

# Phase behavior through pitch and duty cycle and its impact on process window

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## ABSTRACT

Immersion lithography has moved into 45nm node and will soon go into 32nm node. Alternating Phase Shifting Masks (alt. PSM's) are one of the most effective methods to enhance resolution and process window. However there are two major challenges: intensity balancing and quartz dry etch process. The dry etch process requires not only a uniform quartz etch but also a good linearity over a wide range of feature sizes to ensure a 180° phase shift through pitch and duty cycle. Phase errors lead to an image placement error during printing becoming even worse through focus. As feature sizes shrink imaging effects and 3D mask effects impact the phase shift and accurate phase shift measurement becomes extremely important.

In this paper we report on phase shift measurements through pitch and duty cycle on alt. PSM taken on the newly developed phase metrology system Phame<sup>®</sup> and compare them to rigorous 3D simulations. Furthermore we correlate the phase shift measurements to process window data such as maximum exposure latitude.

Through pitch investigations on alt. PSM show that for print pitches below 200nm (wafer level) the phase shift drops significantly below 180° which will lead to an image placement error during printing and a shrinking process window. Furthermore a strong correlation between phase shift and maximum exposure latitude is shown. Largest maximum exposure latitude is achieved for phase shift close to 180°.

Phame<sup>®</sup> enables optical phase shift measurement in critical production features down to 120nm half pitch providing the opportunity to optimize the quartz dry etch process in terms of signature and linearity. This will help to optimize the phase shift of critical features on alt. PSM for largest process window and hence increase end of line yields for reducing overall chip manufacturing costs.

**Keywords:** Phame, PSM, alt. PSM, Phase, Phase metrology, Process Window

## 1. INTRODUCTION

Further extension of 193nm lithography to the next technology nodes and staying at a maximum available scanner NA of 1.35 forces the industry to print at lower k1 which leads to extremely small process windows. Achieving high lithographic yield becomes more challenging than ever before. 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. Alternating phase shifting masks (alt. PSMs) are the most effective way to increase resolution and to maintain a large process window in printing. Precise phase measurement becomes of high importance to ensure correct phase and excellent phase linearity over a wide range of feature sizes as well as a good uniformity across mask. The ITRS 2007 shows that for alt. PSM the phase uniformity stays at  $\pm 1^\circ$  for 45nm and 32nm node. However, the challenging part 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 shift significantly which was already reported in earlier papers. [1, 2] Phame<sup>®</sup>, the phase metrology 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<sup>®</sup> overcomes the limitations of currently available phase measurement strategies which are based on interferometer methods requiring special test features or AFM methods which are measuring the etch depth only.

Although alt. PSM's are most effective to enhance resolution, there are some major challenges in alt. PSM manufacturing:

- Intensity imbalance leading to Image Placement Error (see Figure 1)
- Image Placement Error through focus caused by non correct phase shift
- Phase linearity through pitch and duty cycle over a wide range of feature sizes to maintain large process window

In this study we present new results on alt. PSM focusing on phase investigation through pitch and through duty cycle and correlate the results to process window investigation. After a short introduction into the phase measurement principle on photomasks we discuss the actual tool performance of Phame<sup>®</sup> 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 through duty cycle and through pitch phase results and the impact of phase shift on exposure latitude, a measure of the process window. Additionally we will point out the capability to optimize the phase shift by tuning the dry etch process using in-die phase measurement for phase control.

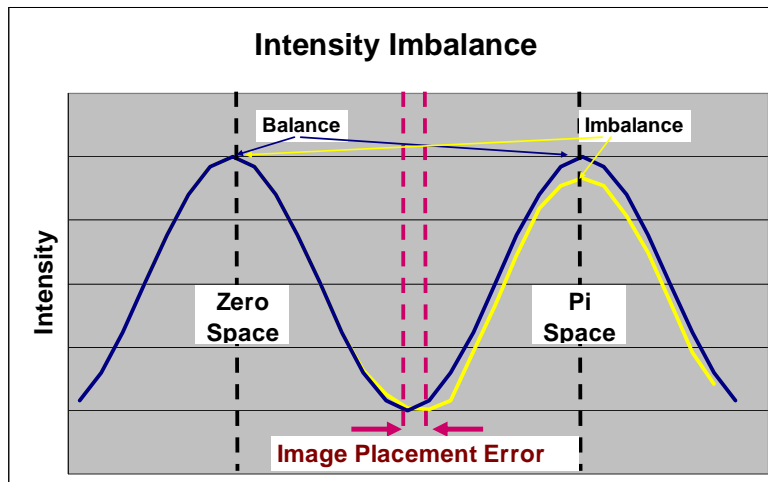


Figure 1: Image Placement Error (IPE) due to intensity imbalance

## 2. PHAME<sup>®</sup> – BASIC WORKING PRINCIPLE

The phase metrology system Phame<sup>®</sup> (Figure 2) 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 scanner NA of 1.6. This enables full compatibility to current and future 193nm immersion scanners down to the 32nm node.



Figure 2: Phase Metrology System Phame®

The 193nm laser is combined with a low sigma illumination unit generating a coherent illumination (i.e. single source point) which is required for phase measurement (Figure 3). 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 3 shows high resolution phase images of an alt. PSM Lines/Space pattern (50nm HP) and a 45nm Inverse Lithography pattern (att. PSM). 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.

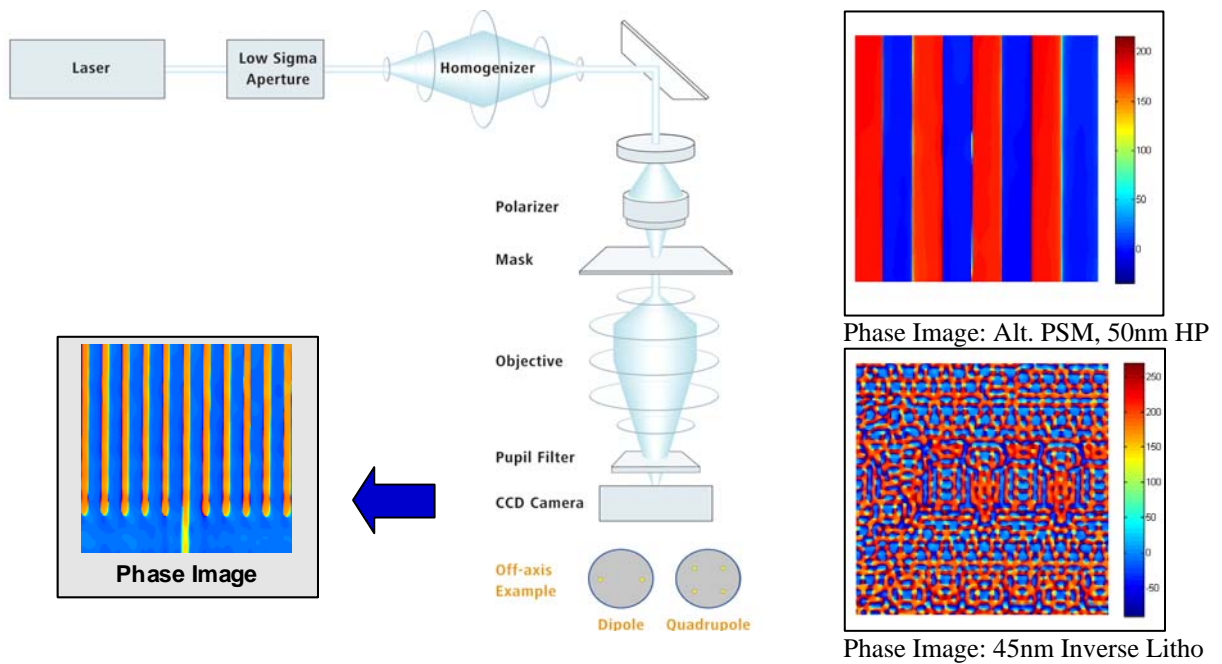


Figure 3: Optical beam path of Phame® (left) and In-die phase images (right)

### 3. PHAME<sup>®</sup> – PERFORMANCE DATA

Before going into phase evaluation through pitch and duty cycle the system performance of Phame<sup>®</sup> needs to be assessed in terms of repeatability. Static phase repeatability has been measured on large reference features (2 $\mu$ m CD at mask) and small features (250nm CD at mask) applying 30 consecutive measurements without mask load and unload. As seen in Figure 4 the static phase repeatability is below 0.3° (3sigma) for both, large and small features. Long term repeatability is acquired over 16 days performing one measurement per day including mask 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 4). This demonstrates the excellent tool stability of the Phame<sup>®</sup> system.

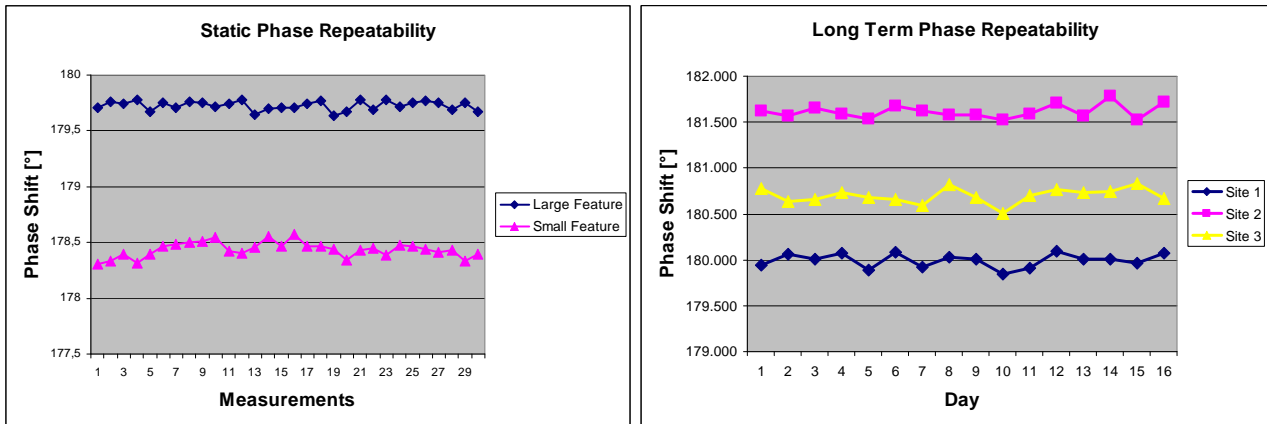


Figure 4: Static phase repeatability measured on small and large features (left) and long term phase repeatability (right)

Furthermore, we investigated fleet matching between different Phame<sup>®</sup> tools. Fleet matching is of utmost importance from the customer's perspective especially if global manufacturing is required. The measurements have been done on several Phame<sup>®</sup> tools using dedicated test plates with different phase values. An example is shown in the left plot of Figure 5 where the phase deviation between the Phame<sup>®</sup> system A and system B is well below 1°. The slope of the correlation is close to one having an excellent correlation factor. The excellent matching between the different Phame<sup>®</sup> systems fulfills the requirements for global manufacturing.

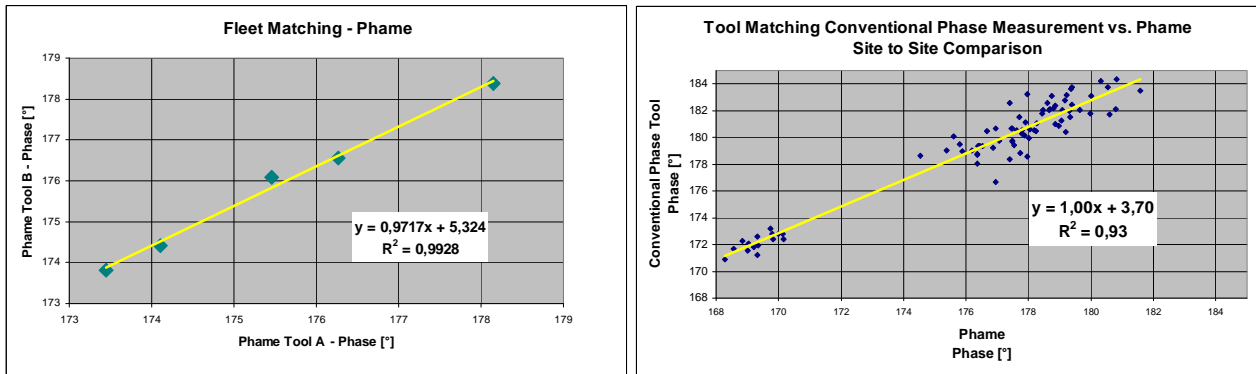


Figure 5: Fleet matching of Phame<sup>®</sup> tools showing excellent correlation and slope close to 1 (left) and Tool matching to conventional phase tool providing excellent correlation with slope of 1 (right)

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<sup>®</sup> and the conventional tool performing a site to site comparison on the different test plates. The right plot in 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<sup>®</sup> shows an excellent performance in terms of repeatability and tool matching.

#### 4. PHASE INVESTIGATION THROUGH DUTY CYCLE AND PITCH

A key requirement for phase shifting masks is to maintain correct phase and excellent phase linearity and uniformity across the mask. Recent investigations have shown that trench profiles and optical properties of the layers impact the phase shift. [2, 5] This effect is getting larger with smaller feature sizes and becomes of high importance for the next technology nodes.

To investigate the phase behavior through duty cycle and through pitch a special alt. PSM test mask was used containing a variety of different CD and pitches. We focused on 45nm node, investigating lines and spaces in a 90nm pitch (wafer scale) with varying duty cycle. Through out the paper duty cycle is defined as Cr line divided by pitch. The through pitch investigation was done using a fixed Cr line CD at 45nm and the pitch was varied from 90nm up to 500nm (wafer scale).

In-die phase shift measurements were carried out on Phame<sup>®</sup> with a NA of 1.2 applying on-axis illumination and y-polarization (along the line). Rigorous 3D simulations of phase have been performed using the simulator EM-suite of Panoramic Technology Inc., which is based on the Finite-Difference Time-Domain method. Coherent 193nm illumination with a single source point and y-polarization has been used to obtain a phase signal in the image plane by the complex output-capability of Panoramic. The NA has been chosen according to the measurements to 1.2. As input parameter for the simulation the CD design data were used and a fixed pi-space bias of 20nm on wafer was considered. Actual measured AFM data have been used as input data for the quartz etch depth. To evaluate the printing performance process window investigations have been performed on AIMS<sup>TM</sup>45-193i using circular illumination, y-polarization and a NA of 1.2. It was already reported earlier that Exposure Latitude data from AIMS<sup>TM</sup>45-193i and Exposure Latitude measurements on wafer show an excellent correlation. [6]

First, we focused on the phase behavior through duty cycle at a constant pitch of 90nm (wafer scale). Figure 6 shows that the measured and the simulated phase follow the same trend. For decreasing quartz space the phase shift drops significantly down. Rigorous effects, getting worse with smaller quartz spaces, impact the phase shift dramatically and the phase value is far away 180°. Furthermore we explored the printing behavior through duty cycle evaluating exposure latitude a measure for process window. The exposure latitude decreases as soon as the phase shift drops down. This leads us to the conclusion that phase shift and process window correlate well for alt. PSM. Phase shift and exposure latitude depend strongly on duty cycle.

The offset between simulation and measurement is mainly due to fact that we had limited actual measurement data available as input parameter, except of the etch depth, which limits the capability of the simulation.

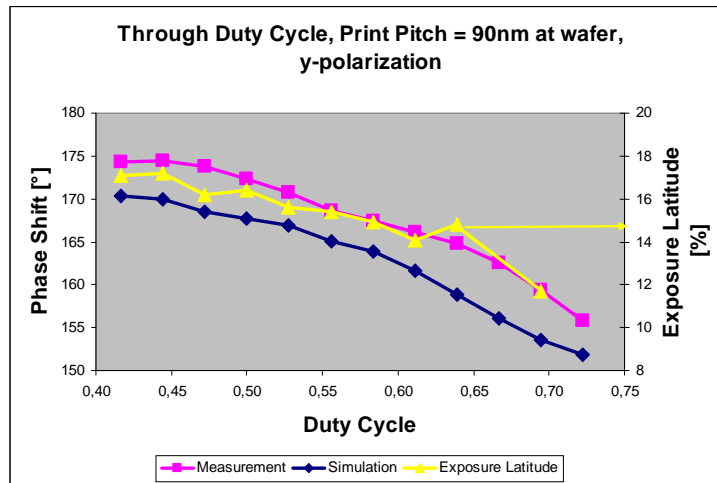


Figure 6: Phase behavior through duty cycle for 90nm pitch showing a strong correlation to Exposure Latitude

Furthermore we investigated the impact of polarization on phase shift. Additionally to y-polarization (along the line) we measured the phase shift through duty cycle applying x-polarization (perpendicular to the line). Figure 7 shows that the phase measurement and the simulation follow the same signature. In this specific case, polarization has almost no impact on phase shift over a wide range. However, for small quartz spaces below 100nm at wafer the impact of polarization gets worse. Phase deviations up to 5° between y- and x-polarization have been measured. The impact of polarization depends

on the duty cycle. For the first time Phame® allows to characterize the impact of polarization on phase shift for real production features.

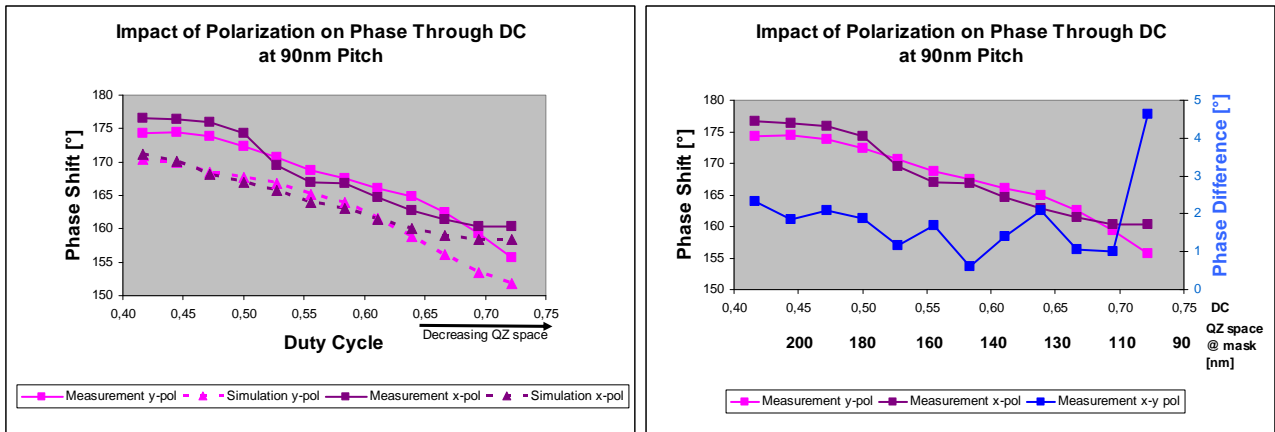


Figure 7: Impact of polarization on phase shift through duty cycle getting worse for small quartz spaces

Phase linearity was investigated on lines and space pattern with a constant Cr line 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 8, left plot). These phase variations are 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.

Additionally to the phase measurements we evaluated the printing performance using AIMS™45-193i measurements. The maximum exposure latitude, a measure for process window was analyzed through pitch. As easily can be seen in Figure 8 (left plot) 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 alt. 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° (Figure 8, right plot). This is a very important result which shows that an alt. PSM has to be optimized to 180° phase shift depending on the in-die feature size in order to get a large process window.

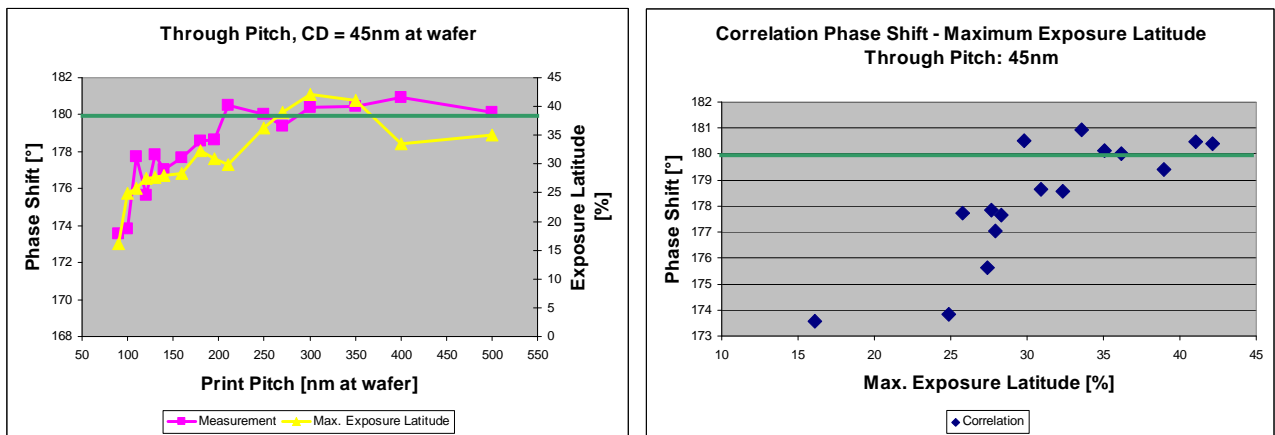


Figure 8: Through pitch phase investigation at constant CD of 45nm (wafer level) and investigation of maximum exposure latitude as measured with AIMS from process window. A strong correlation between phase shift and process window is observed

## 5. INVESTIGATION OF PHASE SIGNATURES

The results on phase investigation through pitch and duty cycle underline the importance of maintaining correct phase shift and good phase linearity over wide range of feature sizes to ensure a large process window during printing. It becomes essential to measure, understand and control any phase related imaging effect. Phame<sup>®</sup> allows for the first time to measure the phase shift in the relevant production features down to 120nm half pitch at mask. This enables the mask makers to measure phase linearity across the feature sizes as well as to investigate phase uniformity across the mask.

Especially for alt. 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. Therefore, we investigated how phase signatures measured by Phame<sup>®</sup> on small in-die features can be used to tune the dry etch process. For the following investigations on phase distribution and phase tuning all phase values have been normalized for proprietary reasons.

To investigate the impact of dry etch process on phase signature a pair of two alt. 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. The 2D contour plots on phase distribution in Figure 9 illustrate that the phase signature can be tuned by dry 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 45nm CD features (wafer scale) measuring 41 points over the mask.

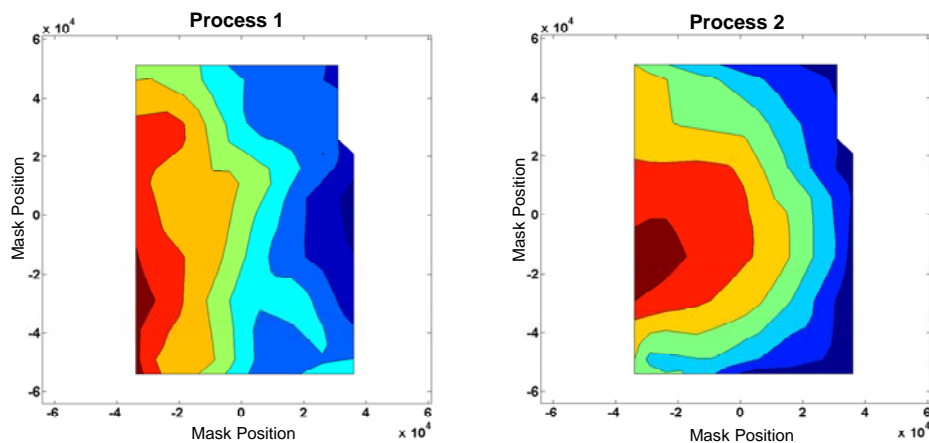


Figure 9: Phase distribution across alt. PSM test masks measured on 45nm CD features (wafer level) showing site to site distribution for process 1 (left) and radial distribution for process 2 (right)

Beside evaluation of process signature we analyzed if the phase value itself can be tuned by etch process variation as well. Therefore, the mean-to-target (MTT) phase value of process 1 was determined by measuring the phase using large test features (which corresponds to the conventional way) and by measuring the phase of the small in-die features. Figure 10 shows that for process 1 for both large and small features the MTT value is significantly off. It is interesting to see that the mean value of the large features is below the target whereas for the small features it is vice versa. Next the etch process was optimized based on the mean values of the small features. This resulted in the new etch process 2. Figure 10 shows that now process 2 brings the small feature phase close to target. The large features are again dramatically off target. Note, that the phase shift measured on large area features changed from significantly below target to significantly above target. This leads us to the conclusion that systematic process tuning by using in-die phase measurement enables the customer to optimize phase uniformity across plate as well as to adjust the absolute phase value. Furthermore it can be seen in Figure 10 that phase control relying on large reference feature measurement only is insufficient and may lead to reduced process window for the critical features during printing. The fact that the phase difference between large and small features is also depending on the etch process makes a calibration between large and small features impossible.

In conclusion the study shows that the dry etch process for alt. PSM impacts the overall phase distribution, the absolute phase value as well as the off-set between small and large features and therefore phase linearity.

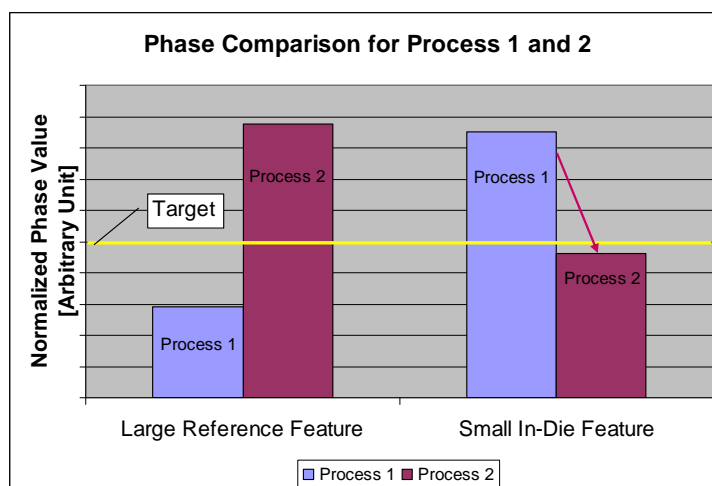


Figure 10: Phase shift comparison between process 1 and process 2. Process 2 has been tuned for optimal phase value for small features and consequently brings the phase shift of the in-die features closer to target

## 6. SUMMARY

This paper shows the viability of Phame<sup>®</sup> to characterize phase behavior through pitch and duty cycle and to control phase linearity and distribution across plate to ensure largest process window during printing.

We have shown that:

- Phase shift depends on duty cycle and pitch
- Phase shift strongly correlates with process window
- Maximum exposure latitude is achieved for phase shift of 180°
- Absolute phase shift value and phase distribution depend on dry etch process
- Phase control on large reference features is insufficient to guarantee largest process window for critical production features

Further extension of 193nm lithography at a maximum NA of 1.35 forces the industry to print at lower k1, making high lithographic yield critical. PSM stay a key solution to enhance resolution and process window for single patterning. Feature sizes going well beyond the lithographic wavelength and increased pattern complexity make the mask more and more to an optical element during printing, which needs to be characterized precisely. Especially for alt. PSM it is important to achieve a phase shift of 180° in order to ensure correct feature printing and large process window. It is important to control the imaging behavior of the mask already during mask making. The through pitch and through duty cycle investigation showed that for print pitches below 200nm the phase shift is significantly impacted by imaging effects, 3D mask effects and polarization. At the same time there is a strong correlation between phase shift and exposure latitude, a measure for process window. Largest maximum exposure latitude is achieved for phase shift of 180°. This makes it essential to measure, understand and control imaging relevant phase effects.

Furthermore it was demonstrated that the phase distribution across plate and absolute phase value can be adapted by optimizing the dry etch process. It was shown that large reference feature measurement is not sufficient to control the phase shift of the critical production features which underlines the importance of in-die phase measurement.

Phame<sup>®</sup> enables the industry to control the phase shift in the critical production features and will enable the mask maker to manufacture perfect alt. PSM with large process window.

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