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IMPACT OF LENS ABERRATIONS AND PARTIAL COHERENCE ON INTRA-FIELD CRITICAL DIMENSIONS OF DARK GATE LINES

by

ARMEN KROYAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

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HOUSTON, TEXAS
MAY, 1997
ABSTRACT

IMPACT OF LENS ABERRATIONS AND PARTIAL COHERENCE ON INTRA - FIELD CRITICAL DIMENSIONS OF DARK GATE LINES

by

ARMEN KROYAN

Across-field variations of lens aberration and partial coherence can have undesirable effects on critical dimension (CD) uniformity and depth of focus (DOF) of printed patterns. The principal objective of this work is to investigate how lens aberrations and partial coherence variations of the light source affect critical dimensions of dark gate lines when using conventional and phase-shifting masks (PSMs) in optical projection systems.

The investigations are done using lithography simulation software tools. These advanced simulators allowed to design different optical projection system setups and diverse types of masks. This allowed to obtain diverse data which reflected the sensitivity of printed gate lines' CDs to variations of partial coherence and lens aberrations. The results are
analyzed and compared suggesting guidelines to methods of maintaining a
tighter control of CD errors in the manufacturing process of integrated
circuits using optical lithography.
ACKNOWLEDGMENTS

I would like to express my thanks to Dr. Tittel and Dr. Levenson for their everyday support and encouragement. They were always able to find time to help and give me advise regardless their busy schedules.

I would also like to thank Mr. Chris Mack and FINLE Technologies for providing the latest version of simulation software Prolith/2 without which most of my studies would be impossible.
# TABLE OF CONTENTS

I. Background ............................................................................................................. 1
   1. Introduction ........................................................................................................ 1
   2. Optics of Projection Tools .................................................................................. 4
   3. Phase - Shifting Masks ....................................................................................... 9
   4. Off - Axis Illumination ....................................................................................... 14
   5. Optical Proximity Corrections ........................................................................... 17

II. Simulations and Results Obtained ....................................................................... 20
   1. Introduction ........................................................................................................ 20
   2. Impact of Partial Coherence on CD Variations
      of Dark Gate Lines ............................................................................................. 22
   3. Normalization of Zernike Polynomial Coefficients ......................................... 30
   4. Impact of Lens Aberrations on CD Variations
      and DOF of Dark Gate Lines .............................................................................. 34

Summary and Conclusions ......................................................................................... 51

Appendix ..................................................................................................................... 53

Bibliography ............................................................................................................... 56
LIST OF FIGURES

Figure 1. Optical Projection System ................................................. 4
Figure 2. Imaging is Limited by Diffraction ...................................... 5
Figure 3. Diffraction Grating ............................................................ 6
Figure 4. Definition of Numerical Aperture ......................................... 7
Figure 5. Making a Phase Shifter ..................................................... 9
Figure 6. Comparison of Conventional and Phase-Shifting Masks .......... 10
Figure 7. Alternating-Aperture Phase-Shifting Mask ......................... 11
Figure 8. Attenuated Phase-Shifting Mask ........................................ 12
Figure 9. Phase-Shifting Masks ...................................................... 13
Figure 10. Off-Axis Illumination Simulates Phase-Shift ....................... 14
Figure 11. Comparison of Off-Axis Illumination and Alternating-
            Aperture PSM ................................................................. 15
Figure 12. Annular and Quadrupole Illuminations ............................... 16
Figure 13. Pattern Distortions ...................................................... 18
Figure 14. Comparison of the OPC Techniques .................................. 18
Figure 15. Reduction of Line-End Shortening Effect ......................... 19
Figure 16. Partial Coherence Parameter .......................................... 22
Figure 17. Binary Intensity Conventional Mask .................................. 24
Figure 18. Binary Intensity Mask with Assisting Lines ....................... 25
Figure 19. Attenuated PSM .......................................................... 26
Figure 20. Attenuated PSM with Assisting Lines ......................... 27
Figure 21. Alternating-Aperture PSM ........................................... 28
Figure 22. Aberration as a Wavefront Deviation ........................... 30
Figure 23. Strehl Test .................................................................. 33
Figure 24a. Impact of Third Order of Spherical Aberration (Z8) on DOF .............................................................................. 39
Figure 24b. Impact of Third Order of Spherical Aberration (Z8) on DOF .......................................................... 40
Figure 25. Comparison of Process Windows from Setup I and Setup II ........................................................................... 44
Figure 26. Tendency of Reduction of DOF in the Absence of Aberrations ........................................................................... 49
Figure 27. Tendency of Reduction of DOF with Aberrations Present .............................................................................. 50
LIST OF TABLES

Table 1. The Lithography Roadmap ............................................. 3
Table 2. Typical.zrn File .......................................................... 35
Table 3. DOF at 10% Exposure from Setup I ................................ 37
Table 4. DOF at 10% Exposure from Setup II ............................... 42
Table 5. DOF at 10% Exposure from Setup III ............................. 46
Table 6. DOF at 10% Exposure from Setup IV .............................. 47
I. BACKGROUND

1. Introduction

The technique which uses light for printing ultra small patterns onto semiconductor wafers to produce the complex integrated circuits is called optical lithography [1,2]. During the last several decades optical lithography has been the principal force behind improvements to integrated circuits despite predictions of its demise [3]. Nowadays resolution of 0.35 \( \mu m \) has become routine using mercury i-line 365 nm wavelength and optical systems with numerical apertures (NA) above 0.55. The lithography roadmap is shown on Table 1 [4].

The SIA National Technology Roadmap for Semiconductors (1995) indicates that we are close to the point where resolution is limited by current optical lithographic technologies [5]. To reduce the sizes of circuit features below 0.25 \( \mu m \), modifications are required in process technology, illumination source wavelength, mask technologies, and optics.

Rayleigh scaling laws of critical dimension (CD) resolution and depth of focus (DOF) have been used for evaluation of a given technology’s performance:

\[
CD = k_1 \times (\frac{\lambda}{NA}),
\]

(1.1)
DOF = ± 0.5 k₂*(λ / NA²) 

where λ is the wavelength and NA - the numerical aperture of the projection lens. k₁ is a parameter which is dependent on process control and imaging technology. For present technological levels k₁ is about 0.7. The parameter k₂ is about 1-2 and is primarily dependent on lens aberrations of the system.

There are still opportunities available for further improvement in optical lithographic technology. We can go to shorter wavelength in the exposure tools (down to 193 nm using excimer lasers), larger numerical apertures, and apply "wavefront engineering" methods.

Wavefront engineering includes several methods to improve CD resolution and depth of focus in spite of the limitations of imaging technology [6]. Among these advanced resolution-enhancement methods are Phase-Shifting Masks (PSMs), Off-Axis Illumination (OAI), and Optical Proximity Correction (OPC).

Thus although conventional imaging becomes more and more difficult, wavefront engineering methods will make it possible to have further significant improvements in resolution, focal depth, and process performance.
Table 1. The Lithography Roadmap.

<table>
<thead>
<tr>
<th>Function</th>
<th>1995 0.35 μm</th>
<th>1998 0.25 μm</th>
<th>2001 0.18 μm</th>
<th>2004 0.13 μm</th>
<th>2007 0.10 μm</th>
<th>2010 0.07 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM (bits)</td>
<td>64M</td>
<td>256M</td>
<td>1G</td>
<td>4G</td>
<td>16G</td>
<td>64G</td>
</tr>
<tr>
<td>microprocessor (logic transistors/cm²)</td>
<td>4M</td>
<td>7M</td>
<td>13M</td>
<td>25M</td>
<td>50M</td>
<td>90M</td>
</tr>
<tr>
<td>ASIC (transistors/cm² auto layout)*</td>
<td>2M</td>
<td>4M</td>
<td>7M</td>
<td>12M</td>
<td>25M</td>
<td>40M</td>
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<tr>
<td>Resolution (μm)</td>
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<td>0.25</td>
<td>0.18</td>
<td>0.13</td>
<td>0.10</td>
<td>0.07</td>
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<tr>
<td>Gate CD control at post etch (nm)</td>
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<td>25</td>
<td>18</td>
<td>13</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Overlay (nm)</td>
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<tr>
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<tr>
<td>Minimum Field Size</td>
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<tr>
<td>#DRAM/Field (mm x mm)</td>
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<tr>
<td>(mm²)</td>
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<td>676</td>
<td>780</td>
<td>936</td>
<td>1144</td>
<td>1400</td>
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<td>0.7**</td>
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<tr>
<td>(full field±10% exposure)</td>
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<td></td>
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<td></td>
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<tr>
<td>Minimum mask count</td>
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<td>20</td>
<td>20</td>
<td>22</td>
<td>22</td>
<td>24</td>
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<td>320</td>
<td>135</td>
<td>TBD</td>
<td>TBD</td>
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<tr>
<td>(per layer/m² @ defect size μm)</td>
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<td>@0.08</td>
<td>@0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mask size (inches) (Quartz)</td>
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<td>6X6</td>
<td>6X6</td>
<td>Next Size</td>
<td>Next Size</td>
<td>Next Size</td>
</tr>
</tbody>
</table>

* ASIC will use maximum available field size.
** Assumes advanced techniques to maximize the usable depth of focus. Further analysis is needed.
2. Optics of Projection Tools

Optical lithography has been widely used to manufacture integrated circuits for decades. Optical projection systems that are used in the lithographic process are called steppers. A basic scheme of such a projection system is shown on Figure 1.

![Diagram of optical projection system](image)

**Figure 1.** Optical Projection System.

The system primarily consists of an illumination source, a system of condenser and objective lenses, a mask or reticle, and a semiconductor wafer covered with photosensitive resist.

The mercury-rare-gas discharge lamp currently is the main illumination source used in steppers, and it produces radiation in the range
between 350 and 450 nm. Several years ago these lamps where operating at g-line or 436 nm wavelength. But recently most of the steppers have mercury lamps exposure wavelength of 365 nm (i-line). Since output of these kind of lamps is weak below 365 nm, other illumination sources have been used for shorter wavelength exposure. These sources are argon fluoride (ArF) and krypton fluoride (KrF) excimer lasers which produce radiation at 193 and 248 nm respectively [7,8].

Recent optical projection systems are considered to be diffraction limited. This implies that the projection lens system is effectively perfect, and only diffraction effects reduce the quality of the final image. For a system to be considered diffraction limited, the Strehl ratio which can be used for evaluation of lens aberrations, should be higher than 0.88. But at the present technological level actual Strehl ratios exceed 0.95.

Figure 2. Imaging is Limited by Diffraction.
Figure 2 shows that at the resolution limit, only the zero and first diffraction orders pass through the lens. The higher diffraction orders miss the lens which causes the reduction of image quality.

In practice the optical systems cannot be perfectly diffraction limited because optical lenses have imperfections such as aberrations. This work demonstrates that lens aberrations must be considered and their effect on the quality of the aerial image is quite significant.

A photomask can be pictured as a diffraction grating which consists of transparent and non-transparent, or bright and dark lines, islands, contacts, and other patterns that can be printed on the semiconductor wafer (Figure 3).

![Diffraction Grating Diagram]

Figure 3. Diffraction Grating.
The numerical aperture (NA) of the lens determines the maximum diffraction order of light that can make it through the lens and forms image on the wafer (Figure 4).

![Diagram of Numerical Aperture](image)

**Figure 4.** Definition of Numerical Aperture.

The typical value of numerical aperture of lenses used in current steppers is about 0.5. State of the art steppers have lenses with NAs as high as 0.63.

From Rayleigh's equations 1.1 and 1.2 it is evident that resolution and depth of focus depend on the exposure wavelength $\lambda$ as well as on numerical aperture $NA$. Hence decreasing the wavelength and increasing the numerical aperture to improve the resolution of smaller critical dimensions leads to a major problem of insufficient depth of focus (the
target level is about 0.8 -1.0 μm [9]. To improve resolution and depth of focus beyond the limits of conventional technologies, a number of advanced resolution-enhancement techniques have been proposed and some of them will be discussed below.
3. Phase - Shifting Masks

Phase-shifting Masks (PSMs) use destructive interference of light to improve resolution and depth of focus of printed features [10]. This method has significant advantages over the conventional method by introducing a 180° phase difference between the light beams transmitted through neighboring clear parts of mask patterns. The main principle used in making a phase-shifter is shown on Figure 5.

![Diagram of making a phase-shifter](image)

**Figure 5.** Making a Phase-Shifter.

The phase difference of light is given by

$$\Delta\varphi = \frac{2\pi (n - 1)d}{\lambda}$$  \hspace{1cm} (1.3)
where \( d \) is the thickness of glass with the index of refraction \( n \). Figure 6 shows a comparison of conventional and phase-shifting masks.

![Comparison of Conventional and Phase-Shifting Masks](image)

**Figure 6.** Comparison of Conventional and Phase-Shifting Masks.

There are many different types of phase-shifting masks. The Alternating-Aperture or Levenson phase-shifting mask produces completely symmetric Fourier diffraction components. This effect results in perfect destructive interference at the image of phase transition [11,12].
Figure 7. Alternating-Aperture Phase-Shifting Mask.

Another common type of mask is called the Attenuated phase-shifting mask [13]. Even though this kind of mask does not produce as strong aerial image improvements as the Alternating-Aperture PSM, its big advantage is that it can be designed, fabricated, and inspected more like a conventional binary intensity mask [14]. In the case of the Attenuated PSM, the dark features shift the phase of light by 180 degrees and are partially transparent (usually about 8-10%). A comparison of conventional mask and attenuated PSM is shown on Figure 8.
Figure 8. Attenuated Phase-Shifting Mask.

This technology has already been applied commercially for the fabrication of contact holes.

There are other phase-shifting masks that use destructive interference to improve the resolution and depth of focus of printed features. Figure 9 depicts various types of phase-shifting masks.
Figure 9. Phase-Shifting Masks.
4. Off-Axis Illumination

Similarly to Alternating-Aperture PSM, off-axis illumination produces a phase-shifting effect that can improve the resolution and depth of focus for periodic patterns with the appropriate spacing (Figure 10) [15].

![Diagram of Off-Axis Illumination](image)

Resolution = 0.5 \( \lambda/NA \)

Figure 10. Off-Axis Illumination Simulates Phase-Shift.

Figure 11 shows that off-axis illumination improves image contrast by converting the case of conventional mask imaging with three Fourier diffraction components in the lens pupil to one similar to the Alternating-Aperture PSM case when there are only two diffraction components.
Figure 11. Comparison of Off - Axis Illumination and Alternating - Aperture PSM.

Off-axis illumination can be annular or quadrupole. The shapes of these types of illumination sources are shown in Figure 12.
Quadrupole illumination can significantly improve the resolution and depth of focus of features with constant orientation on a mask. But in case a mask has features oriented at 45° to the first mask features, this type of aperture can degrade the image quality. Annular illumination was developed to avoid this problem of feature orientation, but it is not as effective as properly engineered quadrupole illumination in terms of enhancement of the resolution and depth of focus [16].
5. Optical Proximity Corrections

Optical Proximity Correction (OPC) plays a very significant role to achieve pattern fidelity and linewidth control. Pattern transfer near the resolution limit is a non-linear process, and neighboring features of the pattern have tendency to change the pattern transfer. The effect of critical dimension variation depending on the pattern density is known as Optical Proximity Effect (OPE). In most of the cases the differences between the printed resist pattern and the original mask pattern are well-enough known. Therefore the patterns on the mask can be pre-distorted in such a way that undesired distortions can be eliminated [17]. The process of mask distortion is called Optical Proximity Correction.

Usually typical changes in a distorted patterns appear in the forms of rounding of corners, shortenings of line-ends, and linewidth variations (Figure 13). Proximity corrections are realized by adding assisting lines, bars, and serifs to the initial mask patterns (Figure 14). In particular serifs are the features which have rectangular forms and can be added to line-ends and corners of mask patterns to eliminate corner rounding and line shortening effects.
Figure 13. Pattern Distortions [17].

Figure 14. Comparison of the OPC Techniques: a) uncorrected mask; b) mask with serifs; c) mask with serifs and assisting lines [17].
Figure 15 shows that gate line-end shortening can be significantly reduced by using a mask with serifs [18].

![Images of masks and wafers](image)

**Figure 15.** Reduction of Line - End Shortening Effect.
II. SIMULATIONS AND RESULTS OBTAINED

1. Introduction

Different values of partial coherence and various lens aberrations of optical projection systems can have undesirable effects on critical dimension patterns that can be even further affected when using advanced resolution enhancement techniques such as phase-shifting masks and optical proximity corrections [19]. Our initial concerns were motivated by the observations that with present aberrations CD control can be worse even if pattern resolution is better, and local values of partial coherence across the exposure field vary possibly causing CD errors [20, 21]. Thus the principal objective of this work was to investigate how lens aberrations and partial coherence variations of the light source affect CD patterns when using conventional and phase-shifting (especially Alternating-Aperture and Attenuated) masks with and without OPC. The main emphasis was on investigation of CD variations of dark gate lines through image simulations. The simulations were mainly based on advanced lithography simulation software tool Prolith/2 v.5.05 by FINLE Technologies and partially on Depict 4.0 by TMA. These programs can model images projected by conventional binary intensity masks as well as phase-shifting
masks with optical proximity corrections, and lens aberrations can be specified by 37 Zernike polynomial coefficients.
2. Impact of Partial Coherence on CD Variations of Dark Gate Lines

Understanding linewidth variations across the exposure field presents a very important problem for the microlithographic industry. One of the factors responsible for linewidth variations could be the variation of values of partial coherence across the exposure field [20].

Partial coherence is defined by a parameter

$$\sigma = \frac{n_c' \sin \theta_c'}{n_i \sin \theta_i} = \frac{NA_c}{NA_i} \quad (2.1)$$

where $NA_c$ is the numerical aperture of the condenser at the side of the imaging lens, and $NA_i$ is the numerical aperture of the imaging lens at the side of the image (Figure 16). In the case of completely coherent illumination $\sigma$ equals 0, and when illumination is completely incoherent, $\sigma$ is infinity [22].

Figure 16. Partial Coherence Parameter.
Reasonable values of partial coherence of illumination sources in current steppers are in the range of 0.3 to 0.7.

The latest version (5.05) of Prolith/2 which was used to evaluate the impact of partial coherence variations on CD patterns, has a mode called Multiple Run which allows calculating and plotting the aerial image and the critical dimensions of the image as a function of a specified parameter such as partial coherence. Using this feature partial coherence was set to vary in the range of 0.3 to 0.7 in steps of 0.05. Different types of masks were designed for 0.25 μm dark gate line with the purpose of understanding which mask types and designs are more sensitive to partial coherence variations. Figures 17 to 21 show aerial image and image CD variations as a function of partial coherence. The optical projection system was set to be aberration-free. Deep UV illumination at a wavelength of 248 nm was used, and the lens numerical aperture was set to 0.5.

Five types of masks were used:

1. Binary Intensity Conventional Mask (isolated dark line without biasing),
2. Binary Intensity Conventional Mask with OPC (0.1 μm assisting dark lines 0.4 μm away from the main feature),
3. Attenuated PSM (8% transparency), biased (0.18 μm),
4. Attenuated PSM (8% transparency), biased (0.20 μm) with OPC (0.1 μm assisting dark lines 0.4 μm away from the main feature),
5. Alternating-Aperture PSM, biased (0.27 μm).
Figure 17. Binary Intensity Conventional Mask: a) Design, b) Aerial Image, and c) Image CD vs Partial Coherence.
Figure 18. Binary Intensity Mask with Assisting Lines: a) Design, b) Aerial Image, and c) Image CD vs Partial Coherence.
Figure 19. Attenuated PSM: a) Design, b) Aerial Image, and c) Image CD vs Partial Coherence.
Figure 20. Attenuated PSM with Assisting Lines: a) Design, b) Aerial Image, and c) Image CD vs Partial Coherence.
Figure 21. Alternating-Aperture PSM: a) Design, b) Aerial Image, and c) Image CD vs Partial Coherence.
The results show that an Alternating-Aperture PSM is the least sensitive to variations of partial coherence. The linewidth variation in this case is practically negligible (about 5-10 nm). For the other masks, OPC, in the form of assisting features, reduces the effects of partial coherence variations by about one third although these effects appear to be small - 30 nm at worst. The isofocal points - focal positions in which aerial image contour lines for different values of partial coherence are intersecting - were moved inward by 25 nm which reduces the effects of defocus. Thus we can conclude that even though the effects of partial coherence variations are small, using the appropriate mask type and design can make these effects practically unnoticeable.
3. Normalization of Zernike Polynomial Coefficients

Aberrations can be described as the deviation of the real behavior of a lens from the ideal or "perfect" imaging behavior. Figure 22 shows that aberrations cause optical path differences (OPD) of the rays which results in the form of departure of aberrated wavefronts from ideal spherical shapes.

![Diagram of aberration and wavefronts](image)

**Figure 22.** Aberration as a Wavefront Deviation.

Using cylindrical coordinates \((\rho, \theta)\) where \(\rho\) is 0 at the center and 1 at the edge of the lens, the aberrated wavefront in the exit pupil is represented as a sum of Zernike polynomials [19],
\[ W(\rho, \theta) = \sum a_i \lambda \ Z_i(\rho, \theta), \]  

(3.1)

where \( Z_i \) are Zernike polynomials and \( a_i \) are coefficients that determine contributions of \( Z_i \) measured in units of wavelength \( \lambda \).

To be able to verify the accuracy of simulations of aberrated images, the Zernike polynomial coefficients should be normalized. There are several ways to normalize them.

The normalization can be done applying the Strehl ratio test [22]. Since coefficients \( a_i \) can vary across the lens field causing CD variations, we should quantify the amount of aberration in the lens by specifying the root-mean-square (RMS) deviation of the wavefront aberration. The RMS can be used for approximation of the Strehl ratio which is based on calculating the ratio of image intensities in the center of the projected image with aberrations present and in their absence. This ratio is only dependent on the total sum of squared Zernike polynomial coefficients,

\[ SR = \exp \left[ -4\pi^2 \sum a_i^2 \right], \]  

(3.2)

where \( a_i \) are Zernike coefficients in units of RMS deviation across the lens pupil (11).

Since in Prolith/2 as well in Depict 4.0 lens aberrations can be defined by a set of 37 Zernike coefficients, we apply the Strehl test for
normalization of each of the coefficients. The tests were done by calculating the aberrated and unaberrated image intensities at the center of isolated contact hole. A 0.25 μm isolated contact hole mask was designed, and the following values of input parameters were used: NA = 0.5, σ = 0.5, λ = 248 nm. The overall results showed that total RMS errors for each of the Zernike coefficients did not exceed 10%. This means that the Strehl ratio was about 0.9 which satisfies the requirement for the optical system to be considered diffraction limited. Figure 23 shows an example of unaberrated and aberrated aerial images of a contact hole for the coefficient Z8 which represents 3rd order spherical aberration.
Figure 23. Strehl Test: a) unaberrated aerial image and b) aberrated aerial image for 3rd order spherical aberration ($Z_8 = -0.115$).
4. Impact of Lens Aberrations on CD Variations and DOF of Dark Gate Lines

As already mentioned in the previously, real optical projection systems are not "perfectly" diffraction limited, and they have aberrations. Since lens aberrations lead to wavefront deviations from the ideal spherical wavefront, it is very important to understand how these wavefront imperfections affect critical dimension uniformity and depth of focus of printed patterns [23,24].

The investigations were performed using four different simulated stepper setups for printing 0.25 µm and 0.18 µm isolated dark gate lines. Prolith/2's simulation models called Multiple Run and Lumped Parameter Model were extensively used for this purpose and allowed diverse data on CD variations, depth of focus, and process windows of printed patterns to be obtained. Typical values of aberration coefficients were defined by a file called typical.zrn that is available in Prolith/2. The aberration data in this file was obtained by direct interferometer readings from a stepper lens. Table 2 shows the Zernike coefficients represented in typical.zrn. At the same time a file called aber.zrn, written in the format required for Prolith/2, was created. The format of this file allowed editing values of Zernike polynomial coefficients which helped to determine the impact of different types of aberrations separately and in groups.
[Version]
4.0
[Data]
0.00
0.00
0.00
-0.874E-01
-0.147E-15
0.325E-15
0.700E-03
-0.1151
-0.123E-14
-0.443E-03
0.355E-02
0.554E-15
-0.413E-14
-0.208E-04
0.382E-02
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0.155E-03
0.613E-05

Table 2. Typical.zrn file. Data is obtained straight from an interferometer for a "typical" commercial lens. Tilt and defocus (Z1, Z2, Z3) are removed.
Table 3 shows the dependence of depth of focus of different types and designs of masks with and without aberrations. In Setup I we were looking at DOF at 10% exposure, and the values of other input parameters were set to: $\lambda = 248 \text{ nm}$, $\text{NA} = 0.5$, $\sigma = 0.5$, $k_1 = 0.5$, resist contrast $\Gamma = 3.0$. 
<table>
<thead>
<tr>
<th>Mask Type</th>
<th>No Aberrations</th>
<th>Aberrations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIM</td>
<td>1.02</td>
<td>0.32</td>
</tr>
<tr>
<td>BIM with OPC (0.1 μm assist 0.4 μm away)</td>
<td>0.90</td>
<td>0.66</td>
</tr>
<tr>
<td>Attenuated PSM</td>
<td>1.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Attenuated PSM with OPC (0.1 μm assist 0.4 μm away)</td>
<td>0.88</td>
<td>0.57</td>
</tr>
<tr>
<td>Alternating-Aperture PSM</td>
<td>0.95</td>
<td>0.18</td>
</tr>
</tbody>
</table>

0.25 μm dark gate line, NA = 0.5, λ = 248 nm, σ = 0.5, Γ = 3.0, k₁ = 0.5.
*Aberrations are defined by typical.zrm file.

Table 3. DOF(μm) at 10% Exposure from Setup I.
From Table 3 the results using Setup I show that in the case of aberrations defined by typical.zrn file, a significant reduction of depth of focus occurs which is below the target level of 0.8 -1.0 μm. At the same time, we can notice that optical proximity corrections in the form of assisting lines improved the DOF by about 100% in the case of using a conventional mask or an Attenuated PSM. OPC also helps in terms of CD uniformity. CD variations were reduced by 30 - 40 nm and the isofocal points moved inward by about 50 nm. These results show that assisting lines improved CD variation control even more with aberrations than without them.

The fact that lens aberrations reduced the depth of focus by about 70% for masks without OPC and about 30% for those without OPC, is still of concern. Using aber.zrn file and changing values of different Zernike coefficients, we were able to determine which type of aberrations is responsible for the reduction of depth of focus. Based on multiple simulations, we found that 3rd order spherical aberration represented by Zernike coefficient Z8, was mainly responsible for the decrease of DOF for each type of mask used in the simulation process. Figure 24 shows how different values of 3rd order spherical aberration affect DOF.
Figure 24a. Impact of 3rd Order Spherical Aberration (Z8) on DOF: a) no aberrations; b) typical.zrn, Z8 = 0.
Figure 24b. Impact of the 3rd Order of Spherical Aberration (Z8) on DOF: c) Z8 = 0.03; d) Z8 = 0.05.
The effect of 3rd order spherical aberration on DOF of a 0.25 μm dark gate line is crucial at least for the used optical projection system.

The next issue was to determine whether changing the process parameters could make printed patterns less sensitive to lens aberrations. For this purpose numerical aperture of the lens was set to 0.6 and a material with higher resist contrast was used \((\Gamma = 6.0)\). Table 4 shows the results obtained from Setup II.
<table>
<thead>
<tr>
<th>Mask Type</th>
<th>No Aberrations</th>
<th>Aberrations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIM</td>
<td>1.08</td>
<td>0.98</td>
</tr>
<tr>
<td>BIM with OPC (0.1 μm assist 0.4 μm away)</td>
<td>0.88</td>
<td>0.91</td>
</tr>
<tr>
<td>Attenuated PSM, Bias 0.18 μm</td>
<td>1.22</td>
<td>0.89</td>
</tr>
<tr>
<td>Attenuated PSM with OPC, Bias 0.2 μm (0.1 μm assist 0.4 μm away)</td>
<td>1.12</td>
<td>1.04</td>
</tr>
<tr>
<td>Alternating-Aperture PSM, Bias 0.27 μm</td>
<td>1.28</td>
<td>1.18</td>
</tr>
</tbody>
</table>

0.25 μm dark gate line, NA = 0.6, λ = 248 nm, σ = 0.5, Γ = 6.0, k₁ = 0.6.

*Aberrations are defined by typical.zrn file.

Table 4. DOF at 10% Exposure from Setup II.
The results show that by increasing the NA and using a high-resist contrast material it is possible to significantly improve DOF, and reduce CD variations of printed lines due to lens aberrations. The reduction of DOF caused by lens aberrations was only about 10-20%, and the DOF was satisfactory for each mask type. At the same time we notice that masks with assisting lines do not perform as well as during Setup I in terms of the improvement of depth of focus although a tendency of moving the isofocal points inward is still present. Thus assist features help to have a better linewidth CD control, but do not improve DOF when a high contrast resist is used.

Big improvements in the size of process windows were achieved during the second simulation. Figure 25 shows a comparison of the CD process windows from both Setup I and Setup II in the case of using Alternating-Aperture PSM. Black regions CD process windows represent the areas in the field in which nominal CDs, sidewall angles, and resist loss are all obtained. To calculate DOF, Prolith/2 creates a focus-exposure matrix and fits rectangles into the overlay of process windows. DOF is the range of focus that keeps the nominal CD and keeps exposure latitude within the range of specified exposure energies.
Figure 25. Comparison of the Process Windows from Setup I (a) and Setup II (b).
Similar simulations were done for 0.18 \( \mu m \) dark gate lines in the case of using exposure tools with \( \lambda = 248 \) nm (Setup III) and \( \lambda = 193 \) nm (Setup IV). In both cases the NAs were set to 0.6 and high-contrast resists (\( \Gamma = 6.0 \)) were used. Tables 5 and 6 show the results from Setup III and Setup IV.
<table>
<thead>
<tr>
<th>Mask Type</th>
<th>No Aberrations</th>
<th>Aberrations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIM</td>
<td>0.51</td>
<td>0.47</td>
</tr>
<tr>
<td>BIM with OPC (0.1 μm assist 0.4 μm away)</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Attenuated PSM, Bias 0.14 μm</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>Attenuated PSM with OPC, Bias 0.15 μm (0.1 μm assist 0.4 μm away)</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td>Alternating-Aperture PSM, No Bias</td>
<td>1.04</td>
<td>0.71</td>
</tr>
</tbody>
</table>

0.18 μm dark gate line, $NA = 0.6$, $\lambda = 248$ nm, $\sigma = 0.5$, $\Gamma = 6.0$, $k_1 = 0.43$.

*Aberrations are defined by typical.zrn file.

Table 5. DOF at 10% Exposure from Setup III.
<table>
<thead>
<tr>
<th>Mask Type</th>
<th>No Aberrations</th>
<th>Aberrations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIM</td>
<td>0.67</td>
<td>0.63</td>
</tr>
<tr>
<td>BIM with OPC (0.1 μm assist 0.4 μm away)</td>
<td>0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>Attenuated PSM, Bias 0.15 μm</td>
<td>0.74</td>
<td>0.70</td>
</tr>
<tr>
<td>Attenuated PSM with OPC, Bias 0.15 μm (0.1 μm assist 0.4 μm away)</td>
<td>0.60</td>
<td>0.63</td>
</tr>
<tr>
<td>Alternating-Aperture PSM, Bias 0.2 μm</td>
<td>0.91</td>
<td>0.79</td>
</tr>
</tbody>
</table>

0.18 μm dark gate line, NA = 0.6, λ = 193 nm, σ = 0.5, Γ = 6.0, k₁ = 0.56.

*Aberrations are defined by typical.zrn file.

**Table 6.** DOF at 10% Exposure from Setup IV.
Both cases showed that going to smaller feature CDs causes reduction of DOF and the only mask that has satisfactory performance was the Alternating-Aperture PSM. Masks with OPC did not improve depth of focus, and the aberrations were not as harmful as in the case of using a high-contrast resist. Figures 26 and 27 show the tendency in the change of depth of focus when we go to smaller feature sizes and shorter wavelengths with and without aberrations, which implies that switch to 193 nm exposure tools will not make a significant improvement in CDs of 0.18 μm dark gate lines.
No Aberrations

![Graph showing DOF (µm) at 10% Exposure vs. Nominal Feature Size (µm) for BIM, Assist BIM, Att PSM, and Altern. PSM with NA = 0.6, Sigma = 0.5, Resist Contrast = 6.0.]

**Figure 26.** Tendency of Reduction of DOF in the Absence of Aberrations.
Figure 27. Tendency of Reduction of DOF with Aberrations Present.
SUMMARY AND CONCLUSIONS

The effects of partial coherence and lens aberrations on critical dimension variations of dark gate lines were studied using simulations. The investigations showed that the impact of partial coherence variations was not very significant and could be reduced by applying optical proximity correction techniques in the form of adding assisting lines to the mask patterns. For the purpose of accurate evaluation of the effects of different types of aberrations on printed patterns, 37 Zernike polynomial coefficients which represent lens aberrations, were normalized using the Strehl test. The impact of aberrations on 0.25 μm and 0.18 μm dark gate lines was studied by analyzing data obtained from simulations using four different optical projection system setups. Based on results the following conclusions can be made:

-- Lens aberrations, represented by typical.zrn file, do not destroy the process window or significantly reduce CD uniformity and DOF if we use optimal numerical aperture and high resist contrast.

-- The variations of values of partial coherence do not significantly impact CD variations of dark gate lines.

-- For a given mask structure there is an optimal numerical aperture which should not necessarily be high.
-- In the case of using optical systems with low numerical apertures and materials with low resist contrasts, the intra-field CD uniformity and DOF of dark gate lines could be sensitive to lens aberrations and especially to 3rd order spherical aberration.

-- Optical proximity corrections do not always improve the CD uniformity and DOF of aberrated images.

-- High resist contrast is more important than high numerical aperture.
APPENDIX

Zernike Polynomials

Zernike polynomials are suitable for representing lens aberration wavefronts being orthogonal within the unit circle for which they are defined [25].

The Zernike polynomials used in Prolith/2 for describing interferometric data are functions of (R,θ) which define the position within the lens pupil in polar coordinates. R is the radius within the pupil and is unity at the edge of the lens, and θ is the angle.

Typically Zernike polynomials are represented by a set of 37 terms. Often the first term is excluded because it represents an unimportant phase-shift which is constant and assumed to be equal 1. The list of the remaining 36 terms is given below.

<table>
<thead>
<tr>
<th>Term</th>
<th>Standard Zernike Polynomial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Z1 R cosθ</td>
</tr>
<tr>
<td>2</td>
<td>Z2 R sinθ</td>
</tr>
<tr>
<td>3</td>
<td>Z3 (2R² - 1)</td>
</tr>
<tr>
<td>4</td>
<td>Z4 R² cos2θ</td>
</tr>
<tr>
<td>5</td>
<td>Z5 R² sin2θ</td>
</tr>
<tr>
<td>6</td>
<td>Z6 (3 R² -2) R cosθ</td>
</tr>
<tr>
<td>7</td>
<td>Z7 (3 R² -2) R sinθ</td>
</tr>
</tbody>
</table>
8. $Z_8 \ (6 \ R^4 - 6 \ R^2 + 1)$
9. $Z_9 \ R^3 \ cos\theta$
10. $Z_{10} \ R^3 \ sin\theta$
11. $Z_{11} \ (4 \ R^2 - 3) \ R^2 \ cos\theta$
12. $Z_{12} \ (4 \ R^2 - 3) \ R^2 \ sin\theta$
13. $Z_{13} \ (10 \ R^4 - 12 \ R^2 + 3) \ R \ cos\theta$
14. $Z_{14} \ (10 \ R^4 - 12 \ R^2 + 3) \ R \ sin\theta$
15. $Z_{15} \ (20 \ R^6 - 30 \ R^4 + 12 \ R^2 - 1)$
16. $Z_{16} \ R^4 \ cos\theta$
17. $Z_{17} \ R^4 \ sin\theta$
18. $Z_{18} \ (5 \ R^2 - 4) \ R^3 \ cos\theta$
19. $Z_{19} \ (5 \ R^2 - 4) \ R^3 \ sin\theta$
20. $Z_{20} \ (15R^4 - 20 R^2 + 6) \ R^2 \ cos\theta$
21. $Z_{21} \ (15R^4 - 20 R^2 + 6) \ R^2 \ sin\theta$
22. $Z_{22} \ (35 R^6 - 60 R^4 + 30 R^2 - 4) \ R \ cos\theta$
23. $Z_{23} \ (35 R^6 - 60 R^4 + 30 R^2 - 4) \ R \ sin\theta$
24. $Z_{24} \ (70 R^8 - 140 R^6 + 90 R^4 - 20 R^2 + 1)$
25. $Z_{25} \ R^5 \ cos\theta$
26. $Z_{26} \ R^5 \ sin\theta$
27. $Z_{27} \ (6 R^2 - 5) \ R^4 \ cos\theta$
28. $Z_{28} \ (6 R^2 - 5) \ R^4 \ sin\theta$
29. $Z_{29} \ (21 R^4 - 30 R^2 + 10) \ R^3 \ cos\theta$
30. $Z_{30} \ (21 R^4 - 30 R^2 + 10) \ R^3 \ sin\theta$
31. $Z_{31} \ (56 R^6 - 105 R^4 + 60 R^2 - 10) \ R^2 \ cos\theta$
32. $Z_{32} \ (56 R^6 - 105 R^4 + 60 R^2 - 10) \ R^2 \ sin\theta$
33. $Z_{33} \ (126 R^8 - 280 R^6 + 210 R^4 - 60 R^2 + 5) \ R \ cos\theta$
34. $Z_{34} \ (126 R^8 - 280 R^6 + 210 R^4 - 60 R^2 + 5) \ R \ sin\theta$
35. $Z_{35} \ (252 R^{10} - 630 R^8 + 560 R^6 - 210 R^4 + 30 R^2 - 1)$
$Z_{36} (924 R^{12} - 2772 R^{10} + 3150 R^8 - 1680 R^6 + 420 R^4 - 42 R^2 + 1)$
BIBLIOGRAPHY


