Compensation of mask induced aberrations 
by projector wavefront control

Peter Evanschitzky\textsuperscript{1}, Feng Shao\textsuperscript{1,2}, Tim Fühner\textsuperscript{1}, and Andreas Erdmann\textsuperscript{1,2}
\textsuperscript{1}Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Schottkystrasse 10, 91058 Erlangen, Germany
\textsuperscript{2}Erlangen Graduate School of Advanced Optical Technologies (SAOT)

ABSTRACT

Rigorous simulation of light diffraction from optical and EUV masks predicts phase effects with an aberration like impact on the imaging performance of lithographic projection systems. This paper demonstrates the application of advanced modeling and optimization methods for the compensation of mask induced aberration effects. It is shown that proper adjustment of the wavefront results in significant reduction of best focus differences between different features.

Keywords: lithography simulation, mask topography effects, wavefront aberrations, process optimization

1. INTRODUCTION

Imaging close to the theoretical resolution limit results in an increasingly tighter focus and aberration budget. This budget is not completely determined by the projection lens. Wafer flatness, mask and wafer alignment, resist thickness, pellicle, laser bandwidth effects and several other factors have to be considered in the definition of the focus budget. Dielectric interfaces of the mask, of the pellicle and of the resist produce a spherical aberration which has to be taken into account in the aberration performance of the system. Recently, experiments by Finders [1] presented significant focus offsets of lines with different pitches and orientations and the reduction of the best focus difference among these features by proper control of the wavefront. This paper highlights the importance of mask-induced aberration effects and investigates the possibility to compensate the mask-induced aberrations by projector wavefront control.

The accurate modeling of light diffraction from optical and EUV mask requires the application of electromagnetic field solvers such as the finite-difference time-domain (FDTD) or the Waveguide method. Rigorous mask diffraction simulations predict mask-induced polarization and phase effects [2]. The phase effects have an aberration like impact on the imaging performance of lithographic projection systems [3, 4]. Zernike analysis of the phase of the diffracted light provides a deeper understanding of the mask induced aberration effects [5, 6]. Typical optical and EUV masks produce polarization dependent astigmatism and spherical aberration. Special care has to be taken in the quantitative interpretation of the results of such Zernike analysis and their impact on the imaging performance. Inclusion of the uncorrected phase of the zero diffraction order provides better results for dense features [6]. However, larger pitches produce high order aberration terms which are difficult to interpret. A phase correction of the zero order can be used to obtain almost pitch independent coefficients with few lower order Zernike terms [5]. In the second approach, the impact of the real phase of the zero order on the image performance has to be separately considered. Moreover, the mask-induced aberration effects depend on the illumination direction of the mask. Different incidence angles in parametric or user defined illuminators with strong off-axis components produce different mask-induced aberrations. Finally, there is an important difference between mask and projector pupil-induced phase deformations. The projector wave aberrations are fixed to the lens pupil. In contrast, mask-induced phase deformations are fixed to specific diffraction orders and weighted by their intensity.

All discussed effects are taken into account by rigorous mask, image and process simulations. In this paper we employ accurate simulation models to investigate the focus and aberration performance of high NA immersion systems. Dedicated spherical aberrations of different order are introduced to the projector lens with the goal to improve the through-focus performance of the system for different feature types and pitches. A genetic algorithm is applied for the optimization of the wavefront in terms of Zernike coefficients. Section 2 provides an overview on the used simulation models
and model parameters. Section 3 presents some typical mask-induced focus shifts for arrays of contact holes with different pitches. A wavefront compensation strategy and a corresponding optimization approach are introduced. The application of the developed simulation and optimization approach to a more complex scenario is described in Section 4. The paper concludes with a summary and outlook.

2. SIMULATION MODELS AND PROCESS SPECIFICATIONS

The Fraunhofer IISB research and development lithography simulator Dr.LiTHO [7] is used for all simulations in this work. The Waveguide method is applied for the rigorous computation of the mask diffraction spectra. Bulk images are computed with a vector imaging model based on an extended Abbe approach [8]. The dependency of the diffraction spectra from the illumination direction of the mask is taken into account by image simulations without the so-called Hopkins approximation [9]. A typical ArF full physical resist model is used for the modeling of the photoresist processing.

All simulations are done for 4× reduction water immersion lithography with a numerical aperture NA = 1.35 and a wavelength \( \lambda = 193 \) nm. The mask is a standard MoSi type attenuated phase shift mask (AttPSM). Simulations are done with unpolarized CQuad illumination (\( \sigma_{\text{in/out}} = 0.7/0.9, \) opening angle = 20°) for contact holes and TE or y-polarized dipole illumination (\( \sigma_{\text{in/out}} = 0.7/0.9, \) opening angle = 40°) for lines, respectively. A 100 nm thick chemically amplified resist is deposited on a silicon wafer with a bottom antireflective coating. The wafer CD data are extracted at the bottom of the simulated profiles. The resist model parameters are obtained by calibration with experimental data.

3. MASK-INDUCED FOCUS SHIFTS AND COMPENSATION STRATEGY

3.1 OBSERVATION OF FOCUS SHIFTS FOR ARRAYS OF CONTACTS

Figure 1 presents simulated process windows of 60 nm contacts with pitches of 120 nm, 140 nm and 160 nm, respectively. The mask size of the semi-dense contacts is adapted to provide the same wafer CD (60 nm) as the dense contacts at the best dose and focus. A pronounced best focus difference between the dense and semi-dense contact arrays can be observed. Such best focus difference between different features limits the available focus budget of the system. The observed variation of the best focus position occurs for an ideal diffraction limited imaging system without any aberrations. Therefore, this best focus aberration cannot be attributed to the projector lens. Instead, it has to be attributed to the mask-induced phase and aberration effects.

Figure 1: Process windows for contacts with different pitches. A pronounced best focus difference of 56 nm and 41 nm respectively between the dense and semi-dense contact arrays can be observed. Simulation parameters are as given in Section 2.
3.2 PROJECTOR WAVEFRONT CONTROL

The improvement of the process windows of the features with different pitches requires a compensation of the mask-induced phase effects. The pitch dependency of these phase effects was already observed in the wavefront analysis of the phase of the diffracted light for different mask pitches [5]. The basic idea of the compensation strategy is explained in Figure 2. The first diffraction orders for different pitches are placed in different positions of the projector pupil. The application of a non-constant phase shift in the projector pupil results in a pitch dependent phase variation of the first diffraction orders. Proper choice of the phase of the pupil wavefront can minimize the pitch dependent phase effects and improve the resulting imaging performance. Due to symmetry considerations the projector pupil wavefront should be presented by even order aberrations such as spherical aberration or astigmatism.

Figure 2: Projection pupil phase map: The application of a non-constant phase shift (here exemplarily spherical $Z_9$) causes a pitch dependent phase variation of the first diffraction orders.

Figure 3 demonstrates the impact of first order spherical aberration ($Z_9$) on the process windows of an array of 60 nm wide semi-dense contact holes with a pitch of 160 nm. An increasing amount of spherical aberration shifts the best focus position of the process window toward negative values. With our sign convention this corresponds to a focus shift closer to the projector lens. Diffraction orders of masks with different pitches pass the projector pupil at different positions. Therefore, the focus shift due to spherical aberration is pitch-dependent. This pitch-dependency of the focus shift belongs to the main characteristics of spherical aberrations [10, 11].
Figure 3: Process windows for 60 nm semi-dense contacts resulting from different $Z_9$ values. The best focus shift caused by an increasing amount of spherical aberration can be observed. Simulation parameters are as given in Section 2.

Figure 4 compares process windows of 60 nm contact arrays with pitches of 120 nm, 130 nm, 140 nm, 150 nm and 160 nm, respectively. According to Figure 1 left the maximum difference between the best focus positions of the process windows of all pitches with a projector pupil without aberrations is 56 nm. In Figure 4 left the application of first order spherical aberration $Z_9 = -85$ m$m$ reduces this maximum best focus difference to 14 nm. On the left side of both Figures 1 and 4 only the two extreme process windows with the maximum best focus difference are shown. Additionally on the right side of both Figures the process window of one further pitch in between is shown. The overlap of the process windows can be further improved by an additional OPC of the mask for different pitches.

Figure 4: Process windows for contacts with different pitches. The maximum best focus difference between all pitches of 56 nm for a pupil without aberrations (shown in Figure 1 left) is reduced to 14 nm for a pupil with a spherical aberration $Z_9 = -85$ m$m$ (this Figure left). Only the two extreme process windows with the maximum best focus difference are shown in Figure 1 and 4 left. Additionally in both Figures right the process window of one further pitch in between is shown. Simulation parameters are as given in Section 2.
Figure 5 presents the computed maximum difference of the best focus positions for 60 nm contact arrays with five different pitches (pitches as mentioned above) versus Zernike coefficients of the projector. The best focus position is determined by the apex of a parabolic fit of the CD data versus focus at the best dose. Special care has to be taken in the selection of a proper focus range for such fit. The parabolic behavior of CD data versus focus occurs only in a certain range around the best focus. Both first \((Z_9)\) and second order \((Z_{16})\) spherical aberration show a pronounced minimum of the maximum best focus difference. The minima of third order and particularly of fourth order spherical aberration \((Z_{25}, Z_{36})\) are less pronounced. The data in Figure 5 are obtained by application of individual Zernike terms. The best result is obtained with first order spherical aberration. The question arises whether combinations of different Zernike terms can provide an additional reduction of the best focus shift for multiple pitches. Finding the best combination of multiple parameter scans would be very time consuming. Therefore, an optimization procedure was developed to identify the best combination of Zernike terms.

![Figure 5: Maximum difference of the best focus positions for 60 nm contact arrays with five different pitches of 120 nm, 130 nm, 140 nm, 150 nm and 160 nm versus projector Zernike coefficients \(Z_9, Z_{16}, Z_{25}\) and \(Z_{36}\). A pronounced minimum for \(Z_9\) and \(Z_{16}\) can be observed. Simulation parameters are as given in Section 2.](image)

### 3.3 OPTIMIZATION PROCEDURE

The goal of the optimization is to achieve a minimum variation of the best focus versus pitch and/or feature orientation. The merit function for the optimization is computed as difference between the largest and smallest best focus value for multiple mask pitches and feature orientations. To provide a general solution for different combinations of Zernikes and feature types, a genetic algorithm [12] is applied for the optimization of the wavefront in terms of Zernike coefficients.

The optimization result for the 60 nm contacts with five pitches as mentioned above and five Zernike terms \(Z_4, Z_9, Z_{16}, Z_{25}\) and \(Z_{36}\) can be seen in Figure 6 left. Compared to the case of first order spherical aberration \((Z_9\) best focus difference 14 nm, see Figure 4 left), the optimum combination of the five Zernike aberration terms with \(Z_4 = -7\) m\(\lambda\), \(Z_9 = -45\) m\(\lambda\), \(Z_{16} = -43\) m\(\lambda\), \(Z_{25} = 23\) m\(\lambda\) and \(Z_{36} = 37\) m\(\lambda\) reduces the best focus difference to 3 nm. In Figure 6 left only the two extreme process windows with the maximum best focus difference are shown. Additionally on the right side the process
window of one further pitch in between is shown. The overlap of the process windows can be further improved by an additional OPC of the mask for different pitches.

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Figure 6: Process windows for contacts with different pitches. The maximum best focus difference between all pitches of 56 nm for a pupil without aberrations (shown in Figure 1 left) is reduced to 3 nm for a pupil with $Z_4 = -7 m\lambda$, $Z_9 = -45 m\lambda$, $Z_{16} = -43 m\lambda$, $Z_{25} = 23 m\lambda$, and $Z_{36} = 37 m\lambda$ (this Figure left). Only the two extreme process windows with the maximum best focus difference are shown in Figure 1 and 6 left. Additionally in both Figures right the process window of one further pitch in between is shown. Simulation parameters are as given in Section 2.

4. WAVEFRONT COMPENSATION FOR MULTIPLE FEATURES

Next, the simulation and optimization approach is applied to a more complex scenario. The example uses the settings of an experimentally investigated scenario which was recently published by Finders [1]. The test case includes 7 different periphery features of memory arrays at the 22 nm node. These are 45 nm vertical lines with pitches of 90 nm, 125 nm, 135 nm, 270 nm, 315 nm, and 90 nm horizontal lines with pitches of 207 nm and 270 nm, respectively. The lines are exposed with a dipole (in/out = 0.7/0.9, opening angle = 40°). The orientation of the lines and the dipole is indicated in Figure 7. The mask CD data of the semi-dense vertical and horizontal lines are adapted to provide target wafer CD (vertical lines 45 nm, horizontal lines 90nm) for all features at the best dose and focus of the dense vertical lines. All other settings are as specified in Section 2.

Figure 7: Orientation of the lines and of the dipole illumination used for the following simulations.

Figure 8 shows the simulated largest best focus difference between all features versus different individual spherical aberration terms. The individual Zernike terms can reduce the best focus difference from 42 nm in the case of a diffraction limited projector lens without aberrations to about 25 nm best focus difference. Combination of multiple Zernike terms
and application of the described optimization procedure provides a further reduction of the best focus difference to 20 nm using a pupil with $Z_9 = -71 \, \text{m}\lambda$, $Z_{16} = 37 \, \text{m}\lambda$, and $Z_{25} = -52 \, \text{m}\lambda$.

Figure 8: Maximum difference of the best focus positions between all features versus projector Zernike coefficients $Z_9$, $Z_{16}$, $Z_{25}$ and $Z_{36}$. A pronounced minimum for $Z_9$, $Z_{16}$ and $Z_{25}$ can be observed. Simulation parameters are as given in Section 2.

Figure 9 compares the overlap of the process windows of the two most critical features (45 nm vertical lines with 90 nm pitch and 125 nm pitch) of the aberration free projector lens and of the lens with the optimized Zernike coefficients (coefficients as mentioned above). The improvement of the overlap of the process window by the optimized wavefront can be clearly seen. Furthermore, the reduction of the maximum best focus difference from 42 nm for the aberration free projector lens to 20 nm for the optimized projector lens can be observed.

Figure 9: Process windows of the two most critical features (45 nm vertical lines with 90 nm pitch and 125 nm pitch) of the aberration free projector lens (left) and of the optimized projector lens using $Z_9 = -71 \, \text{m}\lambda$, $Z_{16} = 37 \, \text{m}\lambda$, and $Z_{25} = -52 \, \text{m}\lambda$ (right). The improved process window overlap and the reduction of the maximum best focus difference from 42 nm to 20 nm can be seen. Simulation parameters are as given in Section 2.
5. CONCLUSIONS AND OUTLOOK

Over the past 30 years, suppliers of lithographic lenses strived to reduce the wave aberrations of their systems and to provide an aberration free imaging. The results of this analysis suggest that the best lithographic performance can be achieved with non-diffraction limited imaging. Instead, optimization of the deformation of the projector pupil wavefront can be used to compensate mask-induced phase and aberration effects. Projector wavefront control enables the compensation of simulated and experimentally measured pitch dependent focus shifts. The combination of spherical aberrations with different orders can provide a significant reduction of the maximum best focus difference of contact holes and of horizontal/vertical lines with different pitches. Inclusion of other Zernike terms such as astigmatism in the optimization procedure can provide a further improvement. The practical application of wavefront control requires providing a good imaging performance for all relevant features. Further extensive and highly accurate simulations and experiments are required to verify whether this goal can be achieved for real layouts.

Although this paper is focused on hyper NA immersion lithography, similar effects can be expected for EUV lithography. Several aberration-like mask induced effects such as tilted process windows were already observed by simulations 10 years ago [13]. Recent simulations [5] demonstrate the importance of these effects and indicate the potential requirement for an improved wavefront control in EUV systems as well. A proper technology for such wavefront control in the EUV regime has still to be identified.

REFERENCES

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