Laterally resolved off-axis phase measurements on 45nm node production features using Phame®

Ute Buttgereit, Sascha Perlitz, Dirk Seidel,
Carl Zeiss SMS GmbH, Carl Zeiss Promenade 10, 07745 Jena, Germany

Kyung m Lee, Malahat Tavassoli
Intel Mask Operation, 2200 Mission College Blvd, Santa Clara, CA 95052

ABSTRACT

As lithography mask process moves toward 45nm and 32nm node, phase control is becoming more important than ever. To ensure an accurate printing both attenuated and alternating PSMs (Phase Shift Masks) need precise control of phase as a function of both pitch and target sizes. However critical target CDs fall much below conventional phase metrology tools capabilities. Interferometer-based phase shift measurements are limited to large CD targets and require custom designed features in order to function properly, which limits phase measurement. AFM (Atomic Force Microscopy) methods are able to capture small feature sizes but do not consider any diffraction effects which are caused by the topography of the features itself when getting close to the used wavelength.

Imaging simulations, both, in a rigorous and a Kirchhoff regime, show the dependency of the phase in the image plane of a microlithography exposure tool on numerical aperture and pitch due to the loss of phase information in the imaging pupil. Additionally, for small features the phase is strongly impacted by polarization and 3D mask effects. For these feature sizes, the image phase does not coincide with the etch depth equivalent phase calculated from the nominal depth and optical constants of the shifter material. Deviations up to 20° have been observed leading to strong variations in the imaging quality and process window variations during scanner printing. Considerations of CD variation between 0 and pi features by simulation show lowest 0/pi CD variation and therefore largest process window if the scanner relevant phase is at 180°. The simulation results illustrate the importance to measure the scanner relevant phase, effective in the image plane of the scanner.

Consequently Zeiss, in collaboration with Intel, has developed a laterally resolving Phase Metrology Tool – Phame® – for in-die phase measurements. The optical metrology tool is able to perform in-die phase measurement on alternating PSM, attenuated PSM and CPL masks down to 120nm half pitch at mask. On-axis measurement results have already been published.

In this paper we elaborate on off-axis phase measurement theory and procedure. Furthermore we present first off-axis measurement results over varying features sizes using different illumination conditions.

Keywords: Phame, phase, phase metrology, scanner phase, polarization, mask, PSM, mask inspection

1. INTRODUCTION

The use of PSM (Phase Shift Mask) combined with high NA and special adapted illumination conditions drives 193nm lithography down to 45nm and even 32nm node. The challenge is that mask complexity increases and process control becomes extremely important. The specification for PSM becomes tighter. For example, the ITRS roadmap specifies that the phase error of alternating phase shifting mask should be +/- 1 degree in 2008. Both alternating and attenuated PSM require accurate and precise phase control to ensure best CD printing performance at wafer lithography steps.

Currently available phase measurement tools require large reference features to function properly. The size of the reference feature exceeds the production relevant features by at least one order of magnitude. The interferometer based phase measurement tools do not account for mask process specific effects like etch loading effects and do not consider diffraction limitations. High resolution AFM (Atomic Force Microscope) measure the etch depth and can resolve features down to 120nm. The etch depth is converted into phase value. However this method does not capture diffraction limitation by NA and pitch as well as rigorous 3D mask effects.

Kirchhoff and rigorous simulation show that imaging effects and rigorous effects need to be considered when going down to 45nm node **[1]**. The knowledge of these effects as well as the limitation of existing tools has driven Zeiss SMS to develop the new phase metrology system – Phame®. The optical metrology tool is able to perform in-die phase measurement on alternating PSM, attenuated PSM and CPL masks down to 120nm half pitch. On-axis measurement results showing the dependence of scanner phase on pitch and the impact of polarization on scanner phase have already been published **[2]**. In this paper we explain the theory and measurement procedure for off-axis measurements. Furthermore we present first off-axis phase images on 45nm node features.

2. PHAME® - PHASE METROLOGY SYSTEM

The introduction of 45nm node using 193nm lithography challenges mask manufactures with respect to mask complexity and steadily increasing specification requirements. The number of critical layers in the design is increasing and the use of PSM is essential. To ensure correct CD printing, accurate and precise control of phase shift becomes more important than ever **[3]**. Rigorous effects and diffraction limitations by scanner NA and mask pitch impact the scanner phase, occurring in the image plane of the scanner and being relevant for the printing process, and need to be considered **[4]**. Conventional phase measurement methods reach there limits because they are not able to capture these effects.

Zeiss novel phase metrology system Phame® takes over the capability of currently existing interferometer based tools measuring in large reference features. Furthermore Phame® measures the scanner relevant phase in the real production features accounting for rigorous 3D-effects and diffraction limitation by mask pitch and scanner NA. All relevant PSM types like alternating PSM, attenuated PSM and CPL mask as well as all types of features can be measured.

The optical beam path of the Phame® is emulating an immersion scanner with a NA going up to 1.6 (see Figure 1). Its 193nm laser combined with a low sigma illumination unit generates a coherent illumination of the mask. The mask is handled face down. The tools high precision imaging optics with 0.4NA, being 1.6NA scanner equivalent, enables full compatibility to future 193nm immersion scanners down to the 32nm node. The CCD-camera is in the same position as the wafer. Phase information is obtained through dedicated phase manipulation by pupil filter and software algorithms. In addition to in-die phase shift, the tool also measures in-die transmission.

Furthermore off-axis illumination can be applied. The required partial coherent illumination settings of a scanner are sampled in consecutive measurements of adjustable intervals, allowing phase control under scanner relevant illumination settings **[5]**. By realizing on- or off-axis illumination all types of PSM can be evaluated. Additionally Phame® does account for polarization.

The tool is S2/S8 certified. The Phame® software has an operator GUI which supports easy production use. Furthermore the tool is fully SMIF compatible and in combination with the optionally available SECS/GEM capabilities the system is suited to match the automation and cleanliness requirements of high-end photomask production.

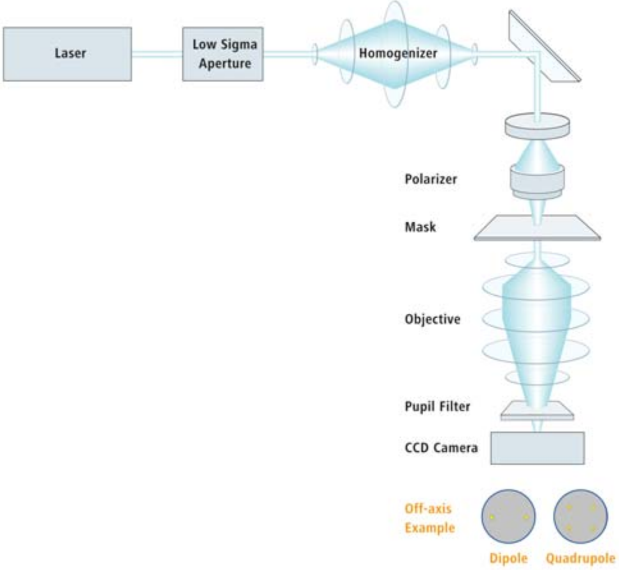

Figure 1: Schematic drawing of phase metrology system Phame®

Phame® tool performance was reported earlier and shows excellent performance in terms of accuracy and repeatability **[6].** The phase shift accuracy is well below 1°, the static phase reproducibility for large reference features is below < 0.2° (3sigma) and for small production features below 0.4° (3sigma). The long term reproducibility is below ±1.2° (3sigma).

3. ON-AXIS MEASUREMENT RESULTS

Phame® on-axis phase shift measurement results have already been reported at Advanced Lithography Symposium and at Photomask Japan.

Figure 2 and Figure 3 show laterally resolved phase shift images measured on alternating PSM. Phame® allows measurement of targets with arbitrary sizes and shapes. Dense lines/spaces, isolated lines or spaces as well as contact holes can be measured.

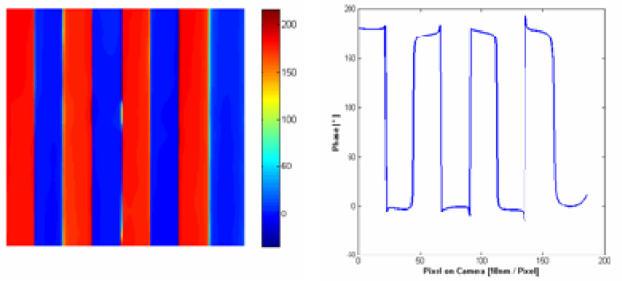

Figure 2: Phase image and profile on 50nm lines/spaces (at wafer), pitch 1:1, Alt. PSM

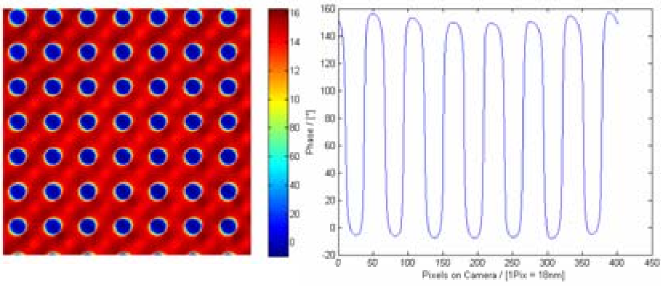

Figure 3: Phase image and profile for 500nm contact hole array, Alt. PSM

On-axis investigations of phase shift behavior on alternating PSM over pitch and duty cycle showed significant variations up to 7°. **[1]** The impact of polarization especially for small print pitches of 100nm at wafer level causes phase differences up to 20° between TM and TE polarization. **[2]**

4. OFF-AXIS MEASUREMENT PROCEDURE

4.1. Off-axis theory

In first approximation off-axis illumination of a scanner can be looked at separate exposures for each source point, for example dipole illumination corresponds to 2 single exposures of opposite source points. Each source point generates phase and amplitude in the image plane. Looking at Phame® each coherent source point generates the scanner equivalent phase and amplitude in the image plane. In the scanner the two images are combined and an incoherent intensity is obtained containing no phase information anymore. How do we get the phase shift information for that kind of illumination?

To explore the off-axis phase we need to look first into the diffraction spectrum, considering the 0th and 1st diffraction order. For an alternating PSM the -1st and 1st diffraction order is captured in the scanner NA and an ideal 2beam interference occurs. The amplitudes for the two first diffraction orders are the same and the diffraction spectrum lies perfectly symmetrical in the pupil. To capture the first diffraction orders for an attenuated PSM or CPL mask with the same scanner NA, off-axis illumination is required. The 1st respectively -1st and 0th diffraction order is captured in the pupil. Looking into the diffraction spectrum, phase and amplitude of the first and 0th diffraction order might differ from each other. Additionally for off-axis illumination asymmetric diffraction spectra occur depending on the feature pitch. This asymmetry causes tilts in the image plane.

Figure 4 shows the scanner equivalent phase image of a single off-axis source point on a pattern consisting of dense lines and spaces and an iso line. Looking on the phase profile along a slice over the iso line strong tilts are observed, whereas almost no tilts occur in the phase profile along a slice over the dense lines and spaces. Simulating the phase image for the same pattern (L/S 1:1, pitch at mask 354 nm, iso line, NA 0.273) we find exactly the same results (Figure 5). If we look at the diffraction spectrum in the pupil there is an asymmetric spectrum for the isolated line causing strong phase tilts in the image plane. The 1st diffraction order of the dense lines and spaces form together with 0th diffraction order an ideal symmetric spectrum in the pupil and there are no phase tilts in the image plane. The conclusion of this investigation is:

- The symmetry of the diffraction spectrum determines the phase tilts in the image plane
- The symmetry of the diffraction spectrum is depending on the pitch

Additionally we found that the measured scanner relevant phase of a single source point does not provide a sufficient off-axis phase result due to tilts occurring in the image plane.

Generally it can be stated that off-axis illumination leads to an asymmetry in the diffraction spectrum. For phase shift value extraction symmetry of the diffraction spectrum is required. Zeiss has developed a new method for off-axis phase shift value extraction which is called High Resolution Phase.

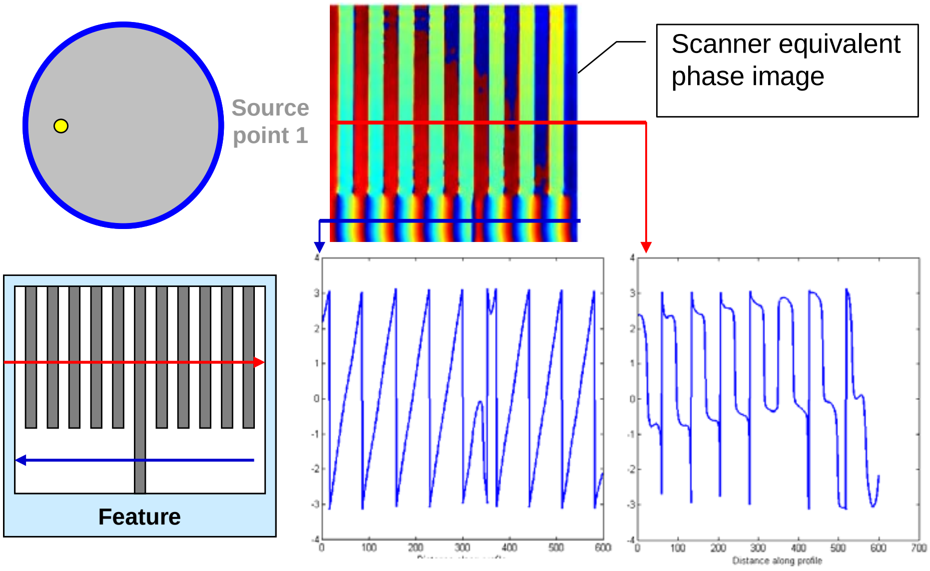

Figure 4: Phame® measurement – scanner equivalent phase shift image, showing strong tilts for the iso line and no tilt for the dense lines

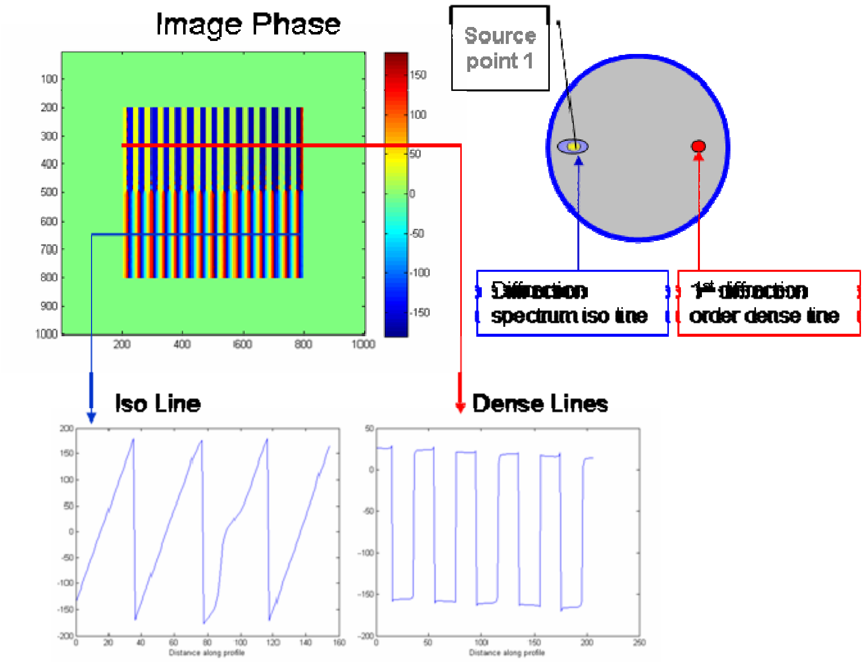

Figure 5: Simulation results – scanner equivalent phase shift image, showing strong tilts for the iso line and no tilt for the dense lines; diffraction spectrum

4.2. High Resolution Phase

In order to extract an off-axis phase shift value diffraction spectrum symmetry is required. Zeiss has developed the High Resolution Phase concept for off-axis phase shift value extraction.

The first source is measured and the diffraction spectrum of the feature for the first source point is obtained. In our example with dense lines and spaces combined with the iso feature we capture the 0th diffraction order, the diffraction spectrum of the iso line and the -1st diffraction order of the dense lines and spaces. The 0th diffraction order is shifted in the pupil with respect to the optical axis due to off-axis illumination. After that the opposite source point is measured and exactly the opposite diffraction spectrum is captured in the pupil, meaning the 0th diffraction order, the diffraction spectrum of the iso line and the 1st diffraction order of the dense lines and spaces. Compared to the first diffraction spectrum of the first source point the 0th diffraction order is now shifted in the opposite direction. For each source point the electrical field can be measured in the Phame®. The electrical field is coherently merged in the pupil. The zero diffraction orders of each source point are algorithmically shifted in that way that they fall together in the optical axis of a fictive pupil (see Figure 6). By applying this procedure a symmetric diffraction spectrum is obtained. In the same time the original NA is doubled, going up from 0.4 to 0.8. The position of the 0th diffraction is determined with sub-pixel accuracy and phase and energy offsets between the fields are corrected.

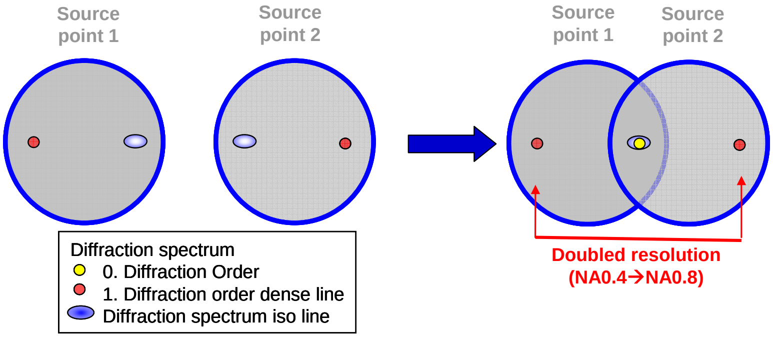

Figure 6: Diffraction spectrum and coherent merge of the electrical fields in the pupil

The so obtained symmetric diffraction spectrum is now propagated into the image plan and high resolution phase image and high resolution intensity image is obtained (see Figure 7). It corresponds to an image which would be obtained by means of an on-axis illumination and a higher NA.

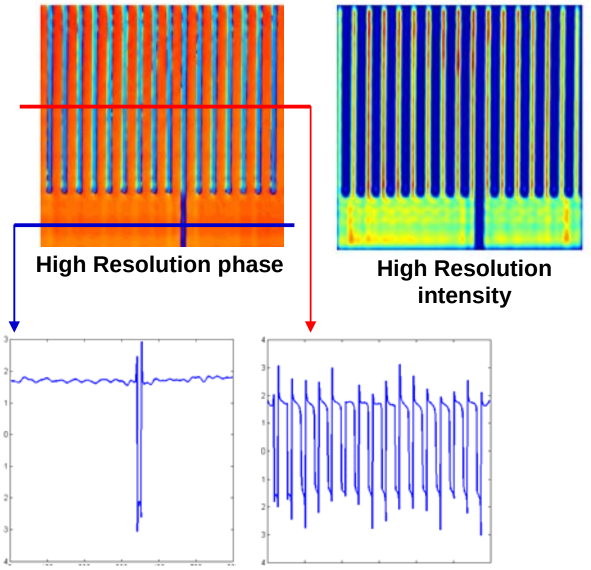

Figure 7: High resolution phase image (left) with corresponding phase shift profile and high resolution intensity (right)

If the phase shift is now evaluated across a slice over the iso line and across a slice over the dense lines and spaces it can be seen in Figure 7 that all tilts are fully removed and a high resolution phase shift value can be extracted.

If different off-axis illumination settings are required, for example annular illumination, the procedure works in the same manner. For annular illumination for example 8 consecutive measurements will be performed. The diffraction spectrum of each single illumination point is obtained. The electrical fields are coherently merged. By shifting the diffraction order in that way that the 0^{th} diffraction orders fall together diffraction spectrum symmetry is obtained. The symmetric diffraction spectrum is propagated into the image plane. High resolution phase image and high resolution intensity image is obtained.

5. OFF-AXIS MEASUREMENT RESULTS

To check the high resolution phase principle we looked first into large feature measurement. A large reference feature on a test mask was measured using on-axis and off-axis illumination. The phase shift angle is proportional to 1/cos(NA). Due to the off-axis angle and the so caused light path difference we expected a phase difference in-between on-axis and off-axis measurement of 2.3°.

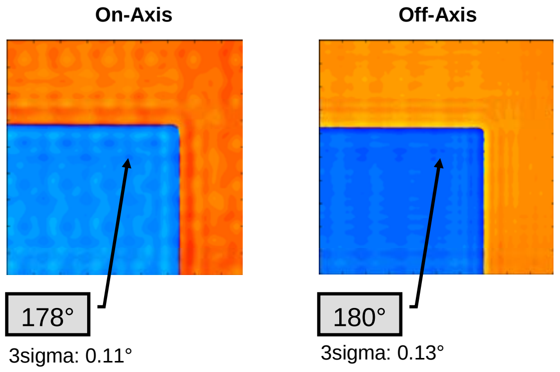

Figure 8: Phase image of a large reference feature with on-axis (left) and off-axis (right) illumination

The Phame® measurement results in Figure 8 confirm our expectation. For on-axis illumination a phase shift value of 178° and for off-axis illumination a phase shift value of 180° was measured. These results provide a first proof of the high resolution phase concept. Additionally we could show good reproducibility values below 0.15° (3sigma) achieved for both measurements.

To evaluate the high resolution phase shift in production features we used a 6% MoSi test mask containing lines and spaces with 45nm CD at wafer level. The pitch was varied from 1:1, 1:2 to 1:3. The dense lines and spaces were combined with an isolated feature. Figure 9 shows the high resolution phase shift images for pitch 1:1 and pitch 1:3.

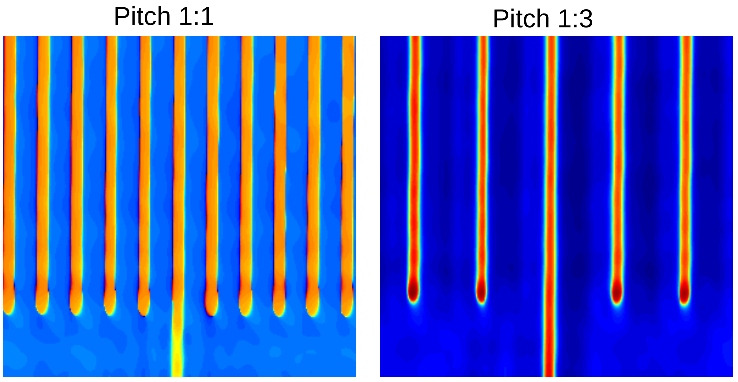

Figure 9: High resolution phase shift image on 45nm CD at wafer pitch 1:1 and pitch 1:3

The phase shift values were evaluated for the dense lines and for the isolated line. For the dense lines a variation of phase shift up to 10° over pitch was observed. For pitch 1:1 and 1:2 the phase shift is close to 180° whereas for the pitch 1:3 the phase shift drops down to 170°. Comparing the phase shift values of dense lines with the phase shift values of the isolated line strong deviation up to 40° were found especially when the isolated line is combined with the dense lines of pitch 1:1. This effect is decreasing as pitch is increasing. In real production features OPC would be used to account for those effects.

The found variations show the importance to evaluate the phase shift in the production features.

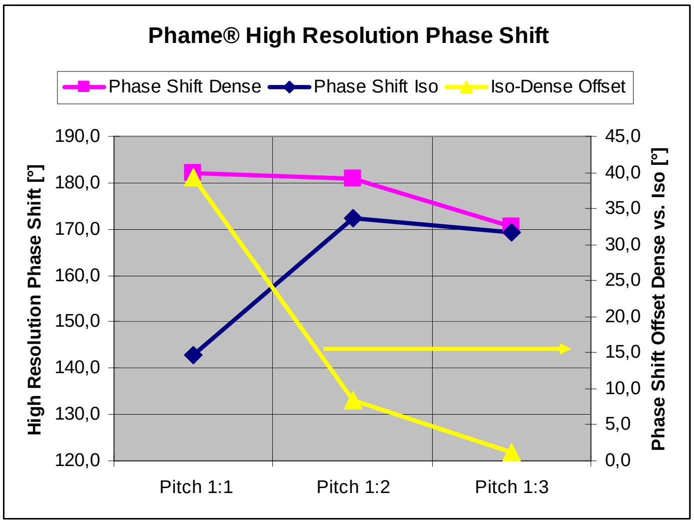

Figure 10: High resolution phase shift over pitch comparing dense lines/spaces vs. iso line

6. SUMMARY

The extension of optical lithography to 45nm node and beyond goes along with increased mask complexity and tightening of specification. The proper use of PSM gets more and more important and the phase shift needs to be qualified exactly in order to achieve accurate CD printing results in the wafer process. Currently available methods run into limitations because they are not capable to consider diffraction limitations by scanner NA and mask pitch as well 3D mask effects. With the transition to the 45nm node and beyond those effects play an important role and needs to be considered. The novel phase metrology system Phame® captures diffraction limitations, rigorous effects and polarization effects. Phame® measures the phase shift in arbitrary production features for on- and off-axis application. On-axis results measured on alternating PSM have already been reported.

The paper presents a new concept for off-axis phase measurement called high resolution phase. The high resolution phase is sensitive to mask phase errors and diffraction spectrum. The functionality of the high resolution phase concept was proven using large feature measurements. The off-axis phase shift value did meet the expected phase shift variation by light path difference using off-axis illumination.

High resolution phase shift measurements on 45nm (wafer level) test features showed strong variations of phase shift over pitch. Additionally significant variations in phase shift up to 40° were observed for dense lines vs. isolated line. This effect is decreasing with increasing pitch.

Phame® measures

- Large reference features with high reproducibility
- In-die phase shift for on-axis application
- High resolution in-die phase shift for off-axis application

Combining those features in one tool Phame® offers new options for process control as well as for R&D processes especially for design, OPC verification.

7. REFERENCES

[1] Kyung m Lee, Malahat Tavassoli, Max Lau, Sascha Perlitz, Ute Buttgereit, Thomas Scherübl, “Study of rigorous effects and polarization on phase shifting masks through simulations and in-die phase measurement” *Proc. SPIE,* SPIE 6518, 65181Y (2007)

[2] Sascha Perlitz, Ute Buttgereit, Thomas Scherübl, Dirk Seidel, Kyung m Lee, Malahat Tavassoli “Novel solution for in-die phase control under scanner equivalent optical settings for 45nm node and below” *Proc. SPIE,* vol.6607.66070Z (2007)

[3] K.Satoh, M.Itoh, T.Satoh, “Mask 3D effect on 45nm imaging using attenuated PSM”, *Proc. SPIE,* vol. 6520.6520J (2007)

[4] Michael Hibbs, Satoru Nemoto and Toru Komizo, “Imaging Behavior of High-Transmission Attenuating Phase-Shift Mask Films,” *Proc. SPIE,* vol. 6349, 63491A (2006)

[5] Toshio Konishi and Yosuke Kojima, “Through-pitch and through-focus characterization of AAPSM for ArF immersion lithography,” *Proc. SPIE,* vol. 6281.62810S (2006)

[6] Sascha Perlitz, Ute Buttgereit, Thomas Scherübl, “Phame™: a novel phase metrology tool of Carl Zeiss for in-die phase measurements under scanner relevant optical settings”, *Proc. SPIE*, vol. SPIE 6518, 65184R (2007).