIGATION INTO OPTICAL NANOLITHOGRAPHY EMPLOYING
WAVEFRONT ENGINEERING TECHNIQUES AND EVANESCENT WAVES
INTERFERENCE

CHUA J. K. 2010

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2010

**Investigation into optical nanolithography
employing wavefront engineering techniques and
evanescent waves interference**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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ABSTRACT

Optical lithography is an important process in the realization and advancement of nanotechnology. This thesis proposes and investigates potential approaches to ameliorate process issues associated to patterning at high resolution as well as to achieve patterning resolution beyond fundamental limitation.

In optical projection lithography, the process window indicates process robustness which will deteriorate significantly, especially when the targeted resolution becomes sub-100nm. A quantitative approach is proposed as a more cost effective and time efficient alternative to commercial simulators to identify the most ideal co-employment scheme of wavefront engineering based on resolution enhancement techniques in terms of process window results. The quantitative approach proposed is based on analysing the power distribution of the zero and first orders of the diffracted source images. Employments of different process conditions of attenuated phase shift masking and off-axis illumination are simulated. The corresponding results suggest that the proposed approach approximates the process window results more accurately than a geometrical analysis approach reported previously. Experimental process window results obtained are analysed and compared to that of the proposed approach. Good correlation between the two is observed.

The laser interference lithography has been employed for cost-effective simulation of optical projection lithography to facilitate research investigations related to the latter. Nonetheless, laser interference lithography is an important and useful technique for fabricating nano-scale periodic features found in a large number of devices. The intensity distributions of two beams interference as well as four beams interference are solved theoretically by modeling the photoresist layer as a sandwiched layer of a stratified tri-layer configuration. Employing a modified grating based interference lithography system and a UV continuous wave laser with operating wavelength (λ) of 364nm, patterning of dense periodic line features as well as two dimensional features with size as small as 0.55λ are realized by single exposure to interference between dual or multiple polarized beams. Process conditions such as polarization and exposure dose for four beams interference

when varied resulted in achievement of different features and distributions. Good agreement between theoretical and experimental results of features distribution and pitch size is observed.

To achieve patterning resolution higher than those of previously discussed approaches, counter-propagating evanescent waves interference, is proposed and investigated as a potential resolution enhancement technique. Intensity distributions of two beams evanescent waves interference and four beams evanescent waves interference are solved theoretically. A modified cellular automata method is employed to simulate two and three-dimensional photoresist features that would result from exposure to evanescent waves interference under different process conditions. To facilitate experimental investigation, the proposed four beams interference lithography system is modified by integrating a custom fabricated optical element to simulate high numerical aperture projection. Theoretical results of features distribution and periodicity agree with that obtained experimentally. Line as well as circular-like features with pitch size as small as $< \lambda/3$ are fabricated, hence demonstrated lithography beyond diffraction limit. Influences of process conditions such as incident beams' polarization state and exposure duration, on profiles of resultant features are investigated and discussed.

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LIST OF ABBREVIATIONS

Abbreviations	Descriptions
AFM	Atomic force microscope
ArF	Argon Fluoride
CA	Cellular automata
CPL	Chromeless phase shifting lithography
DDL	Double dipole lithography
DRAM	Dynamic random access memory
EL	Exposure latitude
ENFOL	Evanescent near-field optical lithography
EUV	Extreme Ultraviolet
FWHM	Full-width at half maximum
GH _L	Lateral Goos-Hanchen shift
GH _T	Transverse Goos-Hanchen shift
HMDS	Hexamethyl disilazane
IC	Integrated circuits
ITRS	International Technology Roadmap for Semiconductor industry
IL	Interference lithography
OPC	Optical proximity correction
OPL	Optical projection lithography (alternatively known as photolithography)
PAC	Photoactive compound
PGMEA	Propylene Glycol Methyl Ether Acetate
PSM	Phase shift mask

Abbreviations	Descriptions
PW	Process window
RETs	Resolution enhancement techniques
SBIL	Scanning beam interference lithography
SEM	Scanning electron microscope
SPP	Surface plasmon polariton
TIR	Total internal reflection
TMM	Transfer matrix method
UV	Ultraviolet
ZPAL	Zone plate array lithography

LIST OF SYMBOLS

Symbols	Descriptions
Λ	Pitch size
λ	Wavelength of exposure source
CD	Critical dimension
NILS	Normalized image log slope
Rf	Reduction factor
NA	Numerical aperture of projection lens.
k_1	Process dependent factor for achievable critical dimension
DOF	Depth of focus
k_2	Process dependent factor for achievable DOF
σ	Partial coherence factor of exposure source. σ_i = Inner partial coherence factor of off-axis illumination source. σ_o = Outer partial coherence factor of off-axis illumination source.
O_a	Opening angle of off-axis illumination.
L_c	Collimating lens
L_o	Objective lens
L_i	Imaging lens
Σ_i	Imaging plane
w	Line width on mask
u, v	Coordinates in frequency domain corresponding to x, y
$S(u, v)$	Exposure source function

Symbols	Descriptions
$M(u, v)$	Mask function
$P(u, v)$	Exit Pupil function in fourier domain
E	Power distribution of diffracted source images
ε	Pupil fill factor based on amplitude analysis of diffracted source image
f_p	Pupil fill factor based on geometrical analysis of diffracted source image
n	Refraction index. Subscript denotes material
κ	Extinction coefficient. Subscript denotes material.
E	Electric field wave equation
$\mathbf{E}$	Electric field wave equation in vector form
$E_{s,p(amp)}$	Electric field amplitude. Written in bold when in vectorial form
$\mathbf{E}_{(amp)}$	Electric field amplitude in array form
I	Intensity.
k	Wavenumber ($k = 2\pi/\lambda$)
	<i>Definitions of superscripted and/or subscripted forms apply as described in text.</i>
$\mathbf{k}$	Wave vector
θ	Incident angle
ϕ	Azimuth angle (rotational angle about z axis)
δ_a	Initial phase of wave a
$\delta_{a,b}$	Relative phase difference between wave a and b
x, y, z	Cartesian spatial coordinates

Symbols	Descriptions
$\hat{e}_x, \hat{e}_y, \hat{e}_z$	Unit direction vector in Cartesian space
t	Time variable
T	Inverse of exposure source frequency
Φ	Azimuth orientation matrix
Θ	Elevation orientation matrix
$\tau_{s,p}^{(a,b)}$	Transmission coefficient for s or p polarized wave transmitting across interface from medium a to medium b .
$\chi'_{s,p}$	Phase change corresponding to $\tau_{s,p}^{(a,b)}$
$\rho_{s,p}^{(b,a)}$	Reflection coefficient for s or p polarized wave in medium a reflected by interface between media a and b
$\mathbf{T}$	Transmission coefficient matrix containing $\tau_{s,p}^{(a,b)}$
$\mathbf{P}$	Reflection coefficient matrix containing $\rho_{s,p}^{(b,a)}$
$F_{s,p}$	Effective transmission coefficient for s or p polarized wave transmitting through top interface into sandwiched medium .
$ F_{s,p} $	Modulus of $F_{s,p}$
$\chi_{s,p}$	Phase change corresponding to $F_{s,p}$
$B_{s,p}$	Effective reflection coefficient for s or p polarized wave in sandwiched medium reflected by bottom interface.
$ B_{s,p} $	Modulus of $B_{s,p}$
$\zeta_{s,p}$	Phase change corresponding to $B_{s,p}$
F_w	Amplitude of downward propagating wave
B_w	Amplitude of upward propagating wave
$\tilde{\tau}_{s,p}^{(a,e)}$	Transmission coefficient for s or p polarized wave in medium e after propagation through stratified stack media of a to e

Symbols	Descriptions
$\tilde{\rho}_{s,p}^{(e,j)}$	Reflection coefficient for s or p polarized wave in medium e after reflection from stratified stack consisting of media of e to j
$\tau_d(\theta'_r)$	Internal transmittance
$\mathbb{F}$	Capillary force
ϖ	Surface tension
α	Contact angle
ν	Viscosity of liquid photoresist
ω_{spin}	Spinning speed of spin coater
$\mathbf{E}_e$	Evanescent electric field wave equation in vector form
$\mathbf{E}_{e(amp)}$	Evanescent electric field amplitude in array form.
$\hat{i}, \hat{j}, \hat{k}$	Position index of a unit cubic cell of discretized photoresist layer in the modified three dimensional cellular automata model.
$C_{\hat{i}, \hat{j}, \hat{k}}^t$	Cell state of unit cubic cell at position denoted by $\hat{i}, \hat{j}, \hat{k}$ at time instance t
$Bn_{\hat{i}, \hat{j}, \hat{k}}^t$	Binary function of unit cubic cell at position denoted by $\hat{i}, \hat{j}, \hat{k}$ at time instance t
h_{diss}	Effective dissolved height of a unit cubic cell
a	Edge length of unit cubic cell
$R_{\hat{i}, \hat{j}, \hat{k}}$	Deveopment rate of unit cubic cell at position denoted by $\hat{i}, \hat{j}, \hat{k}$
t_o	Previous time instance
t_{exp}	Exposure duration
t_{dev}	Development duration
dt	Time step

Symbols	Descriptions
$dC_{\hat{i},\hat{j},\hat{k}}^{dt}$	Change in cell state of unit cubic cell at position denoted by $\hat{i}, \hat{j}, \hat{k}$
γ_{edge}	Correction factor for development due to flow for a neighbour cell sharing an edge with the concerned cell
γ_{vtx}	Correction factor for development due to flow for a neighbour cell sharing a vertex with the concerned cell
r_p	Distance of the boundary point p on crater from the origin as computed in homogeneous development rate test
$\bar{r}$	Radius of crater generated by fitted profile calculated from r_p .

Chapter 1

Introduction

1.1. Background

In the digital age of today, it is hardly an overstatement to claim that integrated circuit (IC) chips are indispensable for the sustenance of daily activities of any technology-dependent economies, a result of their pervasive integration into most if not all technological tools. An IC chip is an integration of transistors. A transistor is a semiconductor device that exploits the electrical properties of semiconductor materials such that its electrical conductivity changes by several orders of magnitude by employing impurity doping and application of electrical field. Also, the IC chip fabrication processes generally require fulfilling two major tasks given below:

- (a) Patterning of three dimensional structures of insulators and conductors which modulate local electric fields and currents.
- (b) Selective doping of regions in the semiconductor to achieve desired local concentration of charge carriers.

The three dimensional structures are created as outlined in Fig. 1-1. The first step of subtractive patterning (Fig. 1-1(a)) is deposition of a film onto the substrate, this is followed by lithography patterning of a positive image of the desired patterns in the photoresist layer which serve as masking layer for the subsequent etching process to transfer the pattern onto the underlying deposited film.

Fig. 1-1 (a) Subtractive patterning process (b) Additive patterning process (c) selective doping

There are three etching techniques-wet etching, plasma etching and reactive ion etching which is the most commonly employed etching technique because it provides adequate though imperfect directionality and selectivity. Due to imperfect etch selectivity, the final etched pattern is dependent on size as well as the shape of the resist patterns. The additive patterning process (Fig. 1-1(b)) starts with lithography photoresist patterning of negative image of the pattern via lithography before deposition process. Deposition consists of techniques such as oxide growth, chemical vapour deposition, physical vapour deposition, evaporation and sputtering. The lithography process is also a necessary step that precedes the

doping process as shown in Fig. 1-1(c). Selective doping is commonly performed using ion implantation technique. In this process, lithography is carried out to form the negative image of the doping region so that the resist patterns block the ions from reaching the substrate.

As aforementioned, the lithography process precedes the deposition, etching and doping processes that are carried out for the formation of circuit design on each layer of an IC chip. Hence, the fabrication process of an advanced IC chip, which typically has 20 or more masking layers of transistors gates and other features such as interconnects, involves large numbers of lithography steps[1]. In this context, it is be approximated that one third of the total manufacturing cost can be attributed to lithographic processing. The importance of the lithography process in IC fabrication stems from its heavy utilization as well as its critical role in propagating the advancement in IC chip technology driven by the Moore's Law.

Six years after the introduction of the first commercial planar transistor in 1959, Gordon Moore, a founder of Fairchild semiconductor and later Intel, observed that the number of electrical components per IC chip was doubling every year, reaching about 60 transistors in 1965 [2]. In Moore's definition, the number of components per chip that would double refers to the number that minimized the cost per component. Based on the extrapolation of the trend for the next decade, he predicted that chips with 64,000 components would be available in 1975. Today, an advanced Intel processor chip carries a few hundred millions transistors as illustrated by Table 1-1 given below.

Microprocessor	Year of Introduction	No of Transistors
4004	1971	2300
8008	1972	2500

8080	1974	4500
8086	1978	29000
Intel286	1982	134000
Intel386 TM processor	1985	275000
Intel486 TM processor	1989	1,200,000
Intel [®] Pentium [®] processor	1993	3,100,000
Intel [®] Pentium [®] II processor	1997	7,500,000
Intel [®] Pentium [®] III processor	1999	9,500,000
Intel [®] Pentium [®] 4 processor	2000	42,000,000
Intel [®] Itanium [®] processor	2001	25,000,000
Intel [®] Itanium [®] 2 processor	2003	220,000,000
Intel [®] Itanium [®] 2 processor (9MB cache)	2004	592,000,000
Intel [®] Itanium [®] Tukwila processor	Targeted for production 2008/9	2,000,000,000

Table 1-1 Transistors increment over the years

The advancement in IC technology is realized by a combination of push factors, which are the technology enablers, and pull factors, which are the commercial incentives. For four decades since its first proposal, the Moore's Law has been the guiding principle for the IC chip technology advancement at proportionately decreasing cost. In current context, the components refer to transistors. Cost is a function of density-representing feature size (i.e. transistor size), which is the average of the linewidth and spacewidth. With the semiconductor industry being able to fabricate at essentially constant cost per area of silicon, fabricating smaller transistors leads to more transistors fabricated per unit area leading at lower fabrication cost per transistor. Smaller transistors, allow for the fabrication of smaller chips thus increasing the throughput potential per wafer. In addition, smaller transistors demonstrate higher processing speed, higher power efficiency, higher reliability in many applications and facilitate the

manufacturing of smaller end products. These technical benefits translate to increased commercial value of each chip and thus higher profit potential. Therefore, the impetus to fabricate smaller and more advanced IC is not just about cost minimization but about profit maximization as well. Moore identified three technology enablers for increasing the number of transistors per chip, namely improvement in device and circuit design, increment in chip area and reduction in features size. Observing that device and circuitry design improvement became decreasingly effective in increasing the transistors per chip, Moore advocated efforts be channeled into the other two technology enablers.

The number of transistors per chip may be increased via increasing chip area but on the premise that defect density is maintained at a satisfactory low level that translates to chip yield high enough to minimize cost and maximize profit. As illustrated in Fig. 1-2, high defect density is always encountered in the initial development stage for chips of smaller technology node.

Fig. 1-2 Variation of defect density for various technology nodes [3].

For high volume fabrication to be commercially justifiable, chips of more advanced technology node have to be manufactured with yield comparable to that of older technology to maintain cost effectiveness and positive return of investment.

The definition of feature size reduction according to the Moore's definition is illustrated in Fig. 1-3 [3].

Fig. 1-3 Cell area decrement against advancement of technology node. Smaller cell area indicates higher feature density. Technology node represents the smallest feature size of a chip which is the width of a transistor [3].

According to the Moore's Law, investments to achieving features size reduction (transistors with smaller width) are commercially justifiable only if they effect a corresponding increment in features density (more transistors per unit area). While post-lithography processes (such as etching), can be employed to achieve smaller features, the lithography process is essentially the only method to achieve higher feature density. Hence, the technology advancement of IC chip is highly dependent on the resolution limit of the lithography process.

1.2. Motivation

The motivation of this project is two folds: to minimize defects associated with lithography and to improve pattern density via overcoming the lithography resolution limit of currently employed techniques.

While defect counts may be contributed by every process, reducing defects caused by the lithography printing failure is especially important in achieving low defect density. This is due to the high execution frequency of lithography printing in the IC chip fabrication. Therefore, one important aspect of lithography process

enhancement is to improve process robustness so that sensitivity of the yield to the feature size is reduced, leading to either smaller technology node with chip yield comparable to that of larger technology node or chip yield improvement is achieved for existing technology nodes.

Another aspect of lithography advancement is to improve printing resolution such that pattern density is increased in tandem with feature size reduction. According to the 2008 edition of the ITRS, the targeted half pitch resolution for DRAM features (line features) is 36nm and smaller (pitch size of 72nm and smaller) by 2012 and that of the contact features (circular features) is 50nm and smaller (pitch size of 100nm)[4]. The current research and technology path to smaller and smaller dimensions has effected a bearing on the resolution of photolithography technique. This led to wide range of unexpected territorial research challenges in the recent past. In reality, at this nanometer scale, conventionally employed resolution enhancement techniques such as phase shift mask and off-axis illumination, are found to be more and more difficult to implement apart from they being no more cost effective tools. As such, the printing resolution limit of the optical lithography is a technology barrier to overcome for the advancement for such opto-nanotechnology.

There are a few types of optical lithography technologies researched or implemented: contact/close proximity lithography[5-7], laser interference lithography[8-11] and the optical projection lithography[12-14] belongs to this category. The contact printing was used in the early days of semiconductor device manufacturing. The device design patterns are printed onto the photoresist by illuminating a photomask, carrying the device pattern, in close proximity or contact with the photoresist. This technique restricts the resolution of the printed

features to that of the mask features. The laser interference lithography is a relatively low cost and simple method to achieve sub-wavelength printing resolution. Though it is capable of parallel printing over an area, only periodic identical features can be printed. The period, Λ , of the repeating features based on interference is theoretically defined by $\lambda/2 \sin \theta$, where λ is the wavelength of the laser source and θ is the half angle subtended between the laser beams. The optical projection lithography (OPL) is a popular optical lithography technique because it allows multiple features to be printed with single light exposure. The minimum half-pitch resolution size, $CD_{half-pitch}$, achievable by an OPL technology is theoretically determined by $CD_{half-pitch} = k_1 \lambda / NA$ where λ is the vacuum wavelength of the irradiation source, NA is the numerical aperture of the projection optics of the system and the value of k_1 indicates the effectiveness of the employed resolution enhancement techniques. In such cases, a resolution enhancement technique that results in a smaller value of k_1 is desired. Wavefront engineering concepts originated from this. With higher resolution requirement, the complexity and therefore cost for implementing these wavefront engineering techniques are found to increase and their corresponding process robustness is found to decrease. With the limiting capability of the wavefront engineering techniques to achieve higher resolution, much work has been done to develop the liquid immersion technique in recent years [15-18]. Though the liquid immersion technique achieves resolution enhancement by a factor equivalent to the refractive index of the immersion liquid, the achievable resolution of the liquid immersion OPL is nonetheless gated by the refractive index of the liquid.

1.3. Objectives

In view of the importance of minimizing lithography related defects by enhancing process robustness and increasing the lithography resolution for the technological advancement of IC chip, this project has the following main objectives, which shall be achieved with original approaches:

- (a) Formulation of a simple approach to improve process window of OPL that simultaneously employs multiple resolution enhancement techniques, based on wavefront engineering techniques.
- (b) Investigation into UV laser assisted multiple beams interference (conventional and near-field) for sub-60nm features fabrication.
- (c) Investigation into the physics and characteristics of the evanescent waves's influencing parameters such as induced state of polarization, wavelength and exposure dose.

1.4. Scope

Process enhancement for optical lithography can be realized via either photochemistry approach or optical engineering approach. The photochemistry approach undertakes issues pertaining to investigation of the interaction between optical energy and chemical elements in the optical lithography system and the subsequent influences on patterning resolution. Development of chemically inert high refractive index liquid for liquid immersion and formation of photoresist with enhanced photosensitivity are typical issues studied as part of the photochemistry approach. On the other hand, the optical engineering approach seeks to realize resolution enhancement via exploitation of properties of optical waves. This

project adopts the optical engineering approach towards enhancing the lithography process and the scope is outlined as given below:

- (a) Development of parallel printing of sub 100nm features over an area with single illumination.
- (b) Fundamental study of attenuated phase-shifting and off-axis illumination as resolution enhancement techniques for OPL.
- (c) Formulation of a quantitative methodology that facilitates efficient identification of parameters for optimal process performance.
- (d) Design a nanolithography technique that exploits the subtle phenomenon of optical wave interactions.
- (e) Propose and development of a lab-based lithography system that facilitates patterning of multi-dimensional features.
- (f) Theoretical models/simulations for the proposed Lab-based lithography systems.
- (g) Numerical modeling of resist features resulted from evanescent waves interference exposure by employment of modified cellular automata method.
- (h) Investigation into the effects of Laser parameters, such as polarization and wavelength on the lithography performance.
- (i) Investigation into different materials and design configurations for fabrication of customized optical elements and the subsequent effects on the lithography performance.
- (j) Analysis and comparison of developed analytical models and numerical simulation results with the obtained experimental results.

A block diagram, describing the research roadmap of the proposed investigation and the various steps carried out, is given in Fig. 1-4.

1.5. Outline of Project

This thesis is divided into six chapters. Each chapter begins with a short note which outlines the main content of that chapter. From Chapter 3 onwards, a brief summary of content and findings is provided at the end of individual chapter.

Chapter 1 provides the outline of the fabrication process of the IC, an essential device extensively employed in the today's world. The importance of the lithography process is underlined. The Moore's Law is reviewed in the context of its influence on the advancement of the IC technology which is necessary for the survival and growth of the semiconductor industry. Based on the background and the motivation, the main objectives and scope of the thesis are discussed. **Chapter 2** is divided into four sections. The first section outlines the important process performance index pertaining to the optical projection lithography. Resolution enhancement techniques based on optical wavefront engineering are reviewed. Parallels and correlations between optical projection lithography and interference lithography are discussed. In the second section, different configurations of interference lithography set-up are reviewed and discussed from the perspective of their suitability for simulating the optical projection lithography. In the third section, optical techniques for achieving patterning resolution beyond diffraction limit are discussed in the context of applicability to optical projection lithography. In the last section, the outcome of the literature review is provided.

Fig. 1-4 Research roadmap: Block diagram representation

The investigation of a heuristic approach for efficient approximation of process window is presented in **Chapter 3**. The discussed approach is based on quantitative analysis of numerically generated diffraction intensity distribution at the fourier plane, which varies with photomask parameters and illumination conditions. The theoretical formulations of approximation factors are presented followed by numerical and experimental analysis. The **Chapter 4** presents the investigation of interference lithography facilitated by a interferometry system that allows simultaneous multiple beams interference in a single exposure. The interference intensity of interference between polarized beams is modeled adopting a matrix-vector product approach and a sandwiched thin film model to represent the photoresist layer. The theoretical analyses are carried out followed by description of the experimental set-up and procedures. An analysis of the obtained experimental and theoretical analyses are carried out and discussed in the last section. The **Chapter 5** presents the investigation of employing evanescent waves interference as a lithography patterning technique to achieve resolution beyond diffraction limit. Theoretical computations of the interference intensity distributions are presented. A modified cellular automata method is presented and employed for simulating the post-development resist features resulted from exposure to polarized evanescent waves interference. The theoretical analysis is followed by detailed description of the modification of the multiple beams interference lithography system to facilitate experimental demonstration of evanescent waves interference lithography, the results of which are analyzed and discussed. Finally the thesis contents are concluded in **Chapter 6** along with suggestions for future work in **Chapter 7**.

Chapter 2

Literature Review

This chapter presents an overview of the state of the art literature on the previous works done in areas relevant to the project. The first section presents a review of the optical projection lithography technique. Important process parameters of this technique are discussed. The resolution enhancement techniques employed for the optical projection lithography in the context of enhancing the process parameters are outlined. This section is followed by a review of the association between the optical projection lithography and interference lithography in the context of how the latter has been employed as a simpler and lower cost alternative to the optical projection lithography in lab-based experimental works. In this regard, different configurations of interference lithography techniques, categorized under the beamsplitting methods, are reviewed in the third section. The fourth section focuses on briefly reviewing the employment of near-field optical lithography printing beyond the diffraction limit in the context of optical projection lithography and conventional interference lithography. In the last section of this chapter, a summary of the literature review is presented in the light of the direction taken in the subsequent chapters.

2.1. Optical Projection Lithography

The optical projection lithography OPL is one form of mask based optical lithography which entails transference of patterns, from a photomask under the exposure to irradiation sources, to a recording medium such as a photosensitive polymer. Mask based lithography techniques have been extensively employed for fabrication of IC chips and micro electro-mechanical systems devices as they enable high resolution complex pattern generation at high volume throughput[19].

Before the introduction of OPL system, the optical proximity printing was widely used. As suggested by its name, the underlying working principle of this technique lies in positioning the photomask in close proximity to the recording medium, separated by a precisely controlled gap[20]. Close proximity between the photomask and the recording medium is essential for minimizing resolution loss induced by optical diffraction [21]. When ultraviolet exposure sources are used in the close proximity printing approach, the minimum sizes that can be printed are around 2 or 3 μm [22]. Employment of irradiation source with shorter wavelength enables smaller features to be printed resulted from the minimization of the adverse effect of diffraction induced resolution loss. One example of close proximity printing using irradiation source of short wavelength is the soft x-ray proximity lithography was first proposed by Spears *et al.* in 1972 [23, 24]. However, choices of materials appropriate for photomask are limited and thus limit the usable range of x-ray wavelengths to be between 0.4nm and 2nm [25-27].

The first OPL system to replace the optical proximity printing is a 1X scanner[28]. The optical scanner projects the image of the photomask through a lens system onto the surface of the wafer. For this system, there is no demagnification of

the image. However the use of a projection system protects the photomask from possible damages due to contact with wafer surface. The reported resolution limit is unsatisfactory for printing of sub-micrometer images [19]. To achieve higher resolution, the image reduction OPL systems are developed. The reduction OPL systems function like inverse microscopes such that the optical projection systems are designed to effect image demagnification.

The first commercialized reduction OPL system, in which a step-and-expose mechanism is employed, was introduced in the early 1980s [20]. The earliest reduction steppers have a resolution limit of $1.25\mu\text{m}$ linewidth at an exposure wavelength of 436nm (the g-line mercury lamp) [29]. In addition, the lens system provides a 4X to 10X reduction of the photomask image. The reduction system further drive down the limit for the minimum image size resolvable [30, 31]. With decreasing lithographic image sizes coupled with increasing chip size, higher numerical aperture and larger field size are required of the OPL system. This leads to difficulty in the lens design and fabrication [32, 33]. To deal with the demand for larger field size result, the step and scan exposure method is devised. In this method, a reduction lens is used to scan the image of a large exposure field onto a portion of a wafer. The wafer is then translated to a new position where the scanning process is repeated [34]. The first step and scan exposure system was developed by the Perkin-Elmer Corporation using an arc-shaped exposure slit. The projection lens had a numerical aperture of 0.35 and used an excimer exposure source (krypton fluoride, KrF) centered at the wavelength of 248nm [32]. A KrF projection lithography tool developed in 1988 is shown in Fig. 2-1.

Fig. 2-1 Schematic diagram of KrF excimer laser stepper [35].

The scanning electron microscope (SEM) image of periodic 500nm periodic line features fabricated by KrF exposure lithography is shown in Fig. 2-2.

Fig. 2-2 Scanning electron micrograph of 500nm equal line and space using 248nm projection lithography with 5X reduction lens system [35].

In 1990, Nomura *et al.* developed an argon fluoride (ArF) excimer laser projection lithography system, with irradiation wavelength of 193nm. Like the KrF projection lithography system, the ArF projection lithography system uses an aspherical projection lens system [36]. The SEM image of 250nm equal line and space features fabricated by the ArF projection lithography system is shown in Fig. 2-3.

Fig. 2-3 Scanning electron micrograph of 250nm line and space fabricated with ArF laser using the aspherical lens[37].

As reported in the literatures, non-optical lithography approaches, such as electron beam lithography and scanning probe lithography, have also been explored as possible options for IC chips fabrication [38-40]. However, due to their slow patterning speed, they are mainly employed for applications for which high throughput is not required such as prototype device fabrication. The most recent development is the zone plate array lithography (ZPAL)[41, 42]. It would probably take a few more years before the industry can consider adopting ZPAL. With the throughput limitations of the non-optical lithography approaches, optical lithography, more specifically the OPL approach, has been and will continue to be the most reliant printing method for the semiconductor manufacturing industry. The mechanism of image formation of OPL is outlined in Annex A. In the following section, the process performance indicators of an OPL system would be discussed.

2.1.1. Process Performance Indicators for Optical Projection Lithography

The optical projection lithography is the mainstream production technique for IC chips fabrication today [43]. For high throughput volume to be realized without compromising on the yield rate, the OPL system has to be tuned for precision and robustness. In this case, the process performance for the OPL would need to be

characterized by quantitative indicators which facilitate parameteric tuning for performance optimization.

2.1.1.1 Spatial Resolution

Theoretically, the heuristic Rayleigh's resolution criterion serves as an approximate measure of resolution. According to Rayleigh's resolution criterion for just resolvable images, the centers of the image patterns should not be nearer than the angular radius of the Airy disc. In this condition, the principal maximum of one image pattern falls directly over the first minimum of the other. The Rayleigh resolution criterion for circular aperture and rectangular slit is presented respectively as [44-50] ,

$$CD_{circ} = 0.61 \frac{\lambda}{NA_{img}} \quad (2-1)$$

$$CD_{rect} = 0.5 \frac{\lambda}{NA_{img}} \quad (2-2)$$

where NA_{img} refers to the numerical aperture of the projection pupil on the image space. In the context of an optical projection lithography system where the mask features size are reduced, the relationship between NA_{img} and the numerical aperture of the entrance pupil on the side of object (i.e. photoimask) is given as,

$$NA_{obj} = Rf \bullet NA_{img} \quad (2-3)$$

where Rf is the reduction factor such that the value of M for current step and scan machine is 0.25 and 0.2 for the 4X and 5X reduction projection lens system respectively.

In optical lithography and integrated circuit fabrication, resolving closely placed features is not the only concern. Equally important is the fidelity of image formation. Furthermore, the formulation of the Rayleigh's criterion is based on the

assumption of a ideal coherent point source. The illumination source used in photolithography is of finite size, hence the partial coherence characteristic of the source. To account for the effect of partial coherence of the illumination and other process parameters such as the photomask type and resists, the Rayleigh's criterion is modified as [46, 47, 49],

$$CD = k_1 \frac{\lambda}{NA} \quad (2-4)$$

where

CD = critical dimension of the feature to be printed

λ = wavelength of the illumination source

NA= numerical aperture of the projection lens system

k_1 = Process-dependent factor

Factors such as pattern configuration, integration scheme and yield target affect the photolithography limit. The theoretical k_1 value ranges from 0.25 to 0.50. The factor k_1 represents the capability of a lithography technique to resolve a desired feature dimension for a given NA of the projection lens system and illumination source. Hence one of the purposes for the application of RETs is to achieve lower k_1 for the same wavelength and NA.

2.1.1.2 Aerial Image Contrast

The image quality can also be evaluated based on image contrast. The image contrast is defined as,

$$contrast = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \times 100\% \quad (2-5)$$

in which $I_{\max}$ is the maximum intensity of the image and $I_{\min}$ is the minimum intensity of the image. The higher the contrast, the more distinct would be the bright and dark regions of a feature. Thus, the image quality would be better. In photolithography, the exact image contrast depends on the type of photoresist used. A contrast of 60% to 70% is generally needed for the current type of photoresists used in the industry. To evaluate image quality for non-periodic feature, the image log slope is used to measure and quantify the slope of the aerial image intensity profile. The normalized image log slope (*NILS*) can be represented by [51, 52],

$$NILS = CD \frac{d(\ln I)}{dx} \quad (2-6)$$

in which I refers to the image intensity and x refers to the spatial position along the linewidth of a line feature. The normalized image log slope is not dependent on the feature size.

2.1.1.3 Depth of Focus

The depth of focus (DOF) is the range of distance, about the best focal plane, over which the dimension of the resultant image varies from designed dimension within tolerance. The DOF is defined as [46, 49, 52-54],

$$DOF = k_2 \frac{\lambda}{NA^2} \quad (2-7)$$

The surface topology of the wafer plane is not planar. In optical projection lithography, large DOF is desirable as it allows image fidelity at all parts of the wafer. The utilization of illumination source of shorter wavelength and high NA projection system has allowed smaller features to be resolved but at the expense of DOF. The shortening of depth of focus with increased resolution is the most serious limitation for optical lithography and may set a practical limit on the NA [54].

2.1.1.4 Process-window curve

The process window refers to the area under the exposure latitude versus defocus curve. Exposure latitude describes the maximum amount of dose variation which can be tolerated before the printed pattern dimensions is out of specification. For any IC design, it is unavoidable that the features of the design are of different sizes. Different features require different optimum doses. Under-exposure or over-exposure would result in the image to be printed out of specification. As the dimension of the pattern for silicon devices is reducing in size, the allowable exposure latitude also reduces. Hence, when comparing two photolithography techniques that are able to resolve the same dimension, the one which allows larger exposure latitude would be preferred. When comparing different photolithography techniques for their process capability, ambiguity may arise if they are compared based on either exposure latitude or DOF. To avoid such ambiguity, the total process window area can be used an evaluation metric. As illustrated by Fig. 2-4 , the DOF at zero exposure latitude achieved by employing technique A is greater than that by employing technique B. Conversely, the exposure latitude at zero DOF achieved by using technique B is greater than that by using technique A.

Fig. 2-4 Total process window comparison between two RETs [52].

However, if a DOF of 800nm is desired for the process, technique A is a better technique for implementation than technique B based on the process window area comparison.

2.1.2. Resolution Enhancement Techniques via Wavefront engineering

In a broader sense, resolution enhancement techniques (RETs) can be defined as any optical technique that enhance the value of the evaluation metrics as mentioned previously. For example, if a technique is able to resolve an image which is also resolvable by the traditional photolithography process but with enhanced DOF, this technique can be considered as a RET. The classical approach to improve resolution would be to develop laser source of shorter wavelength and design optical projection lens of higher numerical aperture. Another approach to resolution enhancement is via wavefront engineering [54]. Wavefront engineering is effected via manipulating the amplitude, the phase, the direction and the polarization of the electromagnetic waves incident on the wafer plane. This chapter presents four types of RETs based on

wavefront engineering, namely off-axis illumination, alternating phase shift mask and the use of attenuated phase shift mask. The off-axis illumination is the manipulation of the wavefront direction. The alternating phase shift mask manipulates the phase of the wavefront. The attenuated phase shift manipulates both the intensity and phase of the transmitted light. For each of the techniques, the theoretical background would be presented followed by simulation results and the latest development in the technique for deep sub-micron lithography application.

2.1.2.1 Partial coherence and off-axis illumination

The illumination source used in the photolithography is of finite size. This means that the light is incident on the mask from a finite range of angles. In the case of coherent illumination, the light is incident on the mask from a single angle. For incoherent illumination, the light is incident on the mask from the full range of angles allowable by the NA_{obj} . In such a case, the illumination source fills up the entire entrance pupil. Since a finite source size allows illumination of the mask from a range of angles smaller than that allowable by NA_{obj} , it is aptly referred to as partial coherent illumination. The partial coherence factor σ measures the spatial extension of the light source relative the size of the NA_{obj} . It can be defined as the sine of the half angle(θ_{ill}) of the illumination cone, divided by the NA_{obj} . It is thus a measure of the angular range of the illumination relative to the angular acceptance of the lens [55]. The partial coherence factor σ can be expressed as [46],

$$\sigma = \frac{NA_{ill}}{NA_{obj}} \quad (2-8)$$

where $NA_{ill} = \sin \theta_{ill}$

The application of partial coherent illumination enable a smaller minimum pitch to be resolved than coherent illumination as illustrated in Fig. 2-5.

Fig. 2-5 Diffracted image of source at the entrance pupil for (a) coherent source and (b) partial coherent source[46, 56]

The correlation between the partial coherent factor of a circular illumination source and the CD is expressed as below [46, 49, 57]

$$CD = \begin{cases} \frac{k'_1 \lambda}{(\sigma+1) NA} & 0 < \sigma < 1 \\ \frac{k'_1 \lambda}{NA} & \sigma = 0 \\ \frac{k'_1 \lambda}{2NA} & \sigma = 1 \end{cases} \quad (2-9)$$

where $k'_1 = (\sigma+1)k_1$. The Eq (2-9) shows that the application of partial coherent illumination for exposure can enhance CD resolution by a factor of $(\sigma+1)$.

The main benefit of off-axis illumination is the enhancement of DOF and hence process window for photolithography. The off-axis illumination improves the resolution by manipulating the direction of the diffraction orders wavefront incident at the wafer plane. When on-axis illumination is used on periodic gratings, at least the first diffraction orders must be collected by the lens for image modulation to be possible. This is because the 0th order does not carry any frequency information. It only contributes to the background energy. Hence, with off-axis illumination, larger angular separation distance between the 0th and 1st diffraction orders of periodic gratings is allowed. Some examples of advanced illumination schemes are illustrated in Fig. 2-6 [58]. These illumination schemes can be achieved by introducing an aperture between the light source and the condenser optics.

Fig. 2-6 Common off-axis illumination configuration: (a) annular (b) dipole (c) quadrupole[58]

The first design of the hardware implementation of annular source for optical lithography system is first mentioned by Reynold [59]. Subsequently in 1989, the Fehrs et al. demonstrated experimentally that using annular illumination achieved higher image contrast and DOF for high spatial frequency 0.4 μm line than using conventional lithography[60]. Though the pitch size resolved is larger than 1 μm , the results were nonetheless encouraging as the exposures were made with 0.28NA projection system and 436nm wavelength exposure source. Since then, there have

been many works reporting different configurations of off-axis illumination and the consequential resolution and DOF improvement. Noguchi *et al.* introduced the CQUEST in 1992 for the 0.35 μm technology node. It was demonstrated experimentally that, exposure with CQUEST illumination, the DOF for printing of 0.30 μm is six times that of using conventional illumination [61]. The application of off-axis illumination has been used through the 0.18 μm and 90nm technology node to the current 65nm technology node. New illumination schemes such as QUASAR illumination, dipole illumination and pattern specific illumination have been proposed for as illumination based resolution enhancement technique [62-71]. For sub-65nm node manufacturing, the double dipole lithography (DDL) has shown great potential [66, 67, 72]. The double dipole illumination technique is a rigorous and meticulous technique. Firstly, a design is decomposed into two sets of patterns- one with all horizontally orientated features and the other with all the vertically orientated features. Then two photomasks would be fabricated according to the two sets of designs. To print the complete design, two exposures would be made, once for each of the photomasks. For the vertically orientated design features, the exposure would be made with a Y-dipole configuration shown in Fig. 2-7 (a). For the horizontally orientated design features, the exposure would be made with a X-dipole configuration shown in Fig. 2-7(b).

Fig. 2-7 Two dipole illumination configurations: (a) Y-dipole illumination for vertically orientated features; (b) X-dipole illumination for horizontally orientated features [67].

The dipole illumination enhances printing resolution and process window for the mask features with orientation that is favorable to the optimum dipole exposure. For the mask features in orthogonal orientation, dipole exposure produces little or no imaging contrast. The DDL technique poses issues like design complexity due to the need to decompose a design into horizontal and vertical orientation with the necessary addition sub-resolution assist features. The cost of ownership for this technique is high due to the two sets of photomasks needed for a single set of pattern. The necessity for double exposures to print a complete design increases processing time hence reduce throughput.

2.1.2.2 Phase Shifting Mask

Phase shifting mask (PSM) modulates both amplitude and phase of the light (electromagnetic field) propagating through them. The PSM enhances the contrast of the resultant image by inducing destructive interference between adjacent fields. This destructive interference is a result of π radians phase difference between the adjacent fields. The phase shifting is achieved by either adding or subtracting “optical” material from the mask substrate at a thickness that corresponds to a π radians phase shift as shown in Fig. 2-8.

Fig. 2-8 Diagram of wavetrain propagation through phase shifted and unshifted position of a mask [73].

For the π radians phase difference between the two adjacent waves, the required thickness of the phase shifter is,

$$thk = \frac{\lambda}{2(n-1)} \quad (2-10)$$

where n is the refractive index of the material and λ is the wavelength of the electromagnetic wave,

There are many variants of PSM, among them the alternating PSM and the attenuated PSM. The theoretical descriptions of alternating PSM and attenuating PSM are given in Annex II, from which the choice . The alternating phase shift mask is first designed and reported by Levenson [74]. Each feature on the alternating phase shift mask is defined by chrome flanked by clear openings with a phase difference of π radians between them. In recent years, the alternating phase shift mask has been shown to be applicable for up to 45nm technology node for the gate level printing [75]. Despite its resolution enhancement capability, the alternating phase shift mask has its issues. The issues are namely intensity imbalance due to transmission and phase error of the aperture, susceptibility to lens aberration due to the use of phases and complexity of implementation for bright field application, in particular gate level printing. For bright field mask, the phase transition region would be unintentionally printed as shown in Fig. 2-9.

Fig. 2-9 A brick pattern defined by a bright-field mask using the alternating phase shifting technique. (a) The alternating phase shift mask top profile layout. (b) The resultant aerial image of the pattern. Phase transition region will be imaged as fine line which is unintended [73].

To remove the residual image, a light field mask is used for a second exposure. Though the trim mask removes most of the residual image, the second exposure will reduce the throughput (i.e. more printing time for per set of wafer [73, 76, 77]. The main disadvantage of the alternating phase shifting technique is mask design complexity for the certain patterns.

The attenuated PSM (also known as the half-tone PSM) for lithography purpose was first proposed by Smith *et al* in 1987 [78, 79]. The main features on the mask are defined by partially transmitting material, the thickness of which produce π radians phase shift with respect to the clear glass regions. The attenuated phase shift mask option has been in practical use since mercury lamp with i-line emission has been used as the illumination source. The material of choice for the phase shifting attenuator was molybdenum silicide (MoSi) based on the i-line ($\lambda=365\text{nm}$) and KrF ($\lambda=248\text{nm}$) as illumination sources[80]. In comparison to the alternating PSM, the attenuated PSM option presents the advantages of single exposure [81]. However, the drawback of the attenuated PSM is the instability of the material property and challenging fabrication control of the complex attenuating film [82]. When

illumination source with shorter wavelength, such as the ArF excimer laser ($\lambda=193\text{nm}$), is used, most material becomes opaque [73]. Materials such as chromium based and other more novel materials have been suggested [83-86]. For 6% attenuated PSM, the transmission and phase control greatly relies on the optical properties and thickness of attenuating materials. The combined implementation of the 6% attenuated PSM with off-axis illumination as a RET for gate level printing has been successful for larger technology node (larger than 100nm) [87, 88] as well as for the sub 100nm technology node [77, 81, 89, 90]. For acceptable process window to be achieved with the 6% or 9% attenuated phase shift mask for 65nm technology node is possible only with aggressive illumination scheme and sub resolution enhancement feature [89]. As the dimension of the gate size reduced further, the dimension tolerance requirement for sub-resolution assist feature will become more stringent. This would increase the fabrication cost for the attenuated PSM [66].

The employment of chromeless phase shift lithography (CPL) as a resolution enhancement for optical projection lithography was first proposed by Toh *et al.* [91]. The CPL technique, also known as transparent phase shifting or phase-shifter edge line eliminates the use of chrome to form patterns [91-93]. Unlike the attenuated phase shifting technique, the π radians phase shifter is etched from the mask glass substrate. The theoretical step size value of the phase shifter is defined by Eq (2-10). There are two types of phase steps, the mesa style and the trench style as shown in Fig. 2-10.

Fig. 2-10 (a) Mesa type chromeless phase shift mask (b) Trench type chromeless phase shift mask where t refers to the thickness of the protruding

phase shifter structure in the case of the mesa type chromeless phase shift mask or the depth of the etched trench in the trench type chromeless mask [94].

In order for CPL mask to be considered as a potential manufacturing option for IC chips fabrication, it must meet several requirements [95, 96]. These include

- 1) the ability to produce useful, manufacturable, and inspectable reticle features from original random logic designs,
- 2) produce wafer features with sufficient CD control and process latitude
- 3) provide a constant CD through pitch,
- 4) produce features with a minimum of line end pullback,
- 5) provide a low-cost implementation.

The pure phase structures can only resolve features in a limited range of sizes before which the phenomenon of “dimension linearity fall off” is observed. This is illustrated in the below in Fig. 2-11. Three zones of features sizes are identified. The zones demarcate the transmission to be assigned. As shown in Fig. 2-11(b), Zone 1 features are constructed with 100% transmission phase shifted structures and Zone 3 features are chrome (binary) structures. Features that fall into Zone 2 are too wide to be defined using the 100% transmission of pure CPL and yet cannot be optimally resolved with a fully chrome structure.

(a)

(b)

Fig. 2-11 (a) The pure phase mask structure can only define features in a limited range of sizes before dimension linearity fall-off is observed for feature sizes beyond 80nm (b) Three zones of feature sizes for chrome application to tune transmission of phase shifter [97].

Such features need to be resolved with partially transmitting phase shifter structure. The partial transmitting is achieved with application of partial shielding chrome patches on the phase shifter as shown in below in Fig. 2-12. The object transmission function for a CPL mask adopts that of an attenuated mask, except that the value of intensity transmission can be varied from a value of 0% to 100% instead of limited to 6% and 9%.

Fig. 2-12 The chrome patches results in partial transmission

Shown in the Table 2-1 is the comparison of the various phase shift mask techniques and the DDL techniques as possible resolution enhancement options for the sub-65nm technology node.

	Sub-65nm RETs Option	Alternating PSM	Attenuated PSM (6%-9%)	CPL	DDL (using chrome mask)
Issues	Design/Lay out Restrictions	Phase conflict, Trim Mask overlay	Minimal	Minimal	Diagonal features are not allowed to be assigned minimum CD
	No of exposures	2	1	1	2
	No of steps for mask fabrication	3	2	2	2
	Key mask specificatio n that could increase cost of mask fabrication	π -phase shifter with undercut.	Very tight tolerance for mask features due to large amplificatio n of mask error at the image plane	Zebra features on the phase shifter for transmissi on control	Mask sets for the horizontal and vertical feature are required to be written at the same time to ensure common CD

	Sub-65nm RETs Option	Alternating PSM	Attenuated PSM (6%-9%)	CPL	DDL (using chrome mask)
			and low aerial image contrast for low k_1 imaging.		target and overlay

Table 2-1 Comparison of the mentioned RETs for implementation for the sub-65nm technology manufacturing [66].

2.1.2.3 Optical Proximity Correction

The optical proximity correction (OPC) refers to the technique of predistorting the features on the photomask so as to enhance the fidelity of the printed pattern to the intended shape [73]. There are four basic OPC approaches [98]. The first approach is known as the catastrophic OPC. The objective of this OPC is to enhance the printability of a certain pattern. The dimension control of the pattern is not critical. The second approach is known as one dimensional OPC. The objective of which is to minimize linewidth variation due to proximity effect. To address this issue, line features of the same designed linewidth would be printed with different dimensions if they are spaced differently from their respective neighbouring features [99]. There are two methods to implement one-dimensional OPC. The first method is known as the selective line biasing as originated by Oberschmidt at IBM [98]. The line features of different periodicity but designed to print with the same linewidth are defined with deliberate under-sizing or over-sizing on the photomask. The line biasing scheme is illustrated in the Fig. 2-13(a). In the second method, sub-resolution assist features are added to the side of the isolated feature on the photomask when off-axis illumination is employed [100]. The dimensions of these assist features are beyond the resolution limit of the exposure condition. The purpose of which is to create a dense effect to projection system but only print the intended feature. This method enhances the

process window of the isolated line feature. The assist feature scheme is illustrated in the Fig. 2-13(b). A third kind of OPC approach aims at rectifying line end shortening, which results from high density design layout on the photomask [98]. To rectify the line-end shortening, serif features and hammer head can be added to the main feature. The fourth OPC approach aims to minimize corner rounding effect. The sharp corner of the mask feature has the same optical effect as pitch size tending towards infinitely small. The only remedy for corner rounding is the application of seriffs to the main feature [101].

Fig. 2-13 Different schemes of optical proximity correction. (a) Biasing (b) assist features (c) Hammer Head (d) Serifs [102]

With demand for smaller and denser features to be printed, the design complexity and implementation difficulty of OPC increases. Consequentially, the cost of photomask fabrication will increase and thus increase the cost of ownership of an OPL system. As such, the employment of the OPL systems for lithography process research is not feasible for research institutions. If the targeted patterns are periodic features, a more economical option than the OPL system comes in the form of the interference lithography.

2.1.3. Optical Projection Lithography simulation via Interference Lithography

While features size of a couple of hundreds nanometer can be readily resolved by the complex yet robust OPL tools used by the IC industry, the operating costs of these tools are high (typical mask set costs for a modern microprocessor exceed \$1 million). Hence, the employment of these tools is only suitable for high-volume, high-product-value manufacturing and is not the most cost-effective option for typical institutes based research works, for which the volume of fabrication is much lower. As such, it is required that, a lab-based optical lithography tool be developed for the purpose of this work. This optical lithography tool should simulate the OPL system, facilitates high resolution printing at relatively low cost.

Recall that the minimum half-pitch resolution size, $CD_{half-pitch}$, achievable by an OPL technology is theoretically determined by $CD_{half-pitch} = k_1 \lambda / NA$. Drawing parallel between the theoretical resolution of IL and that of OPL, the Eq (2-12) may be interpreted as $CD_{half-pitch} = 0.25 \lambda / NA$. It is possible to synthesize the lithographic performance of an OPL system by utilizing a simple interferometric lithography system for applications which require only periodic patterns. The interferometry lithography system can be configured to facilitate the study of polarization effect on imaging and that of the effect of defocus [103, 104]. The interferometric lithography has been widely utilized in the studies for which the findings obtained from printing periodic patterns are applicable to that of printing non-periodic features. These studies include analysis of newly developed photoresist chemistries and emerging lithographic techniques, such as immersion lithography and even EUV lithography [105-109]. Furthermore, most of the features found on the advanced IC chips are either fundamentally periodic or quasi-periodic.

2.2. Interference Lithography

The advancement of nanotechnology has seen the increasing importance of interference lithography (IL) as a fabrication process. The IL has been widely utilized in the studies of newly developed photoresist chemistries and emerging lithographic techniques, such as immersion lithography and EUV lithography [105-109]. In addition to its role as a simulator for the OPL system, IL is itself a useful technique for fabricating periodic features which are found in gratings based applications. The commercial development of the i-line photoresists for projection lithography, coupled with that of the continuous wave Argon ion lasers at 364nm and 352nm, motivated early research efforts into laser assisted IL, exploring the feasibility of employing the photoresist as holography recording medium for lasers at visible wavelengths [110-112]. Lately, there is a rising interest in multiple beams interference as a fabrication technique for advanced devices such as photonic crystals, field emitter arrays and nano-dots array based biosensor [113-117]. This is because multiple beams interference lithography enables fabrication of periodic features with two or more dimensions. Incorporation of IL into template based lithography has been explored and proposed as a cost-effective alternative optical lithography option for more complex patterning process of IC chip fabrication [118, 119]. Here, dense arrayed features typical of transistor gates or contact holes are patterned using IL realized by phase grating mask and projection optics. A second exposure with a trim mask carrying aperiodic features is executed to achieve cell patterning.

Interference of optical waves is the essence of the image formation. Image formation of a complex pattern by an OPL system is the result of the interference of waves with different propagating vectors realized by sophisticated lens systems. If a small number of coherent waves are directed onto a plane in a symmetrical manner

about the normal axis to the plane, the resultant interference intensity distribution on the plane is periodic. This is the basic working principle of the IL. Considering a simple case of two plane waves interference, the theoretical pitch size, CD_{pitch} of the resultant periodic line features is given as,

$$CD_{pitch} = \frac{\lambda}{\sin \theta_{i1} + \sin \theta_{i2}} \quad (2-11)$$

where θ_{i1} and θ_{i2} refer to the incident angle of interfering beam 1 and 2 respectively. If the incident angles of plane waves are symmetrical about the normal axis, Eq (2-11) is reduced to $\lambda/2 \sin \theta_i$, where θ_i is the incident angle. The approximate half-pitch linewidth resolution of the line features from two waves interference is given as,

$$CD_{half-pitch} = \frac{\lambda}{4 \sin \theta_i} \quad (2-12)$$

However, this is at best a rough estimate as the linewidth resolution of photoresist features depends on other process parameters such as exposure dose, development time, concentration of developer and duration of post-exposure bake time.

The IL process can be realized via different configurations of the optical components. The configurations of IL systems may be broadly classified according to the beam splitting method, i.e. amplitude splitting and wavefront splitting, which will be discussed in the following sections.

2.2.1. Wavefront Splitting Configuration

In wavefront-splitting IL system, the interfering waves originate from different spatial regions of the input beams. A common form of wavefront splitting based IL system employs the Lloyd's mirror configuration as illustrated in Fig. 2-14 [11, 120-125]. In Fig. 2-14, “vs” represents virtual source. Interference occurs between the region of the beam that directly impinges the photoresist and the reflected region from

the mirror. The interference between different regions of the beam is more clearly understood as the interference between a portion of the incident beam and that of a virtual source from behind the mirror. In Fig. 2-14(a), the spherical phase front of the diverging beam emanating after the spatial filter allows the interference gratings produced from the exposed photoresist to be free from local and global phase error. However, the hyperbolic phase progression of the grating across the exposed region makes the grating undesirable for employment in metrology applications. To overcome this issue, a collimating lens can be positioned after the spatial filter, as shown in Fig. 2-14(b), to produce an incident beam with planar phase front which produces a linear phase progression of the resultant interference phase grating. Nonetheless, the addition of the collimating lens may result in phase error due to lens aberrations or scattering by particles.

Fig. 2-14 Two methods of implementing Lloyd's mirror IL system (a) noise free spherical phase front configuration (b) planar phase front configuration

The Lloyd's mirror configuration is even implementable for excimer laser with wavelength as short as in the extreme ultraviolet range [124, 126]. Neither of the Lloyd's mirror configurations illustrated in Fig. 2-14 facilitates multiple beam interference so double exposure would be necessary to print two dimensional features. A mirrors-based wavefront splitting method, shown in Fig. 2-15, has been reported to realize four beams interference[127]. The configuration employs two sets of Fresnel bi-mirrors to fold the diverging beam in horizontal and vertical direction onto the sample. However, the configuration is unable to facilitate sub-micron pitch resolution.

Fig. 2-15 Dual Fresnel Bi-Mirror configurations to realize four waves interference

Besides reflection, refraction is another optical phenomenon that can be exploited as an alternative option for wavefront splitting to realize interference. Wavefront splitting by refraction means is achieved using highly transmissive dielectric material with custom designed facets to dictate desired orientation of the wave propagation. A Fresnel bi-prism is employed, as illustrated in the Fig. 2-16, to realize IL.

Fig. 2-16 Non-contact Fresnel bi-prism IL system using a collimated and expanded coherent laser beam.

The incline facets of the bi-prism split the collimated and expanded incident beam into two halves and refracts them in opposite directions. The refracted wave overlaps which result in interference at some distance away from the bi-prism. The facets of the bi-prism create two virtual plane wave sources, vs1 and vs2. Another way of implementing the prism-based wavefront splitting method is as shown in Fig. 2-17(a). The incident beam is introduced onto the side of the inclined facets and

interference is recorded on the flat side of the prism. Though the prism is in contact with the photoresist, the interference between propagating waves takes place. As shown in Fig. 2-17(b), the employment of three facets pyramid prism in the configuration, results in hexagonal lattice periodic two dimensional features generated by three waves interference.

Fig. 2-17 (a) Contact Fresnel bi-prism IL system (b) periodic circular features arranged in hexagonal lattice fabricated by using a three facets pyramid prism with apex top, shown in the bottom right inset [128]. (c) SEM images of three dimensional fcc structure types from four beams umbrella like configuration [129]

If a central wave is introduced by employment of a three facets pyramid prism with flat, one would be able to fabricate three dimensional face-centered cubic photonic

crystals structures as shown in Fig. 2-17(c). It is shown that the pitch size of the features exceeds 1 μ m. With larger elevation angle of the inclined facets of the prism, the angle between the interfering waves increases and hence results in features with smaller pitch size. However, total internal reflection on the inclined facets limits the design of elevation angle range and hence the minimum achievable pitch size of the interference fringes.

2.2.2. Amplitude Splitting Configuration

An amplitude splitting based interferometry system employs a beamsplitter to split the incident beam. Among different configurations of amplitude splitting interferometry systems, the Mach-Zehnder interferometry system is a popular choice of employment where IL is required [112, 130-133]. A basic Mach-Zehnder interferometry configuration for IL is illustrated in Fig. 2-18(a).

(a)

(b)

Fig. 2-18 (a) Mach-Zehnder IL system (b) Modified Mach-Zehnder IL system for excimer laser.

The mirrors are employed to direct the splitted beams onto the photoresist. With the two beams having polarization coherence, electric field interference fringes are recorded in the photoresist exposed to the overlap region of the two beams. An important concern with the Mach-Zehnder configuration is the optical path length difference between the two interferometry arms, which has to be smaller than the coherence length to realize interference. Fortunately, most commercially available UV laser systems today have very narrow linewidth allowing coherence length as long as a few metres. Even an excimer laser can be optimized to have linewidth much smaller than 1pm to result in coherence length of about 4cm. Since the beamsplitter splits the input beam via partial reflection with the splitted beams retaining the spatial size of the incident beam making it is possible to achieve interference within a large area of overlapping region between the two beams. Furthermore, allowance of large optical path length difference makes manual control of the interferometry arms possible. The Fig. 2-18(b) shows a modified Mach-Zehnder IL system that facilitates the employment of excimer lasers which has relatively lower spatial coherence as compared to a continuours wave laser. Complex arrangement of optical components

would be required setting up an amplitude splitting IL system to generate multiple beams interference [134, 135]

Another method to realize amplitude splitting is to exploit the diffraction phenomenon. By replacing the beam-splitter with a diffraction grating, one obtains the grating based IL system illustrated in Fig. 2-19.

Fig. 2-19 Basic configuration of grating based IL system

When the mirrors are tilted such that $\theta_i = \theta_d$, the grating based IL prints periodic features at twice the frequency of the diffracting grating. Higher frequency features are obtained by tilting the mirrors outward to achieve larger θ_i . The interferometry system that uses a diffraction grating as a beamsplitting unit offers more robustness against beam pointing instability than one that uses a conventional plate or cube beamsplitter [136]. With the introduction of lens or spatial filter, the phase fronts of the interferometry arms can be engineered [137, 138]. Like other interference lithography system, the maximum exposed area of a basic grating based IL system is limited by the size of the input beam. With the incorporation of a sophisticated optoelectronic system and electrical signal feedback system to perform in-

situ phase monitoring, beam alignment and automatic wafer stage movement into a grating based dual beams interferometry system, a scanning beam IL (SBIL) system is realized[139-142]. The system, which employs a 355nm laser source, has demonstrated capability to print periodic line features with 200nm pitch size over the entire area of a 12 inch wafer via a scanning exposure method. The impressive precision control system of the SBIL is further exploited to achieve 50nm periodic line features with 100nm pitch size by multiple lithography process [143]. Employing the liquid immersion technique, a basic grating based IL system with a 193nm laser source has demonstrated the fabrication of 32nm line and space features[144]. The liquid immersion technique is realized by directing the interferometry arms through the inclined facets of the bi-prism placed on the photoresist with the immersion liquid.

If excimer laser, such as ArF laser or EUV laser, are employed as the irradiation sources, achromatic configurations, shown in Fig. 2-20, become attractive alternatives to the grating based Interferometry configuration.

(a)

(b)

Fig. 2-20 Achromatic IL for (a) two waves interference to fabricate periodic line features (b) four waves interference to fabricate square arrayed periodic circular features.

The implementation of grating based interferometry system with irradiation sources of short coherence length would require small optical path difference between the interferometry arms, thus demands accurate mirror positioning. Since diffraction is exploited to manipulate the direction of the interfering beams, the achromatic configurations are free of misalignment issues. The Fig. 2-20(a) shows a multiple gratings achromatic configurations [145]. Patterning periodicity is changed by using gratings of different periodicity on the lower level. The Fig. 2-20(b) shows a more compact variation of the achromatic configuration. The illustrated configuration realizes multiple beams interference. One drawback with the compact achromatic configuration is its relatively high cost of implementation due to the number of gratings used. The robustness of the achromatic configuration depends to a large extent on the quality of the diffraction gratings.

2.3. Optical Lithography beyond diffraction limit

The OPL and IL discussed in previous sections are far-field optical lithography techniques since the imaging takes place at distance much greater than the source wavelength away from the source. As with far-field optical imaging techniques, the imaging of resolutions of both techniques are limited by diffraction phenomenon. For the OPL technique, diffraction limitation of the lens system occurs at object side and imaging side as illustrated in Fig. 2-21.

Fig. 2-21 Diffraction limitation at (a) object side and (b) imaging side of the lens system

If the numerical aperture of the lens system at the object side, NA_{obj} is smaller than the diffraction angle of the first order, there will be no image formation. The NA_{obj} of a lens system influences the imaging resolution of the lens system. For a lens system that facilitates demagnifications, NA_{image} of the lens system contributes to the limitation on the image resolution. As shown in Fig. 2-21, NA_{image} is determined by the maximum angular cone of light that propagate from the lens onto the photoresist. Light experiences total internal reflection on the flat side of the lens when the incident angle is larger than the critical angle that defines NA_{image} . By filling the gap between the lens and the photoresist with a liquid with refractive index that closely match that

of the lens, NA_{image} is increased leading to the enhancement of achievable spatial resolution. This is known as liquid immersion technique optical lithography. Although the scientific principles underlying immersion lithography have been known for over 100 years since the common employment of immersion microscope in the 19th century, it is only in recent years had this technology attracted widespread attention in the semiconductor industry. The liquid immersion technique enhances resolution by a factor equivalent to the refractive index of the immersion liquid. However, the irradiation sources that are currently used for optical lithography are in UV to DUV range. At these wavelengths, the highest refractive index among suitable liquids is about 1.6. Therefore, the resolution of the liquid immersion OPL is limited by the diffraction limitation of the immersion system which is dependent on the refractive index of the liquid apart from using a deep UV source.

To achieve optical lithography printing beyond diffraction limits, optical near field effects are exploited. Consider a liquid immersion configuration in which the refractive index of the photoresist is lower than that of the liquid. In this case, light that are incident on the liquid-photoresist interface at angles larger than the critical angle experience total internal reflection (TIR), resulting in the generation of an evanescent wave at the interface. If the incident beams are arranged in counter-propagating orientation, the resultant evanescent waves interference occurs are employed for lithographic patterning. A number of recent literatures have reported on the TIR-generated evanescent waves interference lithography technique, using lasers with shorter wavelengths as irradiation sources to achieve higher resolution features [146-149]. The amplitude of evanescent waves decays exponentially in the direction perpendicular from the liquid-photoresist interface thus limiting the exposure depth. This technique has been studied as early as in the late 1960s by Stetson for the purpose

of holography recording using 638nm wavelength lasers [150, 151]. Besides using the TIR configuration, evanescent waves interference lithography is also realized by the direct exposure of a mask with subwavelength features such as the evanescent near field optical lithography (ENFOL)[152].

The evanescent wave amplitude can be amplified via resonance excitation of surface plasmon via a Kretschmann configuration as shown in the Fig. 2-22 below [153].

Fig. 2-22 Schematic illustration of a Kretschmann configuration

The technique restricts the range of printed features' spatial frequencies and the choice of photoresist. For patterning periodic arrayed features, the Kretschmann configuration offers a maskless approach as opposed to the use of sub-wavelength mask [154, 155]. Surface plasmon interference lithography has also been demonstrated with the employment of subwavelength gratings [156, 157].

A thin metallic film has a unique property of negative refractive index. As such, a thin metallic film is ingeniously exploited as a negative lens employing a planar configuration shown in Fig. 2-23(a), for the purpose of focusing evanescent waves thus facilitating direct pattern transfer from a mask carrying sub-wavelength features without direct contact between the mask and the photoresist.

Fig. 2-23 (a) Schematic illustration of thin silver (Ag) film negative refraction lens configuration. (b) mask feature (top) photoresist features obtained with Ag film (centre) photoresist features obtained with out Ag film (bottom)[157]

As shown in Fig. 2-23(b), the approach is well suited for printing non-periodic features. The presence of Ag film allows photoresist features with smaller linewidth to be printed. It is reported that best image transfer occurs for a specific linewidth of the object features. This is associated to resonance excitation of the surface plasmon on the metallic film. One possible drawback with the technique lies with the difficulty in removing the superlens stack to facilitate post-exposure photoresist development

2.4. Outcome from Literature Review

Optical projection lithography is a complex but highly efficient technique used for industrial applications. The process parameters of optical projection lithography and different wavefront engineering techniques are outlined in the context of resolution enhancement. The definition of resolution enhancement in the context of optical projection lithography does not only refer to the achievable feature size but also the the achievable process window for printing a certain feature size. The process window indicates the reliability and robustness of a technique. To meet the resolution requirement of the current technology, the resolution enhancements techniques are

employed simultaneously hence requiring rigorous investigation for suitable combination of parameters setting.

In contrast to the high cost of optical projection lithography, interference lithography is a low cost parallel technique that enables features to be printed in a large area under a single exposure. Though the interference lithography can only realized printing of periodic patterns, it can be employed to investigate process related issues pertaining to the optical projection lithography since most of the features printed using the optical projection lithography are pseudo-periodic. Different interference lithography configurations are discussed. Compared to other interference lithography set-ups that have been reported, the Grating based Interference Lithography system allows flexibility in polarization modulation and variation in pitch size of printed features. To the best of the author's knowledge, the reported Grating based Interference Lithography systems only facilitate two beams interference but not multiple beams interference. Both optical projection lithography and interference lithography are techniques of which the printing resolution is subjected to diffraction limitation.

To print beyond the diffraction limit, optical energy in the near field would be required for exposure. Evanescent waves imaging as well surface plasmon assisted evanescent waves imaging realized by direct interference and masked approaches are outlined. In terms of direct interference approach, the evanescent waves imaging presents a few advantages over surface plasmon assisted evanescent waves imaging. Unlike the former, the latter require a metallic film to be in optical contact with the photoresist which is challenging to implement. The intrinsic nature of surface plasmon excitation also limits the choice of polarization of the incident beams to one that contains electric field with vector perpendicular to the interface. In comparison to

other near-field interference lithography techniques that require sub-wavelength gratings masks, the TIR-generated evanescent waves interference lithography offers relatively lower implementation cost. Also, in comparison to the large area surface plasmon polariton (SPP) interference lithography, it does not require a precise film coating of specifically selected metal and the highly precise angular direction of the incident beams [145]. In the context of the mask approach, studies suggest that surface plasmon assisted evanescent waves imaging result in better pattern resolution and greater exposure depth. However, the choice of the mask approach is only practical for printing non-periodic features.

Chapter 3

Investigation of Pupil Fill Factors as Process Window Indicators for Dry Optical Lithography

This chapter proposes a quantitative approach to approximate process window for resolution enhancement techniques assisted optical projection lithography. The proposed approach is based on power analysis of diffracted source image. This approach is discussed in comparison to another approach based on the geometrical analysis of diffracted source images. The correlation between the discussed approaches and the process window results is studied using different process conditions of attenuated phase shift masking and off-axis illumination. Preliminary simulation results suggest that power distribution analysis of diffracted source images is a better approach than the one based on geometrical analysis. This observation is further validated by findings from experimental investigations which show high correlation between the variations of the proposed approach and that of the process window.

3.1. Introduction

According to the modified Rayleigh criterion, the highest resolution, R and the depth of focus, DOF , achievable by a dry optical OPL system are given by $R = k_1 \lambda / NA$ and $DOF = k_2 \lambda / NA^2$ respectively, where λ represents the wavelength of the exposure source, NA the numerical aperture of the projection optics, k_1 and k_2 are process dependent factors that incorporate everything in the lithography process that is not wavelength or NA [47, 158]. Much as high resolution is desired for optical projection lithography, DOF is equally important for reliability of the process. A large DOF would allow features to be printed within specification over a large area, of which the surface topology may be uneven. The current dry optical projection lithography systems are designed with high NA projection optics for high resolution printing. However, this would inevitably cause degradation of the DOF , of which the process window is a function. Over the years, a number of resolution enhancement techniques have been researched and developed to allow high resolution printing with enhanced process window, such as using the phase shifting photomask and off-axis illumination.

The CPLTM technology has been developed by the ASML Masktool for patterning sub-65nm features in integrated chip fabrication [66, 159-162]. Two of the resolution enhancement techniques employed in the CPLTM technology for dry optical lithography are the CPLTM mask and the use of off-axis illumination[163]. The CPLTM mask is a special type of phase shift mask. The π -phase shifters, which define the primary features of the circuit patterns, are etched from the glass substrates of the mask blank. The top of the etched phase shifters are deposited

with chrome patches for different transmission coefficient. A CPLTM mask has the following advantages as compared to other type of phase shift masks. When compared to the alternating phase shift masks, the CPLTM mask is relatively easier to be designed and manufactured, especially for two dimensional features. Yet, the lithography performance of the CPLTM mask is comparable to that of the alternating phase shift mask [164]. When compared to the conventional attenuated phase shift masks which have MoSi structures as the phase shifters, the CPLTM mask presents two advantages. Firstly, the CPLTM mask is more easily manufactured than the conventional attenuated phase shift mask. Secondly, the transmission level of the phase shifters of the CPLTM mask can be varied between 0 to 100% with appropriate amount of chrome deposition [165]. This is unlike the conventional attenuated phase shift mask, of which the MoSi phase shifters of either 6% or 18% transmission level. Properties of the photomask features, such as the geometry, intensity transmission and phase shifting property, would influence the corresponding diffraction spectrum at the Fourier domain and therefore the final image.

A number of past literatures have studied the correlation between the diffraction pattern captured at the objective lens and properties of the final image [166-170]. The work of Hsu et al. studied the influence of the intensity transmission of the phase shifters on the CPLTM mask on image properties such as the process window and the image sharpness[170]. The intensity transmission of the phase shifters was shown to influence the intensity of the 0th and 1st order diffraction beams at the objective lens. Their results suggest that, for the printing of dense line features, when the amplitudes of the 0th and the 1st order diffraction beams captured at the objective lens are balanced, the best image contrast and

process window results are obtained. Besides intensity transmission, the illumination source setting is also an important process parameter to investigate since the use of off-axis illumination is another salient feature of the CPLTM technique. The works by Manakali et al. and Lim et al. presented a different concept of the correlation between the process window and the diffraction orders captured at the pupil. Their concept correlates the process window to the extent of overlap between the 0th and $\pm 1^{\text{st}}$ diffraction orders at the pupil. Their works have shown that for printing of dense line features, the maximum possible process window coincide with the maximum overlap between the 0th and the $\pm 1^{\text{st}}$ diffraction orders [168, 169].

The objective of this work is to formulate and compare two pupil-fill factors as process window indicators for dry optical lithography. These two pupil-fill factors are formulated based on the above mentioned concepts of the correlation between the process window and the diffraction orders captured at the pupil. For the purpose of this work, the CPLTM technology is used as a case study. The effects of varying the transmission factor of the phase shifters and the configuration of the illumination source would be studied.

3.2. Theoretical foundation of Pupil-Fill Factors

A simplified model of the OPL system is shown in Fig. 3.1 below. The object lens L_o and the imaging lens L_i represent the complex multi-lens projection optics in a real stepper. As shown in Fig. 3-1, the object lens L_o captures only the lower diffracted orders. The captured diffractions orders are directed through the optical system (as represented by the space between L_o and L_i) to the imaging lens L_i . The L_i converges the electric field onto the imaging plane Σ_i , resulting in

interference of the electric field to form an inverted image of the photomask features.

Fig. 3-1 Schematic representation of the simplified theoretical model of the OPL system

In the OPL system, the photomask is exposed to an extended source. Based on the Abbe's theory of imaging, the extended source is treated as a collection of coherent source points, which behave incoherently to each other [47]. At the entrance pupil plane of L_i , the diffraction spectrum due to a source point is an array of delta functions. Therefore, when the photomask is exposed to an extended source, the resultant diffraction pattern on the entrance pupil plane of L_i is a summation of the diffraction spectrums due to all the source points of the extended source. This results in each diffraction order to be an image of the extended source. Based on the hypothesis, the size and shape of the extended source would influence the electric field at the pupil plane of L_i , and consequently the image formed at Σ_i . The domain of an extended source is defined by its partial coherent parameters, the values of which are factors of the numerical aperture (NA) of the objective lens L_i . A commonly used extended source configuration is the

QuasarTM illumination shown below. As illustrated in Fig. 3-2a, the shape and size of the QuasarTM illumination are defined by its partial coherence parameters σ_o , σ_i and opening angle O_a . The illustration in Fig. 3-2b shows the 0th and the $\pm 1^{\text{st}}$ orders of the diffraction spectrum of periodic line features when the QuasarTM illumination is used for exposure. As shown, the $\pm 1^{\text{st}}$ diffraction orders are captured partially at the entrance pupil plane of L_i .

Fig. 3-2 (a) The QuasarTM illumination source defined by three partial coherence parameters, σ_o , σ_i and O_a . (b) Diffracted beams of the 0th and $\pm 1^{\text{st}}$ order. The $\pm 1^{\text{st}}$ order diffracted beams are partially captured by the pupil. The areas of overlap between the 0th and the 1st diffraction orders are shaded.

In general, an illumination source can be described by a source function $S(u, v) = ss(u, v)\Omega(u, v)$ where $\Omega(u, v)$ describes the geometry of the extended source and $ss(u, v)$ represent the strength of the source point located at position (u, v) . The terms u and v represent the coordinates in frequency domain that corresponds to the x and y coordinates in spatial domain [171]. If the model in Fig. 3-2(a) is assumed to have unity magnification, the optical transfer function of the system can be further simplified to be the pupil function, $P(u, v)$, of the imaging lens L_i [55, 172]. Therefore, the power distribution of the diffraction spectrum at the pupil plane of L_i is defined as,

$$E = S(u, v) \otimes |M(u, v)P(u, v)| \quad (3-1)$$

where $M(u, v)$ represent the normalized diffraction spectrum of the photomask features due to an on-axis unit amplitude source point. It is mathematically represented as a Fourier transformation of the amplitude transmittance function $m(x, y)$. In this work, the investigation is restricted to the case of imaging periodic line features of a CPL mask. Each line feature is assumed to be a π -phase shifter with a amplitude transmission of T , with a linewidth of w and pitch size of Λ . If each of the source points in the extended source has an unit amplitude, the amplitude of the discrete diffraction spectrum is given as [82, 173]

$$M(u) = \left[\Lambda \text{sinc}(\pi\Lambda u) - w\sqrt{T} \text{sinc}(\pi w u) \right] \bullet \sum_{\mathfrak{M}=-\infty}^{\infty} \delta\left(u - \frac{\mathfrak{M}}{\Lambda}\right) \quad (3-2)$$

where $\mathfrak{M}$ refers to the diffraction order.

If the imaging lens L_i is assumed to be a simple lens with no aberration, the pupil function $P(u, v)$ is expressed as [55],

$$P(u, v) = \begin{cases} 1 & \left| \sqrt{u^2 + v^2} \right| \leq NA/\lambda \\ 0 & \text{otherwise} \end{cases} \quad (3-3)$$

The presented theoretical framework suggests that the image at Σ_i can be approximated from the analysis of the diffraction spectrum captured at the pupil plane of L_i . From Eq (3-1) to (3-3), it is shown that the diffraction spectrum is influenced by the illumination source configuration as well as the mask features, such as the intensity transmission, linewidth, and phase shifting. For the case of imaging periodic line features, the amplitude of the $\mathfrak{M}^{th}$ diffraction order captured at L_i , $E_{\mathfrak{M}}$, is modified from Eq (3-1) and given as,

$$E_{\mathfrak{M}} = \begin{cases} S(u, v) \otimes [M_m(u) P(u, v)] & \mathfrak{M} = 0 \\ 2[S(u, v) \otimes [M_m(u) P(u, v)]] & \mathfrak{M} \geq 1 \end{cases} \quad (3-4)$$

where,

$$M_m(u) = \left[\Lambda \text{sinc}(\pi \mathfrak{M}) - w\sqrt{T} \text{sinc}\left(\pi \frac{\mathfrak{M}w}{\Lambda}\right) \right] \bullet \delta\left(u - \frac{\mathfrak{M}}{\Lambda}\right)$$

As shown in Eq (3-4), the amplitude of the higher diffraction order is multiplied by a factor 2 because the higher diffraction orders are spread equally on both side of the 0th diffraction order.

This work focuses on the case in which only the 0th and $\pm 1^{st}$ diffraction orders are captured at L_i . The energy lost in the additional orders results in power lost from the illumination source in the imaging process. Therefore, larger exposure dose would be required for printing dense features as compared to for printing less dense features of the same dimension. During the imaging process, the electric field of the 1st diffraction order would interfere with an equivalent portion of the electric field of the 0th diffraction order to contribute to the contrast

of the image at the Σ_i . The portion of the 0th order beam which does not interfere with the 1st order diffracted beam would contribute to the background intensity and therefore causes image degradation. The intensity difference between that of the 0th and the 1st diffraction order is expressed as a fraction of the total amplitude of the diffraction spectrum at the pupil plane of L_i . This is represented by the pupil-fill factor ϵ given as,

$$\epsilon = \left| \frac{E_{0th} - E_{1st}}{E_{0th} + E_{1st}} \right| \quad (3-5)$$

A zero value for ϵ would mean that there is a perfect amplitude balance between the 0th and the 1st diffraction order at the pupil plane of L_i .

The second concept correlates the process window to the extent of overlap between that of the 0th and $\pm 1^{\text{st}}$ diffraction orders at the pupil plane of L_i . As shown in Fig. 3-2(b), when the QuasarTM illumination is used, the shaded area is area of overlap between the 0th and $\pm 1^{\text{st}}$ diffraction orders. To account for the extent of overlap, a second pupil-fill factor f_p is proposed. If the area of overlap is given as α_o and total area of the diffraction spectrum at the pupil of L_i is given as α_T , f_p , is defined as,

$$f_p = \frac{\alpha_o}{\alpha_T} \quad (3-6)$$

Varying the configuration of the illumination source and the photomask features, the work investigates how accurate the variations of ϵ and f_p would indicate the influences of the process parameters on the process window for image formation. The following section presents the investigation methodology to investigate the validity of the discussed pupil-fill factors.

3.3. Investigations based on Aerial Image Analysis

A numerical approach is employed for this investigation for which a commercially available software, LithocruiserTM, is used for the lithography simulation. The LithocruiserTM has a complete database of ASML lithography systems data to be used for simulation. This enables user to perform the simulation studies using realistic process parameters. The lithography system used for this work is the ASML 1250 which is a dry lithography system with the highest available NA of 0.85. With this software, the diffraction spectrums at the pupil plane of L_i as well as the process window results are obtained. Here, the influence of photoresist is omitted by considering the aerial image only. The process window (PW) of the aerial image is defined as $PW = DOF$ at 10% exposure latitude, as per current industrial standard. The exposure latitude refers to the allowable deviation of the exposure dose for the features to be printed within specification. A source code is written to be used with the computational software, MatlabTM, to calculate the amplitude at L_i and subsequently the corresponding values for ϵ and f_p . The wavelength of the illumination used for the simulation study is 193nm. The NA for the pupil of the lens is fixed at 0.85. The illumination intensity is set with a top hat profile. The desired width for the targeted line features is 60nm (with error tolerance of ± 6 nm) with the pitch sizes ranging from 120 nm to 240nm. For pitch sizes larger than 240nm, the 2nd order diffracted beams would be captured at the pupil. Hence, they are omitted from the study.

3.3.1. Effect of varying annular ring width of illumination source

Simulated printing of dense to semi-dense 60nm line features is carried out. The effect of varying the width of an annular illumination source on the PW for the printing process is investigated. The outer radius (σ_o) of the illumination source is fixed at 0.93. The ring width of the annular illumination source is varied by changing the value of σ_i from 0.3 to 0.69, which is the actual range achievable for 0.85NA with the simulated lithography system. The corresponding PW variation for printing the dense to semi-dense 60nm line features is shown in Fig. 3-3.

Fig. 3-3 The effect of varying σ_i of illumination source on the PW of the 60nm line with pitch size from the dense to semi-dense pitch region.

For printing the dense 60nm line (160nm pitch size), it is observed that larger extent of central obscuration (as indicated by the σ_i value) would result in larger PW. When the σ_i value is 0.69, the maximum PW is achieved. The PW for printing the semi-dense line is generally smaller than that for printing the dense line for all the investigated σ_i values. To print the semi-dense (240nm pitch) line

features, smaller values of σ_i results in larger PW. The largest PW is obtained with a σ_i value of 0.3. The captured diffraction spectrums for the dense and semi-dense 60nm line features are studied. The resultant E_{0th} and E_{1st} of the 0th and 1st order diffracted beams for dense 60nm line features are shown in Fig. 3-4.

Fig. 3-4 The effect of varying σ_i of illumination on the lens field energy of the diffracted beams for dense 60nm line features

The resultant E_{0th} and E_{1st} of the 0th and 1st order diffracted beams for dense 60nm line features are shown in Fig. 3-5.

Fig. 3-5 The effect of varying of illumination on the lens field energy of the diffracted beams for semi-dense 60nm line features

The results show that as the value of σ_i increases, the values of E_{0th} and E_{1st} are reduced. From the results shown in the Fig. 3-4 and Fig. 3-5, the factor ϵ is calculated using Eq. 3-5. The variation of ϵ values and PW with different σ_i values for the case of printing the dense line features and semi-dense line features with an annular illumination are shown in Fig. 3-6.

Fig. 3-6 The correlation between the factor ϵ and the PW for the effect of increasing central obscuration (a) dense (160nm pitch) 60nm line features (b) semi-dense (240nm pitch) 60nm line features

The results in Fig. 3-6(a) show that for printing dense line features, larger σ_i value would result the larger PW but smaller ϵ value. However for printing semi-dense 60nm line features (see Fig. 3-6b), the trend is reversed. In this case, the increase in the σ_i values would results in smaller PW but larger ϵ value. For the same σ_i value, the results have shown that the dense case has larger PW than the semi-dense case. The corresponding ϵ value for the dense case is smaller than that of the semi-dense case. The results suggest a possible correlation between the variation of ϵ values and that of the PW results for different σ_i values. The variation of the overlap factor f_p with increment of σ_i values is illustrated in Fig. 3-7 for the dense and semi-dense line features respectively. From the figures, the results do not suggest a consistent correlation between f_p and PW for printing both dense and semi-dense periodic lines.

Fig. 3-7 The correlation between the overlap factor, f_p and the PW for the effect of increasing central obscuration (a) dense (160nm pitch) 60nm line features (b) semi-dense (240nm pitch) 60nm line features

Since the f_p value indicates the extent of overlap between the 0th and ± 1 st diffraction orders, the results does not support a clear correlation between the PW and the extent of overlap between the diffraction orders. Thus the influence of

source configuration on PW could not be indicated accurately by the variation of the f_p values.

3.3.2. Effect of varying the opening angle of illumination source

To investigate the effect of varying the opening angle of the illumination source, simulated exposures with QuasarTM illumination are carried out. The opening angle, O_a of the QuasarTM source is varied between 30° to 75° while the value of σ_i is maintained at 0.69. The corresponding PW results are compared to that of using annular illumination. The QuasarTM illumination with 90° opening angle represents the annular illumination. The influence of varying the O_a of the QuasarTM illumination on the through pitch PW results for printing the 60nm line features is shown in Fig. 3-8. As compared to the annular illumination, the QuasarTM illuminations provide larger PW for printing the periodic 60nm line features of 140nm pitch size.

Fig. 3-8 The effect of varying O_a of illumination on the PW of the 60nm line with pitch size ranging from the dense to semi-dense region

However, the results suggest that the QuasarTM illumination may not be as effective as the annular illumination in terms of the PW for printing the 60nm lines features with larger pitch sizes. The 45° QuasarTM illumination would achieve the largest PW for the 140nm pitch line features. The diffraction patterns for the dense (140nm pitch) and semi-dense (240nm) 60 nm line features are analyzed. The corresponding the E_{0th} and E_{1st} values are shown in the Fig. 3-9 and Fig. 3-10 respectively. The results show that in both cases, QuasarTM illumination with smaller opening angle O_a , would result in the reduction of E_{0th} and E_{1st} .

Fig. 3-9 The effect of varying O_a of illumination on the lens field energy of the diffracted beams for dense 60nm line features

Fig. 3-10 The effect of varying O_a of illumination on the lens field energy of the diffracted beams for semi-dense 60nm line features

For printing of the dense line features, the results in Fig. 3-11(a) suggest that the variation of the ϵ values indicates the influence of varying O_a on the PW values reasonably well. The maximum PW is achieved with the opening angle that results in the smallest amplitude difference between that of the 0th and 1st diffraction order captured at the pupil plane of L_i .

(a)

(b)

Fig. 3-11 The correlation between the factor ϵ and the PW for the effect of increasing O_a for (a) dense 60nm line features (b) semi-dense 60nm line features

For the semi-dense case, the results in Fig. 3-11(b) suggest a possible critical ϵ value of 0.57 for QuasarTM illumination. When the ϵ value is beyond the critical value, it is shown that there is no PW for printing the semi-dense line features. This indicates that the source configuration does not provide any DOF for 8%EL. However, if the lower EL is allowed, the source configuration may allow some extent of DOF. The variation of the f_p values with different O_a values is illustrated in Fig. 3-12 for the dense and semi-dense line features.

(a)

(b)

Fig. 3-12 The correlation between the overlap fraction f_p and the PW for the effect of increasing angular obscuration (a) dense 60nm line features (b) semi-dense 60nm line features

The results in both figures do not show a consistent correlation between f_p and PW for both cases. In Fig. 3-12(a), the O_a for maximum f_p value does not coincide with that for maximum PW. For printing of the semi-dense line features,

the results in Fig. 3-12(b) suggest that the amount of overlap between the 0th and the 1st diffraction order could be correlated to the PW. However, this correlation is not consistent as have suggested by the earlier results in this work. The results presented so far have shown that variation of the ϵ values is a clearer indicator of the influence of source configuration on the PW as compared to that of f_p . The findings suggest that the PW performance is a function of the diffraction spectrum amplitude but not of the overlap between the diffraction orders. To further validate the notion, the following section presents the study of the influence of intensity transmission of the phase shifters.

3.3.3. Effect of intensity attenuation of phase shifter

The QuasarTM illumination with the O_a value of 45° , $0.93\sigma_o$ and $0.69\sigma_i$ is used in the study. The illumination setting has been shown to achieve the maximum PW results for printing the line features of 140nm pitch size in the previous section. Fig. 3-13 shows the through pitch PW results for the 60nm features, obtained with different intensity transmission for the π -phase shifters on the CPL mask. The results show that the 50% transmission π -phase shifters allow the dense 60nm line features (140nm pitch size) to be printed with largest PW. The PW for printing 60nm wide line features with pitch sizes larger than 140nm would deteriorate for all intensity-transmission.

Fig. 3-13 The effect of increasing intensity transmission of π -phase shifter on the PW of the 60nm line with pitch size ranging from the dense to semi-dense region.

However, the results show that higher intensity transmission imposes a “smoothing” effect on the through-pitch variation of the PW results. Therefore, the results suggest that higher intensity transmission may be more favorable for semi-dense line features in the context of obtaining larger PW. For the semi-dense (240nm pitch size) 60nm line features, the largest PW is achieved by using the 100%intensity transmission π -phase shifters.

The variation of E_{0th} and E_{1st} values with the transmittance of the phase shifter for dense (140nm pitch) periodic 60nm line features is shown in Fig. 3-14. The results in the Fig. 3-14 show that higher intensity transmission reduced the amplitude of the 0th diffraction order but increases that of the 1st diffraction order. As such, this leads to a smaller amplitude difference between the diffraction orders captured at the pupil plane of L_i .

Fig. 3-14 The effect of increasing intensity transmission of the phase shifter on the lens field energy of the diffracted beams for dense 60nm line features

The smallest amplitude difference is obtained when the π -phase shifters has intensity transmission of 50%. Incidentally, the correspondent PW result at this intensity transmission value is the largest. The variation of E_{0th} and E_{1st} values with the transmittance of the phase shifter for semi-dense (240nm pitch) periodic 60nm line features is shown in Fig. 3-15. The results in Fig. 3-15 suggest that, for the semi-dense line features, the intensity transmission of the π -phase shifters does not have an influence on the amplitude of the 0th diffraction order. Higher intensity transmission value for the π -phase shifters increases the amplitude of the 1st diffraction order. Consequently, increment of the intensity transmission values reduces the amplitude difference between the diffraction orders at the pupil plane of L_i .

Fig. 3-15 The effect of increasing transmission of phase shifter on the lens field energy of the diffracted beams for semi-dense 60nm line features

The correlation between the factor ε and the PW for the effect of increasing angular obscuration for dense and semi-dense 60nm line features is illustrated in Fig. 3-16. The results in Fig. 16a and Fig. 16b suggest that the influence of intensity transmission on the PW results can be indicated by the variation of ε values. The correlation between the PW results and f_p is not shown because the f_p values obtained from printing the dense line features and semi-dense line features remained unchanged at 0.41 and 0 respectively. The extent of overlap between the diffraction orders is dependent only on the source configuration and the pitch size of the line features. As shown by Eq(3-6), f_p only accounts for the geometrical areas of the diffraction orders captured by L_i , ignoring the effect of the amplitude.

Fig. 3-16 The correlation between the factor ε and the PW for the effect of increasing angular obscuration (a) dense 60nm line features (b) semi-dense 60nm line features

The results suggest that the variation of f_p values would not be able to indicate the influence of the intensity transmission of the π -phase shifters on the PW.

3.4. Experimental Results and Discussion

The correlations between the variation of ε and process window (PW) in response to variation in process conditions such as feature proximity, mask transmittance as well as source schemes are further investigated numerically and experimentally. In this part of the work, the PW is defined as the product of depth of focus and the corresponding exposure latitude. The exposure latitude is quantitatively determined by $(D_u - D_l)/D_a \times 100\%$, where, D_u is the largest allowable exposure dose before the pattern dimension is printed out of specification, D_l is the lowest allowable exposure dose and D_a is the applied exposure dose. At the time of experimental investigation, the author does not have access to scanner lithography systems which facilitate parametric settings identical to those of the simulation study presented in the previous section. The PW results, shown in Fig. 3-17, are obtained using a scanner lithography system that employs annular shape illumination source with wavelength of 248nm, projection system of 0.68NA and the 6% attenuated phase shift photomask. Line features with pitch sizes beyond 430nm are not included in the experiment because, based on theoretical calculation, the second diffraction order would be captured in the pupil. For the case of printing the periodic 100nm line features, the experimental PW value decreases with larger pitch size.

(a)

(b)

Fig. 3-17 Variation of PW results and ϵ values of printing (a) periodic 100nm line features and (b) periodic 120nm line features. In both cases, the pitch sizes ranging from 300nm to 430nm and exposure source is of annular shape with partial coherence setting of $0.75\sigma_o/0.50\sigma_i$.

The variation of the simulated PW results exhibits reasonable agreement with that of the experimental results. The correlation between the ϵ values and the PW

values through the investigated range of pitch sizes is quantified using the correlation coefficient expressed as follows,

$$\alpha = \frac{\sum_i (PW_i - \overline{PW})(\varepsilon_i - \bar{\varepsilon})}{\sqrt{\sum_i (PW_i - \overline{PW})^2 \sum_i (\varepsilon_i - \bar{\varepsilon})^2}} \quad 0 \leq |\alpha| \leq 1 \quad (3-7)$$

where $\overline{PW}$ and $\bar{\varepsilon}$ represent the mean value of PW and ε respectively. A large absolute α value indicates good correlation. A negative α value suggests inverse relationship between the compared entities. For periodic 100nm line features, the correlation coefficient between the simulated PW results and the ε values, α_{sim} , is -0.994. The correlation coefficient of the experimental PW results and the ε values, α_{expt} , is -0.895. From the PW results of printing the periodic 120nm line features shown in Fig. 3-17(b), the values of α_{sim} and α_{expt} are -0.981 and -0.898. The findings suggest good correlation between the values of ε and PW.

The PW results, shown in Fig. 3-18, are obtained by employing 6% attenuated phase shift photomask and a conventional illumination source with 248nm wavelength. The variation of the simulation result agrees reasonably well with that of the experimental PW results. The ε values vary in an inverse relationship to that of PW results. It is interesting to highlight that the maximum PW value obtained with a pitch size of 320nm is indicated accurately by the minimum ε value. The correlation coefficient of the simulation PW and the ε values is -0.819. The correlation coefficient of the experimental PW and the ε values is -0.832.

Fig. 3-18 Variation of PW results and ϵ values of printing periodic 120nm line features with pitch sizes ranging from 300nm to 430nm with conventional illumination source with partial coherence setting of $0.75\sigma_0$.

To examine the effect of the transmittance of the phase shifters on the PW results, a custom-fabricated CPL mask is employed. The transmittance of the photomask features are either 0 (chrome structures), 0.5 (π -phase shifting structures with alternating arrangement of chrome patches and clear space along its length) or 1 (just π -phase shifting structures). Phase shifting structures with other levels of transmittance are not fabricated on the sample photomask due to budget constraint. The fabrication of phase shifting structure with other transmittance level was technically challenging and is not a cost effective option at the time of this investigation. An ArF-based lithography system (exposure wavelength of 193nm) with a numerical aperture of 0.85NA is employed for the experimental investigation. The targeted features are periodic 60nm line features with pitch size of 160nm. Employing Annular and Quasar illumination schemes, PW and α results for different mask features transmittance values are obtained as shown in Fig. 3-19.

Fig. 3-19 Variation of PW results and ϵ values with transmittance of phase shifters. Exposure source is of annular source shape with partial coherence setting of $0.92\sigma_o / 0.68\sigma_i$.

As shown in Fig. 3-19, with Annular exposure, the obtained simulated PW results and the corresponding ϵ values, α_{sim} , have correlation coefficient of -0.943 between them. The correlation coefficient between the experimental PW results and the ϵ values, α_{expt} , is -0.926. With Quasar exposure, $\alpha_{sim} = -0.944$ and $\alpha_{expt} = -0.849$ are obtained.

The good correlation between the variation of pupil-fill factor and that of PW suggests that the pupil-fill factor potentially employable as a time-efficient approach to identify process conditions, such as the transmittance of mask features and illumination scheme, that would result in best process window results. The methodology for obtaining process window, as employed by most commercial simulation tool, is to compute aerial image at different focal positions with different illumination source amplitude. Another possible application of the pupil-fill factor may be for approximating the appropriate pitch size allocation for sub-wavelength assist features, a form of optical proximity correction scheme, added to

enhance the process window of printing isolated features. The validity of employing the pupil-fill factor as a fast approximation tool is subjected to certain conditions. The formulation of pupil-fill factor assumes perfect parallelity of electric field vector of interfering beams for aerial image formation, thus image degradation due to presence of orthogonal electric field vector is not accountable by the pupil-fill factor. With higher density of mask features, amplitudes of the diffracted waves depend on the electric field polarization vector of the incident beam relative to the mask feature orientation. The diffraction amplitudes are higher if the incident electric field vector is parallel to the length of the mask features. The converse is true if the incident electric field vector is parallel to the length of the mask features. This is due to diffraction induced polarization effect. When the pitch size of mask features approach the illumination wavelength, consideration of diffraction induced polarization effect in computation may be required when applying the pupil fill factor approach to approximate the process window.

3.5. Summary

Two process parameters of the CPLTM technology have been investigated in this work for their influences on the PW results for the dry optical lithography process. The parameters are the illumination source configuration and intensity transmission of the π -phase shifters on the CPL mask. For the dense and semi-dense line features, the 0th and 1st diffraction orders captured at pupil plane of L_i are analyzed using two different approaches. While One accounts for the amplitude difference between the diffraction orders indicated by ϵ , the other accounts for the geometrical overlap areas of the diffraction orders as indicated

by f_p . The results show that the variation of ε correlates reasonably well to the variation of PW results obtained for the investigated process parameters. On the other hand, the results show that the correlation between the variations of f_p with that of the PW results is not apparent. The results suggest that for the case where image formation is only due to the interference between the 0th and 1st diffraction orders, the PW is a function of the amplitude difference between the diffraction orders cap and not of the extent of overlap between them. Therefore, the pupil factor ε , as compared to f_p , could be a more accurate indicator of the influence of the investigated process parameters on the PW for printing dense to semi-dense line features.

Chapter 4

Single Exposure Multiple Beams Interference Lithography

In this chapter, the theoretical background and the related formulations of the intensity distributions of two beams interference as well as four beams interference were given followed by experimental validation. The theoretical interference intensity distributions are derived with the photoresist layer modeled as a sandwiched layer thus taking into consideration into the interference between incident and reflected beams. The theoretical background is followed by a discussion of the design of a modified grating based interference lithography system to facilitate multiple beams interference. Patterning of dense periodic line and circular features are investigated with regards to process conditions, such as polarization state of incident beams and exposure dose.

4.1. Introduction

With the advancement of nanotechnology, the importance of IL becomes increasingly significant and thus this technique deserves further research and development. In this context, this chapter presents the research and investigation carried out in the realm of interference lithography using a modified lensless grating-based system that facilitate interference patterning using either two polarized beams or four polarized beams. In the next section, the theoretical intensity distributions of the interference between two polarized beams as well as those between four polarized beams are presented.

4.2. Theoretical Background

In optical lithography, the key to pattern formation is the phenomenon of interference. The extent of interference between the electric fields of two light waves depends on the mutual orientation of the electric fields. Maximum interference takes place between two parallel electric fields and there would be no interference between orthogonal electric fields. When more than two optical waves interfere, the resulting interference intensity is sensitive to the orientation of the electric fields. To model optical waves interference in three-dimensional space, electric fields vectors are solved by using the mapping matrix method outlined in Appendix A.

4.2.1. Formulation of two beams interference intensity distribution

The simplest form of laser interference involves a pair of co-planar beams, intersecting at a plane. The intensity distribution of the two plane waves interference would be analysed with the photoresist being represented as a sandwiched thin film model

illustrated in Fig. 4-1. In the figure, the first medium is taken as air, the second medium is a photoresist and the last medium is the substrate.

Fig. 4-1 The interference of two incident beams when the photoresist layer is modeled as a thin film.

If the incident plane waves are s-polarized, the electric fields of the incident in the photoresist layer are given as,

$$\mathbf{E}_s^{(1)} \approx |F_s| A_1 \exp \left(j \left(-k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_1 + \chi_s \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad (4-1)$$

$$\mathbf{E}_s^{(2)} \approx -|F_s| A_2 \exp \left(j \left(k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_2 + \chi_s \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad (4-2)$$

and that of reflected beams in the photoresist layer are given as

$$\mathbf{E}_{sr}^{(1)} \approx |B_s| A_1 \exp \left(j \left(-k_r \sin \theta'_r x - k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_1 + \zeta_s \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad (4-3)$$

$$\mathbf{E}_{sr}^{(2)} \approx -|B_s| A_2 \exp \left(j \left(k_r \sin \theta'_r x - k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_2 + \zeta_s \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad (4-4)$$

where $k_r = kn_r$, $\sin \theta'_r = n_1 \sin \theta / n_r$, $\cos \theta'_r = \sqrt{1 - (n_1 \sin \theta / n_r)^2}$, t is the time variable

and T is the inverse of the frequency of the illumination source. The amplitude and phase terms of the effective transmission coefficient for s-polarized or p-polarized

plane wave are given as $|F_{s,p}|$ and $\chi_{s,p}$. Likewise, the amplitude and phase terms of the corresponding effective reflection coefficient are given as $|B_{s,p}|$ and $\zeta_{s,p}$. The effective transmission coefficient and effective reflection coefficient are defined as,

$$|F_{s,p}| \exp(j\chi_{s,p}) = \frac{\tilde{\tau}_{s,p}^{(1,r)}}{1 - \tilde{\rho}_{s,p}^{(r,1)} \tilde{\rho}_{s,p}^{(r,sub)} \tau_d^2(\theta'_r)} \quad (4-5)$$

$$|B_{s,p}| \exp(j\zeta_{s,p}) = \frac{\tilde{\tau}_{s,p}^{(1,r)} \tilde{\rho}_{s,p}^{(r,sub)} \tau_d^2(\theta'_r)}{1 - \tilde{\rho}_{s,p}^{(r,1)} \tilde{\rho}_{s,p}^{(r,sub)} \tau_d^2(\theta'_r)} \quad (4-6)$$

In Eq. (4-5) and (4-6), $\tilde{\tau}_{s,p}^{(1,r)}$ and $\tilde{\rho}_{s,p}^{(r,1)}$ represent the transmission and reflection coefficients of the wave in the photoresist. The term $\tilde{\rho}_{s,p}^{(r,sub)}$ is the reflection coefficient of the wave in the photoresist caused the photoresist-substrate interface. The internal transmittance through the photoresist layer is represented as $\tau_d(\theta'_r)$ which is defined as $\tau_d(\theta'_r) \approx \exp(jk_r \cos \theta'_r d) \exp(-\kappa_r d / \cos \theta'_r)$. The interference intensity distribution in the photoresist for two s-polarized incident beams is obtained as,

$$\begin{aligned} I_{2s} \propto & \frac{1}{2} \exp\left(\frac{-2k\kappa_r z}{\cos \theta'_r}\right) \dots \\ & \times \left[-2A_1 A_2 \left(|B_s|^2 \exp\left(\frac{4k\kappa_r z}{\cos \theta'_r}\right) + |F_s|^2 \right) \cos(2k_r \sin \theta'_r x - \delta_{1,2}) \dots \right. \\ & - 4A_1 A_2 |F_s| |B_s| \exp\left(\frac{2k\kappa_r z}{\cos \theta'_r}\right) \cos(2k_r \sin \theta'_r x - \delta_{1,2} - (\chi_s - \zeta_s)) \dots \\ & \times \cos(2k \cos \theta'_r z) \dots \\ & + (A_1^2 + A_2^2) \left(2|F_s| |B_s| \exp\left(\frac{2k\kappa_r z}{\cos \theta'_r}\right) \cos(2k_r \sin \theta'_r x - (\chi_s - \zeta_s)) \dots \right. \\ & \left. \left. \times |B_s|^2 \exp\left(\frac{2k\kappa_r z}{\cos \theta'_r}\right) + |F_s|^2 \right) \right] \end{aligned} \quad (4-7)$$

where $\delta_{1,2}$ represents the phase difference between beam 1 and beam 2. The period of the intensity variation in the z direction is obtained as $\lambda/2n_r \cos \theta'_r$. If the incident plane waves are p-polarized, the respective electric fields in the photoresist layer are given as,

$$\mathbf{E}_p^{(1)} \approx (-\cos \theta'_r \hat{e}_x - \sin \theta'_r \hat{e}_z) \dots \times |F_p| A_1 \exp \left(j \left(-k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_1 + \chi_p \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \quad (4-8)$$

$$\mathbf{E}_p^{(2)} \approx (\cos \theta'_r \hat{e}_x - \sin \theta'_r \hat{e}_z) \dots |F_p| A_1 \exp \left(j \left(k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_2 + \chi_p \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \quad (4-9)$$

and that of the reflected beams in the photoresist given as,

$$\mathbf{E}_{pr}^{(1)} \approx (\cos \theta'_r \hat{e}_x - \sin \theta'_r \hat{e}_z) \dots \times |B_p| A_1 \exp \left(j \left(-k_r \sin \theta'_r x - k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_1 + \zeta_p \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \quad (4-10)$$

$$\mathbf{E}_{pr}^{(2)} \approx (-\cos \theta'_r \hat{e}_x - \sin \theta'_r \hat{e}_z) \dots \times |B_p| A_1 \exp \left(j \left(k_r \sin \theta'_r x - k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_2 + \zeta_p \right) \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right). \quad (4-11)$$

The corresponding intensity distribution of the interference in the photoresist layer are given as,

$$\begin{aligned}
 I_{2p} \propto & \frac{1}{2} \exp\left(\frac{-2k\kappa_r z}{\cos\theta'_r}\right) \dots \\
 & \times \left[2A_1 A_2 \left(|B_s|^2 \exp\left(\frac{4k\kappa_r z}{\cos\theta'_r}\right) + |F_s|^2 \right) \cos(2\theta'_r) \cos(2k_r \sin\theta'_r x - \delta_{1,2}) \dots \right. \\
 & + 4A_1 A_2 |F_s| |B_s| \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos(2k_r \sin\theta'_r x - \delta_{1,2} - (\chi_s - \zeta_s)) \dots \\
 & \times \cos(2k_r \cos\theta'_r z) \dots \tag{4-12} \\
 & + (A_1^2 + A_2^2) \left(-2|F_s| |B_s| \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos(2\theta'_r) \cos(2k_r \sin\theta'_r x - (\chi_s - \zeta_s)) \dots \right. \\
 & \left. \left. \times |B_s|^2 \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) + |F_s|^2 \right) \right]
 \end{aligned}$$

The Eq (4-7) and Eq (4-12) show that the interference of the incident plane waves and reflected plane waves resulted in the standing wave phenomenon as represented by the sinusoidal variation of the intensity distribution in the z-direction.

4.2.2. Formulation of multiple beams interference intensity distribution

In this section, the theoretical analysis is further extended to the study of simultaneous interference of multiple plane waves, taking the specific case of four beams interference. Due to the vector nature of the electric field of a plane wave, the intensity distribution of the interference between multiple incident plane waves in the photoresist is highly sensitive to the electric field polarization of each plane wave. To simplify the analysis, the incident plane waves are assumed to have the identical incident angle. Same as in the case of two plane waves interference, the multiple plane waves interference is analyzed by having the photoresist modeled as a sandwiched thin medium. The reflected plane waves from the resist-substrate interface would interfere with the incident plane waves. Consider the interference of

multiple s-polarized waves with arbitrary azimuth angle, the implicit general expression for the resultant intensity distribution,

$$I \propto \left\{ \frac{1}{T} \int_0^T \left(\sum_{l=0}^m E_x^{(l)} \right)^2 + \left(\sum_{l=0}^m E_y^{(l)} \right)^2 \right\} \partial t \quad (4-13)$$

where $E_x = E_{xi} + E_{xr}$ and $E_y = E_{yi} + E_{yr}$ in which,

$$E_{xi}^{(l)} \approx |F_s| A_l \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \sin \phi_w \dots \quad (4-14)$$

$$\cos(\chi_s + \delta_l + k_r \sin \theta'_r \cos \phi_w x + k \sin \theta'_r \sin \phi_w y + k_r \cos \theta'_r z - 2\pi t/T)$$

$$E_{xr}^{(l)} \approx |F_s| |B_s| A_l \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \sin \phi_w \dots$$

$$\cos(-(\chi_s + \zeta_s + \delta_l) - k_r \sin \theta'_r \cos \phi_w x - k_r \sin \theta'_r \sin \phi_w y + k \cos \theta'_r z - 2\pi t/T)$$

$$\dots \quad (4-15)$$

$$E_{yi}^{(l)} \approx -|F_s| A_w \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \cos \phi_l \dots \quad (4-16)$$

$$\cos(\chi_s + \delta_l + k_r \sin \theta'_r \cos \phi_l x + k_r \sin \theta'_r \sin \phi_l y + k_r \cos \theta'_r z - 2\pi t/T)$$

$$E_{yr}^{(l)} \approx |F_s| |B_s| \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) A_l \cos \phi_l \dots$$

$$\cos(-(\chi_s + \zeta_s + \delta_l) - k_r \sin \theta'_r \cos \phi_l x - k_r \sin \theta'_r \sin \phi_l y + k_r \cos \theta'_r z - 2\pi t/T)$$

$$\dots \quad (4-17)$$

If the incident plane waves are p-polarized, the corresponding implicit general expression for the interference is given as,

$$I \propto \left\{ \frac{1}{T} \int_0^T \left(\sum_{l=0}^m E_x^{(l)} \right)^2 + \left(\sum_{l=0}^m E_y^{(l)} \right)^2 + \left(\sum_{l=0}^m E_z^{(l)} \right)^2 \right\} \partial t \exp \left(\frac{-4\pi \kappa_r d}{\lambda} \right) \quad (4-18)$$

where $E_x = E_{xi} + E_{xr}$, $E_y = E_{yi} + E_{yr}$ and $E_z = E_{zi} + E_{zr}$ in which,

$$E_{xi}^{(l)} \approx |F_p| A_l \exp\left(\frac{-k\kappa_r z}{\cos \theta_r'}\right) \cos \phi_l \cos \theta_r' \dots \quad (4-19)$$

$$\cos\left(\chi_p + k_r \sin \theta_r' \cos \phi_l x + k_r \sin \theta_r' \sin \phi_l y + k_r \cos \theta_r' z - 2\pi t/T + \delta_l\right)$$

$$E_{xr}^{(l)} \approx |F_p| |B_p| A_l \cos \phi_l \cos \theta_r' \dots$$

$$\cos\left(-(\chi_p + \zeta_p + \delta_l) - k_r \sin \theta_r' \cos \phi_l x - k_r \sin \theta_r' \sin \phi_l y + k_r \cos \theta_r' z - 2\pi t/T\right)$$

$$\dots \quad (4-20)$$

$$E_{yi}^{(l)} \approx |F_p| A_l \exp\left(\frac{-k\kappa_r z}{\cos \theta_r'}\right) \sin \phi_l \cos \theta_r' \dots$$

$$\cos\left(\chi_p + k_r \sin \theta_r' \cos \phi_l x + k_r \sin \theta_r' \sin \phi_l y + k_r \cos \theta_r' z - 2\pi t/T + \delta_l\right)$$

$$\dots \quad (4-21)$$

$$E_{yr}^{(l)} \approx -|F_p| |B_p| A_l \sin \phi_l \cos \theta_r' \dots$$

$$\cos\left(\chi_p + \delta_l + \zeta_p + k_r \sin \theta_r' \cos \phi_l x + k_r \sin \theta_r' \sin \phi_l y - k_r \cos \theta_r' z - 2\pi t/T\right)$$

$$\dots \quad (4-22)$$

$$E_{zi}^{(l)} \approx -|F_p| A_l \exp\left(\frac{-k\kappa_r z}{\cos \theta_r'}\right) \sin \theta_r' \dots$$

$$\cos\left(\chi_p + \delta_l + k_r \sin \theta_r' \cos \phi_l x + k_r \sin \theta_r' \sin \phi_l y + k_r \cos \theta_r' z - 2\pi t/T\right)$$

$$\dots \quad (4-23)$$

$$E_{zr}^{(l)} \approx -|F_p| |B_p| A_l \sin \theta_r' \dots$$

$$\cos\left(-(\chi_p + \zeta_p + \delta_l) - k_r \sin \theta_r' \cos \phi_l x - k_r \sin \theta_r' \sin \phi_l y + k_r \cos \theta_r' z - 2\pi t/T\right)$$

$$\dots \quad (4-24)$$

The derivation of explicit expression representing interference of multiple incident plane waves becomes rigorous when interactions of the reflected plane waves are considered. For purpose of simplification, the theoretical analysis is limited to that of the interference between four incident beams oriented in the umbrella configuration as illustrated in Fig. 4-2.

(a)

(b)

Fig. 4-2 Interference of four incident beams oriented in an umbrella configuration shown in (a) x-z plane and (b) y-z plane

In the four beams umbrella configuration, as shown in Fig. 4-2, the wave vectors of two beams are parallel to the x-z plane and that of the other two are parallel to the y-z plane. If the incident plane waves are s-polarized, the intensity distribution in the photoresist layer is given as,

$$\begin{aligned}
 I_{4s} \propto & \frac{1}{2} \exp\left(\frac{-2k\kappa_r z}{\cos\theta'_r}\right) \sum_{l=1}^2 \left\{ \left[-4A_l A_{l+2} |F_s| \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos(2k_r \cos\theta'_r z + (\chi_s - \zeta_s)) \dots \right. \right. \\
 & \left. \left. - 2A_l A_{l+2} \left(|F_s|^2 + |B_s|^2 \exp\left(\frac{4k\kappa_r z}{\cos\theta'_r}\right) \right) \right] \dots \right. \\
 & \left. \times \cos\left(2k_r \sin\theta'_r \left(\cos\left(\frac{(l-1)\pi}{2}\right)x + \sin\left(\frac{(l-1)\pi}{2}\right)y \right) + \delta_{l,l+2} \right) \right. \\
 & \left. + (A_l^2 + A_{l+2}^2) \left(|F_s|^2 \exp\left(\frac{-2k\kappa_r z}{\cos\theta'_r}\right) + |B_s|^2 \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \dots \right. \right. \\
 & \left. \left. + 2|F_s||B_s| \cos(2k_r \cos\theta'_r z + (\chi_s - \zeta_s)) \right) \right\} \dots
 \end{aligned} \tag{4-25}$$

If the four incident plane waves are p-polarized such that the electric field the intensity distribution can be presented as the superposition of the intensity distributions of three interferences terms given by,

$$I = \frac{-1}{4} \exp\left(\frac{-2k\kappa_r z}{\cos\theta'_r}\right) ((\cos 2\theta'_r - 1) I_{adj} + I_{opp} + I_{sum}) \tag{4-26}$$

where $\cos 2\theta'_r = 1 - \sin^2 \theta / n_r^2$. The intensity distribution of the interference between adjacent incident beams is defined as follows,

$$I_{adj} = I_{1,2} + I_{2,3} + I_{3,4} + I_{4,1} \tag{4-27}$$

where each term on the right side of the Eq (4-27) is defined by the general expression given below,

$$\begin{aligned}
 I_{u,v} \propto & \cos(k_r \sin\theta'_r (x - y) + \delta_{u,v}) \left\{ 2A_u A_v \left(|F_p|^2 + |B_p|^2 \exp\left(\frac{4k\kappa_r z}{\cos\theta'_r}\right) \right) \dots \right. \\
 & \left. + 4A_u A_v |F_p||B_p| \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos(k_r \cos\theta'_r z + (\chi_p - \zeta_p)) \right\}
 \end{aligned} \tag{4-28}$$

where the subscripts (u,v) represent (1,2), (2,3), (3,4) and (4,1). The intensity distribution of the interference between counter-oriented incident beams is defined as follows,

$$I_{opp} \propto \sum_{l=1}^2 \left\{ \left[8|F_p||B_p|A_lA_{l+2} \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos 2\theta'_r \cos(2kn_r \cos\theta'_r z + (\chi_p - \zeta_p)) \dots \right. \right. \\ \left. \left. - 4A_lA_{l+2} \left(|F_p|^2 + |B_p|^2 \exp\left(\frac{4k\kappa_r z}{\cos\theta'_r}\right) \right) \right] \dots \right. \\ \left. \times \cos\left(2k_r \sin\theta'_r \left(\cos\left(\frac{(l-1)\pi}{2}\right)x + \sin\left(\frac{(l-1)\pi}{2}\right)y \right) + \delta_{l,l+2} \right) \right\} \\ \dots \quad (4-29)$$

and

$$I_{sum} \propto \sum_{l=1}^4 A_l^2 \left[2 \left(|F_p|^2 + |B_p|^2 \exp\left(\frac{4k\kappa_r z}{\cos\theta'_r}\right) \right) \cos 2\theta'_r \dots \right. \\ \left. - 4|F_p||B_p| \exp\left(\frac{2k\kappa_r z}{\cos\theta'_r}\right) \cos(2k_r \cos\theta'_r z + (\chi_p - \zeta_p)) \right] \quad (4-30)$$

The term I_{sum} is defined here as the sum of the background intensity of the interference between the incident plane waves and their own reflection.

To validate the presented theoretical approximation model, experimental investigations have been carried out. The objectives of the experimental investigations are to demonstrate the feasibility of employing multiple beams interference as a lithography approach for patterning two dimensional features in a single exposure as well as to explore and study the practical issues in implementing this technique. In the following section, the experimental set-up to realize four beams interference is discussed.

4.3. Experiment Set-Up

The system proposed in this report is different from set-ups reported previously [174-176]. It is based on a lensless approach to realize interference between multiple beams and facilitates the polarization of individual beams. The set-up is illustrated in Fig. 4-3.

Fig. 4-3 Experimental set-up for four beams interference shown in x-z plane.

A circularly polarized input beam, from a coherent UV continuous wave (CW) laser source with 364nm wavelength, is directed perpendicularly onto a custom-fabricated cross grating (Ibsen Photonics Pte Ltd) acting as a multiple beams splitter, diffracting the input beam into circularly polarized multiple beams. An electronic shutter, with a temporal resolution of 10ms, is installed in front of the laser head to modulate the exposure duration. The cross- phase grating is designed to generate high diffraction efficiency four 1st order beams and a suppressed 0th order beam. To simplify the illustration, the set-up is shown in the x-z plane. An illustration of the set-up in y-z plane is identical to that shown in Fig. 4-3. A linear polarizer, mounted in custom fabricated rotating mount, is placed in the optical path of each diffracted beam to

obtain either s-polarized or p-polarized beam. The attenuators are placed to balance the amplitudes of the beams. A hard stop is employed to block the 0th order beam so as to realize four beams interference. The diffracted beams are aligned and directed such that they are about 45° with respect to the z-axis. For this purpose, a right angled roof-top prism with one adjacent face coated to be reflective, is employed. The roof-top prism is positioned on the sample stage such that each of the beams is directed into the clear facet, undergo total internal reflection on the hypotenuse facet and reflected off the reflective facet. A microscope slide is placed in the optical path of each beam to observe the beam spots made by the incident and back-reflected rays. The angle is approximated to be 45° if the two spots remain overlapped when the microscope slide is translated over a distance. After angular adjustment, the interfering beams are directed to overlap on the target sample by translating the mirrors along the x,y and z direction. A dummy sample, an uncoated silicon wafer, is placed on the sample stage to reflect the incident beams. The microscope slide is translated along the optical path of each beam to check the co-planarity as well as the extent of overlap as on the dummy sample between each pair of opposite beams. The opposite beams are co-planar and they overlap on the dummy sample if the beam spots on the microscope slide remain overlap as the slide translates. Overlapping of the two co-planar pairs on the dummy sample is evaluated visually. For this purpose, a glass wafer, with the same thickness of the silicon wafer, would make a better dummy sample due to the fluorescing nature of glass when subjected to UV illumination. The employment of an uncoated silicon wafer as dummy sample allows the checking of imperfect co-planarity between co-planar beam pair. This is observed when the beam spots on the slide separate sideways as the slide is translated along the optical path. Bare silicon wafer is treated with hexamethyl disilazane (HMDS) vapour deposition to promote

adhesion of photoresist to wafer surface. The wafer is then spin-coated with liquid AZ7220 positive tone photoresist (AZ Electronics MaterialTM) at 1500rpm followed by soft bake at 110°C for 90sec. After exposure to the interfering beams, the photoresist is developed in AZ300MIF for 60 secs. The obtained experimental results are presented and discussed in the following section.

4.4. Results and Discussion

4.4.1. Two beams interference

A silicon substrate, coated with 1000nm of AZ7220 resist, is exposed to the interference between a co-planar pair of s-polarized incident beams. The powers of the beams are measured to be 2.03mW and 2.06mW respectively. The corresponding beam irradiance in the photoresist are estimated to be equal to 63.33mW/cm^2 and 64.11mW/cm^2 respectively. The resist is exposed for duration of 260ms. The exposed sample is developed for duration of 60sec and observed under the scanning electron microscope (SEM). The SEM picture of the resist line features is shown in Fig. 4-4.

Fig. 4-4 Pattern collapse (as indicated by the white arrows) caused by capillary force resulted by surface tension of liquid trapped in between the line features

At the bottom of the above figure, the total length of the white dots represent 1µm.

The average width of the line features is found to be $130.69\text{nm} \pm 4.51\text{nm}$. The period

is $257\text{nm} \pm 1.36\text{nm}$ which closely agrees with the theoretically approximated value of 257nm . Some of the resist line features are observed to have collapsed which may be attributed to the capillary force effect. This arises from the surface tension of the liquid trapped between the line features. The capillary force, $\mathbb{F}$, acting on the line feature is theoretically predicted as [177],

$$\mathbb{F} = \sigma(\text{height of feature}) \left(\frac{2 \cos(\text{contact angle})}{\text{width of space}} \right) \quad (4-31)$$

where σ is the surface tension of the liquid-resist interface and “contact angle” refers to the contact angle of the liquid-resist interface. As suggested by the above equation, the capillary force effect is proportional to the aspect ratio which is (height of feature)/(width of space). The average width of space is found to be $138\text{nm} \pm 6\text{nm}$. Therefore, to reduce the capillary force, attempts are made to achieve resist coating of smaller thickness. The final resist thickness is empirically related to resist viscosity (ν) and spinning speed (ω_{spin}) as follows [177],

$$\text{thickness} \propto \frac{\nu^{pv}}{\sqrt{\omega_{spin}}} \quad (4-32)$$

In Eq (4-32), the value of pv ranges from 0.4 to 0.6. To prepare liquid AZ7220 resist of different viscosity, fixed amount of AZ7220 is dissolved in different amount of PGMEA. A higher PGMEA-to-AZ7220 ratio results in a solution with lower viscosity. The diluted AZ7220 is then spin coated at 1500rpm onto 4” wafers. The achievable resist thickness for different concentrations of AZ7220 quantified by the PGMEA to AZ7220 ratio as shown in Fig. 4-5. It is observed that the achieved thickness decreases exponentially with increasing PGMEA-to-AZ7220 ratio (i.e. lower viscosity). Also, the non-uniformity of the measured thickness, as indicated by the

standard deviation, increases when the PGMEA-to-AZ7220 ratio value is larger than 2.5.

Fig. 4-5 Final resist thickness achieved with PGMEA to AZ7220 ratio

Therefore, the concentration ratio of 2.5:1 is adopted which allowed photoresist thickness of $170\text{nm} \pm 11\text{nm}$ to be achieved. The samples are exposed to interference between two s-polarized incident beams as well as two p-polarized beams to investigate the effect of polarization line features profile. Representing a 170nm thick photoresist layer by a sandwiched thin film, the intensity profiles of two s-polarized beams interference in the photoresist layer are computed and shown in Fig. 4-6. The simulation result, given in x-z plane, shows that the intensity contrast of the interference fringes at $z=0$ is close to 1. The absence of a bottom anti-reflection coating resulted in interference between the downward traveling wave and the reflected wave. As such, there would be regions of high and low intensity distribution along the z direction. This would lead to standing wave effect in the side wall of the resist pattern after development. A positive tone photoresist, AZ7200, is employed in the simulation.

Fig. 4-6 Simulated cross-sectional interference intensity profiles in the photoresist layer obtained with two s-polarized incident beams.

Therefore, the intensity distribution correlates directly to the dissolution rate. The SEM images of samples exposed to the interference of two s-polarized incident plane waves are shown in Fig. 4-7. It is observed that exposure duration of 60ms does not allow enough dose energy to result in well-defined line features as shown in Fig. 4-7(a). An exposure duration of 120ms results in line features with average width of $167.69\text{nm} \pm 7.06\text{nm}$ as shown in Fig. 4-7(b). The resist in the high intensity regions was shown to be dissolved completely. A longer exposure duration of 170ms results in line features with smaller average width of $137.82\text{nm} \pm 7.68\text{nm}$ as shown in Fig. 4-7(c).

(a)

(b)

(c)

Fig. 4-7 Top-down SEM image of the line features fabricated by two s-polarized incident beams interference using exposure duration of (a) 60ms (b) 120ms (inset: top-view) (c) 170 ms (inset: top-view).

The standing wave effect is not observed in the SEM cross-section image. The photoresist thickness is about 172.30nm. This may be attributed to the anti-reflection effect realized by a thin layer of photoresist-HMDS layer formed above the substrate [178, 179].

The interference between two p-polarized beams is investigated. The powers of the beams are measured to be 1.94mW and 1.96mW. The corresponding approximated irradiance values are estimated to be equal to 60.34mW/cm^2 and 61.15mW/cm^2 respectively. According to Eq (4-12), the interference term is

modulated by the cosine of the incident angle of the two beams. The simulated intensity profile of two p-polarized beams interference in the 170nm photoresist layer is shown in Fig. 4-8. The simulated interference fringes have a contrast of 0.647 at $z=0$.

Fig. 4-8 Simulated cross-sectional interference intensity profiles in the photoresist layer obtained with two p-polarized incident beams.

The top-down SEM image of line features obtained from exposure to two p-polarized incident beams interference is shown in Fig. 4-9. It is observed that the average linewidth of the features fabricated from two p-polarized incident beams interference is $149.89\text{nm} \pm 5.05\text{nm}$, which is about larger than that of the line features obtained from exposure to two s-polarized incident beams interference.

Fig. 4-9 Top view of line features fabricated in 170nm thick resist by exposing to 2 p-polarized interfering beams for duration of 170ms .

The theoretical and experimental results show that lower intensity contrast translates to bigger linewidth and poorer features' profile. In the next section, single exposure multiple beams interference approach would be discussed.

4.4.2. Multiple Beams Interference

In the previous section, the effect of polarization in the case of two beams interference is shown to influence the contrast of the interference fringes which in turn determine the contrast of the photoresist line features. In the case of multiple beams interference, the intensity distribution of the interference is much more sensitive to the polarization state of the incident beams. Consider the interference between four s-polarized incident beams, the corresponding intensity distribution in the x-y plane of the resist layer at $z=0$ is shown in Fig. 4-10(a) and the three dimensional intensity distribution is shown in Fig. 4-10(b). The simulation results are obtained based on the assumption that both beams are equal in intensity.

(a)

Fig. 4-10 Simulated intensity distribution of interference of 4 s-polarized incident beams in (a) the x-y plane (b) three dimensional perspective.

The interference of four s-polarized incident beams results in an intensity distribution equivalent to superposition of two sets of line fringes that are orthogonal to each other. Three distinct intensity regions are identified to facilitate clarity in subsequent description. They are namely “L” that represents the low intensity regions, “M” that represents the mid-intensity regions and “H” that represents the high intensity regions. The overall interference intensity distribution of four s-polarized incident beams configuration results from the summation of two sets of periodic lines patterns orthogonal to each other. The periodic lines parallel to x and y direction results from the interference between the electric field components parallel to the x –direction and that parallel to the y-direction respectively. The “L” regions results from the superpositioning of the intensity minimas of the electric field components parallel to the x direction and that parallel to the y direction. Likewise, the “H” regions results from the superpositioning of the intensity maximas of the electric field component parallel to the x direction and that parallel to the y direction. On the other hand, the “M” regions are where the intensity maxima of one component superpose with the

minimas of the other. The standing wave effect is seen in the simulated intensity profile in the z- direction given in Fig. 4-10(b). The profile in the diagonal plane is similar to that shown in Fig. 4-6. Exposures of AZ7220 photoresist to four s-polarized incident beams were carried out experimentally. The powers of the four s-polarized beams are measured to be 2.03mW, 2.06mW, 2.07mW and 2.13mW. The correspondent irradiance values of the transmitted beams are 63.33mW/cm², 64.11 mW/cm², 64.42 mW/cm² and 66.20mW/cm². The SEM images of resist features obtained using different exposure durations are shown in Fig. 4-11.

(a)

(b)

(c)

Fig. 4-11 SEM images square array circular resist features resulted from exposure to four s-polarized incident beams for duration of (a) 40ms (b) 50ms (c) 60ms

An exposure duration of 40ms resulted in periodic circular-like holes with average diameter of $166.34\text{nm} \pm 9.42\text{nm}$. The holes are arranged in almost a square array formation. The period along x-direction is $252.36\text{nm} \pm 9.37\text{nm}$ and that along the y-direction is $263.5\text{nm} \pm 8.39\text{nm}$. The difference between the theoretical approximated period and those obtained experimentally is within 5%. With longer exposure duration of 50ms, the holes increase in size and the “links”, which correspond to the mid-intensity region, decreases in their widths as shown in Fig. 4-11(b). Eventually, with exposure duration of 60ms, sufficient exposure dose is accumulated in the mid-intensity regions to result in complete clearance of the photoresist, hence leaving behind periodic circular pillars with an average diameter of $128.14\text{nm} \pm 4.00\text{nm}$ as shown in Fig. 4-11(c). At the time of the experimental investigation, the cross-section profile of the samples could not be analyzed without damaging the resist profiles due to tool limitation. Hence, the standing wave in the sidewalls of the two dimensional features cannot be verified experimentally.

In another study, the interference of four p-polarized incident beams is investigated. For the simulation of interfering four p-polarized beams, all four beams are assumed to be of equal intensity. The corresponding intensity distribution in the x-y plane at $z=0$ is shown in Fig. 4-12(a) and the three dimensional intensity distribution is shown in Fig. 4-12(b).

(a)

(b)

Fig. 4-12 Simulated intensity distribution of interference of 4 p-polarized incident beams in (a) the x-y plane (b) three dimensional perspective.

The simulation result suggests that different intensity distribution can be achieved by altering the polarization states of the incident beams without changing their orientation. With the angle of incidence of the interfering beams in air kept at $\theta = 45^\circ$, the corresponding incident angle of the beams in the photoresist, θ_r is $<45^\circ$. As suggested by Eq (4-26) and Eq (4-29), the interference between four p-polarized beams includes I_{opp} . From the simulation result, the low intensity regions “L”, mid-intensity regions “M” and the high intensity regions “H” are identified. The overall interference intensity distribution of four p-polarized incident beams configuration can be resolved into two components: a) intensity of the interference between electric field components parallel to the x-y plane. b) intensity of the interference between electric field components parallel to the z-direction. The “L” regions results from the superpositioning of the intensity minimas of the electric field component parallel to the x-y plane and that parallel to the z direction. Likewise, the “H” regions results from the superpositioning of the intensity maximas of the electric field component parallel to the x-y plane and that parallel to the z direction. On the other hand, the “M” regions are where the intensity maxima of the electric field component parallel to the x-y plane superpose with the intensity minimas of of the electric field component parallel to z direction. The standing wave effect is seen in the simulated intensity profile in the z- direction given in Fig. 4-12(b). The measured powers of the four p-polarized incident beams are equal to 1.94mW, 1.96mW, 2.04mW and 1.99mW. The corresponding irradiance values are 60.34mW/cm², 61.15mW/cm², 63.55mW/cm² and 61.9 mW/cm².

(a)

(b)

Fig. 4-13 SEM images of hexagonal array circular-like resist features resulted from exposure to four p-polarized incident beams for duration of (a) 30ms (b) 60ms

The SEM images of the fabricated features, shown in Fig. 4-13, are found to agree well with the simulated results. With exposure duration of 30ms, the circular-like features, which are periodically distributed in hexagonal array, have an average diameter of $196.8\text{nm} \pm 11.47\text{nm}$. The white rimmed box, shown in Fig. 4-13(a), depicts the area that correlate well with the obtained simulation data. As shown, the resist in the “M” regions are not developed completely during the stipulated development time. High contrast periodic circular features, distributed in diamond array, are obtained when

diamond array, are obtained when exposed for 60ms (see Fig. 4-13(b)). The resultant circular features have an average diameter of $161.7\text{nm} \pm 5.00\text{nm}$. The experimentally obtained average pitch sizes in the x direction, y direction and the diagonal direction are $512.50\text{nm} \pm 3.54\text{nm}$, $523.33\text{nm} \pm 9.43\text{nm}$ and $375\text{nm} \pm 7.07\text{nm}$ respectively. These experimental results agree well (with less than 5 % error) with the theoretical values: The respective pitch sizes in the x and y directions are 510nm each and that along diagonal direction is 353.6nm.

4.5. Summary

The conventional interference lithography is investigated in this chapter. Fabrication of line features with periodicity of 257nm from beams interference is demonstrated experimentally. Simulation results show that fringes of the interference between s-polarized incident beams shows higher contrast than those of the p-polarized incident beams. This finding is well supported by the experimental results, which show that the interference of s-polarized incident beams results in photoresist line features (average linewidth = 137.82nm) with smaller line-width and better contrast than the line features obtained with the interference of p-polarized incident beams which have an average linewidth of 149.89nm. Also, the fabrication of close packed periodic circular-like features was realized by employing interference between four polarized beams. With four s-polarized interfering beams, square array distribution of circular features, with average pitch size of 257.8nm in x and y direction, are obtained. Photochemistry reaction of the photoresist to accumulated exposure dose has been exploited, by varying the exposure duration, to obtain either holes with average diameter as small as 166.34nm or circular pillar-like features with average diameter of 128.14nm. Employment of four p-polarized interfering beams results in hexagonal array distribution of circular pillar features with average diameters

of 161.7nm and with pitch size of 517.89nm in x and y direction, and 375nm along the diagonal direction.

Chapter 5

Evanescant Waves Interference Lithography

This chapter presents the investigation of lithography beyond diffraction limit via employment of evanescent waves interference. The theoretical formulations of intensity distributions of two beams evanescent waves interference and four beams evanescent waves interference are presented. A modified cellular automata method for modeling photoresist development process is proposed. The design and integration of a custom fabricated optical element into the four beams interference lithography system, followed by sample preparation procedure, are presented. Two beams and four beams evanescent waves interference lithography are analyzed theoretically followed by experimental validation. Influences of polarization of incident beams and exposure dose on lithography performance are explored.

5.1. Introduction

The patterning resolutions of OPL and IL are generally enhanced by employing liquid immersion configurations of OPL and IL [15, 16, 180-182] but are, nonetheless, subjected to diffraction limit that is determined by the refractive index of the immersion liquids. This chapter presents the study of an approach to achieve optical lithography printing beyond diffraction limits by exploiting optical near field effects. In these approaches, light is allowed to undergo total internal reflection (TIR) on the liquid-photoresist interface leading to the generation of evanescent waves at the interface. Hyper-resolution patterning is realized by engineering the propagation of evanescent waves to effect interference between them. Evanescent waves interference was first proposed and demonstrated for holography recording [150, 151]. Recent literatures have proposed and studied the UV laser assisted version of this technique for lithography application [146, 183]. However, achievements of these works have been limited to the fabrication of only periodic line features using two beams evanescent waves interference. In this regards, the work reported in this chapter encompasses two beams evanescent waves interference lithography and further extension of the technique to realize multiple counter-propagating evanescent waves interference to achieve single exposure patterning of nanoscale periodic two dimensional features. In the following section, the theoretical modeling of evanescent waves interference and photoresist dissolution process are detailed.

5.2. Theoretical Background

5.2.1. Modeling of Evanescent waves interference

Consider that a plane wave propagates from medium 1 to medium 2. The incident medium has a refractive index value of n_i and is placed in perfect optical contact with a weakly absorbing medium, of which the complex refractive index value is $\hat{n}_r = n_r + j\kappa_r$ in which n_r is the real part of the refractive index and κ_r is the extinction coefficient. The weakly absorbing medium is also optically less dense than the incident dielectric medium such that $n_r < n_i$. The incident angle of the plane wave at the interface between the dielectric medium and the optically less dense material is given by $\theta_i^{(l)}$. The corresponding azimuth angle is given by $\phi_i^{(l)}$. When the incident angle, $\theta_i^{(l)}$ of $\mathbf{E}_i^{(l)}$ at the interface is larger than the critical angle such that $\sin \theta_i^{(l)} > n_r/n_i$, TIR occurs and an evanescent wave, $\mathbf{E}_e^{(l)}$, is generated. The corresponding lateral Goos-Hanchen shift is indicated by GH_L . The concept of generating evanescent wave by TIR in a three dimensional space is illustrated by Fig. 5-1. In the context of this chapter, the optically less dense medium represent the photoresist. The photoresist is modeled as a semi-infinite media since the evanescent wave does not propagate through the thickness of the photoresist. Here, we assume that the transverse Goos-Hanchen shift, GH_T , is negligible. This is a valid assumption for the purpose of this study since the transverse Goos-Hanchen shift is small after a single reflection [184]. Hence, the azimuth angle of the evanescent wave would be the same as that of the incident wave. The expression for the resultant evanescent wave, $\mathbf{E}_e^{(l)}$, suppressing the time-dependence, is given as follows [185],

$$\mathbf{E}_e^{(l)} = \mathbf{E}_{e(amp)}^{(l)} \exp\left(i \frac{2\pi n_i}{\lambda} (\sin \theta_i^{(l)} \cos \phi_i^{(l)} x + \sin \theta_i^{(l)} \sin \phi_i^{(l)} y)\right) \dots \quad (5-1)$$

$$\times \exp\left(-\frac{2\pi n_i}{\lambda} \left(\sqrt{\sin^2 \theta_i^{(l)} - (n_r/n_i)^2} + \kappa_r\right) z\right)$$

Fig. 5-1 Evanescent wave generated by TIR in three dimensional space

The expression in the Eq. (5-1) shows that the evanescent wave propagates at the interface(x-y plane) between the incident and transmitted medium. The amplitude of the evanescent wave decays exponentially in the z direction. The terms n_{ri} and $\mathbf{E}_e^{(l)}$ refers to n_r/n_i and the electric field vector of the evanescent wave in Cartesian space respectively. The electric field vector of the resultant evanescent wave in Cartesian space can be correlated to that of the incident wave by Eq. (A-14) of Appendix A, from which the general expression of the electric vector of an evanescent wave is obtained as,

$$\mathbf{E}_e^{(l)} = \begin{bmatrix} \left| \tau_{s(l)}^{(i,r)} \right| \sin \phi_i^{(l)} E_{s(amp)}^{(l)} \exp(-j \chi_{s(l)}'^{(i,r)}) + \left| \tau_{p(l)}^{(i,r)} \right| \cos \theta_r^{(l)} \cos \phi_i^{(l)} E_{p(amp)}^{(l)} \exp(-j \chi_{p(l)}'^{(i,r)}) \\ - \left| \tau_{s(l)}^{(i,r)} \right| \cos \phi_i^{(l)} E_{s(amp)}^{(l)} \exp(-j \chi_{s(l)}'^{(i,r)}) + \left| \tau_{p(l)}^{(i,r)} \right| \cos \theta_r^{(l)} \sin \phi_i^{(l)} E_{p(amp)}^{(l)} \exp(-j \chi_{p(l)}'^{(i,r)}) \\ \left| \tau_{s(l)}^{(i,r)} \right| \sin \theta_r^{(l)} E_{p(amp)}^{(l)} \exp(-j \chi_{p(l)}'^{(i,r)}) \end{bmatrix} \dots \quad (5-2)$$

When the incident wave is s polarized, the resultant electric vector of the evanescent wave is,

$$\mathbf{E}_e^{(l)} = \begin{bmatrix} |\tau_{s(l)}^{(i,r)}| \sin \phi_i^{(l)} E_{s(amp)}^{(l)} \exp(-j\chi_{s(l)}'^{(i,r)}) \\ -|\tau_{s(l)}^{(i,r)}| \cos \phi_i^{(l)} E_{s(amp)}^{(l)} \exp(-j\chi_{s(l)}'^{(i,r)}) \\ 0 \end{bmatrix} \quad (5-3)$$

where

$$|\tau_{s(l)}^{(i,r)}| = \frac{2 \cos \theta_i^{(l)}}{\sqrt{\left[\kappa_r \left(1 + \sqrt{q(\theta_r^{(l)})} \right) / \left(n_r \sqrt{q(\theta_r^{(l)})} \right) + n_{ri} \cos \theta_i^{(l)} \right]^2 + \left(\sqrt{q(\theta_r^{(l)})} + (\kappa_r / n_i) \cos \theta_i^{(l)} \right)^2}} \quad \dots \quad (5-4)$$

$$\chi_{s(l)}'^{(i,r)} = \tan^{-1} \left(\frac{\left(\sqrt{q(\theta_r^{(l)})} + (\kappa_r / n_i) \cos \theta_i^{(l)} \right)}{\left[\kappa_r \left(1 + \sqrt{q(\theta_r^{(l)})} \right) / \left(n_r \sqrt{q(\theta_r^{(l)})} \right) + n_{ri} \cos \theta_i^{(l)} \right]} \right) \quad (5-5)$$

When the incident wave is p polarized, the resultant electric vector of the evanescent waves is,

$$\mathbf{E}_e^{(l)} = \begin{bmatrix} |\tau_{p(l)}^{(i,r)}| \cos \theta_r'^{(l)} \cos \phi_i^{(l)} E_{p(amp)}^{(l)} \exp(-j\chi_{p(l)}'^{(i,r)}) \\ |\tau_{p(l)}^{(i,r)}| \cos \theta_r'^{(l)} \sin \phi_i^{(l)} E_{p(amp)}^{(l)} \exp(-j\chi_{p(l)}'^{(i,r)}) \\ |\tau_{p(l)}^{(i,r)}| \sin \theta_r'^{(l)} E_{p(amp)}^{(l)} \exp(-j\chi_{p(l)}'^{(i,r)}) \end{bmatrix} \quad (5-6)$$

where,

$$|\tau_{p(l)}^{(i,r)}| = \frac{2 \cos \theta_i^{(l)}}{\left(\cos \theta_i^{(l)} + \kappa_r / \left(n_i \sqrt{q(\theta_r^{(l)})} \right) \right)^2 + n_{ri}^2 q^2(\theta_r^{(l)})} \quad (5-7)$$

$$\chi_{p(l)}'^{(i,r)} = \tan^{-1} \left\{ \frac{n_{ri} q(\theta_r^{(l)})}{\cos \theta_i^{(l)} + \kappa_r / \left(n_i \sqrt{q(\theta_r^{(l)})} \right)} \right\} \quad (5-8)$$

$$\cos \theta_r^{(l)} \approx \exp \left(-j \frac{n_r q(\theta_r^{(l)})}{\kappa_r (1 + \sqrt{q(\theta_r^{(l)})})} \right) \sqrt{\frac{\kappa_r^2 (1 + \sqrt{q(\theta_r^{(l)})})^2}{n_r^2 q(\theta_r^{(l)})} + q^2(\theta_r^{(l)})} \quad (5-9)$$

and

$$\sin \theta_r^{(l)} \approx \frac{n_i \sin \theta_i^{(l)}}{n_r} \quad (5-10)$$

In the above Eqs, $q(\theta_r^{(l)})$ is defined as $(n_i \sin \theta_i^{(l)} / n_r)^2 - 1$. When there are m

numbers of waves incident at the interface, with incident angles larger than the critical angle, the resultant evanescent waves interfere with each other. As a result,

the summation of the electric field is $\mathbf{E}_e^{(T)} = \sum_{l=1}^m \mathbf{E}_e^{(l)}$. The intensity distribution of

the evanescent wave interference is proportional to time-averaged square of the electric field via the relationship which is further simplified to $I_e \propto E_e^2 = \mathbf{E}_e^{(T)} \bullet \mathbf{E}_e^{*(T)}$, where $\mathbf{E}_e^{*(T)}$ is the conjugate of $\mathbf{E}_e^{(T)}$, when the time-dependent component is suppressed. Applying the general theoretical framework, the general expression that describes a general three-dimensional interference intensity profile resulted from m numbers of counter-propagating evanescent waves with planar phase fronts is given as follows,

$$E_e^2|_{s,p} = E_e^2|_{s,p}^x + E_e^2|_{s,p}^y + E_e^2|_{s,p}^z \quad (5-11)$$

In Eq (5-11), $E_e^2|_{s,p}^x$, $E_e^2|_{s,p}^y$ and $E_e^2|_{s,p}^z$ represent x , y and z components of the squared electric field amplitude of the evanescent wave interference generated by multiple incident beams that are either s-polarized or p-polarized. The general expression for $E_e^2|_{s,p}^x$, $E_e^2|_{s,p}^y$ and $E_e^2|_{s,p}^z$ is given as,

$$E_e^2|_{s,p}^{\zeta} = \left\{ \left[\sum_{l=1}^n E_{\zeta(amp)}^{(l)} \left| \tau_p^{(i,r)}(\theta_i^{(l)}) \right| \cos(kn_i \phi^{(l)} + \chi_{s,p}^{(l)} + \delta^{(l)}) \exp(-k Q^{(l)} z) \right]^2 + \left[\sum_{l=1}^n E_{\zeta(amp)}^{(l)} \left| \tau_p^{(i,r)}(\theta_i^{(l)}) \right| \sin(kn_i \phi^{(l)} + \chi_{s,p}^{(l)} + \delta^{(l)}) \exp(-k Q^{(l)} z) \right]^2 \right\} \quad \dots \quad (5-12)$$

where $\phi^{(l)} = \sin \theta_i^{(l)} \cos \phi^{(l)} x + \sin \theta_i^{(l)} \sin \phi^{(l)} y - \sqrt{n_{ri}^2 - \sin^2 \theta_i^{(l)}} z$,

$Q^{(l)} = n_r \sqrt{q(\theta_r^{(l)})}$ and $E_{\zeta(amp)}^{(w)}$ represent the electric field amplitude components corresponding to either x , y or z directions. The term $\theta_i^{(l)}$ refers to the incident angle of the beam and $\phi^{(l)}$ refers to the azimuth angle about the z -axis. The amplitude attenuation factor and the phase shift of the complex Fresnel transmission coefficients for s or p polarized incident plane waves are represented by $\left| \tau_{s,p}^{(i,r)} \right|$ and $\chi_{s,p}^{(i,r)}$ respectively. Theoretical expression for different of evanescent waves interference configurations are derived from the Eq (5-11) and Eq (5-12).

Here, two beams evanescent waves interference is realized by employing a TIR set-up as illustrated in the Fig. 5-2.

Fig. 5-2 Schematic illustration of a possible set-up to realise TIR generated evanescent waves interference lithography

In Fig. 5-2, ideal optical contact between the incident medium (high-index prism) and the second medium (photoresist) is assumed. The interface between the prism and the photoresist is represented at $z=0$. The two plane waves have the same incident angle, θ_i , at the interface between a high refractive index glass prism and the photoresist. The incident angle is defined to be larger than the critical angle (θ_c). Both the prism and photoresist are assumed to be homogenously isotropic with refractive index represented by n_i and $n_r + j\kappa_r$ respectively. If the two incident beams $\mathbf{E}_i^{(1)}$ and $\mathbf{E}_i^{(2)}$ are assumed to be plane waves, s-polarized with equal amplitude, A , the theoretical intensity field of the resultant evanescent interference in the photoresist is given as ,

$$I_e|_{2s} \propto E_e^2|_{2s} = 2A^2 \left| \tau_p^{(i,r)} \right|^2 \exp(-2kQz) (1 + \cos(2kn_i \sin \theta_i x)) \quad (5-13)$$

where $Q = n_r \sqrt{q(\theta_r')}$ and $q(\theta_r') = (n_i \sin \theta_i / n_r)^2 - 1$. The theoretical intensity distribution for evanescent interference between counter-propagating evanescent waves generated by two p-polarized incident plane waves, $E_e^2|_{2p}$, is given as,

$$E_e^2|_{2p} = \frac{1}{2} A^2 \left| \tau_p^{(i,r)} \right|^2 \exp(-2kQz) \times \dots \quad (5-14)$$

$$\left\{ 4G^2 \cos(2kn_i \sin \theta_i x) + 2n_{ir}^2 (1 - \cos 2\theta_i) (1 - \cos(2kn_i \sin \theta_i x)) \right\}$$

where in Eq. (5-14),

$$G = \sqrt{\frac{\kappa_r^2 \left(1 + \sqrt{q(\theta_r')} \right)^2 + q^2(\theta_r')}{n_r^2 q(\theta_r')}}}$$

For four beams evanescent waves interference, the corresponding configuration is shown in Fig. 5-3. The figure illustrates four incident plane waves directed into a prism with equal angle of incidence, θ_i , with respect to the Z-axis.

The incident plane waves are oriented such that one pair is co-planar in X-Z plane and that of the other in the Y-Z plane. The four evanescent waves generated by TIR of incident beams counter-propagate towards each other along the X-axis and the Y-axis.

Fig. 5-3 Schematic illustration of a possible set-up to realize single exposure counter-propagating four evanescent waves interference

If the four equal amplitude incident plane waves shown in Fig. 5-3 are s-polarized, the theoretical intensity distribution of the evanescent interference is given as

$$E_e^2|_{4s} = 2A \left| \tau_p^{(i,r)} \right|^2 \exp(-2k Q z) \{ \cos(2kn_i \sin \theta_i x) + \cos(2kn_i \sin \theta_i y) - 2 \} \quad (5-15)$$

For the case of four p-polarized incident plane waves, the corresponding theoretical intensity distribution of the evanescent interference is given as,

$$\begin{aligned} E_e^2|_{4p} = & \frac{1}{2} A \left| \tau_p^{(i,r)} \right|^2 \exp(-2k Q z) \{ \dots \\ & 4G^2 [\cos(2kn_i \sin \theta_i x) + \cos(2kn_i \sin \theta_i y)] \dots \\ & - 4n_{ir}^2 \cos 2\theta_i + 8G^2 + 4n_{ir}^2 \dots \\ & + n_{ir}^2 (1 - \cos 2\theta_i) \times \dots \\ & [4 \cos(2kn_i \sin \theta_i (x - y)) - 4 \cos(2kn_i \sin \theta_i (x + y)) \dots \\ & - 4 \cos(2kn_i \sin \theta_i (x - y)) - 4 \cos(2kn_i \sin \theta_i (x + y))] \} \end{aligned} \quad (5-16)$$

where $n_{ir} = n_i/n_r$. In the study of lithography process, it is important to understand how intensity distribution correlates to the resultant resist features. In the next section, a numerical method for computing the resist topology that would result from exposure is presented.

5.2.2. Modeling of photoresist dissolution process

During the optical lithography process, the electric field of the optical image invokes photochemistry reaction in the photoresist. A typical UV sensitive positive tone photoresist is composed of resin doped with photoactive compound (PAC). The PAC of the tone photoresist absorbs the energy from standing evanescent waves. The optically excited PAC converts into carboxylic acid which renders the resin soluble in developer reagents. For the same type of photoresist, it is understood here that higher light intensity increases the rate of change of the photoactive compound concentration into carboxylic acid. With higher carboxylic acid concentration, the resin template would dissolve at faster rate in the developer during the development process. On the other hand, the unexcited PAC in the unexposed region inhibits the dissolution of the resin [186-188]. As such, after the photoresist is exposed to the evanescent waves, the volume of the photoresist would be composed of regions with varying dissolution rates that are directly related to the evanescent wave intensity profile. Therefore, in regions where there is no exposure, the corresponding dissolution rates in these regions would be almost negligible.

During the development process, the developing reagent dissolves the exposed photoresist in an isotropic manner. Various forms of cellular automata (CA) numerical technique have been reported for simulating photoresist

development process in both two dimensional and three dimensional spatial domain, showing good agreement between the simulated and experimental results [189, 190]. In addition to the proven level of accuracy, the CA technique is straightforward in implementation as it allows user to employ regular spatial and temporal discretization in modeling the physical system and does not require iteration to obtain the solution at a cell. In this work, we employed a modified three dimensional CA algorithm that follows closely, to the one proposed by Karafyllidis [191]. The exposed photoresist domain is divided into identical cubic CA cells, each with edge length a . Unlike previous works, the algorithm implemented in this work considers all the neighboring cells in the computation sub-domain when solving for the local state of the concerned cell. The local state of each CA cell is defined as the ratio of its etched volume to its total volume and the computation sub-domain is illustrated in Fig. 5-4.

Fig. 5-4 The neighbourhood of the $(\hat{i}, \hat{j}, \hat{k})$ cell.

Based on the Fig. 5-4, we represent the amount of each cubic cell at position $(\hat{i}, \hat{j}, \hat{k})$, dissolved at an time instant, t , by its local state, $C_{i,j,k}^t$ which is defined as follows,

$$C_{\hat{i},\hat{j},\hat{k}}^t = h_{diss} / a \quad (5-17)$$

where h_{diss} is the height dissolved in the development process. Based on the definition, the initial value for $C_{\hat{i},\hat{j},\hat{k}}^t$ is assigned zero and when the computed value exceeds one, a value of one is assigned. We further introduce the differential cell state terms, dC_{adj} , dC_{edg} and dC_{vtx} which represent the change of the central cell state (cell for which the state to be solved) due to the flow of the developer from adjacent, edge and vertex cells positions at the new time instance, after one time step of dt from the time instance t_o . In comparison to Karafyllidis' method, the, the modification employed by the method presented in this thesis is the inclusion of vertex cell position in the computation of the height dissolution of the concerned cell. An adjacent neighboring cell shares one face with the central cell, an edge neighboring cell shares an edge with the central cell and a vertex neighboring cell shares a corner vertex with the central cell. In comparison to Karafyllidis' method, the, the modification is the inclusion of vertex cell position in the computation of the height dissolution of the concerned cell. As such, the central cell state at the new time instance defined here as,

$$C_{\hat{i},\hat{j},\hat{k}}^{t_o+dt} = C_{\hat{i},\hat{j},\hat{k}}^{t_o} + dC_{adj}^{dt} + dC_{edg}^{dt} + dC_{vtx}^{dt} \quad (5-18)$$

Assuming that the dissolution rate of the central cell to be $R_{\hat{i},\hat{j},\hat{k}}$, terms are defined as follow,

$$dC_{adj}^{dt} = \frac{\left(\left(C_{\hat{i}+1,\hat{j},\hat{k}}^{t_o} + C_{\hat{i}-1,\hat{j},\hat{k}}^{t_o} + C_{\hat{i},\hat{j}+1,\hat{k}}^{t_o} + C_{\hat{i},\hat{j}-1,\hat{k}}^{t_o} \right) + Bn_{\hat{i},\hat{j},\hat{k}+1}^{t_o} + Bn_{\hat{i},\hat{j},\hat{k}-1}^{t_o} \right) R_{\hat{i},\hat{j},\hat{k}} dt}{a} \quad (5-19)$$

$$dC_{edg}^{dt} = \gamma_{edg} \left(\left(C_{\hat{i}+1, \hat{j}+1, \hat{k}}^{t_o} + C_{\hat{i}-1, \hat{j}+1, \hat{k}}^{t_o} + C_{\hat{i}+1, \hat{j}-1, \hat{k}}^{t_o} + C_{\hat{i}+1, \hat{j}-1, \hat{k}}^{t_o} \right) \dots \right. \\ \left. + Bn_{\hat{i}+1, \hat{j}, \hat{k}+1}^{t_o} + Bn_{\hat{i}-1, \hat{j}, \hat{k}+1}^{t_o} + Bn_{\hat{i}, \hat{j}+1, \hat{k}+1}^{t_o} + Bn_{\hat{i}, \hat{j}-1, \hat{k}+1}^{t_o} \dots \right. \\ \left. + Bn_{\hat{i}+1, \hat{j}, \hat{k}-1}^{t_o} + Bn_{\hat{i}-1, \hat{j}, \hat{k}-1}^{t_o} + Bn_{\hat{i}, \hat{j}+1, \hat{k}-1}^{t_o} + Bn_{\hat{i}, \hat{j}-1, \hat{k}-1}^{t_o} \right) \frac{2R_{\hat{i}, \hat{j}, \hat{k}}^2 t_o dt}{a^2} \quad (5-20)$$

$$dC_{vtx}^{dt} = \gamma_{vtx} \left(Bn_{\hat{i}+1, \hat{j}+1, \hat{k}+1}^{t_o} + Bn_{\hat{i}-1, \hat{j}+1, \hat{k}+1}^{t_o} + Bn_{\hat{i}+1, \hat{j}-1, \hat{k}+1}^{t_o} + Bn_{\hat{i}+1, \hat{j}-1, \hat{k}+1}^{t_o} \dots \right. \\ \left. + Bn_{\hat{i}+1, \hat{j}+1, \hat{k}-1}^{t_o} + Bn_{\hat{i}-1, \hat{j}+1, \hat{k}-1}^{t_o} + Bn_{\hat{i}+1, \hat{j}-1, \hat{k}-1}^{t_o} + Bn_{\hat{i}+1, \hat{j}-1, \hat{k}-1}^{t_o} \right) \frac{3\sqrt{3}}{8a^3} R_{\hat{i}, \hat{j}, \hat{k}}^3 t_o^2 dt \quad (5-21)$$

From Eq (5-19) to (5-21), those terms in the form of $Bn_{I,J,K}^{t_o}$ are binary functions for the corresponding cell position they represent and are defined as,

$$Bn_{I,J,K}^{t_o} = \begin{cases} 1 & C_{I,J,K}^{t_o} = 1 \\ 0 & \text{otherwise} \end{cases} \quad (5-22)$$

where I may represent $i-1$, i or $i+1$ and likewise for J and K . As shown in Eq (5-19) to (5-21), the binary switch function is implemented at those cell positions with $K = \hat{k} - 1$ or $K = \hat{k} + 1$. The hypothesis for the choice of implementation is that the central cell would not be exposed to developer from the higher or lower cell positions until the resist elements occupying those positions are completely dissolved. The time step, dt is defined as, $a/4R_{\max}$ where $R_{\max}$ refers to largest elemental development rate value in the simulation domain. In this work, the terms γ_{edg} and γ_{vtx} are parameters used to model the indirect flow of developer from the edge cell positions and from the vertex cell positions. The best values for γ_{edg} and γ_{vtx} are computed using the homogenous development rate test which is shown and discussed in the next section.

5.3. Methodology

5.3.1. Homogenous development rate test

The modified 3D CA model is evaluated using a homogeneous etch-rate distribution function [191] to determine the values of γ_{edg} and γ_{vtx} in Eq (5-20) and Eq (5-21), and their effectiveness to describe the effects from the edge and vertex cells. The cells are assigned the same development rate value. At the beginning of the simulation, all the cell states are assigned value of zero except for the one at the centre of the top surface. For the CA model proposed here, the optimum γ_{edg} and γ_{vtx} values, with which the generated profile has the closest conformity to that of a hemispherical crater, are searched. For this purpose, we adopt a statistical approach which is explained with the aid of Fig. 5-5.

(a)

(b)

Fig. 5-5 Schematic illustration of statistical approach to determine optimum γ_{edg} and γ_{vtx} .

Each computed boundary point, p , is quantified by its distance from the origin given by $r_p = \sqrt{x_p^2 + y_p^2 + z_p^2}$. The fitted profile is generated by assuming a perfect

semi-circle or full circle with a radius of $\bar{r}$, given by $\bar{r} = \sum_{p=1}^N r_p / N$ where N refers

to the number of computed boundary points used for the analysis. We characterized the computed profile by the standard deviation of the computed boundary points from that of a fitted perfect sphere. A smaller standard deviation value would infer that the computed profile has a higher conformity to a spherical profile. The standard deviation, is computed as follows,

$$\text{standard deviation} = \left(\frac{\sum_{p=1}^N r_p^2 - \left(\sum_{p=1}^N r_p \right)^2 / N}{N} \right)^{1/2} \quad (5-23)$$

Range of values for γ_{edg} and γ_{edg} are investigated to identify the combination that would generate the smallest standard deviation value. The corresponding results, given in Fig. 5-6, are obtained from having values for γ_{edg} and γ_{vtx} varied from 0.1

to 1.0 with coarse step size of 0.1 with the same total number of time steps.

Fig. 5-6 Contour distribution of standard deviation with respect to coupled variation γ_{edg} and γ_{vtx} , (a) coarse variations of γ_{edg} and γ_{vtx} values (b) fine variations of γ_{edg} and γ_{vtx} values.

After identifying the possible combinations of γ_{edg} and γ_{vtx} values, the analysis is repeated, using a smaller range of values and smaller step size of 0.01. The results in Fig. 5-6(b) suggest that the best γ_{edg} and γ_{vtx} values are 0 and 0.04 respectively, yielding a standard deviation value of 4.29nm. By employing the obtained γ_{edg} and γ_{vtx} values, the CA model is simplified to consist of only Eq (5-19) and Eq (5-21). This finding is different from that reported by Karafyllidis, which has shown that the height dissolution caused by developer in the vertex cell is negligible. The result for the homogenous development rate, shown in Fig. 5-7, is obtained with the optimum γ_{edg} and γ_{vtx} values. The generated crater showed a reasonably good hemispherical profile. This result suggests that the proposed CA model is reasonably accurate in simulating the isotropic nature of the resist etching mechanism during the resist development process. Besides cellular automata, another widely used numerical scheme for simulating resist development is the fast

marching level set method formulated by Sethian [192]. This method is efficient in handling large computation domain and accurate in simulating resist topologies with complex geometries as in the case of lithography simulation for semiconductor chip fabrication.

(a)

(b)

(c)

Fig. 5-7 (a) Three dimensional perspective of the crater generated by the CA model. (b) Computed profile on the x-y plane at $z=0$ (c) Computed profile on the x-z plane through $y=0$.

In the next section, we would investigate and discuss the resist structures after exposures to the evanescent waves interference intensity by employment of the CA model, with the optimum γ_{edg} and γ_{vtx} values obtained in this section.

5.3.2. Simulation of resist topology

The employed computation scheme for the simulation investigations is illustrated in Fig. 5-8. The computation of 3D intensity distribution is followed by computation of the corresponding development rate distributions in the photoresist using the Mack's enhanced model [193]. Subsequently, the modified CA method, as discussed in the previous section, is employed to generate the resultant resist features.

Fig. 5-8 Outline of computation scheme for obtaining simulated photoresist structures

To compute the positional development rates of the photoresist domain in response to the normalized intensity profile, we adopt a value of $1\text{mW}/\text{cm}^2$ for unit normalized intensity value. The development process is then simulated, employing the modified CA method, to obtain the subsequent post-development resist profile.

5.4. Experimental set-up and procedure

5.4.1. Choice of prism geometry

A TIR set-up to realize evanescent waves is realized by introducing the custom fabricated prism, which is kept in optical contact with the photoresist. There can be two possible geometries for the prism, a pyramid prism or a rectangular prism. In the context of four interfering beams, rectangular prism is easier to fabricate in comparison to pyramid prism that has four inclined sidewalls. The use of the rectangular prism also contributes to the overall compactness of the set-up by minimizing the required translation of the sample stage when the system is prepared for evanescent waves interference lithography process. Fig. 5-9 (a) and (b) shows the required translation range of the substrate stage, z_{shift} , along the z

direction when incorporated with the pyramid prism and the rectangular prism respectively. As illustrated in the figures, the respective z_{shift} , are defined as below,

$$z_{shift} = \begin{cases} \frac{S_{prism}}{2} \left(\frac{1}{\tan \theta_m} - \sin \theta_d / \sqrt{1 - \frac{\sin^2 \theta_m}{n_{prism}^2}} \right) & \text{rectangular prism configuration} \\ \frac{S_{mirror}}{2} \left(\frac{1}{\tan \theta_m} - \frac{1}{\tan(90^\circ - \alpha)} \right) & \text{pyramid prism configuration} \end{cases} \quad \dots \quad (5-24)$$

where n_{prism} refers to the refractive index of the prism.

(a)

Fig. 5-9 Comparison of translation of substrate stage, z_{shift} along the z-direction between (a) rectangular prism-based configuration and (b) pyramid prism-based configuration. The actual configurations are repeated in the y-z plane but are illustrated in x-z plane for simplicity

Eq. (5-24) shows that the rectangular prism configuration allow smaller z_{shift} since $S_{prism} \ll S_{mirror}$. As discussed, the employment of rectangular prism more advantageous than that of the pyramid prism in the context of incorporation into the interference lithography system. It is also easier to implement the rectangular prism than a pyramid prism in the interference lithography set-up. In the case of using pyramid prism, the mirrors have to be tilted through an angle equal to $(\theta_i - \theta_d)/2$. Here, θ_d is the diffraction angle of the first order beams and θ_i is the targeted incident angle of interfering beam on the bottom facet of the prism. When θ_i is large, the mirrors would have to be mounted in Gimbal mirror mounts that facilitate large range of tilt angle. Employing the rectangular prism, refraction of the incident beams are exploited to facilitate large incident angle at the prism-

photoresist interface thus allowing the planes of the mirrors to remain parallel to the z-axis. In this regard, refractive index of the prism plays an important role in realizing the targeted incident angle of the beams. This will be discussed in greater depth in the following section.

5.4.2. Choice of prism material

Incorporating the rectangular prism into the grating-based interference lithography system, the ray trace of the beam propagation through the rectangular prism is shown in Fig. 5-10.

Fig. 5-10 Ray trace of beam propagating through the rectangular prism

The incident angle θ_i as shown in Fig. 5-10 is defined as,

$$\theta_i = 90^\circ - \sin^{-1} \left(\frac{\sin 45^\circ}{n_i} \right) \quad (5-25)$$

where n_i is the refractive index of the incident medium. There is no lack of options for high refractive index glass which possess high internal transmittance for light with wavelength in the UV regime. However, there is limited choice of high refractive index contact fluid. At UV wavelength, most high refractive index liquid become highly absorbent, are intrinsically toxic and crystallize when subjected to UV irradiation. After a thorough survey of commercially available

refractive index liquids, the refractive index liquid, n_D1700 from Cargille Lab Pte Ltd, USA, is identified as the best option for the contact fluid. It has a refractive index, n_f of 1.808 at 364nm. A range of n_i values is investigated to identify a suitable material for the prism such that TIR occurs at the interface between the contact fluid and the photoresist as shown in Fig. 5-11.

Fig. 5-11 Variation of $\Delta\theta$ with respect to employed incident medium

In the above figure, the term $\Delta\theta$ is defined as,

$$\Delta\theta = 90^\circ - \sin^{-1}\left(\frac{\sin 45^\circ}{n_i}\right) - \sin^{-1}\left(\frac{n_r}{n_i}\right) \quad (5-26)$$

where n_t refers to either n_r or n_f . A suitable material for the prism should have a refractive index that falls in the range defined as,

$$\begin{aligned} 90^\circ - \sin^{-1}\left(\frac{\sin 45^\circ}{n_i}\right) - \sin^{-1}(1.808/n_i) &\leq 0 \\ 90^\circ - \sin^{-1}\left(\frac{\sin 45^\circ}{n_i}\right) - \sin^{-1}(1.684/n_i) &\geq 0 \end{aligned} \quad (5-27)$$

The result suggests that the refractive index value of the prism material should be between 1.83 and 1.93, as indicated by the arrows in Fig. 5-11. The higher the

refractive index value of the incident medium, the smaller the period of the resultant fringes. However, the employment of higher incident medium has an adverse on the decay depth, and thus the exposure depth, of the evanescent interference field. The decay depth of an evanescent wave is given as,

$$z_{\text{decay}} = \frac{\lambda}{2\pi\sqrt{(\sin \theta_i / n_{ti})^2 - 1}} \quad (5-28)$$

In Eq (5-28), the term n_{ti} is ratio n_t/n_i where n_t and n_i are the refractive index of the transmission medium and incident medium respectively. The variation of decay depth of an evanescent wave with incident angles is illustrated for different n_{ti} in Fig. 5-12. The results in Fig. 5-12 are obtained by assuming a light source with wavelength of 364nm. If the employed incident medium has a refractive index much higher than the transmission medium, the decay depth would be smaller.

Fig. 5-12 Influence of n_{ti} and θ_i on the decay depth of evanescent waves

Taking into consideration the requirements and constraints, NLAF36 from Schott Glass™, with a real refractive index of the 1.849 at 364nm, is identified as a suitable material for the prism.

5.4.3. Sample Preparation

A bare single-sided Si wafer is subjected to HMDS priming. This is followed by spin coating at 1500rpm with AZ7220 positive tone resist, diluted with PGMEA at a ratio of 1:2.5, to a thickness of $170\text{nm} \pm 11$. Soft-bake on a hot-plate at 110°C for 90sec is carried out to harden the photoresist. The wafer is then left to cool at room temperature at 23°C for 2 min. The cooled wafer is then diced into smaller samples each with size approximately $20 \times 20\text{mm}$. The NLAF36 rectangular prism is placed atop of a dummy sample on the stage and the stage and the mirrors are manually adjusted till the beams in the prism are observed, through the clear sides of the rectangular prism, to overlap as shown in Fig. 5-10. Fine positioning for achieving co-planarity, angular alignment and overlapping of the interfering beams is facilitated by observing the beam spots on a microscope slide as it is translated along the optical path of each interfering beam. To prepare for exposure, the NLAF36 rectangular prism is placed on the sample with $0.070\mu\text{l}$ of $n_D 1700$ contact liquid introduced between them using a micropipette. Pressure is applied on the prism against the sample to spread the contact liquid over the sample as well as to rid excess contact liquid to achieve a thin layer of contact liquid between the prism and the photoresist. After exposure, the contact liquid on the sample is removed by running de-ionized water. The sample is air-blown to dryness using nitrogen gun before subjecting to 60sec of development process. After development, the sample is dipped in de-ionized water for 10sec before air-blown to dryness for further observation.

5.5. Results and Discussion

5.5.1. Two beams evanescent waves interference lithography

The simulation employed an illumination source with 363.8nm wavelength. At this wavelength, the incident medium and the optically less dense recording medium have refractive index values of 1.849 and $1.684-0.0191i$ respectively. According to Snell's law, the critical incident angle at the prism-photoresist interface is 65.61° . The given values correspond to those of NLAF36A glass and AZ7200 positive tone photoresist. The modeling parameters for AZ7200 photoresist are obtained from the database of a commercial lithography simulator Prolith v6.1TM. We assume perfect optical contact between the prism and the photoresist made possible by a layer of lossless liquid with refractive index matched to that of the prism. The intensity values of the evanescent waves interference are computed and then post-processed to simulate resist exposure and development kinetics. In this work, it is assumed that no prebake or post-exposure bake is included in the process flow and hence there is no consideration of thermal-induced effect on the resist such as PAC diffusion or decomposition.

The incident plane waves were orientated such that they are incident on the prism-resist interface at 67.51° to realise total internal reflection at the interface and consequently generate counter-propagating evanescent waves. The periodicity of the evanescent interference fringes can be deduced as $\lambda/2n_p \sin \theta_i$. The profiles of $E_e^2|_{2s}$ and $E_e^2|_{2p}$ in the cross-section of the photoresist are shown in the Fig. 5-13 below. The simulation results show that both configurations produce interference fringes with the same periodicity. Comparing the peaks of the

interference fringes at the interface ($z=0$), the $E_e^2|_{2p}$ values are found to be higher than the $E_e^2|_{2s}$ values.

(a)

(b)

Fig. 5-13 (a) $E_e^2|_{2s}$ distribution generated by the two s-polarized incident plane waves and (b) $E_e^2|_{2p}$ distribution generated by the two p-polarized incident plane waves.

Since p-polarized plane wave carries electric field component in x and z direction, the resultant evanescent waves interference intensity, $E_e^2|_p$, would therefore consist of x and z components. It would be interesting to understand the contribution by

each of the two components to the $E_e^2|_p$ distribution. The distribution of the x component of $E_e^2|_p$, $E_{ex}^2|_{2p}$ and the z component of the same. $E_{ez}^2|_{2p}$, are shown in Fig. 5-14 .

(a)

(b)

Fig. 5-14 The X-Z plane distribution of (a) $E_{ex}^2|_{2p}$ and (b) $E_{ez}^2|_{2p}$ of evanescent waves interference generated by p-polarized incident plane waves in the resist.

The peaks of the interference fringes of the two components are shown to be half period out of phase with respect to each other. The analytical results agree with those of the analytical studies reported in the literature [153, 194, 195]. The

$E_{ex}^2|_{2p}$ values (see Fig. 5-14(a)) are shown to be smaller than $E_{ez}^2|_{2p}$ values (see Fig.

5-14(b)) by an order larger. From Eq 5-6, the amplitudes of the electric field components, parallel to the x and z direction, of evanescent waves interference generated by a p-polarized incident plane wave are modulated by cosine and sine function of the incident angle. Hence, for large incident angle close to 90° , z component of the evanescent wave becomes dominant.

It is well understood that the penetration depth of evanescent wave decreases with larger incident angle. The through-depth intensity decay profiles, with respect to change at the centre of each bright fringe are illustrated in Fig. 5-15.

(a)

(b)

Fig. 5-15 Effect of incidence angle values on the through-depth intensity profiles of two beams evanescent waves interference fringes generated by (a) s-polarized incident beams and (b) p-polarized incident beams

The figures illustrate the effect of changing incident angle on through-depth intensity, under the influence of polarization of the incident beams. In both s-polarized and p-polarized incident beams configuration, the intensity at the interface ($z=0$) and the intensity through depth decreases with increasing incidence angle. The results also suggest that the evanescent waves interference fringes generated by p-polarized incident beams has larger exposure depth than the fringes generated by s-polarized incident beams.

5.5.1.1 Simulation Study

For this part of the work, the development duration is fixed at 60secs. The profile of a resist line feature is characterized by the width at the position corresponding to half of the feature height (FWHM) and the aspect ratio. The aspect ratio is defined as the ratio of the height to FWHM. While the pitch size of the periodic line features is determined by the periodicity of the interference fringes, the FWHM and aspect ratio of each line feature depend on the exposure dose, which is controlled by the exposure duration in this work. The effects of exposure duration on aspect ratio of the resultant 100nm pitch size periodic line features are illustrated in Fig. 5-16.

Fig. 5-16 Effect of exposure duration on aspect ratio of periodic line features of both s-polarized and p-polarized configuration.

When the exposure duration exceeds 30secs, the aspect ratio of the features obtained from the p-polarized configuration decreases sharply. The sharp decrement of aspect ratio phenomenon can be explained with illustrations of the cross-section resist profiles shown in Fig. 5-17. According to the simulations, it becomes apparent that the reduction in the aspect ratio is a result of resist height reduction. The loss of resist height occurs when the exposure duration is long enough for regions exposed to the weak $E_{ex}^2|_p$ component to receive substantial accumulated exposure dose to result in subsequent dissolution within the defined development time.

Fig. 5-17 Cross-section resist profile of two p-polarized incident plane waves configuration corresponding to t_{exp} of (a) 20secs (b) 30secs (c) 40 secs.

On the other hand, for the s-polarized configuration, the aspect ratio increases with increasing exposure duration. It is shown here, by comparison of the aspect ratio variation results and with reference to Fig. 5-13, the importance of high intensity contrast to achieve high aspect ratio features for evanescent waves interference lithography. Two mechanisms have been identified for the aspect ratio increment with increasing exposure duration, which are illustrated with the Fig. 5-18(a).

(a)

(b)

Fig. 5-18 (a) Effect of exposure duration on h and $FWHM$ for s-polarized configuration. (b) Resist profile of periodic line features for s-polarized configuration with exposure duration of 120secs .

The first mechanism of aspect ratio increment occurs when exposure duration increases from 0secs to 50secs. The aspect ratio increment results from a simultaneous increase of h and decrease of $FWHM$ of the line features. The second mechanism of aspect ratio increment occurs when exposure duration increases beyond 50secs. Here, the aspect ratio increment results predominantly from an increase of h of the line features. It is also observed that the rate of h increment decreases with larger exposure duration, thus indicating that employment of larger exposure will no longer increase the value of h or aspect ratio beyond a certain limit. As shown in Fig. 5-18b, when the resist is exposed for 120secs, the resultant periodic line features have aspect ratio of almost 10.7, with corresponding $FWHM$ and h values of 15nm and 160nm respectively. The results of the experimental investigations of two beams evanescent waves interference are presented in the next section.

5.5.1.2 Experimental Investigation

Lithography patterning using interference between two counter-propagating evanescent waves is investigated here. One set of experimental data are obtained by employing two s-polarized incident beams and the other by two p-polarized incident beams. The power measurements of the two s-polarized incident beams are 2.03mW and 2.05mW. The correspondent irradiance values on fluid-photoresist interface are approximated to be 20.74mW/cm^2 and 20.995mW/cm^2 . The approximated irradiance values are computed by assuming a perfect elliptical beam shape on the interface. The power measurements of the two p-polarized incident beams are 1.94mW and 1.96mW. The correspondent irradiance values on fluid-photoresist interface are approximated to be 19.76mW/cm^2 and 20.03mW/cm^2 . The influence of the exposure duration on the

feature profile is shown in Fig. 5-19. As seen in Fig. 5-19, the FWHM values of the resultant line features are observed to be decreasing with increasing exposure duration for both s-polarized and p-polarized incident beams configurations.

Fig. 5-19 Influence of exposure duration on FWHM of periodic line features fabricated using two beams evanescent waves interference.

No feature is observed on sample obtained with 500ms of exposure suggesting that the accumulated exposure dose is insufficient to result in significant features. Employing evanescent waves interference generated by two p-polarized incident beams, line features with the highest aspect ratio of 0.44 are obtained by 2070ms of exposure. For the case of employing two s-polarized incident waves, the achievable highest aspect ratio of 0.37 is realized using 2000ms exposure duration.

The AFM images of the resist line features obtained with 2000ms of exposure to evanescent waves interference generated by s-polarized incident beams configuration are shown in Fig. 5-20. The results in Fig. 5-20 show that the line features corresponding to the s-polarized incident beams configuration have periodicity of $107.37\text{nm} \pm 2.58\text{nm}$ and those corresponding to p-polarized incident beams configuration have periodicity of $106.93\text{nm} \pm 1.94\text{nm}$. The experimentally

obtained periodicity is in good agreement with the theoretically obtained value of 106.1nm.

(a)

(b)

Fig. 5-20 Three dimensional AFM image of periodic lines fabricated using evanescent waves generated by (a) two s-polarized incident beams with exposure duration of 2000ms and (b) two p-polarized incident beams; with exposure duration of 2070ms.

Employing the s-polarized incident beams configuration, the obtained line features have an average FWHM of $55.60\text{nm} \pm 1.79\text{nm}$ and average depth of $20.73\text{nm} \pm 0.92\text{nm}$. The line features obtained with p-polarized incident beams

configuration have an average FWHM of $60.76\text{nm} \pm 4.57\text{nm}$ and average depth of $26.51\text{nm} \pm 1.81\text{nm}$. The following section presents a study of four beams evanescent waves interference with emphasis on the influence of polarization state of the incident beams on the subsequent intensity distributions.

5.5.2. Four beams evanescent waves interference lithography

In this section, the squared electric field distributions of interference between four beams evanescent waves are presented. The results, shown in Fig. 5-21, are obtained with the four incident plane waves having the same electric field polarization state. In the figures shown, the X-Y plane at $Z=0$ represent the interface between prism and the photoresist, and the negative Z positions refers to the corresponding depth in the photoresist layer. The intensity profiles in both cases are obtained with the incident beams directed such that they have θ_{in} value of 67.5° . The pitch size between the centres of subsequent high intensity regions are found to be less than that achievable by a conventional interference method with the same exposure wavelength and the incident angles.

(a)

(b)

Fig. 5-21 Normalized square electric field distribution profile of interference between four counter-propagating evanescent waves: (a) $E_e^2|_{4s}$ generated by four s-polarized incident plane waves and (b) $E_e^2|_{4p}$ generated by four p-polarized incident plane waves

The interfacial $E_e^2|_{4s}$ profile indicates that the interference pattern results from a superposition of periodic linear fringes parallel to the Y axis and those parallel to the X-axis formed by interference between the evanescent waves that counter-propagate along X-axis and by those along the Y-axis, respectively. An evanescent wave generated by s-polarized incident plane wave maintains the polarization state of the incident plane waves. Thus, when four evanescent waves counter-propagate along the X and Y axial directions, interference between the evanescent waves that propagate along the same axis occurs but there would not be interference between the evanescent waves with wave vectors perpendicular to each other since the electric fields vectors are orthogonal to each other as well. The superposition of the interference fringes result in mid-intensity regions between adjacent high intensity regions and low intensity regions. When the

incident plane waves are of p -polarization state, the corresponding interfacial $E_e^2|_{4p}$ profile shown in Fig. 5-21 (b) is remarkably different from that produced by s -polarized incident plane waves. The cross sectional intensity profiles along the diagonal in Fig. 5-21 show the intensity decay exponentially with increasing depth into the photoresist layer. The electric field vector of the p -polarized incident plane wave can be resolved into two components, one parallel to the interface and the other parallel to the z -direction. Hence, one can resolve the corresponding evanescent waves interference intensity profile into these two components as, $E_{e(xy)}^2|_{4p}$, the interference profiles due to the electric field components parallel to the x - y plane, and $E_{e(z)}^2|_{4p}$ that due to the electric field components parallel to the z -direction shown in Fig. 5-22.

Fig. 5-22 (a) $E_{e(xy)}^2|_{4p}$ profile and (b) $E_{e(z)}^2|_{4p}$ profile at the interface along the diagonal direction

A spatial phase offset of $\pi/2$ between $E_{e(xy)}^2|_{4p}$ and $E_{e(z)}^2|_{4p}$ profile is observed.

The angle of incidence employed for the incident planes result in the electric field component parallel to the z plane to have larger amplitude than that of the x - y component since the x - y components and the z component of the evanescent

electric field are modulated by cosine and sine function of the incident angle respectively. The presence of $E_{e(xy)}^2|_{4p}$ deteriorates the fringe contrast of the interference pattern and the repercussion of this phenomenon on lithography performance would be studied in subsequent section.

A summary of analytical expressions for the interference profiles at interface ($z=0$) and periodicity is given in Table 5-1 .

	p-polarized	s-polarized
$E_e^2 _{4s,p}$	$\mathbf{A} \left[\cos(kn_i \sin \theta_i y) + \cos(kn_i \sin \theta_i x) \right]^2 + \dots$ $\mathbf{B} \left[\sin^2(kn_i \sin \theta_i y) + \sin^2(kn_i \sin \theta_i x) \right]$ <p>where,</p> $\mathbf{A} = \frac{4A \tau_p ^2}{n_{ri}^2} \left \sin^2 \theta_i - n_{ri}^2 \right ,$ $\mathbf{B} = \frac{4a \tau_p ^2}{n_{ri}^2} \sin^2 \theta_i$ $n_{ri} = \frac{n_r}{n_i}$	$4 \tau_s ^2 A^2 \left(\sin^2(kn_i \sin \theta_i y) + \dots \right)$ $\sin^2(kn_i \sin \theta_i x)$
$\Lambda_{x,y}$	$\lambda/n_i \sin \theta_i$	$\lambda/2n_i \sin \theta_i$
Λ_{diag}	$\lambda/\sqrt{2}n_i \sin \theta_i$	

Table 5-1 Summary of analytical expressions $E_e^2|_{4s,p}$ at interface ($z=0$) and periodicity along X, Y and the diagonal.

For study of optical lithography process, it is necessary to include the consideration of the photoresist reaction to the optical energy, the evanescent waves interference in this case. So far, by employing four s-polarized incident plane waves and four p-polarized incident plane waves, the interference profiles of the two configurations have been shown. To further investigate the corresponding

resist profiles that may result from the interference profiles, the positional development rate was computed for each of the three configurations and the CA method was employed to obtain the corresponding resist topology.

5.5.2.1 Simulation Study

The simulation study, based on the modified CA model, employs a fixed exposure duration of 50s for all considered cases. For computation simplicity, we have assumed that the highest intensity value of the evanescent wave interference generated by the four p-polarized incident plane waves correspond to a value of 1mW/cm^2 . For the same exposure duration, the photoresists in the three configurations receive different level of exposure dose since the respective highest positional intensity values are different. Hence it is expected that different intensity profiles would require different development times to realize substantial depth in the corresponding topology. With lower intensity, it is expected that longer development time is required and vice versa. The photoresist exposed by the four p-polarized incident plane waves configuration is developed for 60 sec. Subsequently, the development duration for the two other cases, with lower intensity values, are estimated as follow, $t'_{dev} = I_{max}^{ref} / I'_{max} \times t_{dev}^{ref}$ where I_{max}^{ref} refers the maximum intensity value of the referenced set (i.e. the four p-polarized incident plane waves configuration), I'_{max} refers the maximum intensity value of the investigated set and t_{dev}^{ref} refers to the development duration employed for the referenced set. The resultant resist topologies for the four p-polarized incident beams and four s-polarized incident beams configurations are shown in Fig. 5-23.

(a)

(b)

Fig. 5-23 Simulated resist topology corresponding to evanescent interference generated by (a) four s-polarized incident plane waves (b) four p-polarized incident plane waves

As the intensity decay exponentially with increasing distance away from the interface, the resultant features were shown to exhibit sidewall profiles that tapered in an exponential manner. Hence, to characterize the resist features, the width of the feature is taken at the half-height position, z_{half} which is defined as $z_{half} = (z_{max} - z_{min})/2 + z_{min}$, where z_{max} refers to the highest point of the resist

feature and $z_{\min}$ refers to the lowest point. For the four p -polarized incident plane waves configuration, the interference intensity profile results in cross-line grating as profiled by the dashed line. The width of the grating at z_{half} is 36nm ($\cong 0.10\lambda$) with a pitch size of 126nm and the width of the intersection regions is 80nm ($\cong 0.22\lambda$). The height of the grating was found to be 255nm resulting in an height-to-width aspect ratio of 7. As shown in Fig. 5-23(b), the nano-pillars, resulted from the four s-polarized incident plane waves configuration, correspond to the low intensity regions. Each nano pillar has a height of 225nm and diameter of 28nm (0.08λ) at z_{half} , with height-to-width ratio of almost 10. The nano-pillars are distributed in a square array format with average pitch size of 141.4nm along the diagonal direction and 105nm along the X and Y direction. The simulated results in Fig. 5-23(a) and (b) suggest that the diameter holes or the nano-pillar is smaller than the half of the pitch size. This is due to both intensity modulation by the photoresist as well as the exponential decay of the evanescent intensity in the direction away from the interface. The employment of the four beams evanescent waves interference to fabricate two dimensional features is investigated experimentally as well and the observations presented in the following section.

5.5.2.2 Experimental Investigation

Lithography patterning using interference between four counter-propagating evanescent waves is investigated here. One set of experimental data are obtained by employing four s-polarized incident beams and the other by four p-polarized incident beams. The power measurements of the four s-polarized incident beams are 2.03mW, 2.05mW, 2.07mW and 2.13mW. The correspondent irradiance

values on fluid-photoresist interface are approximated to be 20.74mW/cm^2 , 20.99mW/cm^2 , 21.09mW/cm^2 and 21.67mW/cm^2 . The power measurements of the four p-polarized incident beams are 1.94mW , 1.96mW , 2.04mW and 1.99mW . The correspondent irradiance values on fluid-photoresist interface are approximated to be 19.76mW/cm^2 , 20.02mW/cm^2 , 20.81mW/cm^2 and 20.28mW/cm^2 . The atomic force microscope (AFM) images shown in Fig. 5-24 are of resist features obtained after exposure to four evanescent waves interference generated by s-polarized incident beams. Employing evanescent waves interference generated by four s-polarized incident beams, SEM analysis of the samples obtained by 500ms exposure reveals no observable periodic features. For longer exposure duration of 1000ms and 1500ms, square arrayed periodic circular features are achieved as shown in Fig. 5-24.

(a)

(b)

(c)

Fig. 5-24 SEM image of square arrayed two dimensional resist features fabricated using evanescent waves interference generated by four s-polarized incident beams obtained with (a) 1000ms (b) 1500ms (inset: positions of peak (P), saddle (S) and valley (V)) (c) 2000ms (d) 3D AFM image of sample obtained with 1500ms exposure.

The features have an average pitch size of $148.5\text{nm} \pm 3.92\text{nm}$ along the diagonal direction, $107.71\text{nm} \pm 2.95\text{nm}$ along x direction, and $104.82\text{nm} \pm 4.09\text{nm}$ along y direction. The experimental pitch size measurements agree well with the theoretical ones with difference percentage of -1.49%, 1.03% and -1.67% respectively. Using the AFM, the average full width at half maximum (FWHM) of the features is measured at $86.02\text{nm} \pm 7.45\text{nm}$ for the samples obtained with 1000ms exposure and $66.53\text{nm} \pm 6.40\text{nm}$ for those obtained with 1500ms exposure. The large standard deviation could be a result of intensity non-uniformity in the cross-section of each interfering beam. The average height of the features obtained with 1000ms and 1500ms exposure is $17.59\text{nm} \pm 2.88\text{nm}$ and $21.63\text{nm} \pm 3.85\text{nm}$ respectively. The three dimensional AFM image of the sample obtained with 1500ms exposure is shown in Fig. 5-24(c). When subjected to exposure of 2000ms, morphologies of the resultant samples as observed under the SEM (as

shown in Fig. 5-24(d) suggest possible interference patterns but are not sufficiently distinctive for meaningful quantitative measurement.

The resist features obtained with evanescent waves interference generated by p-polarized incident beams are shown in Fig. 5-25.

(a)

(b)

(c)

(d)

Fig. 5-25 SEM image of hexagonal arrayed two dimensional resist features fabricated using evanescent waves interference generated by four p-polarized incident beams obtained with (a) 750ms (inset: positions of peak (P), saddle (S) and valley (V)) (b) 1000ms (c) 1500ms (d) 3D AFM image of sample obtained with 750ms exposure.

The SEM images of samples obtained from 750ms, 1000ms and 1500ms exposure are shown in Fig. 5-25 (a), (b) and (c) respectively. The crater-like features have an average pitch size of $150.03\text{nm} \pm 2.94\text{nm}$ along the diagonal direction,

208.67nm $\pm$ 5.98nm along x-direction and 211.084nm $\pm$ 8.677nm along the y-direction with corresponding percentage error of -0.48%, -0.21% and 0.99% from respective theoretical values. Using AFM, the average FWHM measurements of the nano crater-like features obtained with 750ms, 1000ms and 1500ms exposure are 68.37nm $\pm$ 7.52nm, 84.00nm $\pm$ 3.28nm and 105.79nm $\pm$ 9.45nm respectively with corresponding depth of 48.11nm $\pm$ 7.52nm, 32.19nm $\pm$ 3.84nm and 22.23nm $\pm$ 4.19nm. As such, periodic holes with highest aspect ratio ($\approx$ 0.70) are obtained with 750ms exposure duration. The corresponding three dimensional AFM image is shown in Fig. 5-25(d). The profile of the features agrees with the simulated shown in Fig. 5-23(a). Polarization of the incident beams has been shown to be a significant optical parameter that influences the intensity distribution of four beams evanescent waves interference and hence the achievable features.

5.6. Summary

The EW interference is studied as lithography technique to pattern both one and two dimensional features. The theoretical model of the evanescent wave in a three dimensional Cartesian space is presented. The general analytical expressions and results of evanescent waves interference generated by both two s-polarized and two p-polarized incident plane waves are presented. The modified CA algorithm is employed to simulate the resist removal process during the post-exposure development stage. Two beams and four beams evanescent waves interference lithography were investigated theoretically and experimentally, in which the effect of polarization state and exposure duration of the incident beams was studied. Using exposure of two beams evanescent waves interference, fabrication of periodic line features, with average linewidth (measured as FWHM) as small as

55.6 nm and average pitch size of 107.15nm, is demonstrated. Employing the two p-polarized incident beams configuration, the line features obtained showed larger average depth and higher aspect ratio than that obtained using two s-polarized incident beams configuration. However, the aspect ratios of the obtained periodic line features are smaller than 0.5 regardless of polarization and exposure duration. This may be attributed to contrast loss in the resist latent image resulted from beam pointing instability as well as possible fluctuating optical phase difference between the incident beams. When four s-polarized incident beams are employed to generate four evanescent waves interference, square arrayed circular pillar like features are fabricated. These pillar-like features have an average pitch size of 106.27nm in the x and y direction. Through appropriate exposure duration control, features with average diameter as small as 66.53nm can be fabricated. The averaged height of the fabricated features is smaller than 30nm. Nanoscale crater-like features are fabricated by employing evanescent waves interference generated by four p-polarized incident beams. These crater-like features have an average pitch size of 209.87nm along the x-direction and y-direction and features with average FWHM as small as 68.37nm have been achieved with corresponding average depth of 48.11nm and aspect ratio of 0.7. Close agreement between the simulation and experimental results in terms of the features pitch size and distribution is observed.

The results suggest that single exposure evanescent waves interference lithography technique is a potential fabrication technique for a wide range of devices such as photonic crystals, nano-field emitters, nano-needles arrays and nano-wells in biochips for biomedical applications, and nanoelectronics devices. The employment of the evanescent waves lithography is not without its challenges

and faces limitation imposed by the technology available at the time of the investigation. The beam pointing instability may have restricted achievable aspect ratio of the resultant features. In this regards, a phase lock system to compensate beam pointing stability would be discussed in greater detail in Appendix C. In the same section, the discussion also proposed the employment of the phase lock system, coupled with phase modulation units, to achieve interesting periodic features by modulating relative phase difference between incident beams. The main fundamental limitation of evanescent waves interference is its inability to provide through depth exposure of the photoresist regardless of the photoresist thickness. This is due to exponential decay of amplitude across the phase front of the evanescent wave. In this regard, transferring the photoresist pattern to the underlying substrate is a challenge when implementing evanescent waves interference lithography. One possible solution to this problem is to integrate evanescent waves interference as part of top surface imaging lithography process [196-198]. The photoresist is exposed to evanescent wave interference followed by silylation of the exposed regions by subjecting the sample to vaporized hexamethyl disilane. Anisotropic oxygen plasma etching process (such as reactive ion etching) is then executed. The silylated exposed regions act as mask to oxygen plasma etching, thus allowing the latent image formed by the silylated regions to be transferred into the rest of the resist layer.

The presented results have demonstrated the feasibility of achieving multi-dimensional nanopatterning at resolution beyond diffraction limit by employing evanescent waves interference lithography. The scope for further research and development in this thrust area is highlight in Chapter 7.

Chapter 6

Conclusion

Whole research work done towards the achievement of the desired project objectives is summarized and concluded in this chapter. Also, the significant contributions made during the course of research are stated in sequence.

6.1. Conclusion

The process performance indicators of the optical projection lithography are outlined in the literature review. As the optical projection lithography is heavily employed for industrial manufacturing purpose, resolution enhancement techniques are employed not just to achieve higher printing resolution but also to enhance process robustness which is reflected by the process window. The profile of a photoresist feature is closely associated to the aerial image which is formed from the fourier components diffracted from the mask. The fourier components strongly are influenced by the mask features and the illumination source. A pupil fill factor, accounting for the power difference between the 1st order and 0th order fourier components, is formulated as an approximate process window indicator. The effect on process window and pupil-fill factor by process parameters: i) attenuation of phase-shifted masking, ii) pitch size of mask features and iii) partial coherence setting of off-axis illumination source are investigated. The absolute correlation between the variation of the pupil factor and that of process window

under different exposure conditions and target features are summarized in Table 6-

1.

Varying process parameters influencing process window	Target Features	Exposure condition	Absolute correlation between pupil fill factor and process window	
			$ \alpha_{\text{sim}} $	$ \alpha_{\text{expt}} $
Varying Pitch sizes	120nm periodic line features	Conventional shaped illumination source ($\lambda = 248\text{nm}$); 0.68NA 6% attenuated phase shift photomask	0.819	0.832
		Annular shaped illumination source ($\lambda = 248\text{nm}$); 0.68NA 6% attenuated phase shift photomask	0.981	0.898
	100nm periodic line features	Annular shaped illumination source($\lambda = 248\text{nm}$); 0.68NA 6% attenuated phase shift photomask.	0.994	0.895
Transmittance of phase shifting photomask features	60nm periodic line features with	Annular illumination source($\lambda = 193\text{nm}$) 0.93NA	0.943	0.926
		Quasar illumination source ($\lambda = 193\text{nm}$), 0.93NA	0.944	0.849

Table 6-1 Summary of absolute correlation between pupil fill factor and simulated process window results($|\alpha_{\text{sim}}|$) as well as experimentally obtained process window results ($|\alpha_{\text{expt}}|$).

The pupil-fill factor values are shown to vary inversely with respect to that of process window values, with high correlation to both simulated and experimentally obtained process window results. This finding suggests that the pupil-fill factor offer an efficient and fairly accurate approach to identify parameter settings for mask design and illumination to obtain favorable process window result. However, the pupil-fill factor does not account for polarization effect.

Wavefront engineering techniques such as attenuated phase-shift masking and exposure with partial coherent off-axis illumination source facilitates enhancement of linewidth resolution and the process window. The printable pitch size is however fundamentally limited by the diffraction. With the objective of investigating lithography beyond diffraction limit, a multiple beams interference lithography system, employing a custom-fabricated two dimensional gratings as a beam-splitter, is designed and built for the purpose. Mirrors are used to reflect the diffracted beams to overlap on the photoresist, thus exposing it to the interference created in the overlapped region.

Lithographic printing by exposure to either two polarized beams interference or four polarized beams interference has been performed. Periodic line features with pitch size of 257nm (0.71λ) and average linewidth smaller than 140nm (0.36λ) are fabricated by two beams interference. Effect of polarization on two beams interference patterning is studied. Due to higher intensity contrast, the periodic line features fabricated by s-polarized interfering beams shows more defined profile under SEM examination than those fabricated by p-polarized interfering beams. No standing wave effect is observed in the cross-section of the samples despite the absence of anti-reflection coating. When exposure with four beams interference is carried out, periodic circular features with sub-200nm

resolution are obtained. The array arrangements of the features are found to be dependent on the polarization of the interfering beams. Square array distribution of circular feature and hexagonal array periodic circular features are obtained by using four s-polarized interfering beams and four p-polarized incident beams respectively. Photochemistry reaction of the photoresist to accumulated exposure dose has been exploited by varying the exposure duration to obtain either holes or pillar-like features. In terms of features distribution and pitch size, simulation agrees well with the experimental results

The conventional IL set-up is essentially a diffraction limited system since the pitch size resolution of the fabricated features is $> \lambda/2$. To pattern features with pitch resolution beyond diffraction limit, optical near field effect, namely evanescent waves interference, is explored and employed. A high index prism is integrated into the proposed lithography system to facilitate the generation of interference between counter-propagating evanescent waves induced by TIR. Conventional UV photoresist is employed in this process. Fabrication of line features with linewidth of almost $\lambda/6$ and average pitch size smaller than $\lambda/3$ has been demonstrated using two beams evanescent waves interference. Line obtained by employing p-polarized incident beams configuration displayed higher average aspect ratio than those obtained using s-polarized incident beams configuration. With four beams evanescent waves interference, fabrication of square arrayed circular-like pillars and hexagonal arrayed circular-like hole are achieved by using s-polarized and p-polarized incident beams respectively. In terms of distribution and features pitch size, close agreement between simulation and experimental results is observed. From the experimental observations, achieving high aspect ratio (>1.0) features using evanescent waves interference with the proposed system

is challenging unless beam pointing stability and stable phase difference between the incident beams are realized. Alternatively, laser with very high power may be employed to achieve sufficient exposure within shorter exposure duration. The amplitude of evanescent wave decay exponentially along the direction perpendicular to the photoresist surface, thus evanescent waves interference lithography is a convenient technique to fabricate surface relief structure. However, if through depth exposure of the photoresist is desired, further modifications to the evanescent waves interference lithography process would be required. Patterning resolution achieved experimentally by the evanescent waves interference and that achieved by conventional lithography is summarized in Table 6-2.

6.2. Main contributions

This thesis has presented the salient features of optical nanolithography employing wavefront engineering techniques and evanescent interference from two perspectives: (i) to achieve higher robustness in high resolution printing via process window enhancement within diffraction limitation and (ii) to achieve higher printing resolution beyond diffraction limitation by near-field interference approach. The main contributions of this thesis are summarized as follow:

- 1) A quantitative process window approximation method is formulated and experimentally validated. The method correlates intensity distribution of diffracted source image to process window realized by simultaneous employment of variable attenuated phase-shifted masking and partial coherence off-axis illumination.
- 2) Three-dimensional intensity distributions of two polarized beams as well as four polarized beams conventional interference, employing a stratified thin films model are formulated.

- 3) Design and set up of a four beams interferometry system. Demonstrated two polarized beams as well as four polarized beams conventional interference lithography using the proposed system. Influences of state of polarization of incident beams and accumulated exposure dose on the lithography performance are analysed.
- 4) Three-dimensional intensity distribution of two beams as well as four beams polarized evanescent waves interference are formulated.
- 5) The cellular automata numerical method is modified and employed to simulate the resultant three-dimensional resist profile resulted from exposure to evanescent waves interference.
- 6) The proposed interferometry system is modified by integrating a custom-fabricated prism into the set-up to effect a high NA optical lithography system. Nano-scale lines as well as different two dimensional features, with resolution beyond diffraction limit, are fabricated. The effects of polarization, accumulated exposure dose and phase shifting are illustrated and analyzed.

Based on the research issues identified in this work, a few possible areas for future investigations are proposed and are discussed in greater detail in the following chapter.

Configurations	Conventional Interference Lithography		Evanescent waves Interference Lithography	
	Array distribution and Average pitch Size	Feature type and average size	Array distribution and Average pitch Size	Feature type and average size
2 s-polarized incident beams	Periodic lines; 257nm	Linewidth: 137.82nm $\pm$ 7.68nm	Periodic lines; 107.15nm	Linewidth: 55.60nm $\pm$ 1.79nm
2 p-polarized incident beams		Linewidth: 149.89nm $\pm$ 5.05nm		Linewidth: 60.76nm $\pm$ 4.57nm
4 s-polarized incident beams	Square array; 257.87nm along x and y direction	Hole diameter: 166.34nm $\pm$ 9.42nm Pillar diameter: 128.14nm $\pm$ 4.00nm	Square array; 106.26nm along x and y direction	Pillar Diameter: 66.53nm $\pm$ 6.40nm
4 p-polarized incident beams	Hexagonal array; x-direction: 517.89nm along x and y direction 375nm along diagonal direction	Pillar diameter: 161.7nm $\pm$ 5.00nm	209.87 along x and y direction 150.03nm along diagonal direction	Hole diameter: 68.37nm $\pm$ 7.52nm

Table 6-2 Patterning resolution of conventional interference lithography and evanescent waves interference lithography.

Chapter 7

Future Work

In this chapter, possible future studies in the context of resolution enhancement for optical lithography are proposed and discussed sequentially.

Three main areas for further research and development are identified and proposed in this chapter. Firstly, the pupil-fill factor can be revisited to account for the effect of employing polarized illumination source on the resultant process window. Secondly, the four beams interference lithography system can be modified to compensate for beam pointing instability and to facilitate phase modulation and monitoring. Thirdly, frustrated total internal reflection will be exploited and modified to realize through depth exposure which is not achievable by evanescent waves interference. The proposed future studies are discussed in greater detail in the following sections.

7.1. Modification of pupil-fill factor

In Chapter 3 of this work, the study of the correlation between the pupil-fill factor values and the process window values based on scalar approach has been presented. The illumination source employed in the study is unpolarized, hence the image intensity at an image plane results from the superposition of electric fields of all directions. A scalar approach suffices in this case since the dominant

contribution to the image intensity comes from the interference between electric fields that are perfectly parallel to each other. However, method of obtaining the pupil fill factor will have to be modified to account for the effects of employing polarized illumination source which becomes increasingly significant for printing smaller features with high NA projection optics [199-202]. On one hand, the employment of suitably polarized illumination offers potential resolution enhancement [203-205]. On the other hand, lithography performance of polarized illumination coupled with high NA projection has been shown to be more sensitive to mask topology and optical properties of the mask materials [206-208]. The modified pupil fill factor may be helpful for solving advanced mask design problems especially identifying suitable mask materials for minimal birefringence effect that leads to mask induced polarization [209-211].

7.2. Phase locking and monitoring for four beams interferometry lithography system

While the modified four beams interference lithography system is employed in this work as a lab-based optical projection lithography system simulator, it has been demonstrated to be equally functional as low cost nanolithography system. To further improve the lithography performance of the system, a phase lock system would be required to provide the positional stability of the interference fringes. Without a phase lock system, beam pointing instability and changes in relative optical path difference between the interfering beams may adversely affect the positional stability of the fringes that lead to poor intensity contrast and photoresist features with poor profiles subsequently. This is especially so when long exposure duration is required to effect sufficient exposure dose such as the case of evanescent waves interference lithography. The intended

phase lock system will consist of a phase monitoring module as well as a phase modulating module. In previous works, a phase lock system has been developed for a two beams interferometry system [140, 212-214]. A four beams interferometry system which requires simultaneous phase monitoring and phase modulating of four interfering beams warrants a modified phase monitoring system configuration. Besides polarization, multiple beams interference is sensitive to phase difference between the interfering beams. Therefore, phase difference may be exploited as a process parameter to fabricate periodic features with complex geometry given that phase locking is realizable. Towards this end, the phase modulation unit for each of the incident beams may also be tuned to achieve the desired effect. Preliminary simulation study on employing phase modulation in multiple evanescent waves interference to achieve periodic complex features is also carried out and presented in the Appendix C.

7.3. Frustrated Total Internal Reflection assisted lithography with patterning beyond diffraction limit

Evanescent wave's interference lithography facilitates patterning resolution beyond diffraction limit. However, this technique has its drawbacks associated to the intrinsic characteristic of evanescent wave. Firstly, the amplitude of an evanescent wave decays exponentially in the direction transverse to the interface. This trait makes through-depth exposure of the photoresist difficult thus limiting the practicality of the technique. Secondly, optical contact between the prism and the photoresist is required for realization of evanescent waves interference lithography. This is made possible by introducing a high refractive index liquid matched to the prism between the two entities so that counter-propagating

evanescent waves are generated at the liquid-photoresist interface. Commercially available high refractive index prisms are well-suited for employment in the technique but not most high refractive index liquids due to their corrosive behavior towards photoresist, high toxicity and their molten state of existence at room temperature. As such, the refractive index of the high refractive index liquid becomes a gating parameter for the achievable patterning resolution.

To enhance exposure depth of evanescent waves interference, evanescent waves can be amplified directly by coupling to the surface plasmon polariton using a Kretschmann configuration. Adaptation of this technique for lithography application are previously reported[153, 156, 215]. However, optical contact between the incident medium and the photoresist is required thus the limitation associated to the second drawback cannot be ameliorated. In this regard, an alternative solution is to convert evanescent wave into propagating mode. To convert evanescent waves back into propagating waves, negative refraction by material is required, such as the employment of a thin conductive metallic film [157, 216] or photonic crystal layer for the same purpose [217-219]. Negative refraction by metallic film is highly dependent on incident angle. Two dimensional and three dimensional photonic crystals lens are difficult to fabricate especially when the exposure wavelength is smaller than the visible range. To circumvent the limitations, the near-field optical phenomenon of frustrated total internal reflection is proposed as a potential solution. This technique can be realized by positioning the photoresist at subwavelength separation from the prism so that optical energy tunnels across the gap from the prism and into the photoresist as a propagating wave. Optical tunneling occurs as long as the beam is incident on the exit face of the prism at angle not exceeding the critical angle

defined by the refractive index of the photoresist and that of the prism. However, the amplitude of the tunneled wave in the photoresist decreases with increase in the difference between the refractive index values of the prism and gap medium as well as increase in the gap distance. In this context, a stratified dielectric media configuration for amplified frustration of evanescent waves is discussed in Appendix D.

Appendix A

Derivation of Mapping Matrices for using semi-infinite layer model and sandwiched layer in stratified media model

This Appendix details an approach (referred to as the mapping matrix method in this report) for solving electric field in two types of model, namely the semi-infinite dielectric layers and the sandwiched layer in a stratified dielectric media model. The models assumed each of the media be homogeneous and isotropic. In the following section, the mapping matrix is discussed for solving electric field in a most basic configuration, which is a single homogeneous and isotropic medium.

A.1. Solving three-dimensional electric field of plane wave in a single homogeneous and isotropic medium

Consider a plane wave propagating in a medium that is source-free, homogeneous and isotropic as illustrated in Fig. A- 1.

Fig. A- 1 A plane wave propagating in a source-free, homogeneous and isotropic medium

A plane of incidence is defined here as the plane that contains both the wave vector, $\mathbf{k}$ and the electric field amplitude vector, $\mathbf{E}_{p(amp)}$. The electric field amplitude vector $\mathbf{E}_{s(amp)}$ is perpendicular to the plane that contains $\mathbf{k}$ and the electric field amplitude vector, $\mathbf{E}_{p(amp)}$. Since the medium is assumed to be isotropic, the direction of the Poynting vector of the plane wave is in the same direction of the wave vector, and hence the orientations of $\mathbf{E}_{s(amp)}$ and $\mathbf{E}_{p(amp)}$. From Fig. A- 1, the wave vector in Cartesian space is expressed as,

$$\mathbf{k} = (\sin \theta \cos \phi \hat{e}_x + \sin \theta \sin \phi \hat{e}_y + \cos \theta \hat{e}_z) k \quad (\text{A-1})$$

It is observed that the $\mathbf{E}_{s(amp)}$ is parallel to the x-y plane and has only components parallel to $\hat{e}_x$ and $\hat{e}_y$. Resolving $\mathbf{E}_{s(amp)}$ into its components in Cartesian space, one obtains,

$$\mathbf{E}_{s(amp)} = (\sin \phi \hat{e}_x - \cos \phi \hat{e}_y) E_{s(amp)} \quad (\text{A-2})$$

Likewise, $\mathbf{E}_{p(amp)}$ is given as follow,

$$\mathbf{E}_{p(amp)} = (\cos \theta \cos \phi \hat{e}_x + \cos \theta \sin \phi \hat{e}_y - \sin \theta \hat{e}_z) E_{p(amp)} \quad (\text{A-3})$$

In Eq. (A-2) and (A-3), $E_{s(amp)}$ and $E_{p(amp)}$ are the electric amplitudes in the s-polarization and p-polarization planes respectively. By using F to represent either electric field amplitude vector or wave vector, the $\hat{e}_x$, $\hat{e}_y$ and $\hat{e}_z$ components of the wave vector and electric fields are obtained from equations (A-1) to(A-3) as,

$$F_x = \sin \phi E_s + \cos \theta \cos \phi E_p + \sin \theta \cos \phi k \quad (\text{A-4})$$

$$F_y = -\cos \phi E_s + \cos \theta \sin \phi E_p + \sin \theta \sin \phi k \quad (\text{A-5})$$

$$F_z = -\sin \theta E_p + \cos \theta k \quad (\text{A-6})$$

Expressing the equations (A-4) to (A-6) in matrix form ,

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} \sin \phi & \cos \theta \cos \phi & \sin \theta \cos \phi \\ -\cos \phi & \cos \theta \sin \phi & \sin \theta \sin \phi \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} E_s \\ E_p \\ k \end{bmatrix} \quad (\text{A-7})$$

The 3X3 matrix maps the electric field or wave vector from the *spk* system to the Cartesian system. The mapping matrix can be further decomposed into a product of two matrices, one to be referred to as azimuth angle matrix and the other to be elevation orientation matrix. Hence, given electric field of a plane wave in the *spk* system, the corresponding electric field in the Cartesian system is expressed as,

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \mathbf{\Phi} \mathbf{\Theta} \begin{bmatrix} E_{s(amp)} \\ E_{p(amp)} \\ 0 \end{bmatrix} = \mathbf{\Phi} \mathbf{\Theta} \mathbf{E}_{(amp)} \quad (\text{A-8})$$

where

$$\mathbf{\Phi} = \begin{bmatrix} \sin \phi & \cos \phi & 0 \\ -\cos \phi & \sin \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{A-8a})$$

is the azimuth angle matrix and,

$$\mathbf{\Theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \quad (\text{A-8b})$$

is the elevation orientation matrix. It is seen that array $\mathbf{E}_{(amp)}$ of (A-8) is a modified Jones vector representation of the light polarization. As such a wave propagating in an arbitrary orientation can be expressed as,

$$\mathbf{E} = \mathbf{\Phi} \mathbf{\Theta} \mathbf{E}_{(amp)} \exp \left(-j \left(\mathbf{\Phi} \mathbf{\Theta} \begin{bmatrix} 0 \\ 0 \\ k \end{bmatrix} \right)^T \times \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) \quad (\text{A-9})$$

In Eq (A-9), T indicates transposition. So far, the presentation deals with resolving electric field amplitude vector in a system which consists of a single

homogeneous and isotropic medium. In the next section, the matrix treatment will be applied to resolve for electric field amplitude vector in isotropic layered medium.

Solving three-dimensional electric field of plane wave in semi-infinite layers

The simplest case of a layered media system is one that consists of two semi-infinite layers as illustrated in Fig. A- 2.

Fig. A- 2 A plane wave, with the wave vector $\mathbf{k}_1$, propagating in a two semi-infinite media system.

Both medium 1 and medium 2 are assumed to be dielectric, isotropic and homogeneous. As shown, $\mathbf{k}_1$, $\mathbf{k}_{1r}$ and $\mathbf{k}_2$ refer to the wave vectors of the plane wave incident on the interface, reflected plane wave and transmitted plane wave respectively. Given that the medium 1 is non-absorptive with refractive index n_1 and medium 2 is weakly absorptive with refractive index $n_r + j\kappa_r$. The wave vector of the transmitted plane wave, $\mathbf{k}_2$, in medium 2 is defined as,

$$\mathbf{k}_2 \approx (k_2 \sin \theta'_2 \cos \phi \hat{e}_x + k_2 \sin \theta'_2 \sin \phi \hat{e}_y + k_2 \cos \theta'_2 \hat{e}_z) \quad (\text{A-10})$$

Where

$$k_2 = k(n_2 + j\kappa_2),$$

Using the following approximations,

$$\sin \theta_2 \approx \frac{n_1 \sin \theta_1}{n_2} = \sin \theta'_2 \quad (\text{A-11})$$

$$(n_2 + j\kappa_2) \cos \theta_2 \approx n_2 \cos \theta'_2 + j \frac{\kappa_2}{\cos \theta'_2} \quad (\text{A-12})$$

Where $\cos \theta'_2 = \sqrt{1 - \left(\frac{n_1 \sin \theta_1}{n_2} \right)^2}$, $\mathbf{k}_2$ can be expressed as follow,

$$\mathbf{k}_2 \approx k \left(\frac{n_1 \sin \theta_1}{n_2} \cos \phi \hat{e}_x + \frac{n_1 \sin \theta_1}{n_2} \sin \phi \hat{e}_y + \sqrt{1 - \left(\frac{n_1 \sin \theta_1}{n_2} \right)^2} + j \frac{\kappa_2}{\cos \theta'_2} \hat{e}_z \right) \quad (\text{A-13})$$

From Eq (A-8), the relationship between the electric field of the transmitted plane wave and that of the incident plane wave is obtained as,

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \mathbf{\Phi} \mathbf{\Theta}_{2t} \mathbf{T} \begin{bmatrix} E_{s(amp)} \\ E_{p(amp)} \\ 0 \end{bmatrix} \quad (\text{A-14})$$

where,

$$\mathbf{\Theta}_{2t} \approx \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta''_2 & \sin \theta'_2 \\ 0 & -\sin \theta'_2 & \cos \theta''_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 - \frac{1}{2} \left(\frac{n_1 \sin \theta_1}{n_2} \right)^2 & \frac{n_1 \sin \theta_1}{n_2} \\ 0 & -\frac{n_1 \sin \theta_1}{n_2} & 1 - \frac{1}{2} \left(\frac{n_1 \sin \theta_1}{n_2} \right)^2 \end{bmatrix} \quad (\text{A-15})$$

where n_1 and n_2 represent the refractive index of the medium 1 and medium 2 respectively.

$\mathbf{T}$ is the transmission matrix defined as,

$$\mathbf{T} = \begin{bmatrix} \tau_s^{(1,2)} & 0 & 0 \\ 0 & \tau_p^{(1,2)} & 0 \\ 0 & 0 & \tau_s^{(1,2)} \end{bmatrix} \quad (\text{A-16})$$

in which $\tau_s^{(1,2)}$ and $\tau_p^{(1,2)}$, represent the transmission coefficients for s and p components of the electric field modified from Fresnel equations respectively as,

$$\tau_s^{(1,2)} \approx \frac{2n_1 \cos \theta_1 (n_1 \cos \theta_1 + n_2 \cos \theta'_2) - j2n_1 \cos \theta_1 \kappa}{(n_1 \cos \theta_1 + n_2 \cos \theta'_2)^2 + \kappa^2 / \cos^2 \theta'_2} \quad (\text{A-17})$$

$$\tau_p^{(1,2)} \approx \frac{2n_1 \cos \theta_1 (n_1 \cos \theta'_2 + n_2 \cos \theta_1) - j2n_1 \cos \theta_1 (n_1 \kappa_2 / (n_2 \cos \theta'_2) + \kappa_2 \cos \theta_1)}{(n_1 \cos \theta'_2 + n_2 \cos \theta_1)^2 + (n_1 \kappa_2 / (n_2 \cos \theta'_2) + \kappa_2 \cos \theta_1)^2} \quad \dots \quad (\text{A-18})$$

The wave vector of reflected plane wave $\mathbf{k}_{1r}$, in medium 1, is defined as,

$$\mathbf{k}_{1r} = (\sin \theta_1 \cos \phi \hat{e}_x + \sin \theta_1 \sin \phi \hat{e}_y - \cos \theta_1 \hat{e}_z) k \quad (\text{A-19})$$

It is shown in Fig. A- 2 that the reflected plane wave maintains the azimuth angle of the incident plane wave. However, the elevation angle of the reflected plane wave with respect to z -axis is $\pi - \theta_1$. Therefore, it can be deduced that the elevation matrix for the reflected wave, Θ_r , is defined as,

$$\Theta_r = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\pi - \theta_1) & -\sin(\pi - \theta_1) \\ 0 & \sin(\pi - \theta_1) & -\cos(\pi - \theta_1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos \theta_1 & -\sin \theta_1 \\ 0 & \sin \theta_1 & \cos \theta_1 \end{bmatrix} \quad (\text{A-20})$$

From Eq (A-8), the relationship between the electric field of the reflected plane and that of the incident plane is defined as,

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \Theta \Theta_r \mathbf{P} \begin{bmatrix} E_s \\ E_p \\ 0 \end{bmatrix} \quad (\text{A-21})$$

$\mathbf{P}$ represents the reflection matrix defined as,

$$\mathbf{P} = \begin{bmatrix} \rho_s^{(1,2)} & 0 & 0 \\ 0 & \rho_p^{(1,2)} & 0 \\ 0 & 0 & \rho_s^{(1,2)} \end{bmatrix} \quad (\text{A-22})$$

in which $\rho_s^{(1,2)}$ and $\rho_p^{(1,2)}$, represent the reflection coefficients for the s and p component of the electric field respectively and are modified from Fresnel equations as,

$$\rho_s^{(1,2)} \approx \frac{\cos^2 \theta'_2 (n_1 \cos \theta_1 - n_2 \cos \theta'_2)(n_1 \cos \theta_1 + n_2 \cos \theta'_2) - \kappa_2^2 - j2\kappa_2 n_1 \cos \theta_1}{\cos^2 \theta'_2 \left[(n_1 \cos \theta_1 + n_2 \cos \theta'_2)^2 + \kappa_2^2 / \cos^2 \theta'_2 \right]} \quad \dots \quad (\text{A-23})$$

$$\rho_p^{(1,2)} \approx \frac{(n_1^2 \cos^2 \theta'_2 - n_2^2 \cos^2 \theta_1) + (n_1 \kappa_2 / n_2 \cos \theta'_2)^2 - (\kappa_2 \cos \theta_1)^2}{(n_1 \cos \theta'_2 + n_2 \cos \theta_1)^2 + (n_1 \kappa_2 / n_2 \cos \theta'_2 + \kappa_2 \cos \theta_1)^2} + \dots$$

$$+ j \frac{-2n_1 \kappa_2 \cos \theta_1 \cos \theta'_2 + 2n_1 \kappa_2 \cos \theta_1 / n_2 \cos \theta'_2}{(n_1 \cos \theta'_2 + n_2 \cos \theta_1)^2 + (n_1 \kappa_2 / n_2 \cos \theta'_2 + \kappa_2 \cos \theta_1)^2} \quad (\text{A-24})$$

While the modified Fresnel formulae can be readily employed for solving electric field in a two semi-infinite layers model, a different approach is required for a sandwiched layer of a stratified media configuration. This approach is presented in the following section.

A.2. Solving three-dimensional electric field of plane wave in a sandwiched layer of a stratified media model

This section discusses the extension of the mapping matrix method to the case of solving the electric field in a sandwiched layer of a stratified media configuration as illustrated in Fig. A- 3.

Fig. A-3 Multilayer dielectric stack of which the electric field in the l^{th} is to be solved.

To simplify the theoretical analysis into a 2D problem, the wave vector, is contained in the y - z plane. The total positional electric field in the sandwiched l^{th} layer is the summation of the electric field in the downward propagating wave and that of the upward propagating wave expressed as,

$$\begin{aligned} \mathbf{E}_T(x, y, z) &= \mathbf{E}_{(amp)}^{(f)} \exp\left(i\mathbf{k}_l^{(i)} \cdot \mathbf{r}^{(i)}\right) + \mathbf{E}_{(amp)}^{(f+1)} \exp\left(i\mathbf{k}_l^{(r)} \cdot \mathbf{r}^{(r)}\right) \\ &= \left\{ \mathbf{E}_{(amp)}^{(f)} \exp\left(jk_{lz}^{(i)} \hat{e}_z \cdot (z - z_f) \hat{e}_z\right) + \mathbf{E}_{(amp)}^{(f+1)} \exp\left(jk_{lz}^{(r)} \hat{e}_z \cdot (z_{f+1} - z) \hat{e}_z\right) \right\} \dots \\ &\quad \times \exp\left(jk_{ly}^{(i)} \hat{e}_y \cdot (y \hat{e}_y)\right) \end{aligned} \quad \dots \quad (\text{A-25})$$

where $\mathbf{E}_{(amp)}^{(f)}$ is the electric field amplitude of the downward propagating wave in the l^{th} layer at the interface z_f , $\mathbf{E}_{(amp)}^{(f+1)}$ is the electric field amplitude of the upward propagating wave in the l^{th} layer at the interface z_{f+1} and assuming the l^{th} layer to be absorptive, $k_{lz}^{(i)} = k_z^{(i)}(n_l + i\kappa_l)$ and $k_{lz}^{(r)} = k_z^{(r)}(n_l - i\kappa_l)$. Using Eq (A-14),

$\mathbf{E}_{(amp)}^{(f)}$ is defined as

$$\mathbf{E}_{amp}^{(f)} = \begin{bmatrix} E_x^{(f)} \\ E_y^{(f)} \\ E_z^{(f)} \end{bmatrix} = \mathbf{\Phi} \mathbf{\Theta}_t \tilde{\mathbf{T}}^{(o,l)} \begin{bmatrix} A_s \\ A_p \\ 0 \end{bmatrix} \quad (\text{A-26})$$

where

$$\mathbf{\Phi} = \begin{bmatrix} \sin \phi & \cos \phi & 0 \\ -\cos \phi & \sin \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{A-27})$$

is the azimuth angle matrix,

$$\mathbf{\Theta}_t = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_t & \sin \theta_t \\ 0 & -\sin \theta_t & \cos \theta_t \end{bmatrix} \quad (\text{A-28})$$

is the elevation orientation matrix of downward propagating wave, in which θ_t refers to the transmitted angle in the l^{th} layer. The transmission coefficients matrix, $\tilde{\mathbf{T}}^{(o,l)}$ is defined as,

$$\tilde{\mathbf{T}}^{(o,l)} = \begin{bmatrix} F_s & 0 & 0 \\ 0 & F_p & 0 \\ 0 & 0 & F_s \end{bmatrix} \quad (\text{A-29})$$

where,

$$F_{s,p} = \frac{\tilde{\tau}_{s,p}^{(o,l)}}{1 + \tilde{\rho}_{s,p}^{(l,o)} \tilde{\rho}_{s,p}^{(l,N)} \tau_d^2(\theta_r')} \quad (\text{A-30})$$

in which $\tilde{\tau}_{s,p}^{(o,l)}$ is the transmission coefficient of the wave in layer l at z_f , $\tilde{\rho}_{s,p}^{(l,o)}$ is the reflection coefficient of the wave in layer l at z_f and $\tilde{\rho}_{s,p}^{(l,N)}$ is the reflection coefficient of the wave in layer l at z_{f+1} . In similar fashion, $\mathbf{E}^{(f+1)}$ is defined as,

$$\mathbf{E}_{amp}^{(f+1)} = \begin{bmatrix} E_x^{(f+1)} \\ E_y^{(f+1)} \\ E_z^{(f+1)} \end{bmatrix} = \mathbf{\Phi} \mathbf{\Theta}_r \mathbf{P}^{(f+1)} \begin{bmatrix} E_{s(amp)} \\ E_{p(amp)} \\ 0 \end{bmatrix} \quad (\text{A-31})$$

It is observed from that the reflected plane wave maintains the azimuth angle of the incident plane wave. Consider the reflected plane wave in the l^{th} layer, the corresponding wave vector $\mathbf{k}_l^{(r)}$ is defined as,

$$\mathbf{k}_l^{(r)} = (\sin(\pi - \theta_t) \cos \phi \hat{e}_x + \sin(\pi - \theta_t) \sin \phi \hat{e}_y - \cos(\pi - \theta_t) \hat{e}_z) k \quad (\text{A-32})$$

Therefore, it can be deduced that the elevation matrix for the reflected wave, $\mathbf{\Theta}_r$, is defined as,

$$\mathbf{\Theta}_r = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos \theta_t & \sin \theta_t \\ 0 & -\sin \theta_t & -\cos \theta_t \end{bmatrix} \quad (\text{A-33})$$

The reflection coefficient matrix $\tilde{\mathbf{P}}^{(f+1)}$ is defined as,

$$\tilde{\mathbf{P}}^{(l,N)} = \begin{bmatrix} B_s & 0 & 0 \\ 0 & B_p & 0 \\ 0 & 0 & B_s \end{bmatrix} \quad (\text{A-34})$$

where

$$B_{s,p} = \frac{\tilde{\tau}_{s,p}^{(o,l)} \tilde{\rho}_{s,p}^{(l,N)} \tau_d^2(\theta'_r)}{1 - \tilde{\rho}_{s,p}^{(l,o)} \tilde{\rho}_{s,p}^{(l,N)} \tau_d^2(\theta'_r)} \quad (\text{A-35})$$

$\tilde{\rho}_{s,p}^{(l,N)}$ is the fresnel reflection coefficient at z_{f+1} . To solve for $\tilde{\tau}_{s,p}^{(o,l)}$, $\tilde{\rho}_{s,p}^{(l,o)}$ and $\tilde{\rho}_{s,p}^{(l,N)}$, $\tilde{\tau}_{s,p}^{(o,N)}$ and $\tilde{\rho}_{s,p}^{(o,N)}$ for the entire stack has to be solved, which can be achieved conveniently by the transfer matrix method (TMM). The TMM is employed to relate the electric amplitudes of downward propagating wave (A_o)

and upward propagating wave (B_o) in the incident medium to those in the last medium, A'_N and B'_N respectively given as follows [220],

$$\begin{bmatrix} Fw_o \\ Bw_o \end{bmatrix} = \mathbf{D}_o^{-1} \prod_{l=1}^{N-1} \mathbf{D}_l \mathbf{X}_l \mathbf{D}_l^{-1} \mathbf{D}_N \begin{bmatrix} Fw'_N \\ Bw'_N \end{bmatrix} \equiv \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix} \begin{bmatrix} Fw'_N \\ Bw'_N \end{bmatrix} \quad (\text{A-36})$$

where,

$$\mathbf{D}_l = \begin{cases} \begin{bmatrix} 1 & 1 \\ n_l \cos \theta_l & -n_l \cos \theta_l \end{bmatrix} & \text{for } s \text{ wave} \\ \begin{bmatrix} \cos \theta_l & \cos \theta_l \\ n_l & -n_l \end{bmatrix} & \text{for } p \text{ wave} \end{cases} \quad (\text{A-37})$$

is the dynamical matrix,

$$\mathbf{X}_l = \begin{bmatrix} \exp(jk_z(n_l + i\kappa_l)d_l) & 0 \\ 0 & \exp(-jk_z(n_l - j\kappa_l)d_l) \end{bmatrix} \quad (\text{A-38})$$

is the propagation matrix assuming that the layer has a non-zero extinction coefficient. The term k_z is the z component of the wave vector and d_l is the thickness of the layer. The 2X2 matrix representing the series multiplication in Eq (A-36) is referred to as the transfer matrix for the N layers stratified dielectric media. If the last layer is assumed to be semi-infinite, it can be deduced that there is no upward propagating plane wave in the last medium. Hence, by letting $B'_N = 0$ and expansion of Eq (A-36), the following is obtained,

$$\begin{bmatrix} Fw_o \\ Bw_o \end{bmatrix} = \begin{bmatrix} \mathbf{M}_{11}Fw'_N \\ \mathbf{M}_{21}Bw'_N \end{bmatrix} \quad (\text{A-39})$$

The transmission coefficient and reflection coefficient of N layers obtained from Eq (A-39) respectively as follow,

$$\tilde{\tau}_{s,p}^{(o,N)} = \frac{Fw'_N}{Fw_o} = \frac{1}{M_{11}} \quad (\text{A-40})$$

$$\tilde{\rho}_{s,p}^{(o,N)} = \frac{Bw_o}{Fw_o} = \frac{M_{21}}{M_{11}} \quad (\text{A-41})$$

Though solving M_{11} and M_{21} becomes complicated when N is large, their solutions can be handled by a computation program. Subsequently, the entire stack is divided into two sub-stack as illustrated in Fig. A- 4 and TMM is repeated for each of the sub-stack to solve for $\tilde{\tau}_{s,p}^{(o,l)}$ and $\tilde{\rho}_{s,p}^{(l,N)}$.

(a)

(b)

Fig. A- 4 (a) Sub-stack I consisting of incident medium to l^{th} layer (b) Sub-stack II consisting of l^{th} layer to last medium.

With reference to Fig. A- 4(a), the electric field amplitudes Fw'_l and Bw'_l can be related to Fw_o and Bw_o using transfer matrix method and expressed as follows,

$$\begin{bmatrix} Fw_o \\ Bw_o \end{bmatrix} = \mathbf{D}_o^{-1} \prod_{m=1}^{l-1} \mathbf{D}_m \mathbf{X}_m \mathbf{D}_m^{-1} \mathbf{D}_l \begin{bmatrix} Fw'_l \\ Bw'_l \end{bmatrix} \equiv \begin{bmatrix} \mathbf{M}_{11I} & \mathbf{M}_{12I} \\ \mathbf{M}_{21I} & \mathbf{M}_{22I} \end{bmatrix} \begin{bmatrix} Fw'_l \\ Bw'_l \end{bmatrix} \quad (\text{A-42})$$

From the above equation, the solution for the Fw'_l and Bw'_l can be obtained as function of the elements of the transfer matrix, Fw_o and Bw_o given as follows,

$$Fw'_l = \frac{\mathbf{M}_{22I} Fw_o - \mathbf{M}_{12I} Bw_o}{\mathbf{M}_{11I} \mathbf{M}_{22I} - \mathbf{M}_{12I} \mathbf{M}_{21I}} \quad (\text{A-43})$$

$$Bw'_l = \frac{-\mathbf{M}_{21I} Fw_o + \mathbf{M}_{11I} Bw_o}{\mathbf{M}_{11I} \mathbf{M}_{22I} - \mathbf{M}_{12I} \mathbf{M}_{21I}} \quad (\text{A-44})$$

By normalizing both sides of the Eq (A-43) and (A-44) by Fw_o , the transmission and reflection coefficients at the interface z_f in layer l is obtained as,

$$\tilde{\tau}_{s,p}^{(o,l)} = \frac{\mathbf{M}_{22I} - \mathbf{M}_{12I} \rho_{s,p}^{(o,N)}}{\mathbf{M}_{11I} \mathbf{M}_{22I} - \mathbf{M}_{12I} \mathbf{M}_{21I}} \quad (\text{A-45})$$

$$\tilde{\rho}_{s,p}^{(l,o)} = \frac{-\mathbf{M}_{21I} + \mathbf{M}_{11I} \rho_{s,p}^{(o,N)}}{\mathbf{M}_{11I} \mathbf{M}_{22I} - \mathbf{M}_{12I} \mathbf{M}_{21I}} \quad (\text{A-46})$$

where $\tilde{\rho}_{s,p}^{(o,N)}$ refers to the transmission coefficient for either s or p wave through the full stack as obtained from Eq.(A-41). In similar fashion, the transfer matrix method is applied to sub-stack II as shown in Fig. A- 4(b) and the following relationship is expressed as,

$$\begin{bmatrix} Fw_l \\ Bw_l \end{bmatrix} = \mathbf{D}_o^{-1} \prod_{m=l}^{N-1} \mathbf{D}_m \mathbf{X}_m \mathbf{D}_m^{-1} \mathbf{D}_l \begin{bmatrix} Fw'_N \\ Bw'_N \end{bmatrix} \equiv \begin{bmatrix} \mathbf{M}_{11II} & \mathbf{M}_{12II} \\ \mathbf{M}_{21II} & \mathbf{M}_{22II} \end{bmatrix} \begin{bmatrix} Fw'_N \\ Bw'_N \end{bmatrix} \quad (\text{A-47})$$

from which Bw_l is obtained as,

$$Bw_l = M_{21\text{II}} Fw'_N \quad (\text{A-48})$$

Normalize both sides of the Eq (A-48) by Fw_o , the reflection coefficient for either s or p wave in medium l caused by the interface z_{f+1} is obtained as,

$$\tilde{\rho}_{s,p}^{(l,N)} = M_{21\text{II}} \tilde{\tau}_{s,p}^{(o,N)} \quad (\text{A-49})$$

For completeness of explanation, the Fw_l is given as,

$$Fw_l = M_{11\text{II}} Fw'_N \quad (\text{A-50})$$

Where Fw_l is the amplitude of the wave in medium l , incident at the interface z_{f+1} just before transmission. Recall that the Eq (A-45) and Eq (A-49) are coefficients with reference to the incident electric field amplitude at the top of the stack.

Appendix B

Polarized two waves interference in two semi-finite media configuration

A.3. Two beams interference

A pair of co-planar beams, one with amplitude A_1 and the other with A_2 , intersects at a plane with equal oblique angle θ_I with reference from the z-axis is illustrated in Fig. B- 1.

Fig. B- 1 Interference between a pair of s polarized incident plane waves

As illustrated in the figure, the case is simplified such that the plane of incidence is parallel to the x-z plane. Letting both plane waves be s-polarized such the orientations of electrical field amplitude vectors of the plane waves are perpendicular to the x-z plane. Introducing δ_1 and δ_2 as initial phases of the individual plane wave, the electric field of the plane waves in the second medium are expressed respectively as,

$$\mathbf{E}_s^{(1)} \approx \left| \tau_s^{(I,r)} \right| A_1 \cos \left(-k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi}{T} t + \delta_1 + \chi_s \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad \dots \quad (\text{B-1})$$

$$\mathbf{E}_s^{(2)} = - \left| \tau_s^{(I,r)} \right| A_2 \cos \left(k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi}{T} t + \delta_2 + \chi_s \right) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \hat{e}_y \quad \dots \quad (\text{B-2})$$

where T is the inverse of the source frequency, $\left| \tau_s^{(I,r)} \right|$ is the amplitude factor of the transmission coefficient for s-polarized incident electric field and χ_s is the corresponding induced phase shift resulted from the transmission.

The corresponding irradiance of the interference between the two plane waves measures the time averaged of the square of the total electric field and is given as,

$$I \propto \left\langle \left(\mathbf{E}_s^{(1)} + \mathbf{E}_s^{(2)} \right) \cdot \left(\mathbf{E}_s^{(1)} + \mathbf{E}_s^{(2)} \right) \right\rangle \quad (\text{B-3})$$

$$= \left| \tau_s^{(I,r)} \right|^2 \left\{ \frac{A_1^2}{2} + \frac{A_2^2}{2} - A_1 A_2 \cos \left(2k \sin \theta x - \delta_{1,2} \right) \right\} \exp \left(\frac{-2k \kappa_r z}{\cos \theta'_r} \right)$$

The period of the sinusoidal intensity distribution, Λ , along the x direction is obtained from Eq (B-3) as $\Lambda = \lambda / 2 \sin \theta$. The term $\delta_{1,2}$, defined as $\delta_1 - \delta_2$, is the phase difference between the incident plane waves, and results in spatial shift of the sinusoidal intensity distribution. In the context of interference lithography, it is highly desirable that $\delta_{1,2}$ remains stable with respect to time so that the interference intensity distribution remains stable in position as the latent image is formed in the photoresist. This initial phase difference relates to the mutual coherence of the two plane waves and hence may arise from the intrinsic property of the illumination source. In this connection, the two plane waves should have high temporal and spatial coherence. Another cause of fluctuating $\delta_{1,2}$ is the

changes in relative optical path difference between the two plane waves as a result of air flow and especially prominent when the ambient humidity is high.

The intensity contrast, Ctr_{2s} , of the sinusoidal interference intensity at $z = 0$ is given as,

$$Ctr_{2s} = \frac{A_1 A_2}{A_1^2 + A_2^2} \quad (\text{B-4})$$

Consider the case is modified such that the plane waves are p-polarized as shown in Fig. B- 2.

Fig. B- 2 Interference between a pair of p polarized incident plane waves

The electric field of a p polarized plane wave is parallel to the x-z plane. The expression for the harmonic electric field of the two incident plane waves are given as,

$$\mathbf{E}_p^{(1)} = \left| \tau_p^{(I,r)} \right| A_1 \cos \left(-k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_1 + \chi_p \right) (-\cos \theta'_r \hat{x} + \sin \theta'_r \hat{z}) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \quad \dots \quad (\text{B-5})$$

$$\mathbf{E}_p^{(2)} = \left| \tau_p^{(I,r)} \right| A_2 \cos \left(k_r \sin \theta'_r x + k_r \cos \theta'_r z - \frac{2\pi t}{T} + \delta_2 + \chi_p \right) (-\cos \theta'_r \hat{x} - \sin \theta'_r \hat{z}) \exp \left(\frac{-k \kappa_r z}{\cos \theta'_r} \right) \quad \dots \quad (\text{B-6})$$

The corresponding intensity distribution of the interference between the two plane waves is obtained as,

$$I \propto \left| \tau_p^{(I,r)} \right| \left\{ \frac{A_1^2}{2} + \frac{A_2^2}{2} - A_1 A_2 \cos(2\theta'_r) \cos(2k \sin \theta x - \delta_{1,2}) \right\} \exp\left(\frac{-2k \kappa_r z}{\cos \theta'_r} \right) \quad (\text{B-7})$$

The corresponding contrast at $z = 0$ is given as,

$$Ctr_{2p} = \frac{2 \cos 2\theta'_r A_1 A_2}{A_1^2 + A_2^2} \quad (\text{B-8})$$

Comparing equation (B-8) to (B-4), one is able to predict that the contrast of interference fringes obtained from p-polarized plane waves is always worse than that obtained from s-polarized plane waves. From Eq (B-8), it becomes apparent that the interference term is modulated by $\cos(2\theta'_r)$ which is defined as $\cos 2\theta'_r = 1 - \sin^2 \theta / n_r^2$. If $n_r > n_1$, $Ctr_{2p} > 0$ regardless of incident angle in air (θ) but decreases as θ increases.

A.4. Four waves interference

In a case whereby the multiple incident plane waves are s-polarized such that their electric field vectors are perpendicular to their respective plane of incidence, the implicit general expression for the interference between them is given as

$$I_{4s} \propto \frac{\left| \tau_s^{(I,r)} \right|^2}{T} \int_0^{t_{\text{exp}}} \left[\sum_{l=1}^4 A_l \cos(H_s/2) \sin(\phi_l) \right]^2 + \left[\sum_{w=1}^4 A_w \cos(H_s/2) \cos(\phi_l) \right]^2 \partial t \quad \dots \quad (\text{B-9})$$

where t_{exp} is the exposure duration which is presumably much larger than T and ϕ_l is the azimuth angle of the individual beam.

If the multiple incident plane waves are p-polarized, the implicit general expression for the interference,

$$I_{4p} \propto \frac{|\tau_p^{(I,r)}|^2}{2T} \int_0^{T_{\text{exp}}} (1 + \cos(2\theta'_r)) \left[\left[\sum_{l=1}^4 A_l \cos(H_p/2) \sin(\phi_w) \right]^2 + \left[\sum_{l=1}^4 A_l \cos(H_p/2) \cos(\phi_l) \right]^2 \right] + \dots$$

$$(1 - \cos(2\theta'_r)) \left[\sum_{l=1}^4 A_l \cos(H_p/2) \right] \partial t \quad \dots \quad (\text{B-10})$$

where in Eqs (B-9) and (B-10),

$$H_{s,p} = 2(\chi_{s,p} + \delta_{1,2}) + 2k_r \cos \theta'_r z + 2k_r \sin \theta'_r \sin \phi_l y + 2k_r \cos \theta'_r \sin \phi_l x - 4\pi t/T$$

$$\dots \quad (\text{B-11})$$

Consider the interference between four plane waves arranged in an umbrella configuration as shown in Fig. B- 3.

Fig. B- 3 Illustration of the configuration of simultaneous interference of four incident plane waves $E^{(1)}$, $E^{(2)}$, $E^{(3)}$ and $E^{(4)}$ shown in (a) x-z plane (b) y-z plane

The plane waves are arranged such that the x-z plane is the plane of incidence for $E^{(1)}$ - $E^{(2)}$ pair and the y-z plane is the plane of incidence for the $E^{(2)}$ - $E^{(4)}$ pair.

The intensity distribution in the photoresist for the interference of the four s-polarized incident plane waves is obtained from equation (B-9) as,

$$I_{4s} \propto \left| \tau_s^{(I,r)} \right|^2 \exp \left(\frac{-2k\kappa_r z}{\cos \theta'_r} \right) \times \dots \left\{ \frac{\sum_{l=1}^4 A_l^2}{2} - A_2 A_4 \cos(2k \sin \theta y + \delta_{2,4}) - A_1 A_3 \cos(2k \sin \theta x + \delta_{1,3}) \right\} \quad (\text{B-12})$$

The above equation suggests the interference intensity distribution is a summation of sinusoidal intensity distribution along y axis and another along x-axis. This suggest that the same result as sequential exposure of two plane waves interference, such that the two exposures are carried out with the sample rotated 90° . From Eq (B-12), the expression for the contrast of the intensity distribution at $z = 0$ is obtained as,

$$Ctr_{4s} = \frac{A_2 A_4 + A_1 A_3}{\sum_{l=1}^4 A_l^2} \quad (\text{B-13})$$

If the four plane waves are p polarized, the interference distribution is obtained as,

$$I_{4p} = I_{4 \text{ beams}} - \cos 2\theta'_r (I_{1,3} + I_{2,4}) + (1 - \cos 2\theta'_r) (I_{1,2} + I_{2,3} + I_{3,4} + I_{1,4}) \exp \left(\frac{-2k\kappa_r z}{\cos \theta'_r} \right) \dots \quad (\text{B-14})$$

where,

$$I_{4 \text{ beams}} \propto \frac{\left| \tau_p^{(I,r)} \right|^2 \sum_{l=1}^4 A_l^2}{2}$$

$$I_{1,3} \propto \left| \tau_p^{(I,r)} \right|^2 A_1 A_3 \cos(2k \sin \theta x + \delta_{1,3})$$

$$I_{2,4} \propto \left| \tau_p^{(I,r)} \right|^2 A_2 A_4 \cos(2k \sin \theta y + \delta_{2,4})$$

$$I_{1,2} \propto \left| \tau_p^{(I,r)} \right|^2 A_1 A_2 \left\{ \frac{1}{2} \cos(k_r \sin \theta_r (x - y) + \delta_{1,2}) \right\}$$

$$I_{2,3} \propto \left| \tau_p^{(l,r)} \right|^2 A_2 A_3 \left\{ \frac{1}{2} \cos(k \sin \theta (x+y) + \delta_{2,3}) \right\}$$

$$I_{3,4} \propto \left| \tau_p^{(l,r)} \right|^2 A_3 A_4 \left\{ \frac{1}{2} \cos(k \sin \theta (x-y) + \delta_{3,4}) \right\}$$

$$I_{1,4} \propto \left| \tau_p^{(l,r)} \right|^2 A_1 A_4 \left\{ \frac{1}{2} \cos(k \sin \theta (x+y) + \delta_{1,4}) \right\}$$

As suggested by Eq. (B-14), the interference of four p-polarized plane waves consists of the superposition interference between counter oriented plane waves pair ($I_{1,3}$ and $I_{2,4}$) and interference between adjacent plane waves (i.e. $I_{1,2}$, $I_{2,3}$ etc). The contrast of the interference intensity distribution at $z = 0$ is obtained as,

$$Ctr_{4p} = \frac{2 \cos 2\theta'_r (A_1 (A_3 - A_2 - A_4) + A_2 (A_4 - A_3) - A_3 A_4) + 2 (A_2 + A_4) (A_1 + A_3)}{\sum_{l=1}^4 A_l^2} \quad \dots \quad (B-15)$$

The contrast of the interference pattern generated by four p-polarized beams are modulated by $\cos 2\theta'_r$.

Appendix C

Phase modulation for multiple beams evanescent waves interference lithography

Multiple beams evanescent waves interference is sensitive to the relative phase difference as well as polarizations of the incident beams just as in conventional multiple beams interference lithography. In this connection, modulation of relative phase difference between polarized incident beams so as to achieve different nanoscale patterns by evanescent wave interference patterns is explored. When all incident plane waves are of identical polarization states, introducing relative phase difference between any pair of incident waves in the same incidence plane would result in spatial displacement of the interference pattern but the general profile does not change. However, by using incident plane waves with different states of polarization and introducing relative phase difference, one would be able to modulate the interference between parallel electric fields of the evanescent waves. However, orthogonal electric fields do not interfere and adds to the background intensity to reduce the fringes contrast. The concept of employing incident beams to achieve interference patterns with different polarization states would still require that oppositely directed incident beams have parallel electric field components. In this regard, the interference profile generated when the evanescent waves generated by one pair of s-polarized counter-oriented incident beams is coupled to that of a p-polarized pair is

investigated. It was observed that such a configuration would result in periodic features with dumb-bell shape geometry when a larger incident angle of 72° is employed. The contrast of each dumb-bell shaped feature can be modulated by introducing relative phase difference between counter-oriented incident plane waves. In lithography context, optical intensity contrast of a feature directly influences its subsequent resist profile. For a dumb-bell shaped feature, the region at which intensity contrast is the most critical is across the waist since low intensity contrast at this region would most likely result in distorted resist profile. To investigate the optimum relative phase difference between the incident plane waves' pair, different values of relative phase difference are introduced between the two pairs of counter-oriented incident plane waves. The phase shift assigned between counter-oriented incident plane waves 1 and 3 is represented by $\delta_{1,3}$ and that between incident plane waves 2 and 4 by $\delta_{2,4}$. When $\delta_{a,b}$ takes on a positive value, it means that the incident plane wave b has a phase lead with respect to incident plane wave a , where a refers to either 1 or 2 and b refers to 3 or 4. Conversely, a negative value would then mean a phase lag. For each pair of counter-oriented incident plane waves, the phase difference values are varied from -135° to 135° with step size of 45° . For each combination of $\delta_{1,3}$ and $\delta_{2,4}$, the variation of intensity contrast of the waist of an individual feature is shown in Fig. C- 1a. The combination of phase difference values which yield the highest intensity contrast across the waist region (shown by the dotted white line) are assigned to the respective incident plane waves pair. The corresponding intensity profile is shown in Fig. C- 1b. From the result, it is observed that a few possible combinations of relative phase difference values can yield the highest contrast values.

(a)

(b)

Fig. C- 1 Color map of the variation of intensity contrast across the dotted white line with different combinations of phase shift (a) between beams 1 and 3, and between 2 and 4; (b) Interference intensity profile obtained with the best combination of phase difference that correspond to the highest contrast along the dotted white line (across the waist of a dumb-bell shaped feature)

Employing a pair of co-planar s-polarized incident beams and an orthogonal pair of co-planar p-polarized incident beams with phase difference of $\delta_{1,3} = \pi/2$ and $\delta_{2,4} = -\pi/2$ respectively, the resultant normalized intensity distribution on X-Y

plane at interface ($z=0$) is shown is shown in Fig. C- 1(b). Employing an exposure duration of 10sec and fluence of $1\text{mW}/\text{cm}^2$, The corresponding simulated resist topology is shown in Fig. C- 2.

Fig. C- 2 Resist topology corresponding to evanescent interference generated by two s-polarized incident plane wave and two p-polarized incident plane waves with $\delta_{1,3} = \pi/2$ and $\delta_{2,4} = -\pi/2$

As shown in Fig. C- 2 , saddle-like topologies are typically formed at two regions. One region is at the waist of each dumb-bell shaped low intensity region and the other between adjacent dumbbell-shaped regions as identified in the Fig. C- 1(b). The saddles at these two regions were found to have a height difference of 35nm. The resultant resist topology is that of periodic three-dimensional features since the saddles are located periodically. If the same benchmark that was used to characterize the feature width in previous two cases is applied, the resist contour in the X-Y plane at the position of $z_{half} = -60\text{nm}$ is obtained as shown as follows.

Fig. C- 3 Resist contours (black regions) in X-Y plane at $z_{half} = -60nm$.

The result shows that at the half-height position, the resist contour is that of periodic dumb-bell shaped nanostructures. The result suggests that it is possible to realize the formation of periodic dumb-bell shaped nanostructures features, albeit with precise control of resist thickness, for nano-scale frequency selective surface structure (FSS)[221], coplanar waveguide fed antenna array [222], defected ground structure [223].

Appendix D

Enhancement of frustrated evanescent wave by single dielectric coating

This section presents the investigation of the design of a stratified four dielectric media configuration for the purpose of realizing resonant amplification of frustrated total internal reflection. The proposed stratified four dielectric media configuration is shown in Fig. D- 1. Unlike previous works [224, 225], the configuration would be investigated with the aim to realize enhanced frustration through the optical barrier.

Fig. D- 1 Schematic illustration of four-media configuration

The intended application of the configuration is for the purpose of realizing patterning resolution beyond the limit achievable by conventional optical lithography. In this context, the first medium (with refractive index n_1) represents either the prism in a modified interferometry lithography system as proposed in this thesis or the last lens element in an optical projection lithography system. The last medium (with refractive index n_4) represents the photoresist layer and the third

medium represents the gap medium. Any reflected energy from the photoresist-substrate interface is ignored based on the assumption of the presence of a perfect anti-reflection coating. The electric field amplitudes of forward and backward propagating waves in the first medium (Fw_1 and Bw_1 respectively) can be correlated to those in the photoresist (Fw'_4 and Bw'_4 respectively) and are given below[220],

$$\begin{bmatrix} Fw_1 \\ Bw_1 \end{bmatrix} = \mathbf{D}_1^{-1} \prod_{l=2}^3 \mathbf{D}_l \mathbf{X}_l \mathbf{D}_l^{-1} \mathbf{D}_4 \begin{bmatrix} Fw'_4 \\ Bw'_4 \end{bmatrix} \equiv \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} Fw'_4 \\ Bw'_4 \end{bmatrix} \quad (\text{D-1})$$

Where $\mathbf{D}_l$ represent the dynamical matrix given as,

$$\mathbf{D}_l = \begin{cases} \begin{bmatrix} 1 & 1 \\ n_l \cos \theta_l & -n_l \cos \theta_l \end{bmatrix} & \text{for } s \text{ wave} \\ \begin{bmatrix} \cos \theta_l & \cos \theta_l \\ n_l & -n_l \end{bmatrix} & \text{for } p \text{ wave} \end{cases} \quad (\text{D-2})$$

and $\mathbf{X}_l$ represent the propagation matrix given as

$$\mathbf{X}_l = \begin{bmatrix} \exp(jk_z(n_l + i\kappa_l)d_l) & 0 \\ 0 & \exp(-jk_z(n_l - j\kappa_l)d_l) \end{bmatrix} \quad (\text{D-3})$$

Using the TMM, we obtained a common general expression for the transmittance just after the interface between n_3 and n_4 for both s and p-polarized incident plane,

$Tr_{s/p}$, given as below,

$$Tr_{s/p} = \left| \frac{4a_1 a_2^2 a_{c3}^2 a_4}{C \cosh^2 \beta_{c3} + D \sinh 2\beta_{c3} + N \sinh^2 \beta_{c3}} \right|^2 \quad (\text{D-4})$$

Where

$$\beta_{c3} = k \sqrt{n_1^2 \sin^2 \theta_1 - n_3^2} d_3$$

$$C = a_{c3}^2 \left[a_2^2 (a_1 + a_4)^2 \cos^2 \beta_2 + (a_2^2 + a_1 a_4)^2 \sin^2 \beta_2 \right] ,$$

$$D = \frac{1}{2} a_2 a_{c3} (a_1^2 - a_2^2) (a_{c3}^2 + a_4^2) \sin 2\beta_2$$

$$N = \begin{cases} a_2^2 (a_1 a_4 - a_{c3}^2)^2 \cos^2 \beta_2 + (-a_{c3}^2 a_1 + a_2 a_4)^2 \sin^2 \beta_2 & \text{s-polarized} \\ a_2^2 (-a_1 a_4 + a_{c3}^2)^2 \cos^2 \beta_2 + (a_{c3}^2 a_1 - a_2 a_4)^2 \sin^2 \beta_2 & \text{p-polarized} \end{cases}$$

$$\beta_2 = kn_2 \sqrt{1 - \left(\frac{n_1 \sin \theta_1}{n_2} \right)^2} d_2$$

$$a_l = n_l \cos \theta_l \quad l = 1 \dots 4$$

$$a_{c3} = \sqrt{n_1^2 \sin^2 \theta_1 - n_3^2}$$

The expression given in Eq. (D-4) shows that both s and p polarized incident plane waves have the identical theoretical expression except for the sign convention in the expression for the coefficient N. The influences of incident angle, refractive index and the thickness of the sandwiched layers on the frustrated evanescent wave transmittance to the photoresist layer are investigated for the case of s-polarized incident plane wave.

In the investigation for a suitable refractive index of the second medium, the refractive indices of the first, third and last layers should be fixed. The first medium is assigned a refractive index value of 1.94. The third medium is assumed to be an air gap ($n_3 = 1.00$) and serves as an optical barrier. For the last medium, the refractive index value is set at 1.69, a typical value for photoresist. The thickness values of the second and third media, d_2 and d_3 , are fixed at 91nm ($\lambda/4$ where $\lambda = 364\text{nm}$). The transmittance for different values of n_2 for s-polarized and p-polarized incident plane waves is illustrated in Fig. D- 2.

(a)

(b)

Fig. D-2 Influence on transmittance of (a) s-polarized and (b) p-polarized incident plane waves, by varying n_2

When the value of n_2 is 1.94, the configuration is effectively a trilayer system that consists of just the incident medium, air gap and the transmitting medium. The

resultant transmittance is non-zero even at $\theta_1 > \sin^{-1} n_3/n_1$ due to frustration of the evanescent wave, which is made possible by the thin air gap. Here, if we assume that imaging is created by perfect interference of light beams, the resolution of the image would depend on the transmittance of the light beams at high incidence angles. Conventional lithography resists typically have intensity contrast threshold of 0.3[153]. We define the transmittance threshold angle (θ_t) as the largest incident angle beyond which the resultant $Tr_{s/p}$ value falls below 0.3. In the context of lithography, where the incident medium represents the last lens element of the projection system, a larger θ_t may contribute to resolution enhancement as a result of effective NA increment. As observed in Fig. D- 2(a), the value of θ_t for s-polarized incident plane wave is 37.4° . A larger θ_t value of 40.7° is achieved by changing the second medium to be of a refractive index equal to that of the photoresist (i.e. $n_2 = n_4$). If the incident plane wave is p-polarized, the value of θ_t remains around 39.0° for different n_2 values as observed in Fig. D- 2(b). The transmittance remains non-zero even when $\theta_1 > \sin^{-1} n_2/n_1$. This is because the evanescent energy may still frustrate across the band gaps. The incident angle beyond which there is no transmittance is defined as the cut-off angle θ_{co} . The approximated value of θ_{co} is $\theta_{co} = \sin^{-1} n_t/n_i$ where n_t and n_i represent the refractive index of the last medium and that of the incident medium respectively. When there are two consecutive layers of band gaps, as in the case where $n_2 = 1.44$, the approximation is still valid if the combined thickness of the band gaps is less than the wavelength of the optical source. However, if the last medium is of

higher refractive index than the incident medium, the value of θ_{co} is approximated by $\theta_{co} = \sin^{-1} n_{lw}/n_i$ where n_{lw} is the lowest refractive index of the stack.

Besides the refractive index of the layers, the thickness of individual layer is the other parameter influencing the transmittance in the last medium. Fixing the d_3 at 91nm, d_2 is varied from 91nm and the corresponding effect on transmittance varying is illustrated in Fig. D- 3. When d_2 is equal or larger than wavelength, it becomes apparent in Fig. D- 3(a) that the transmittance of the s-polarized incident plane wave fluctuates cyclically with a long range decaying profile with increasing incident angle θ_1 . It is observed that when the incident angle is between 41° to 43° , the transmittance values are larger or equal to the 0.3 threshold transmittance. However, a loss band precedes this gain band where the incident angle ranges between 37.5° and 41° , at which the transmittance values are less than 0.3. If the value of d_2 is increased further, it may be possible to increase the frequency of fluctuation, resulting in larger number of local maxima with transmittance value satisfying the minimum threshold value.

(a)

(b)

Fig. D-3 Influence on transmittance (a) s-polarized and (b) p-polarized incident plane waves, by varying thickness of medium 2 (d_2).

This would effectively increase the value of θ_{it} , but affect the modulation by the decaying exponential profile due to hyperbolic terms in the denominator. The hyperbolic terms can be understood as the characteristic functions of the optical energy barrier represented by medium 3. The cyclical variation results from the trigonometric terms as given in the expressions for the coefficients A, B and C. This results in the local minima and maxima. As observed, the value of d_2 directly determines the periodicity of the cyclical variation. Larger d_2 value results in higher fluctuation frequency, suggesting increased sensitivity of the optical path length to incident angle variation. The periodic fluctuation of the transmittance is significantly less pronounced for p-polarized incident plane as observed in the Fig. D- 3(b).

In order to achieve a larger θ_{it} with a value equal or near to that of θ_{co} , the thickness d_3 , is altered with the value of d_2 fixed at 2912nm (8λ), the resultant

transmittance is shown in Fig. D- 4. The effect of the optical barrier in the configuration is mathematically represented by the hyperbolic terms in the denominator of Eq(D-1). As the thickness d_3 approaches zero, the cosh term approaches unity while the sinh term approaches zero, leading to increment of resultant transmittance. A smaller thickness would mean easier frustration of evanescence energy. Hence, the value of θ_{tt} converges to that of θ_{co} . The transmittance profile of s-polarized incident plane shown in Fig. D- 4(a) displays almost negligible resonating effect when the value of d_3 is reduced to 1nm (to simulate the case of almost physical contact such that there is almost no optical barrier). When d_3 is halved from 91nm to 45nm, θ_{tt} value is increased from 41.1° to 58.6° is achieved for s-polarized incident plane wave realized by the amplification of resonating effect. When d_3 is further reduced to 10nm, unity transmittance can be achieved at discrete incident angles as large as 56.2° and θ_{tt} value increased to almost 60.0°.

(a)

(b)

Fig. D- 4 Influence on transmittance spectral by varying thickness of optical barrier (d_3)

Previous study by Salomon has shown that for the case of a specific incidence angle, the barrier can be of a finite thickness for the transmittance to be resonantly amplified [226]. Though the transmittance fluctuates periodically, it is observed that the values of the local minima remain above 0.3 until the incident angle is close to the θ_{co} . The transmittance profile of a p-polarized incident plane, as shown in Fig. D- 4(b), displays resonating effect when d_3 is 10nm as well as 1nm. When $d_3 = 45nm$, the transmittance of p-polarized incident wave at larger incident angle is enhanced such that θ_u increases from 38.9° to 46.9° . By employing $d_3 = 10nm$, the transmittance of p-polarized incident wave, unlike that of s-polarized incident wave, cannot achieve unity value at incident angles larger than 35° . Nonetheless, the largest achievable θ_u for incident p-polarized wave is 59.2° which is an improvement from that of the baseline configuration in which $n_2 = 1.94$ and $d_2 = d_3 = \lambda/4$. The lack of resonance effect is believed to be the

reason that the p-polarized incident plane wave does not show an improvement in θ_{it} as significant as that of s-polarized incident wave. In the context of two beams interference lithography application, large θ_{it} value translates to sufficient transmittance (≥ 0.3) at high incident angle to cause photochemistry effect in the resist (the last medium), leading to resolution enhancement. The patterning resolution enabled by the modified configuration in comparison to that of the baseline configuration is illustrated in Table D- 1.

	Pitch size of periodic line fringes	
	s-polarized incident beams	p-polarized incident beams
Baseline configuration: $n_1 = n_2 = 1.94$; $n_3 = 1.00$ $d_2 = d_3 = 91nm$	142.7nm	149.4nm
Modified configuration: $n_1 = 1.94$; $n_2 = 1.69$; $n_3 = 1.00$ $d_2 = 2912nm$; $d_3 = 45nm$	109.9nm	128.5nm
Modified configuration: $n_1 = 1.94$; $n_2 = 1.69$; $n_3 = 1.00$ $d_2 = 2912nm$; $d_3 = 10nm$	108.3nm	109.2nm

Table D- 1 Comparison between baseline and proposed configuration in terms of achievable pitch size resolution, computed using the largest θ_{it} value.

When $d_3 = 45nm$, the modified configuration realizes resolution enhancement of 23.0% and 14.0% for s-polarized and p-polarized incident plane wave respectively in comparison to the baseline configuration. In the same context, if d_3 is further reduced to 10nm, resolution enhancement of 30% and 26.8% is realized for s-

polarized incident and p-polarized incident plane wave respectively. While employing $d_3 = 10\text{nm}$ facilitates resolution enhancement, such a small gap thickness makes it important to consider the performance sensitivity of the configuration to the variation of the gap thickness d_3 . The performance sensitivity is defined here as the rate of transmittance change with increasing d_3 and expressed as $\partial T / \partial d_3$. The values of $\partial T / \partial d_3$ at different d_3 values is shown in Fig. D- 5.

Fig. D- 5 The transmittance sensitivity of modified configuration for different values of d_3

As observed from Fig. D- 5, at $d_3 = 10\text{nm}$, the rate of change of transmittance per unit variation of d_3 is -0.043nm^{-1} and -0.065nm^{-1} for s-polarized and p-polarized incident plane wave respectively. The results translate to corresponding change of 12.3% and 13.1% from transmittance values of 0.35 and 0.48 of s-polarized and p-polarized incident plane wave for per unit change in d_3 . The thickness variation can arise from surface roughness and imperfect planarity of the surface of the second medium and that of the last medium. Recent advancement in

angstrom polishing techniques demonstrated the capability of reducing average roughness to 0.5nm[227, 228]. Therefore, it is practically possible to achieve the lithography resolution enhancement with less than 10% transmittance variation by applying the modified configuration with $d_3 = 10nm$ as given in Table D-1. When employing the modified configuration for interference between unpolarized incident beams, it is important to consider the difference in phase shift between the electric wave components in the s-polarization and p-polarization planes since the resultant interference pattern is the summation of the interference between the s-polarized and that of the p-polarized components. The phase shift for the s-polarized and p-polarized incident wave is illustrated in Fig. D- 6.

Fig. D- 6 Phase shift for s-polarized and p-polarized incident plane wave

As shown in Fig. D- 6, the phase shift difference between the s-polarized waves and p-polarized waves increases with increasing incident angle. If the interference between unpolarized incident beams are performed at large incident angles with the employment of the modified configuration, the interference fringes between the s-polarized components would not overlap perfectly with that between the p-

polarized components. This leads to contrast degradation of the resultant interference fringes.

In the configuration discussed so far, we have assumed that the last medium, representing the resist, has a lower refractive index than the incident medium. Using a resist with the same refractive index as that of the incident medium, resonant tunneling structure can be realized. In this configuration, a single slab of material identical to that of the incident medium can be introduced in between the incident medium and the last medium, leaving the air gap as illustrated. The configuration proposed here realized resonant tunneling using a single dielectric coating of the incident medium as opposed to multiple alternating stratified dielectric configuration (1D photonic crystal) as reported previously [229]. The multiple alternating dielectric configuration supports resonant tunneling at only one specific angle, whereas the proposed configuration supports resonant tunneling at multiple discrete incident angles. In comparison to the double barrier configuration, the proposed configuration offers easier implementation [230]. This is because the double barrier configuration requires a free-standing thin dielectric material between the incident medium and the transmission medium. One common drawback of the proposed configuration and the double barrier configuration is the sensitivity of the optical performance of the configurations to variation in the thickness of the optical barrier.. In this context, the proposed configuration is an easier alternative to the double barrier configuration for achieving desired performance since the latter has two air gaps.

Enhancement of evanescent wave frustration across an optical barrier using only a dielectric medium is numerically demonstrated in this paper. To achieve effective transmittance (≥ 0.3) in the last medium over a large range of incident

angles, the second dielectric medium has to be index-matched to the last medium. With further tuning of the thickness values of the second and the third medium (optical barrier), it is shown that it may be possible to achieve unity transmittance at discrete, but closely spaced incident angles within the full range defined by the theoretical cut-off limit. The enhanced transmittance at higher incident angle can be exploited to achieve resolution enhancement in interference lithography. In addition, the modified configuration may have other potential applications than lithography and waveguide design is one such example.

Annex I

The Basics of Aerial Image Formation for Optical Projection Lithography System

The essential optical imaging system of an OPL tool consists of an illumination source, a photomask, an objective lens and an image plane in the photoresist coated wafer. The key optical phenomenon that characterized the optical imaging system is Fraunhofer diffraction which can be modeled using the Fourier method. The theoretical model described in this annex assumes the Kirchoff boundary condition.

I.1. Coherent Imaging

When a plane wave from an on axis monochromatic source point with unit amplitude, illuminates a photomask that is mathematically described by the electric field transmittance of the mask patterns in $x-y$ plane as $m(x, y)$, the resultant electric field of the diffraction pattern of the mask is just the Fourier transform of $m(x, y)$ given as [231-233],

$$\begin{aligned} M(u, v) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} m(x, y) \exp[-i2\pi(ux + vy)] dx dy \\ &= FT\{m(x, y)\} \end{aligned} \tag{I-1}$$

where the symbol FT represents the Fourier transform and u and v are the spatial frequencies. The spatial frequencies are defined in the diffraction plane ($x' - y'$ plane) in terms of the angle of diffraction such that,

$$u = \frac{n_m x'}{\lambda z} = \frac{n_m \sin \theta_m^{(x)}}{\lambda}; \quad v = \frac{n_m y'}{\lambda z} = \frac{n_m \sin \theta_m^{(y)}}{\lambda} \quad (\text{I-2})$$

where z is the distance along the optical axis between the photomask and the diffraction plane, n_m is the refractive index of the surrounding medium in between and θ_m is the maximum half angle of the diffracted light that enter the entrance pupil of the lens from the mask side. When the lens system is assumed to be lossless and is designed to realize image reduction, the pupil lens function $P(u, v)$ is obtained by [232],

$$P(u, v) = P_{ideal}(u, v) \times \text{Radiometric Correction}$$

$$= P_{ideal}(u, v) \left(\frac{1 - \frac{\lambda^2 (u^2 + v^2)}{n_m^2 R^2}}{1 - \frac{\lambda^2 (u^2 + v^2)}{n_w^2}} \right) \quad (\text{I-3})$$

where $P_{ideal}(u, v)$ represents the ideal pupil function given as,

$$P_{ideal}(u, v) = \begin{cases} 1 & \sqrt{u^2 + v^2} < NA/\lambda \\ 0 & \sqrt{u^2 + v^2} > NA/\lambda \end{cases} \quad (\text{I-4}) \text{For}$$

The term NA represents the numerical aperture at the entrance pupil of the lens and is given as $NA = n_m \sin \theta_m^{(\max)}$. The final coherent aerial image intensity is given as,

$$I_{img}(x, y) = \left| FT^{-1} \{ M(u, v) \cdot P(u, v) \} \right|^2 \quad (\text{I-5})$$

The coherent imaging model is the basis of partially coherent imaging model which is obtained by applying the concept of oblique plane wave illumination.

I.2. Partial Coherent imaging

The illumination sources employed in the lithography tool has a finite size. Such an illumination source can be treated as a collection of source points that are spatially incoherent to each other. From each of the illumination source points that are off-axis from a location on the photomask, a plane waves is emitted and impinged on the photomask at oblique angle. When the photomask is illuminated by the oblique illumination, the diffraction pattern will be shifted, with respect to the lens, by an amount given as $u' = \sin \theta' \cos \phi / \lambda$ and $v' = \sin \theta' \sin \phi / \lambda$. The electric field at the imaging plane is expressed as[232-234],

$$\begin{aligned} E(x, y, u', v') &= FT^{-1} \{ M(u, v) P(u + u', v + v') \} \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M(u, v) P(u + u', v + v') \exp(i2\pi((u + u')x + (v + v')y)) du dv \end{aligned} \quad (I-6)$$

The resultant aerial image intensity due to a single oblique source point is given as,

$$\begin{aligned} I(x, y, u', v') &= \iiint_{-\infty}^{\infty} P(u + u', v + v') P^*(\tilde{u} + u', \tilde{v} + v') M(u, v) M(\tilde{u}, \tilde{v}) \times \dots \\ &\quad \exp(i2\pi((u - \tilde{u})x + (v - \tilde{v})y)) du dv d\tilde{u} d\tilde{v} \end{aligned} \quad (I-7)$$

By adopting Abbe's extended source method, the resultant image from partial coherent illumination can be computed as the summation of images due to coherent on-axis and oblique illumination.

Employing Hopkin's reformulation of the Abbe's extended source method to compute partial coherent imaging, the resultant aerial image intensity is given as[231, 232, 235, 236],

$$I_{total}(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} TCC(u, v, \tilde{u}, \tilde{v}) M(u, v) M^*(\tilde{u}, \tilde{v}) \times \dots \exp(i2\pi((u - \tilde{u})x + (v - \tilde{v})y)) \partial u \partial v \partial \tilde{u} \partial \tilde{v} \quad (I-8)$$

where $S(u', v')$ represents the source function and $TCC(u, v, \tilde{u}, \tilde{v})$ is the transmission cross-coefficient given as,

$$TCC(u, v, \tilde{u}, \tilde{v}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(u + u', v + v') P^*(\tilde{u} + u', \tilde{v} + v') S(u', v') \partial u' \partial v' \quad (I-9)$$

The TCC is the description of the interaction between two separate pupil points during image formation.

Annex II

Theoretical description of phase shifting photomask

A phase shifting mask modulates not only the amplitude of the transmitted electric field but the phase of the transmitted light as well. While many types of phase shifting masks have been investigated, most of these masks are based on the resolution enhancing principle of the alternating phase shifting mask and attenuated phase shifting mask. This chapter presents the theoretical description of the alternating phase shift mask and attenuated phase shifting mask. For clarity purpose, the mathematical description considers an ideal, one-to-one imaging lens, coherent source point illumination and one-dimensional profile.

II.1. Alternating Phase Shift Mask

An alternating phase shift mask consists of chrome features, which defined the line features, flanked by 100% transmitting spaces as shown in Fig. II- 1.

Fig. II- 1 Alternating phase shift mask with periodic features with space width d and pitch p .

Alternating spaces are etched so that light that transmit through consecutive spaces would have a phase difference of π radian. The transmission function of an

alternating phase shift mask (PSM) with space width d and a pitch size p , under the Kirchoff boundary condition, is given as[237],

$$m(x) = \text{rect}(x/d) \otimes \sum_{n=-\infty}^{\infty} \delta(x - np) - \text{rect}((x - p)/d) \otimes \sum_{n=-\infty}^{\infty} \delta(x - np) \quad (\text{II-1})$$

The corresponding spectrum is[50, 76],

$$\begin{aligned} M(u) &= FT\{m(x)\} \\ &= \sum_{n=-\infty}^{\infty} \frac{\sin(n\pi d/2p)}{n\pi} \delta\left(u - \frac{n}{2p}\right) - \sum_{n=-\infty}^{\infty} \exp(i2\pi pu) \frac{\sin(n\pi d/2p)}{n\pi} \delta\left(u - \frac{n}{2p}\right) \\ &= \sum_{n=-\infty}^{\infty} \frac{\sin(n\pi d/2p)}{n\pi} [1 - (-1)^n] \delta\left(u - \frac{n}{2p}\right) \\ &\quad \dots \quad (\text{II-2}) \end{aligned}$$

From the above equation, it is apparent that there is no zeroth order (where $n=0$) and the even orders (where $n = \pm 2, \pm 4, \pm 6 \dots$) diffraction pattern do not exist. For the case of dense periodic line patterns where only the first orders ($n=-1$ and 1) are captured at the pupil plane of the lens, the resultant aerial image can be treated as the interference of the two first order beams which are located at the spatial frequencies of $\pm 1/2p$. Under s-polarized illumination (electric field vector parallel to the length of the line features), the resultant aerial image from two beam imaging in the case of the alternating PSM is obtained as[50, 237],

$$I(x) = 2a_1^2 \left(1 + \cos\left(\frac{2\pi}{p}x\right) \right) \quad (\text{II-3})$$

where $a_1 = \sin(\pi d/2p)/\pi$ is the amplitude of the first order diffraction pattern.

If the same dense pitch pattern is printed with a binary mask, the resultant aerial image intensity is given as,

$$I(x) = a_0^2 + 4a_0a_1 \cos\left(\frac{\pi}{p}x\right) \quad (\text{II-4})$$

where a_0 is the amplitude of the zero order diffraction pattern and a_1 is the amplitude of the first order diffraction pattern. From Eq(II-3) and Eq (II-4), the theoretical advantages of alternating PSM over binary mask are two folds. Firstly, the alternating PSM is able to resolve images with pitch size half of that can be resolved by the binary mask. Secondly, the aerial image from the alternating PSM has a theoretical contrast value of one but not so for the aerial image from binary mask.

II.2. Attenuated Phase Shift Mask

Consider a attenuated PSM with general repeating line/space transmittance function (with pitch p) as shown in Fig. II- 2,

Fig. II- 2 Attenuating phase shift mask with periodic features with space width d and pitch p .

If the space has a width of d and is assumed to have a transmittance of 1, the line features, which are defined by attenuated phase shifting material on the photomask, have a relative amplitude transmittance of t_{ps} and induce a relative phase shift of π radian. The transmission function of this attenuating phase shift mask is given as[237],

$$m(x) = \text{rect}(x/d) \otimes \sum_{n=-\infty}^{\infty} \delta(x-np) - t_{ps} \text{rect}\left((x-(p+d)/2)/d\right) \otimes \sum_{n=-\infty}^{\infty} \delta(x-np) \quad (\text{II-5})$$

The resulting diffraction pattern as obtained from exposure of the attenuated phase shift mask under coherent s-polarized on-axis illumination would be [50, 82],

$$M(u) = \sum_{n=-\infty}^{\infty} a_n \delta\left(u - \frac{n}{p}\right) \quad (\text{II-6})$$

where,

$$a_0 = \left(1 + t_{ps}\right) \left(\frac{d}{p}\right) - t_{ps}$$

$$a_n = a_{-n} = \left(1 + t_{ps}\right) \left(\frac{\sin(n\pi d/p)}{n\pi}\right), n \neq 0 \quad (\text{II-7})$$

From a three beams interference model, the aerial image can be derived given as,

$$I(x) = a_0^2 + 2a_1^2 + 4a_0a_1 \cos(2\pi x/p) + 2a_1^2 \cos(4\pi x/p) \quad (\text{II-8})$$

The corresponding NILS is defined as,

$$NILS = (p - d) \frac{d \ln(I(x))}{dx} = 4\pi \frac{a_0}{a_1} \quad (\text{II-9})$$

As seen from Eq (II-9), the employment of attenuated phase shift mask, with appropriate choice of transmittance for the phase shifting features, would improve the resolution of printed image via NILS improvement. For the case of three beam imaging, the best NILS is obtained when a_0 is small and a_1 is large.

List of Publications

Journal

1. Chua, J. K., Murukeshan, V. M., Tan, S. K., *et al.*, *Four beams evanescent waves interference lithography for patterning of two dimensional features*. Optics Express, 2007. **15**(6) pp. 3437-3451
2. Chua, J. K., Murukeshan, V. M., Tan, S. K., *et al.*, *Investigation of pupil-fill factors as process window indicators for dry optical lithography*. Optics and Laser Technology, 2008. **40**(1) pp. 142-55.
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4. Murukeshan, V. M., Jeun Kee, C., Tan, S. K., *et al.*, *Modeling of subwavelength resist grating features fabricated by evanescent waves interference*. Optical Engineering, 2008. **47**(12) pp. 129001 (9pp).
5. Jeun Kee Chua, V.M. Murukeshan, *Patterning of two dimensional nanoscale features using Grating Based Multiple Beams Interference Lithography*. Physica Scripta, 2009 **80** pp. 015401 (5pp)
6. Jeun Kee Chua, V.M. Murukeshan, *UV laser assisted multiple evanescent waves lithography for near-field nanopatterning*, Micro & Nano Letters, 2009. **4**(4), pp. 210-14.
7. Jeun Kee Chua, V.M. Murukeshan, *Resonant amplification of frustrated evanescent waves by single dielectric coating*, Optics Communications, 2010. **283**(1), pp. 169-175.
8. Jeun Kee Chua, V.M. Murukeshan *et al.*, *Quantitative Process Window Approximation Method for Deep UV Photolithography*, Submitted to Optics and Laser Engineering (Under review)

Conference

1. J.K. Chua, V.M. Murukeshan, S.K. Tan, *et al.*, *Evaluation of Various Types of Off-axis Illuminations for 65nm Node ArF Lithography using Chromeless Phase Shifting Mask*. ICMAT 2005, Symposium H: Silicon Microelectronics: Processing to Packaging, 2005. **Poster Session**.
2. J.K. Chua, V.M. Murukeshan, S.K. Tan, *et al.*, *Study of Off-axis Illuminations for 65nm Node ArF Lithography using Chromeless Phase Shifting Mask*. Symposium of Microelectronics: Nanotechnology Process, 2005 pp. 102-103 (Oral Presentation).
3. Jeun Kee Chua, V.M. Murukeshan *et al.*, *Single Exposure Grating Based Dual Beams Interference Lithography for Printing of Nanoscale Features*, ICMAT&IUMRS-ICA 2009, Symposium K: Nano Patterning & Surface Characterization (Oral Presentation)

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