Coping With the Impact of Lens Aberrations in the Context of Wavefront Engineering

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Abstract

Variations of lens aberrations of optical projection systems can have undesirable effects on critical dimension (CD) uniformity and depth of focus (DOF) of printed microelectronic circuit patterns. The principal objective of this paper is to investigate how lens aberrations along with variations of partial coherence of the illumination source of an optical stepper affect critical dimensions of dark gate lines when using conventional and phase-shifting masks (PSMs) with and without optical proximity corrections(OPC).

The investigations are performed using lithography simulation software tools which help to evaluate different optical projection systems and diverse types of masks. For the purpose of accurate evaluation of the effects of different types of aberrations on printed patterns, 37 Zernike polynomial coefficients representing lens aberrations were normalised using the Strehl test. The impact of aberrations on 0.25 μm and 0.18 μm dark gate lines is studied by analysing data obtained from simulations using four different optical projection system set-ups. The results show that lens aberrations do not significantly reduce CD uniformity and DOF or destroy the process window if we use an optimal numerical aperture (NA) and high resist contrast. It was observed that high resist contrast is more important than NA in terms of dealing with the impact of lens aberrations. The effectiveness of masks with OPC for aberrated images was analysed, and we have been able to show that OPC does not always improve CD uniformity and DOF.

This paper describes methods for maintaining tighter control of CD errors in the manufacturing process of integrated circuits using optical lithography.

Keywords: lens aberrations, depth of focus, optical proximity corrections.

1. Introduction

Various lens aberrations of optical projection systems along with variations of partial coherence within the field can have undesirable impact 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.[1] Our initial concerns were motivated by observations that with present lens aberrations CD control can be worse even if pattern resolution is better, and local values of partial coherence across the exposure field vary leading to CD errors.[2, 3] Thus the principal objective of this work was to investigate how lens aberrations and partial coherence variations of the light source can affect CD patterns when using conventional and phase-shifting (especially for alternating-aperture and attenuated) masks with and without OPC. The main emphasis was on an investigation of CD variations of dark gate lines using image simulations. The simulations were mainly based on an advanced lithography simulation software tool Prolith/2 provided by FINLE Technologies and partially on Solid-C by Sigma-C and Depict by TMA Inc. These programs can model images projected by conventional binary intensity masks as well as phase-shifting masks with optical proximity corrections, and lens aberrations that can be specified by 37 Zernike polynomial coefficients.

0277-786X/98/$10.00

2. Impact of Partial Coherence on CD Variations of Dark Gate Lines

The impact of variations of partial coherence was studied independently from lens aberrations. Prolith/2 which was used to evaluate this impact on CD patterns, which has a mode called Multiple Run which allows calculating and plotting the aerial image and also the critical dimensions of the image as a function of a specified parameter such as partial coherence. Since reasonable values of partial coherence of illumination sources in current steppers are in the range of 0.3 to 0.7, 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 evaluating which mask types and designs are more sensitive to partial coherence variations. 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 as depicted in Fig.1 were evaluated:

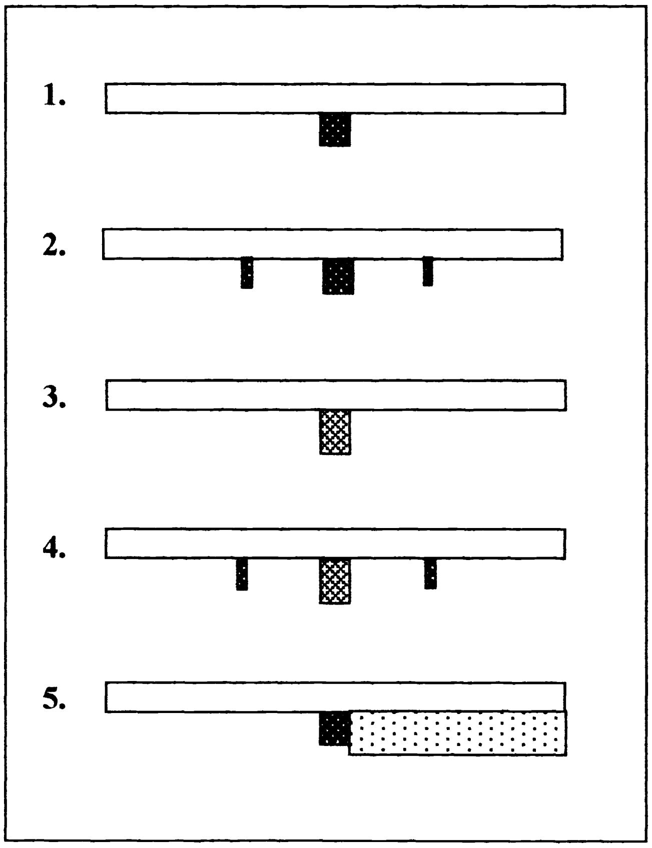

Figure 1. Mask Types and Designs.

1. Binary Intensity Conventional Mask (isolated dark line without biasing),
2. Binary Intensity Conventional Mask with OPC (0.1μm assisting dark lines placed 0.4μm from the main feature),
3. Attenuated PSM (8% transparency), biased (0.18μm),
4. Attenuated PSM (8% transparency), biased (0.20 μm) with OPC (0.1 μm assisting dark lines placed 0.4μm from the main feature),
5. Alternating-Aperture PSM, biased (0.27 μm).

The results show that 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). These results show the effectiveness of Alternating-Aperture PSM technology in terms of intrafield linewidth variation control which is in agreement with the work done at Hewlett Packard.[4] In the cases with other masks, we can notice that OPC, in the form of assisting features, reduces the effects of partial coherence variations by about one third although these effects appeared to be small - 30 nm at worst (Fig. 2, 3). The isofocal points were moved inward by 25 nm which reduces the effects of defocus. Thus we can conclude that even though the effects of partial coherence - focal positions at which aerial image contour lines for different values of partial coherence are intersecting - variations were small, using a proper mask type and design we can make those effects practically unnoticeable.

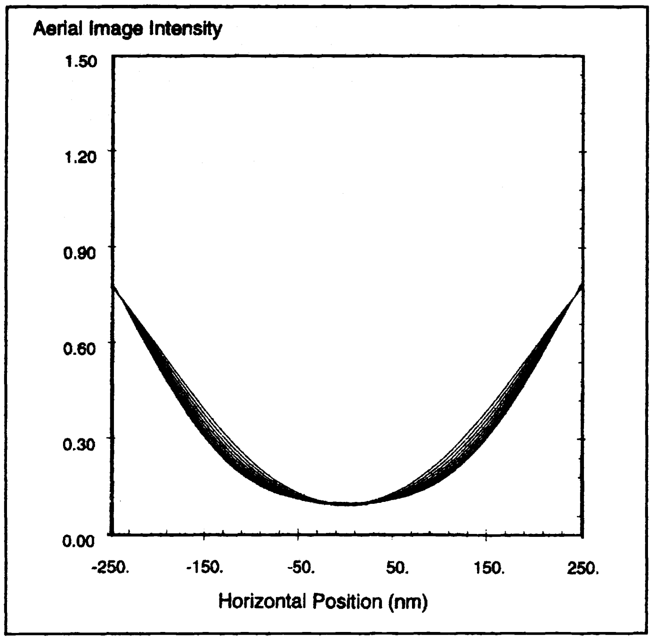

Figure 2. Effects of Partial Coherence Variations in Case of a Binary Intensity Mask.

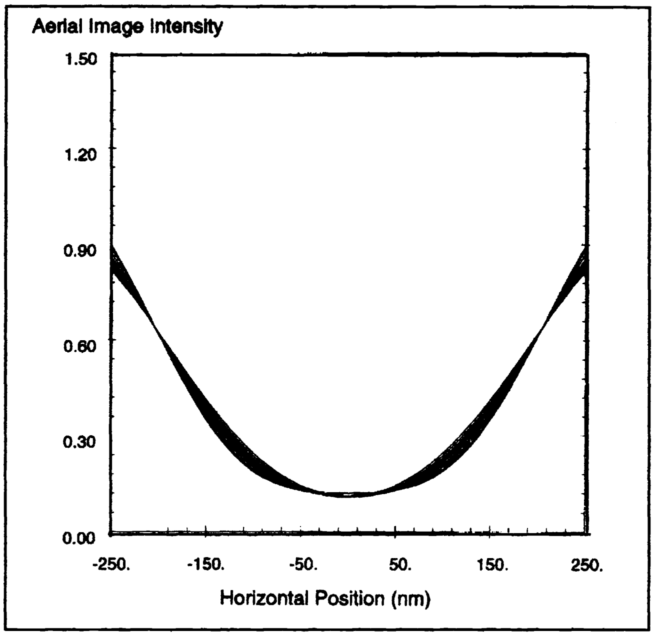

Figure 3. Effects of Partial Coherence Variations in Case of a Binary Intensity Mask with Assist Features.

3. Normalization of Zernike Polynomial Coefficients

To verify the accuracy of simulations of aberrated images, the Zernike polynomial coefficients should be normalized. This can be accomplished in several ways.

The normalization can be performed by applying the Strehl ratio test.[5] Since Zernike coefficients a_i can vary across the lens field causing CD variations, we quantify the amount of lens aberration by specifying the root-mean-square (RMS) deviation of the wavefront aberration. The RMS deviation can be used for an approximation of the Strehl ratio which is based on calculating the ratio of image intensities in the center of the projected image in the presence and absence of aberrations. This ratio is dependent on the total sum of squared Zernike polynomial coefficients,

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

where a_i are Zernike coefficients in units of RMS deviation across the lens pupil.[1]

Hence we apply the Strehl test for normalization to each of the 37 Zernike coefficients utilizing our simulation tools. The tests were done by calculating the aberrated and unaberrated image intensities at the center of an 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 an optical system to be considered diffraction limited.

4. Impact of Lens Aberrations on CD Variations and DOF of Dark Gate Lines

As already mentioned previously, real optical projection systems are not "perfectly" diffraction limited, and they exhibit lens aberrations. Since these 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.[6, 7]

The investigations were performed using four different simulated stepper configurations 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 were obtained by direct interferometer readings from a stepper lens. 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 allowed us to determine the impact of different types of aberrations separately and in groups.

In Setup I a DOF at a 10% exposure level was specified, and the values of the other input parameters were set to: $\lambda = 248$ nm, NA = 0.5, $\sigma = 0.5$, $k_1 = 0.5$, and a resist contrast $\Gamma = 3.0$. 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 (Table 1). At the same time, we notice that optical proximity corrections in the form of assisting lines improved the DOF by about 100% when 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 present than without them.

Mask Type	No Aberrations	With Aberrations
BIM	**1.02**	**0.32**
BIM with OPC	**0.90**	**0.66**
Attenuated PSM	**1.00**	**0.27**
Attenuated PSM with OPC	**0.88**	**0.57**
Alternating-Aperture PSM	**0.95**	**0.18**

Table 1. DOF (μm) at 10% Exposure Level from Set-up I.

The fact that lens aberrations reduced the depth of focus by about 70% for masks without OPC and about 30% for those with 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 led to a 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 (Fig. 4).

The next issue was to determine whether changing the process parameters could make printed patterns less sensitive to lens aberrations. For this purpose the numerical aperture of the lens was set to 0.6 and a resist with higher contrast was used ($\Gamma = 6.0$). The results show that by increasing the NA and using a high-contrast resist material it is possible to significantly improve DOF, and reduce CD variations of printed lines due to lens aberrations (Table 2). 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 assist lines do not perform as well as for Setup I in terms of the DOF improvement although a trend of moving the isofocal points inward is still present. Thus assist features provide better linewidth CD control, but do not improve DOF when a high contrast resist is used.

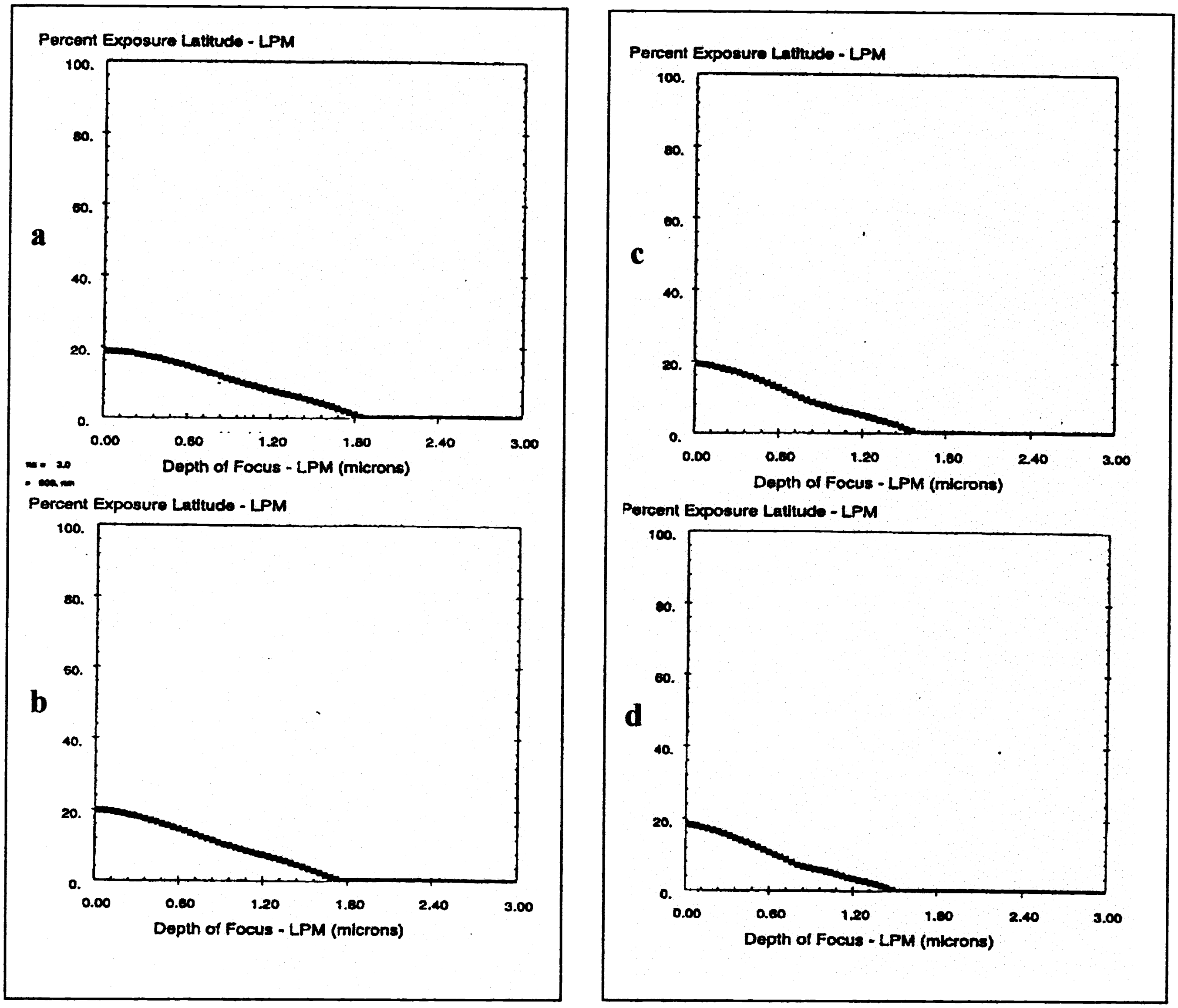

Figure 4. Impact of 3rd Order Spherical aberration (Z8) on DOF: **a)** No aberrations, **b)** Typical.zrn, Z8 = 0, **c)** Z8 = 0.03, **d)** Z8 = 0.05.

Mask Type	No Aberrations	With Aberrations
BIM	1.08	0.98
BIM with OPC	0.88	0.91
Attenuated PSM	1.22	0.89
Attenuated PSM with OPC	1.12	1.04
Alternating-Aperture PSM	1.28	1.18

Table 2. DOF (μm) at 10% Exposure Level from Set-up II.

Similar simulations were done for 0.18 μm dark gate lines in the case of using exposure tools with λ = 248 nm (Setup III) and λ = 193 nm (Setup IV). In both cases the NAs were set to 0.6 and high-contrast resists (Γ = 6.0) were used. Both cases showed that going to smaller feature CDs causes a reduction of DOF and the only mask that has satisfactory performance was the Alternating-Aperture PSM (Table 3, 4). Masks with OPC do not improve depth of focus, and the aberrations are not as detrimental when using a high-contrast resist. Surprisingly, the results show that changing to 193 nm exposure tools does not lead to a significant improvement in CDs of 0.18 μm dark gate lines.

Mask Type	**No Aberrations**	**With Aberrations**
BIM	**0.51**	**0.47**
BIM with OPC	**0.45**	**0.45**
Attenuated PSM	**0.53**	**0.50**
Attenuated PSM with OPC	**0.48**	**0.49**
Alternating-Aperture PSM	**1.04**	**0.71**

Table 3. DOF (μm) at 10% Exposure Level from Set-up III.

Mask Type	**No Aberrations**	**With Aberrations**
BIM	**0.67**	**0.63**
BIM with OPC	**0.59**	**0.60**
Attenuated PSM	**0.74**	**0.70**
Attenuated PSM with OPC	**0.60**	**0.63**
Alternating-Aperture PSM	**0.91**	**0.79**

Table 4. DOF (μm) at 10% Exposure Level from Set-up IV.

5. Summary and Conclusions

The effects of partial coherence and lens aberrations on critical dimension variations of dark gate lines were studied based on computer simulations. The investigations showed that the impact of partial coherence variations was not 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 systems. Based on the results obtained 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 an 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 does not have to be necessarily 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 can 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.
- A high resist contrast is more important than a high numerical aperture.

6. References

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