Phame™: a novel phase metrology tool of Carl Zeiss for in-die phase measurements under scanner relevant optical settings

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ABSTRACT

Meeting the demands of the lithography mask manufacturing industry moving toward 45nm and 32nm node for in-die phase metrology on phase shifting masks, Zeiss is currently developing an optical phase measurement tool (Phame™), providing the capability of extending process control from large CD test features to in-die phase shifting features with high spatial resolution.
In collaboration with Intel, the necessity of designing this optical metrology tool according to the optical setup of a lithographic exposure tool (scanner) has been researched to be fundamental for the acquisition of phase information generated from features the size of the used wavelength. Main cause is the dependence of the image phase of a scanner on polarization and the angle of incidence of the illumination light due to rigorous effects, and on the imaging NA of the scanner due to the loss of phase information in the imaging pupil.
The resulting scanner phase in the image plane only coincides with the etch-depth equivalent phase for large test features, exceeding the size of the in-die feature by an order of magnitude.

In this paper we introduce the Phame™ phase metrology tool, using a 193nm light source with the optical capability of phase measurement at scanner NA up to the equivalent of a NA1.6 immersion scanner, under varying, scanner relevant angle of incidence for EAPSMs and CPLs, and with the possibility of polarizing the illuminating light. New options for phase shifting mask process control on in-die features will be outlined with first measurement results.

Keywords: **Phame, phase, phase metrology, scanner phase, polarization, off axis illumination, mask, mask inspection**

1. INTRODUCTION AND MOTIVATION

The use of Phase Shift Masks (PSM) for wafer printing with 193nm scanners of high or even hyper numerical apertures (NA) and especially adapted illumination conditions pushes the resolution limit of optical lithography towards 45nm and 32nm node. The complexity of the mask increases steadily and highly accurate and precise phase control is essential to ensure high yields in production.

Currently the phase is measured using interferometer based metrology tools which are limited to the evaluation of phase in large reference features extending the size of the production features by one order of magnitude. Another common strategy is the use of high resolution AFM tools capable of measuring the etch depth in production relevant features but having the lack of not being able to consider 3D mask effects **[1]**.

Extensive simulations both in Kirchhoff and rigorous regime show that the phase strongly depends on Numerical Aperture (NA) of the scanner, on the pitch of the mask/wafer and on rigorous 3D mask effects. Figure 1 shows the results of a Kirchhoff simulation for an ideal AA-PSM having an etch depth equivalent phase of 178°. It can clearly be seen that the image phase for a scanner with 1.2NA is deviating from the etch depth equivalent phase depending on the print half pitch and on the NA due to the loss of phase information in the imaging pupil of the scanner. Phase jumps occur once additional diffraction orders enter the pupil. Significant changes in the image phase versus the etch depth phase are seen especially for smaller nodes. Only for large features the etch depth equivalent phase coincides with the scanner relevant phase.

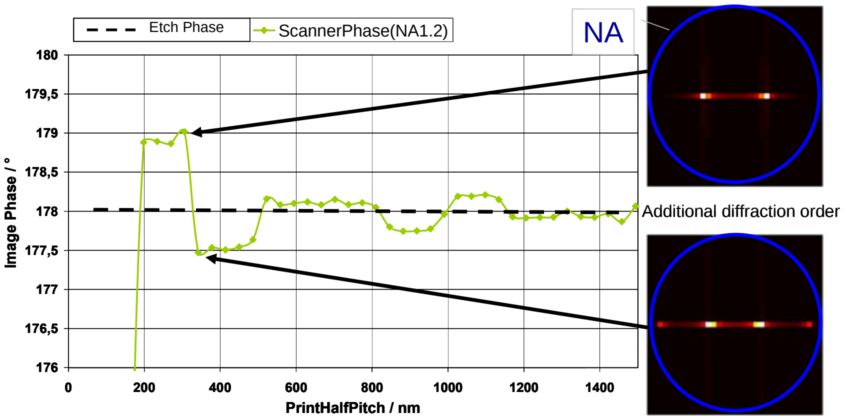

Figure 1: Kirchhoff simulation on AA-PSM showing the pitch and NA dependency of image phase for a NA 1.2 scanner compared to the etch depth equivalent phase

If rigorous effects are taken into account deviations in the scanner phase up to 18° can be observed **[2]**. Figure 2 shows the result of a rigorous simulation using a 1.6NA scanner considering an AA-PSM which has an ideal phase of 180° at the minimum print half pitch of 62.5nm at wafer level. The corresponding etch depth equivalent phase which would be represented by large features results in 162° phase only. Additionally to the impact of 3D mask effects the pitch and NA dependency is to be seen. The resulting scanner phase in the image plane of the scanner only coincides with the etch-depth equivalent phase for large test features, exceeding the size of the in-die feature by an order of magnitude. This illustrates that it is essential to measure the phase in the production relevant features to ensure an accurate printing of the PSM.

Zeiss is developing an optical phase metrology tool – Phame™, providing the capability of measuring phase and transmission in production relevant features with high lateral resolution under scanner relevant optical settings.

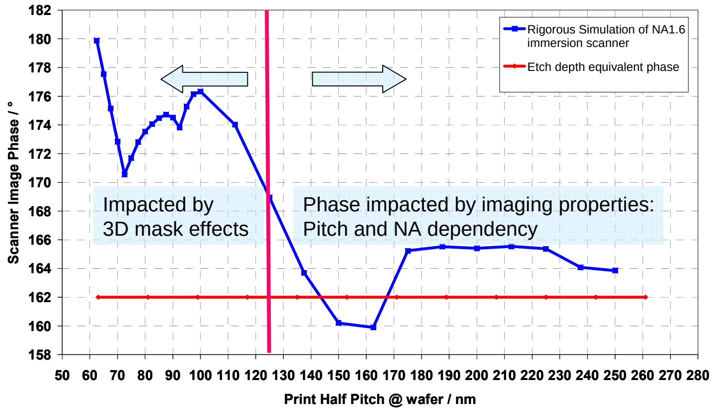

Figure 2: Rigorous simulation on AA-PSM showing up to 18° deviation from image phase for a NA 1.6 scanner compared to the etch depth equivalent phase

2. PHAME^{TM}: PHASE METROLOGY SYSTEM

2.1. Phame^{TM}: Set up and measurement modes

As lithography mask process moves towards 45nm and 32 nm nodes, phase becomes more important as ever. Both alternating and attenuated PSM need precise phase control over pitch and target size.

Zeiss is currently developing an optical phase measurement tool Phame^{TM} providing the capability of extending process control from large CD test features to in-die phase shifting features with high spatial resolution. In collaboration with Intel it was found that it is essential to design the phase metrology tool according to the optical set up of the lithographic exposure tool/scanner to acquire the phase information generated from features sizes in the range of the wavelength. The Phame^{TM} is the first tool world-wide which enables the industry to measure the scanner relevant phase for all types of PSMs in-die, under scanner relevant settings, considering polarization.

The optical beam path of the Phame^{TM} is comparable to that of an immersion scanner with an NA going up to 1.6 (see Figure 3). The 193nm laser combined with a low sigma illumination unit generates a coherent illumination of the mask. The mask is handled face down. On-axis or off-axis illumination can be applied according to the PSM type like AA-PSM, EA-PSM or CPL. Partial coherent illumination settings of a scanner can be sampled in consecutive measurements of adjustable intervals, allowing phase control under scanner relevant illumination settings **[3]**. The high precision imaging optics with a 0.4NA, being 1.6NA scanner equivalent, enables full compatibility to future 193nm immersion scanners down to the 32nm node. Phase information is acquired by phase manipulation and algorithms. The CCD-camera is in the same position as the wafer. Beside in-die phase value the in-die transmission is measured as well.

The Phame^{TM} is based on the newly developed AIMS^{TM}45-193i mechanical platform with a high accuracy air bearing stage and robotic mask handling system with SMIF interface. In combination with the optionally available SECS/GEM capabilities the system is fully suited to match the automation and cleanliness requirements of high-end photomask manufacturing.

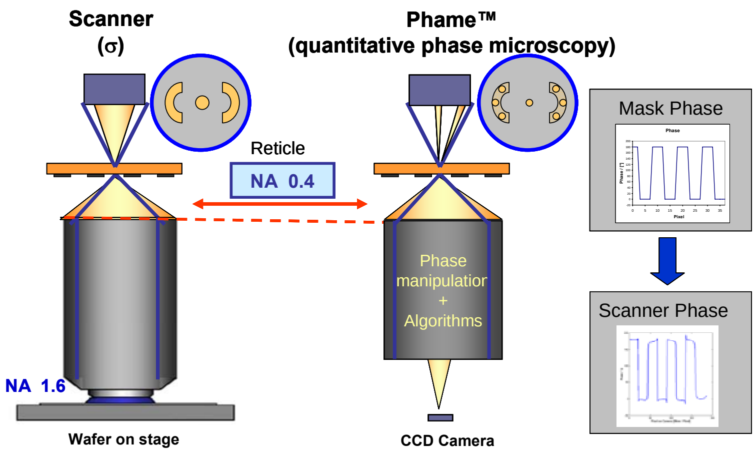

Figure 3: Schematic drawing of Phase Metrology Tool Phame™

Three different measurement modes shown in Figure 4 will be available:

- Manual measurement mode
- Histogram analyses
- Defining area and automatic area detection

Intensity and phase images are acquired during the measurement. The phase profile can be generated manually by choosing a slice along the phase image showing the corresponding phase values over this slice. Another option is the histogram analyses averaging the phase values over the complete measurement area. This can be used for quality assurance after cleaning of EA-PSM. Additionally areas can be defined or automatically detected by the software within the phase image and averaged phase differences can be evaluated. A correlation between the defined areas can be done which is a perfect feature for repair verification or for evaluation of optical proximity effects.

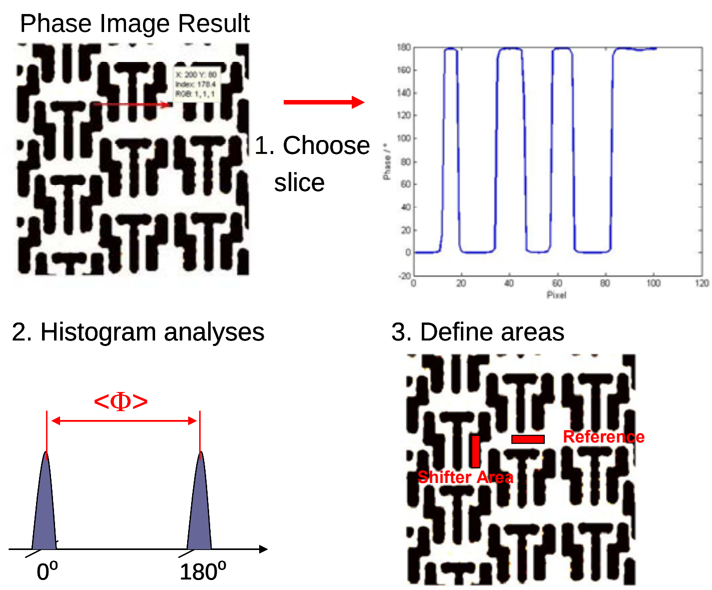

Figure 4: Phame™ measurement modes

2.2. Phame™ measurement results

The Phame™ alpha tool is currently available for on-axis measurements. First measurements have been carried out on test masks with varying feature sizes. Different feature types like line and spaces as well as contact holes have been measured. For the first time, phase images and profiles measured in production relevant features, representing the scanner relevant phase, are presented below.

An Intel AA-PSM test mask having lines and spaces with different pitches and varying duty cycle has been measured. Figure 5 shows the coherent intensity image and the corresponding profile across the image for lines and spaces with 100nm pitch at wafer level. The corresponding phase image and phase profile is shown in Figure 6. Proximity effects due to the finite extension of the phase grating influence the phase value of each line, which further support the necessity of laterally resolved phase measurements.

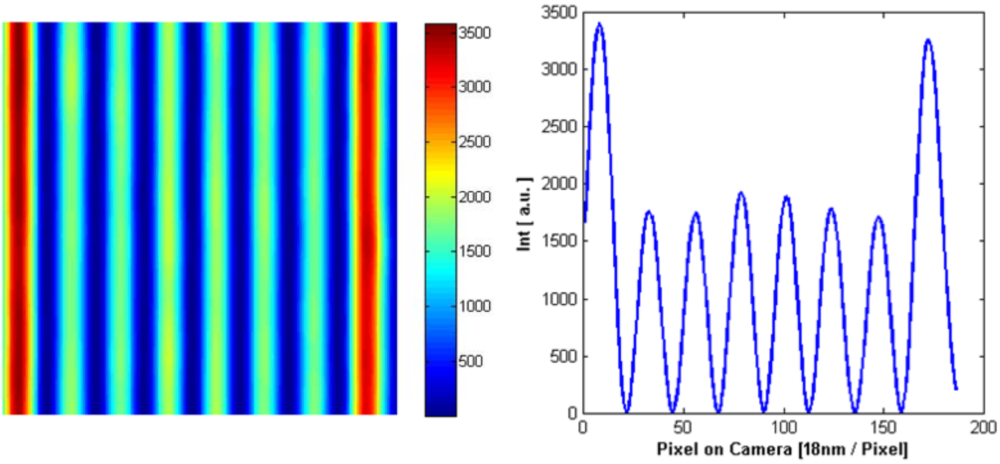

Figure 5: Intensity image and profile of L/S with 100nm pitch at wafer level

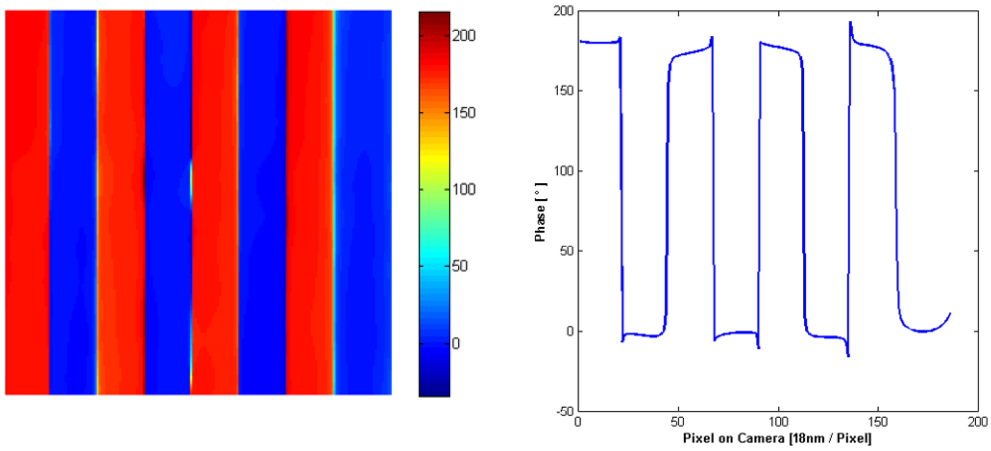

Figure 6: Corresponding phase image and profile of L/S with 100nm pitch at wafer level

2.3. Performance of Phame™

The on-axis alpha tool performance has been evaluated in terms of phase accuracy and phase repeatability.

For large features above 2µm the phase calculated from the etch depth coincides with the scanner relevant phase. Therefore AFM measurements on large feature sizes have been chosen for correlation measurements to investigate the phase accuracy of the Phame™. Features with a line width of 5µm having a target etch depth of 240nm, 180nm and 120nm respectively have been measured on AFM and Phame™. Figure 7 shows that for large feature sizes the phase measured by Phame™ matches very well with the phase which is calculated from the AFM etch depth measurements. The phase difference is well below 1° except for the nominal etch depth of 120nm. This deviation needs to be further investigated.

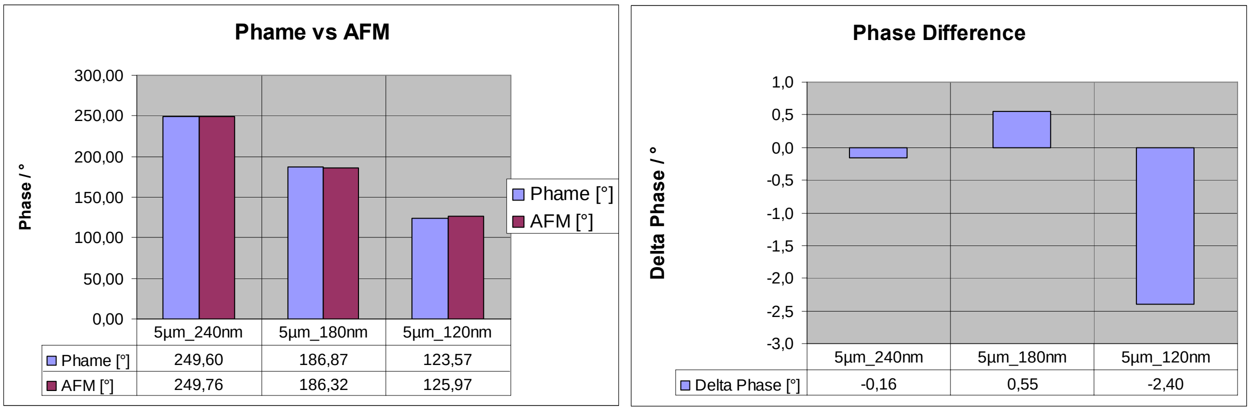

Figure 7: Comparison between phases measured by Phame™ and calculated from AFM depth measurement

For phase repeatability of the Phame™ small features with a pitch of 80nm and 160nm at wafer level on an Intel test mask have been measured. For the 160nm pitch the duty cycle varies from 0.23 (30nm – 130nm) up to 1.67 (100nm – 60nm). Figure 8 shows phase repeatability values between 0.15° and 0.3° for production relevant features. For the 5µm reference feature the phase repeatability is close to 0.1° which is competitive to existing tools.

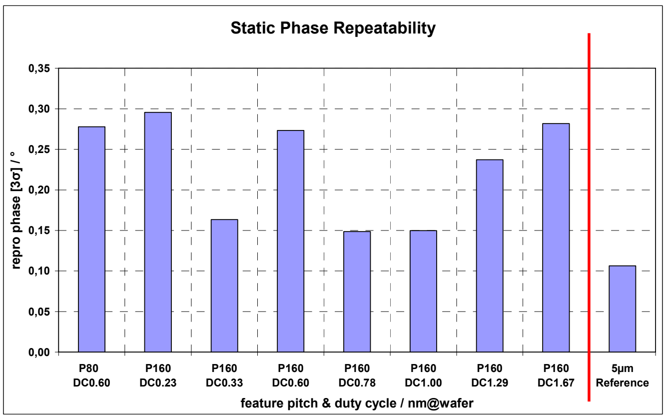

Figure 8: Static phase repeatability of Phame™ for production relevant features and 5µm reference feature

2.4. Phame^{TM} application

193nm lithography moves towards 45nm and 32nm node. Ever shrinking feature sizes require the use of PSM, both EA-PSM and AA-PSM. Due to ever more increasing requirements on PSM features, precise control of phase values is required in order to ensure best CD performance at wafer level steps. As outlined in the previous sections phase measurements in the production relevant features become essential.

Phame^{TM} is the first metrology tool worldwide which enables the industry to specify and to measure phase as well as transmission in in-die features. The integration of Phame^{TM} for in-die phase control and monitoring in production helps to optimize PSM material etch and PSM cleaning process. In-die phase measurements after PSM material etching combined with etch depth measurement to collect further data on etch process will enhance process optimization and production yield. Before and after cleaning in-die phase control provides fast feedback loops for cleaning process optimization.

The capability of Phame^{TM} to study local phase variations within a small region of interest as well as over the whole mask provides lithographers and mask makers a perfect instrument to improve OPC (optical proximity correction) strategies and applications. Furthermore Phame^{TM} can be used to optimize mask balancing and to enhance process window. Additionally, other than contrast information, the Phame™ provides an optimization target parameter value for mask balancing, the scanner relevant phase reaching 180°. Thus integrating Phame^{TM} in R&D and process development helps to shorten the design and manufacturing cycles especially once the mask design becomes more and more complex with tighter nodes.

3. CONCLUSION

Simulations show that the phase in the image plane of the scanner is strongly impacted by the scanner NA, the pitch of the mask and rigorous 3D mask effects, especially for features sizes close to the resolution limit. For accurate printing of a PSM for 45nm or even 32nm node it is essential to measure the scanner relevant phase in the production features to ensure high production yield.

Zeiss in cooperation with Intel has built a phase metrology alpha tool – Phame^{TM} for lateral resolving in-die phase and transmission targeting the 45nm and 32nm node. Phame^{TM} enables the industry to measure:

- In-die phase
- Scanner relevant phase
- Polarization effects on in-die phase

On-axis measurements on tests mask have been carried out. First phase images and phase profiles on production relevant features have been presented.

The Phame^{TM} alpha tool shows phase accuracy below 1°. The static phase reproducibility is between 0.15° and 0.3° for small features and below 0.2° for large reference feature.

The use of Phame^{TM} for fast mask house process control and optimization of process window will help to enhance the yield for production. Implementing the tool for R&D process development to optimize OPC process and mask balancing shortens the time for design optimization

4. OUTLOOK

The phase metrology tool Phame^{TM} is currently being upgraded for in-die phase measurements under varying angle of incidence. Consequently off-axis measurements on CPL masks and EA-PSM will be performed. Furthermore the impact of polarization effects on phase will be investigated. In further studies the use the of Phame^{TM} in-die measurements to investigate optical proximity effects and to optimize mask balancing for accurate wafer printing of 45nm and 32nm node features will be evaluated.

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