Investigation of phase distribution using Phame® in-die phase measurements

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

ABSTRACT

As lithography mask processes move toward 45nm and 32nm node, mask complexity increases steadily, mask specifications tighten and process control becomes extremely important. Driven by this fact the requirements for metrology tools increase as well. Efforts in metrology have been focused on accurately measuring CD linearity and uniformity across the mask, and accurately measuring phase variation on Alternating/Attenuated PSM and transmission for Attenuated PSM.

CD control on photo masks is usually done through the following processes: exposure dose/focus change, resist develop and dry etch. The key requirement is to maintain correct CD linearity and uniformity across the mask. For PSM specifically, the effect of CD uniformity for both Alternating PSM and Attenuated PSM and etch depth for Alternating PSM becomes also important. So far phase measurement has been limited to either measuring large-feature phase using interferometer-based metrology tools or measuring etch depth using AFM and converting etch depth into phase under the assumption that trench profile and optical properties of the layers remain constant. However recent investigations show that the trench profile and optical property of layers impact the phase. This effect is getting larger for smaller CD's. The currently used phase measurement methods run into limitations because they are not able to capture 3D mask effects, diffraction limitations or polarization effects. The new phase metrology system – Phame® developed by Carl Zeiss SMS overcomes those limitations and enables laterally resolved phase measurement in any kind of production feature on the mask. The resolution of the system goes down to 120nm half pitch at mask level.

We will report on tool performance data with respect to static and dynamic phase repeatability focusing on Alternating PSM. Furthermore the phase metrology system was used to investigate mask process signatures on Alternating PSM in order to further improve the overall PSM process performance. Especially global loading effects caused by the pattern density and micro loading effects caused by the feature size itself have been evaluated using the capability of measuring phase in the small production features. The results of this study will be reported in this paper.

Keywords: phase, phase metrology, Phame, PSM, CD, mask metrology

1. INTRODUCTION

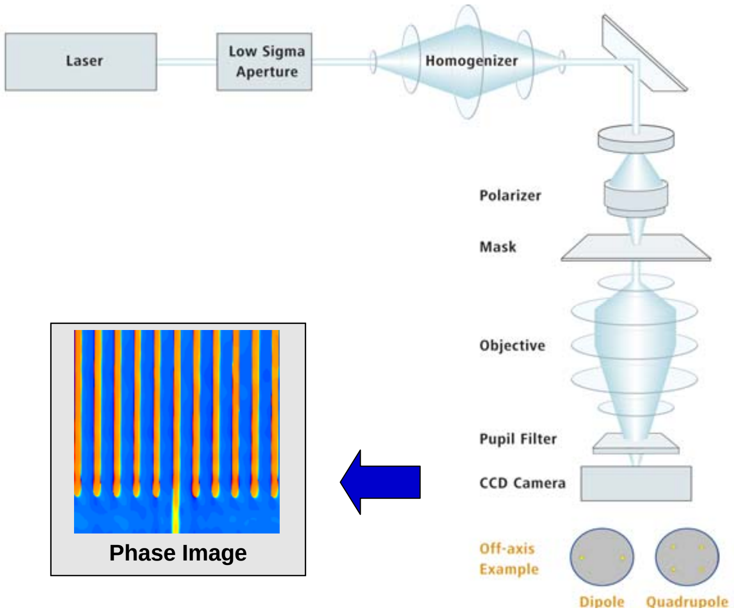
The insertion of 193nm immersion lithography along with strong optical proximity correction (OPC), phase shifting masks (PSM) and special adapted illumination settings allows further extension of technology to 45nm and 32nm node. At the same time mask complexity increases and mask specification tighten which makes process control extremely important. With feature sizes going beyond the lithographic wavelength and pushing lithography to extreme low k1 factors the mask itself becomes more and more an optical element in the printing process and its performance needs to be characterized precisely. Concluding from the ITRS roadmap PSM remain the key solution to stay with single exposure at low k1. Therefore precise phase measurement becomes of high importance to ensure correct phase and good phase linearity and uniformity across mask for Alternating PSM and Attenuated PSM. Especially for Alternating PSM the ITRS 2007 shows that the phase uniformity stays at ± 1° for 45nm and 32nm node. The challenging part however is that the minimum feature size on mask decreases down to 85nm. In these regions imaging effects as well as topography effects impact the phase significantly which has been already published in earlier papers [1, 2]. Phame®, the phase measurement system developed by Carl Zeiss SMS [3] addresses the phase measurement for all types of PSM including imaging effects, polarization effects and 3D mask effects and helps the mask maker to understand and control any phase related imaging effect. With the capability of measuring phase shift in real production features under scanner relevant illumination conditions Phame® overcomes the limitations of currently available phase measurement strategies which are based on interferometer or AFM methods. In this study we present new results on Alternating PSM with focus on the investigation of local process signatures. After a short introduction into the phase measurement principle on photomasks we discuss the actual tool performance of Phame® emphasizing on short and long term repeatability as well as fleet matching and tool matching to conventional phase measurement tools. In the main part we present and discuss the impact of different processes on the phase distribution across the mask showing the sensitivity of the phase measurement principle.

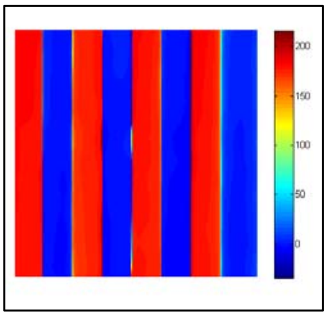
2. PHAME® – BASIC WORKING PRINCIPLE

The phase metrology system Phame® (Figure 1) is an optical system which allows actinic high resolution phase shift measurement down to 120nm half pitch on mask for all types of phase shifting masks. [4] On- and off-axis illumination including polarization can be applied using a mask side NA going up to 0.4 which is equivalent to 1.6 scanners NA. This enables full compatibility to current and future 193nm immersion scanners down to the 32nm node.

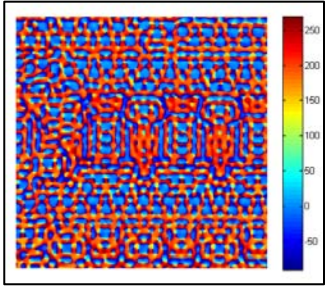
The 193nm laser is combined with a low sigma illumination unit generating a coherent illumination (i.e. single source point) of the mask which is required for phase measurement (Figure 2). The mask is handled face down and the CCD-camera is in the same position as the wafer in the actual scanner. Phase information is obtained through dedicated phase manipulation by pupil filter and software algorithms. Figure 2 shows high resolution phase images of an Alternating PSM Lines/Space pattern (50nm HP) and 45nm Inverse Lithography pattern. Especially the phase image on the Inverse Lithography illustrates the capability of Phame® to resolve phase images with high spatial resolution. Off-axis phase measurement is realized by applying consecutive measurements of single source points according to the scanner relevant illumination settings (e.g., dipole illumination is the measurement of two opposite source points). In addition to in-die phase shift, the tool also measures in-die transmission.

Figure 1: Phase Metrology System Phame®





Phase Image: Alt. PSM, 50nm HP



Phase Image: 45nm Inverse Litho

Figure 2: Optical beam path of Phame® (left) and In-die phase images (right)

3. PHAME® – PERFORMANCE DATA

Before going into evaluation of process dependent phase distribution on Alternating PSM we evaluated the system performance of Phame® in terms of static and long term repeatability. Static phase repeatability has been measured on large test features (2µm CD at mask) and small features (250nm CD at mask) applying 30 consecutive measurements without mask load and unload. As seen in Figure 3 the static phase repeatability is below 0.3° (3sigma) for both, large and small feature. Long term repeatability is shown here over 16 days performing one measurement per day including load and unload. Three different sites on a test mask have been measured and evaluated. The 3sigma value of the long term repeatability is well below 0.4° (see Figure 3). This demonstrates the excellent tool stability of the Phame® system.

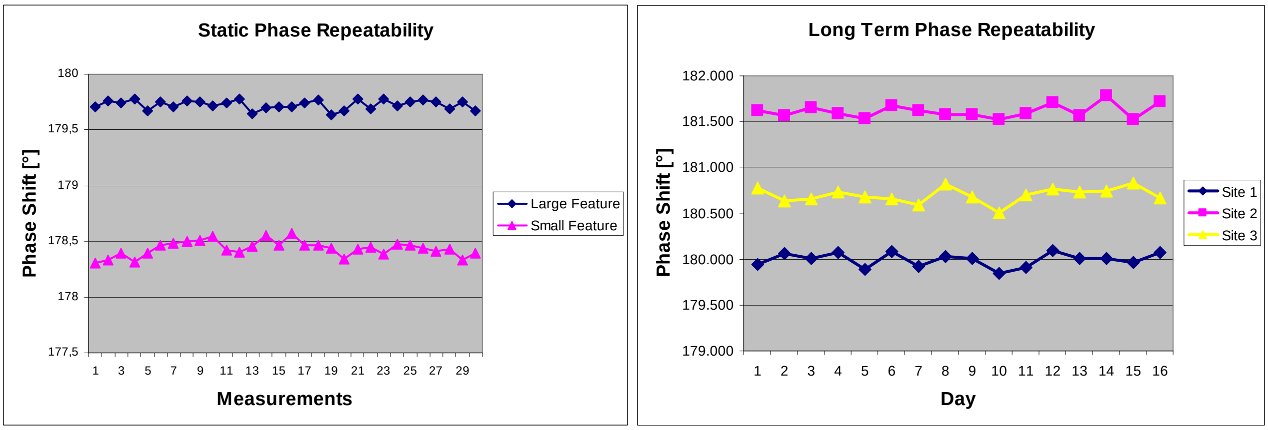


Figure 3: Static phase repeatability measured on small and large features (left) and long term phase repeatability (right)

Furthermore we spent effort in fleet matching between different Phame® tools, which is gaining more and importance from the customer's perspective especially if global manufacturing is required. The measurements have been done on several Phame® tools using dedicated test plates producing different phase values. An example is shown in Figure 4 where the phase deviation between the Phame® system A and system B is well below 1°. The slope of the correlation is close to one having an excellent correlation factor. So the matching between the Phame® systems fulfills the requirements for global manufacturing.

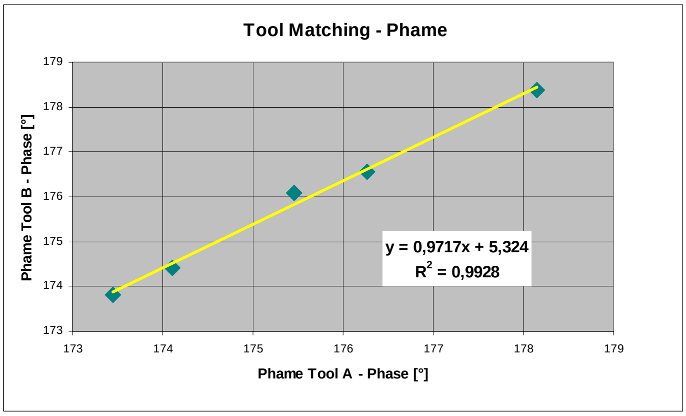


Figure 4: Fleet matching of Phame® tools showing excellent correlation and slope close to 1

Another important point from the user's perspective is the matching of the new phase metrology system with already existing conventional phase measurement tools. Different test plates have been manufactured representing different phase values. A cross measurement was done on Phame® and the conventional tool performing a site to site comparison on the different test plates as well as a plate to plate comparison based on the phase mean values of each plate. Figure 5 shows that the correlation of the measured data leads to a slope of one with a correlation factor close to one. This is an excellent correlation result for the tool matching and of special importance for the user because it guaranties the connectivity to already existing measurement data. Overall, Phame® shows an excellent performance in terms of repeatability and tool matching.

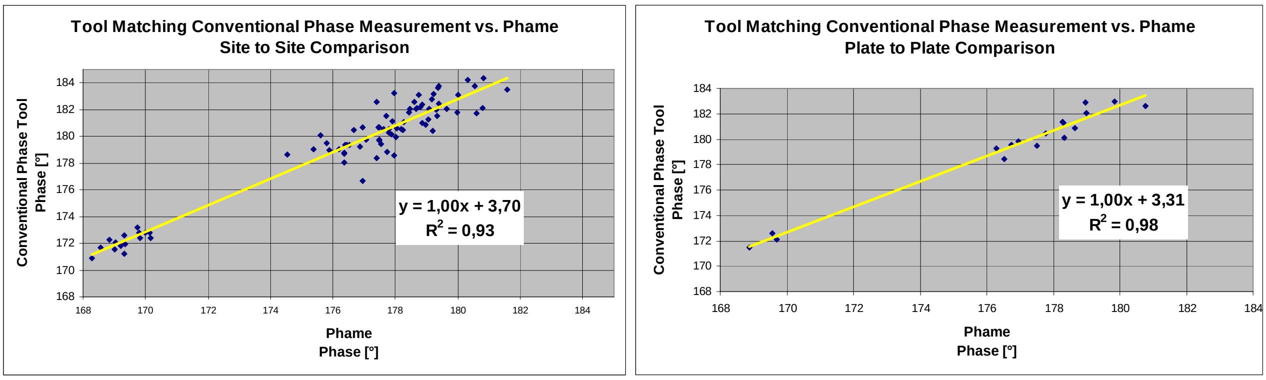


Figure 5: Phase matching to conventional phase measurement tool on dedicated test plates based on site to site comparison (left) and phase mean value plate to plate comparison (right) showing a slope of 1

4. INVESTIGATION OF PROCESS SIGNATURES ON ALT. PSM

A key requirement for phase shifting masks is to maintain correct phase and good phase linearity and uniformity across the mask. Recent investigations have shown that trench profile and optical properties of the layers impact the phase shift. [2, 5] This effect is getting larger with smaller feature sizes. Especially for Alternating PSM optimization of the quartz dry etch process becomes crucial in order to guarantee a 180° phase shift over a wide range of feature sizes. The importance of phase linearity was investigated on lines and space pattern on Alternating PSM with a constant CD of 45nm (wafer level) and varying pitch. The through pitch phase measurements show impressively that the phase shift is significantly dropping down from 180° for print pitches below 200nm (wafer level) (see Figure 6). This phase variation is due to imaging effects, caused by NA and pitch, as well as 3D mask topography effects. The impact of 3D mask effects is increasing with decreasing feature size and becomes critical with the transition to 45nm node and beyond.

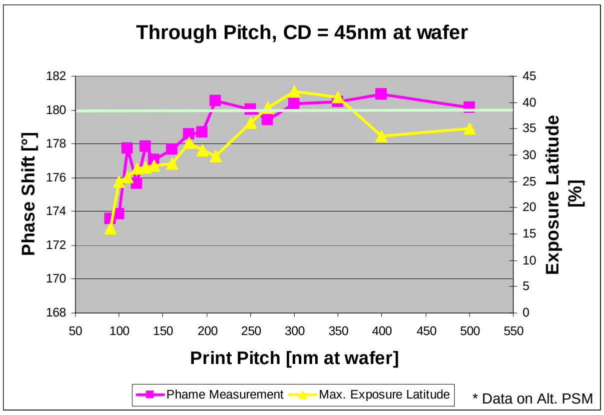


Figure 6: Through pitch phase investigation at constant CD of 45nm (wafer level) and investigation of maximum exposure latitude as measure for process window. A strong correlation between phase shift and process window is observed

Additionally to the Phame® measurements we performed AIMS™45-193i measurements to evaluate the printing performance. Similar to the Phame® measurement a NA of 1.2 was used and we evaluated the maximum exposure latitude, a measure for process window. As easily can be seen in Figure 6 there is a strong correlation between phase shift and process window. As soon as the phase deviates from 180° the maximum exposure latitude decreases significantly from about 35% to 15%. For Alternating PSM a phase value off 180° goes along with an increasing zero diffraction order amplitude which leads to a decreased depth of focus or decreased maximum exposure latitude and therefore to decreased process window. Largest process window is achieved for phase values of 180°.

Concluding from these investigations it becomes essential to measure, understand and control any phase related imaging effect. Phame® allows for the first time to measure the phase shift in the relevant production features down to 120nm half pitch at mask. This enables measurement of phase linearity across the feature sizes as well as investigation of phase distribution across the mask.

For the following investigations on phase distribution and phase tuning all phase values have been normalized for proprietary reasons. To investigate the impact of etch loading effects on phase shift first a test mask has been used containing 2µm CD targets and 180nm CD targets (mask level dimension) next to each other. A sample plan of 56 measurement points for each target size was measured. The left graph in Figure 7 shows that the global distribution of the phase values across the plate is similar for small and large feature targets. But, even if the absolute phase values are not shown here, there is a considerable off-set between large and small feature targets. Further down we will discuss if this off-set can be calibrated.

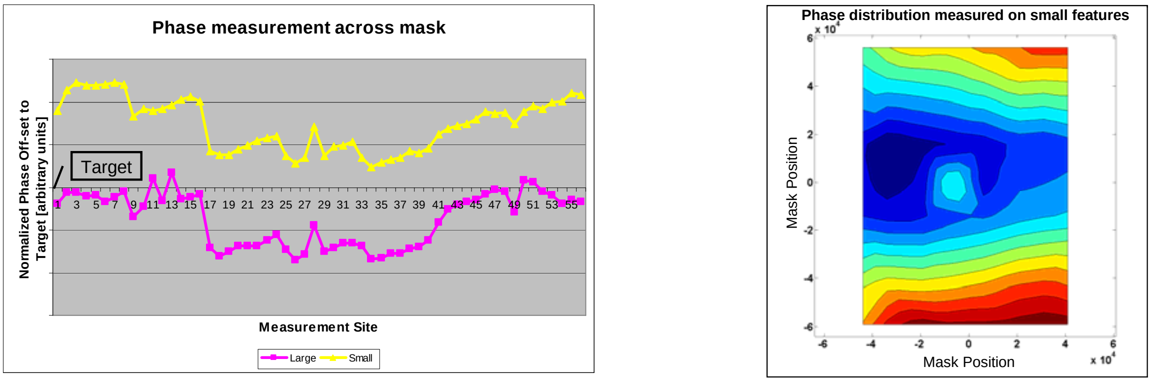


Figure 7: Phase measurement across mask taken on 2µm CD and 180nm CD (left) and phase distribution across mask on 180nm CD features (right) (dimension are mask level dimension)

The right plot in Figure 7 shows the phase distribution across the plate measured on 180nm CD targets (=45nm CD at wafer level). The 2D plot leads us to the conclusion that the signature of the etch process is reflected. To further prove this and to check if the phase distribution can be tuned by the etch process a pair of two Alternating PSM test plates has been taken containing the same pattern. The etch process was slightly changed applying process 1 and process 2 respectively on these test plates.

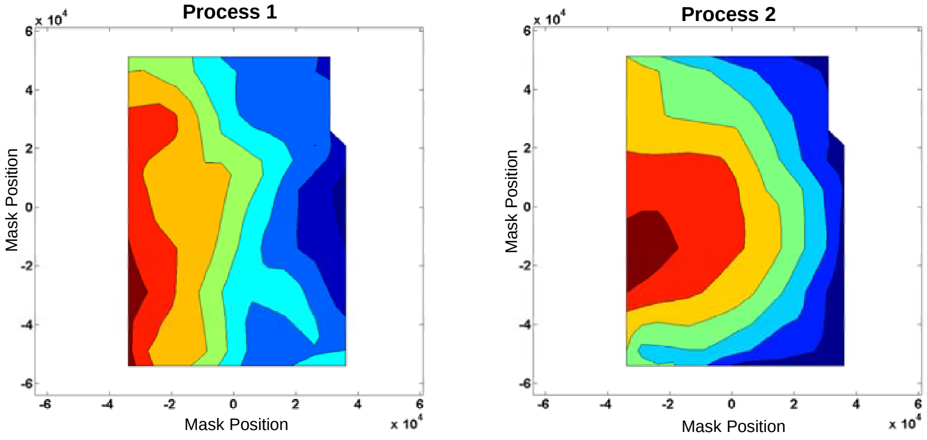


Figure 8: Phase distribution across Alt. PSM test masks measured on 180nm CD features (mask level) showing site to site distribution for process 1 (left) and radial distribution for process 2 (right)

The 2D contour plots on phase distribution in Figure 8 verify that the phase signature can be tuned by etch process variation. The application of process 1 on the test plate 1 leads to a site to site distribution whereas process 2 shows a radial distribution. The phase measurements have been taken on 180nm CD features measuring 41 points over the plate.

Beside evaluation of process signature we investigated if the phase value itself can be tuned by etch process variation as well. Figure 9 shows that the small feature phase value achieved by process 1 is significantly different from the phase value achieved by process 2. Even if the absolute values are not shown here the difference in phase is obvious. Furthermore it can be seen that process 2 brings the small feature phase into target. This means with systematic process tuning and in-die phase measurement the customer can optimize phase uniformity across plate as well as adjust the absolute phase value.

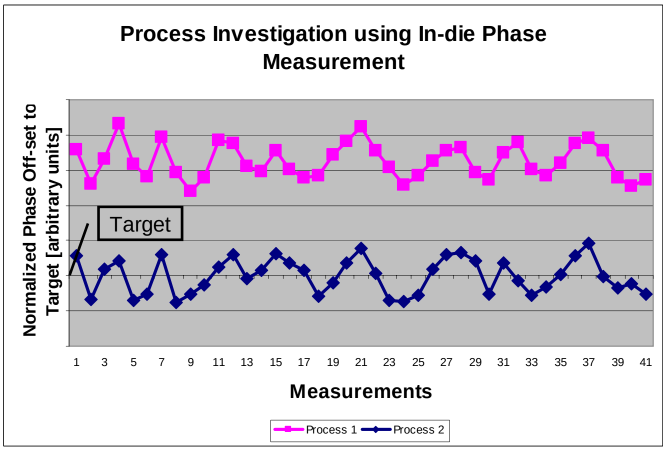


Figure 9: In-die phase shift measurement on 180nm CD targets across the plate comparing phase shift values for process 1 and process 2

Next, we analyzed the phase difference between small feature targets and large feature targets and the question if there is a way of calibrating this off-set.

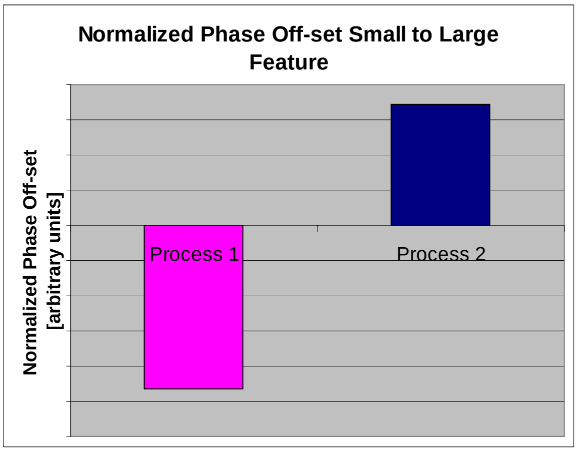


Figure 10: Comparison of phase shift difference between large feature (2µm CD at mask) and small feature (180nm CD at mask) for process 1 and process 2 – scaling is similar as in Figure 9

Figure 10 shows the phase difference between large feature target and small feature target for process 1 and process 2 respectively. The scaling has been chosen similar to Figure 9. The graph demonstrates very impressively that the off-set between large and small features is not constant. Process 2 shows a smaller off-set between large and small features than process 2. Furthermore the off-set goes in different direction. This makes a calibration between large and small features impossible and emphasizes that in-die phase measurement is essential.

It turns out that the dry etch process for Alternating PSM impacts the general phase distribution, the absolute phase value as well as the off-set between small and large features and therefore phase linearity.

5. CONCLUSION

In this paper we have worked out the viability of Phame® to control phase linearity and phase signatures and optimize process window. It was shown that:

- Phase shift shows a strong correlation to process window
- Largest process window is achieved at 180°
- Dry etch process impacts phase distribution
- Dry etch process impacts absolute phase value across feature sizes
- Phase off-set between small and large features is not constant

Further extension of 193nm lithography to 45nm and beyond increases the complexity of masks and mask processes and tightens the requirements on process control and metrology systems. The ITRS roadmap shows that for 32nm node the minimum mask feature size falls dramatically beyond the lithographic wavelength which leads to further aggressive OPC and illumination settings. The mask becomes more and more an optical element in printing and its performance needs to be characterized precisely. PSM will remain a key solution to print with single exposure at low k1. For Alternating and Attenuated PSM phase control becomes more important than ever. Imaging effects and 3D mask effects impact the phase shift and the printing performance of the mask. It becomes crucial to guarantee a correct phase over a wide range of feature sizes and to maintain good phase uniformity across the mask.

In this paper we have shown that for Alternating PSM the phase shift through pitch for constant CD of 45nm (wafer level) is impacted by imaging and 3D mask effects. For print pitches below 200nm the phase drops significantly down. At the same time the maximum exposure latitude, a measure for process window, decreases as well. There is a strong correlation between phase shift and process window. Largest process window is achieved for phase shift of 180°. This demonstrates that it becomes essential to understand and control any phase effect related to printing.

Furthermore we have demonstrated that Phame® enables measurement of phase shift over a wide range of feature sizes, addressing phase linearity, and phase uniformity across the plate. By optimizing the etch process the phase distribution across plate can be improved. Additionally it was verified that the absolute phase value of small features can be adapted as well by tuning the etch process. It was shown that there is an off-set between the phase values of large features and small features which is not constant. This makes a calibration impossible and underlines the importance of in-die phase measurement.

Phame® enables the industry to measure, understand and control phase related printing effects and to optimize the mask for perfect printing.

REFERENCES

[1] Ute Buttgereit, Robert Birkner, Dirk Seidel, Sascha Perlitz,Vicky Philipsen, Peter De Bisschop, "Phame® - phase measurements on 45nm node phase shift features", *Proc.SPIE* , Vol. 7028, 70282Z (2008)

[2] T. Konishi, Y. Kojima, Y. Okuda, V. Philipsen, L.H.A. Leunissen, L. van Look, "Through-pitch and through-focus characterization of AAPSM for ArF immersion lithography", *Proc. SPIE*, vol. 6281.62810S (2006)

[3] 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)

[4] 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.6518, 65184R (2007)

[5] Komizo, Toru; Nemoto, Satoru; Kojima, Yosuke; Ohshima, Takashi; Yoshii, Takashi; Konishi, Toshio; Chiba, Kazuaki; Kikuchi, Yasutaka; Otaki, Masao; Okuda, Yoshimitsu, "Evaluation of quartz dry etching profile for the PSM lithography performance", Proc. SPIE, vol. 5853 (2005)