Study of rigorous effects and polarization on phase shifting masks through simulations and in-die phase measurements

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ABSTRACT

As lithography mask process moves toward 45nm and 32nm node, phase control is becoming more important than ever. Both attenuated and alternating PSMs (Phase Shift Masks) need precise control of phase as a function of both pitch and target sizes. However conventional interferometer-based phase shift measurements are limited to large CD targets and requires custom designed target in order to function properly, which limits phase measurement.

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, polarization, and on the so-called balancing of the mask for features close to the size of the used wavelength. 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. Additionally, for PSMs generating phase jumps deviating from 180°, the resulting phase in the image plane of a microlithography exposure tool depends on the transmitted diffraction orders through the aperture of the imaging system.

Consequently Zeiss, in collaboration with Intel, has started the development of a laterally resolving Phase Metrology Tool (Phame™) for in-die phase measurements.

In this paper we present this optical metrology tool capable of phase measurement on individual line/spaces down to 120nm half pitch. Alternating PSM, Attenuated PSM, Cr-less masks were measured on various target sizes and simulations were performed to further demonstrate the capability and implication of this new method to measure the scanner relevant phase in-die, taking into account NA, polarization, and rigorous effects.

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

1. INTRODUCTION AND MOTIVATION

Due to ever more stringent requirement on photomask features, PSMs (phase shift mask) are now widely used as well as traditional binary photomasks. Both EAPSM (embedded attenuated PSM) and AAPSM (alternating aperture PSM) require precise control of phase values in order to ensure best CD performances at wafer lithography steps. This includes measurement of phases post PSM material etch, and also measurement of etch depth to collect further data on etch.

Traditionally, photomask phase measurement was done using interferometer-based tools which requires specific target shapes and relatively large target sizes in order to function properly. Measurement of small features (<600nm) for example, has been very challenging using interferometer based phase measurement tools. Also with 65nm node and beyond, phase tends to vary widely at near the resolution limit, so there is a strong need for measuring phases directly from targets with small CD sizes, located in the device region instead of in the mask perimeter.

This paper proposes and demonstrates a new method of measuring phases, capable of measuring targets far smaller than what current phase metrology tools are capable of, and can meet phase measurement requirements for 45 and 32nm process generation. Overview of phase metrology system is given, and its repeatability capability and comparison to AFM based tool was made. Also data was compared against RCWA (rigorous coupled wave analysis) results created from CD SEM and AFM depth measurement results. Also it is possible to measure variation of phases from targets within given field of view, instead of obtaining one phase value from given target. This allows study of local phase variation within a small region of interest as well as over the whole mask. It is expected to replace existing phase measurement tools and used for in-die phase measurement of various types of PSM structures.

2. IN-DIE PHASE MEASUREMENT ON AAPSM

In traditional phase measurement methods, targets were usually placed in mask perimeter area called 'frame', which does not get printed on actual wafers. Since this method does not consume any device region, it was considered advantageous in terms of saving spaces on devices. However, with ever tightening phase measurement requirements it has become necessary to measure phases directly from the device region which represents real device feature sizes and shapes **[1]**. Traditional phase metrology methods are not very effective in handling this in-die targets, since it generally requires targets to have specific shape/size. New method is much more flexible, thus allowing measurement of targets with arbitrary sizes and shapes without burden of complicated pre-processing steps. This ability of measuring 'in-die' target is another advantage this method has over the traditional methods.

2.1. Test Mask Design

In this study, an AAPSM plate containing nested lines/spaces of various duty cycles and pitches were prepared. Intel's 65nm generation technology was used on it, and for this test we used targets with pitches (= two space CD + two line CD) ranging from 160nm ~ 1000nm (wafer level dimension). Smallest line measured is 30nm, and smallest space was 32.5nm (wafer level). Duty cycles were varied from 1:1 up to 1:4. Targets were measured on AFM for etch depth, on CD SEM for CDs. Large targets were also measured on conventional interferometer-based tools.

2.2. Phase Metrology System

The use of Phase Shifting Masks (PSM) combined with especially adapted illumination settings and high or even hyper NA scanners pushes 193nm lithography down to 45nm node and even below. Masks and mask processes become more and more complex. It is essential to characterize all relevant mask parameters accurate and precise. 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. The Phame^{TM} is the first tool world-wide which enables the industry to measure the scanner relevant phase for all types of PSM's in-die under scanner relevant settings considering polarization.

The optical beam path is comparable to that of an immersion scanner with an NA going up to 1.6 (see Figure 1). 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. The high precision imaging optics with a 0.4 NA, being 1.6 NA 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.

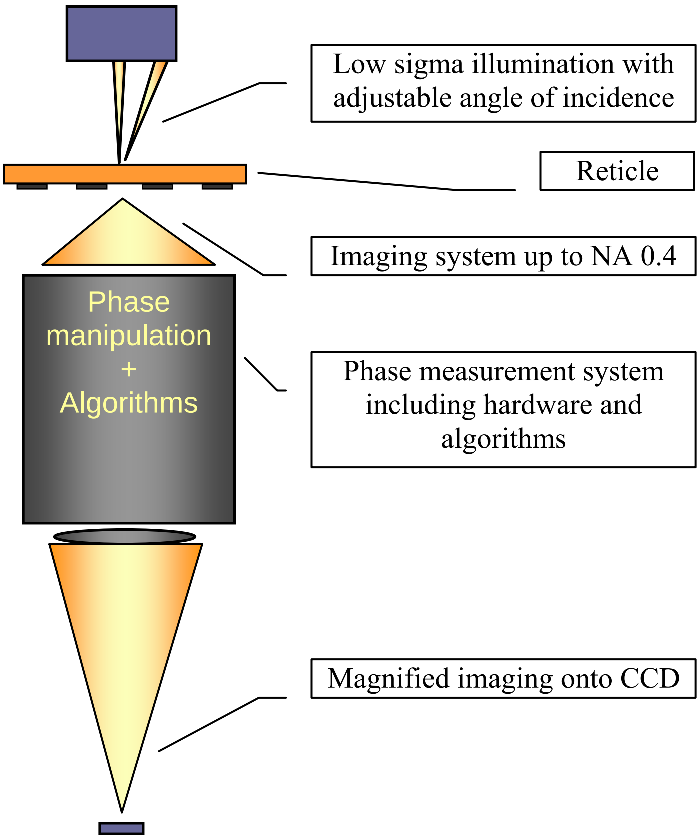

Figure 1 Schematic drawing of Phase Metrology Tool Phame^{TM}

2.3. Performance of Phase Metrology System

The Phame^{TM} alpha tool is available for on-axis measurements. Tool performance has been evaluated for phase accuracy and phase repeatability.

For large features above 2µm the phase calculated from etch depth coincides with the scanner relevant phase. Therefore AFM measurements have been chosen to investigate the phase accuracy for the Phame^{TM}. Features with a line width of 5µm having an etch depth of 240nm, 180nm and 120nm respectively have been measured on AFM and Phame^{TM} (Figure 2).

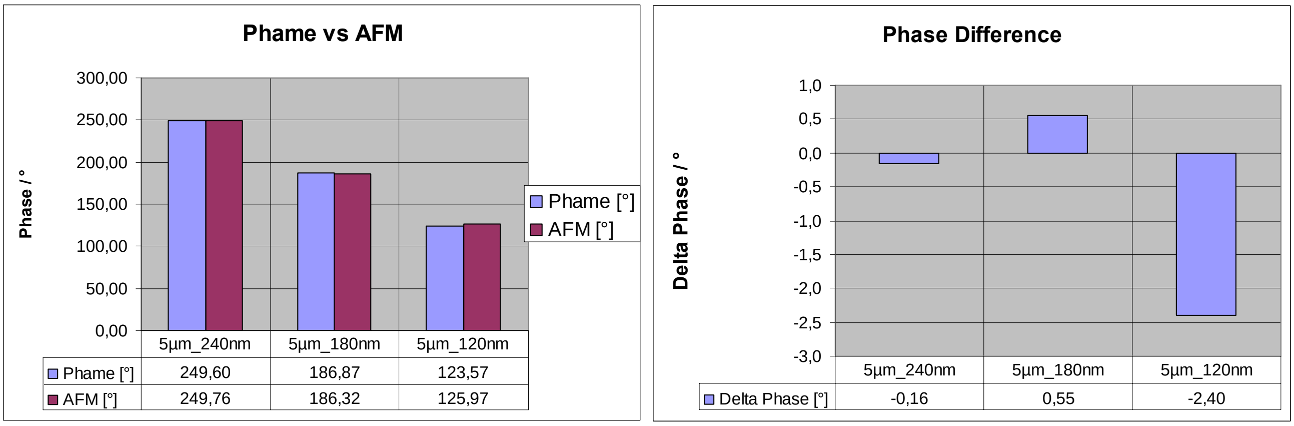

Figure 2: Comparison between phases measured by Phame^{TM} and calculated from AFM depth measurement on large features

The phase repeatability has been evaluated on large features as well as on small features. For the large features the 5µm structures with the different etch depths have been used. Small features have been measured on an AAPSM evaluating wafer level print pitches from 160nm down to 80nm with varying duty cycle (Figure 3).

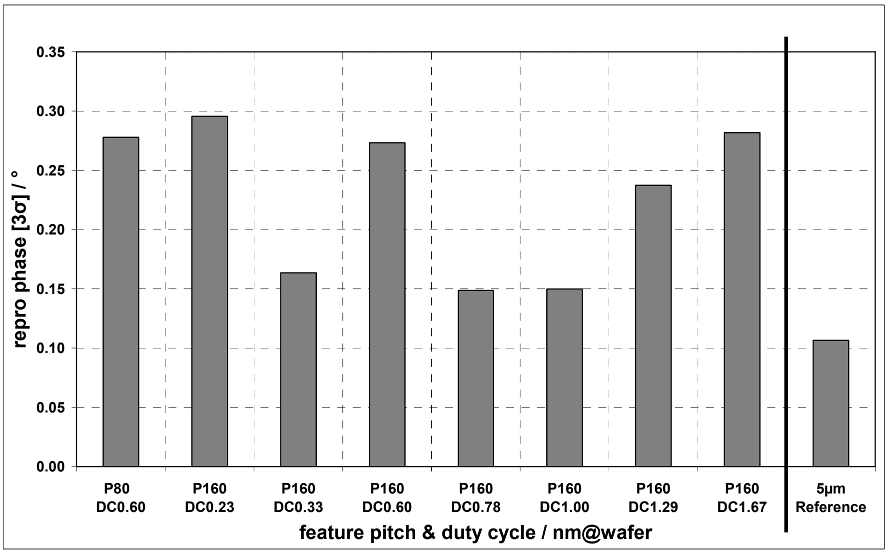

Figure 3 Static reproducibility of Phame™ on small features (P: pitch, DC: duty cycle) and on a 5µm reference feature

3. RESULTS AND DISCUSSION

3.1. Kirchoff Simulations on phase behaviour through pitch and duty cycle

In order to understand the behaviour of the scanner relevant phase occurring in the image field of a scanner, simulations had been performed both in a rigorous and a Kirchhoff regime, assuming an unpolarized illumination system. The Kirchoff simulation assumes the mask near field to be perfectly reaching an edge depth equivalent phase separating the impact of the aperture of the imaging system from rigorous effects. Figure 4 shows the phase behaviour through pitch of an ideal AAPSM in a Kirchhoff simulation. Assuming an etch depth equivalent near field phase shift of 178° it can bee seen that the scanner relevant phase coincides with the near field phase for large features exceeding the size of the used wavelength by an order of magnitude but increasingly oscillates around the near field phase for decreasing feature sizes.

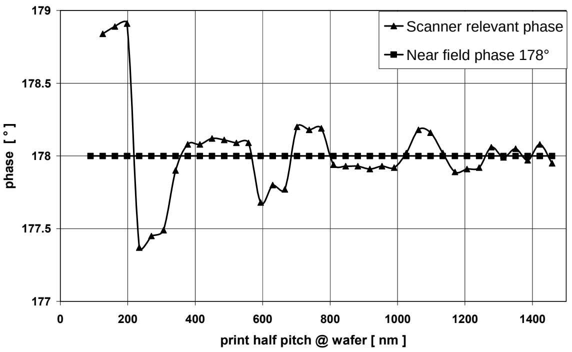

Figure 4 Kirchhoff simulation of scanner (NA1.6) relevant phase through pitch for an AAPSM of etch depth equivalent (near field) phase of 178°

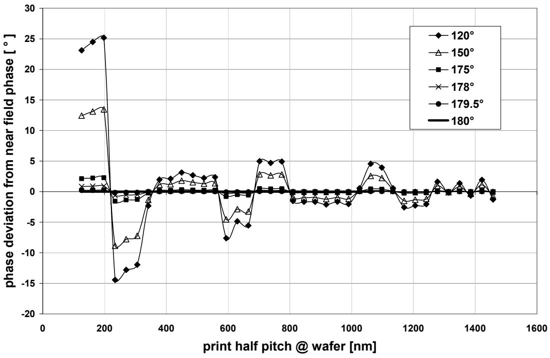

Figure 5 Kirchhoff simulation for scanner relevant phase through pitch for an AAPSM of varying etch depth equivalent (near field) phase

The Oscillation effects are caused by loss of transferred information due to the aperture stop of the imaging system. Oscillation points occur when additional diffraction orders are passing through the imaging aperture. As can be seen in Figure 5 , the phase oscillations increase for near field phase shifts increasingly deviating from 180° and vanish at 180° because of the diffraction spectrum becoming

3.2. Rigorous Simulations and intensity balancing

Researching the rigorous effects of an AAPSM **[2]** a simulator using an RCWA solver had been used. First the used 3D topography of the mask feature was optimized to generate 180° phase shifts in the image field for a mask pitch of 500 nm printing a line width at waver level of 62.5 nm. The optimized mask parameters where set to an etch depth fequivalent phase of 162°, an undercut of the quartz etched line of 12nm on each side and a chrome line duty cycle of 0.67. These parameters were held constant for simulations of varying pitch. In order to see the deviations of 3D mask effects from the phase oscillations caused by the imaging aperture, the through pitch behaviour in a Kirchhoff regime is plotted in Figure 6 as well. For small features approaching the resolution limit of the imaging system (here mask NA 0.4) rigorous mask effects cause phase deviations up to 9°.

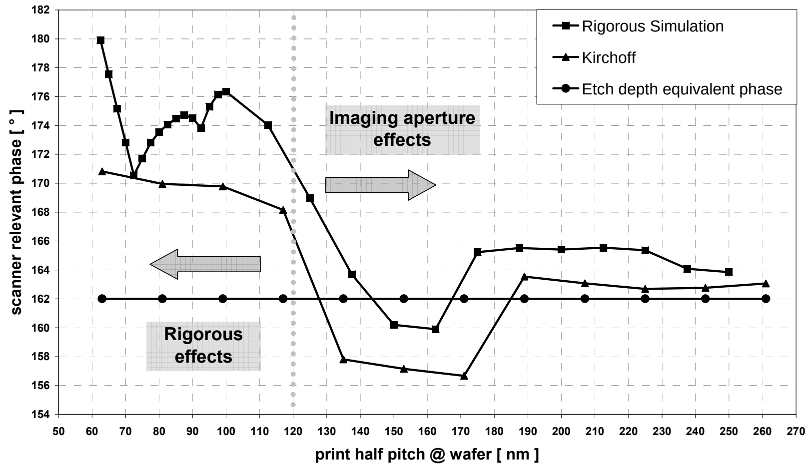

Figure 6 Kirchhoff and rigorous simulation of scanner relevant phase for an AAPSM of etchd depth equivalent. (near field) phase of 162° for varying pitch. Feature optimized to have a scanner equivalent phase of 180° at 62.5nm print half pitch

For AAPSM intensity balancing effects are of great impact on process control. Due to rigorous diffraction effects the peak intensities of etched (π) and un-etched (0) lines deviate from one to another causing so-called 0/π CD variations in the image. The peak intensities and consequently the printed CDs of neighbouring lines show mostly opposite behaviour through focus for 0 and pi apertures on the mask **[3]**. First the scanner relevant phase for coherent illumination as measured on the Phame™ tool was simulated for two CDs (50 nm and 40.5nm @ wafer) with varying etch depth, plotted in Figure 7 as the etch depth equivalent phase on the x axis. Simulating the scanner image under partial coherent circular illumination ($\sigma_{Illum} = 0.3$) for the same topographies and taking the focal 0/π CD variance as a criterion for intensity balancing, the optimized scanner image phase of 180° was found at different etch depths for both lines leading to minimized focal 0/π CD variances in the scanner image.

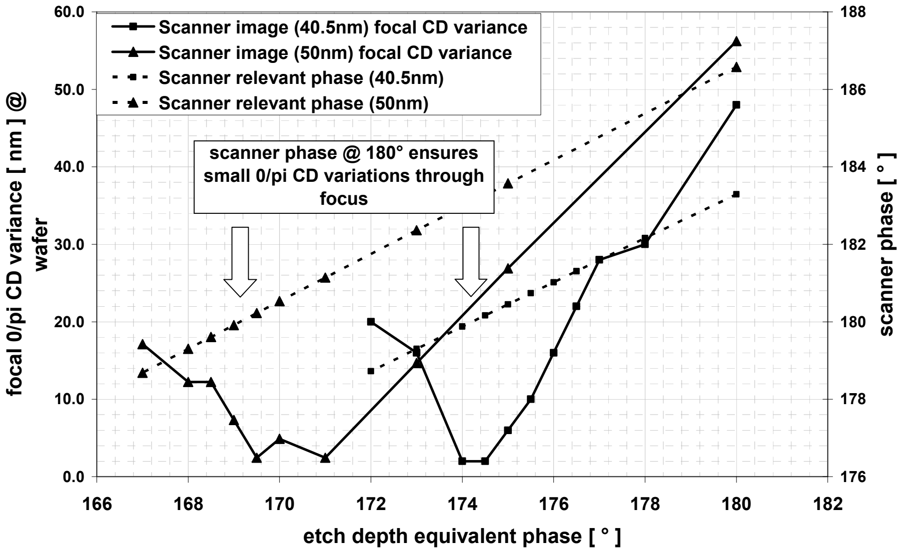

Figure 7 Broken lines / right y-axis: Rigorous simulation of scanner relevant phase for two feature sizes (40.5nm & 50nm) over varying etch depth (etch depth equivalent phase); Solid lines / left y-axis: Rigorous simulation of 0/π focal CD variance of neighbouring lines resembling intensity balancing qualities of the mask for a $\sigma_{Illum} = 0.3$ scanner (NA1.6) image; The minimum CD variance (maximum process window) coincides with a scanner relevant phase of 180°

3.3. Phame™ phase measurements and comparison to rigorous simulations

The capability to measure in-die scanner relevant phase on the phase metrology tool Phame™ was now evaluated using the AAPSM test reticle (Sec 2.1) manufactured by Intel. Test measurements were performed for varying duty cycle from 0.23 (30nm-130nm) to 1.67 (100nm-60nm) at a constant pitch of 160nm at wafer level and for varying pitch from 100nm to 480nm at wafer level at a constant duty cycle of 1. A topography model of the mask was generated to simulate the expected phase. To further increase the accuracy of the simulation, AFM and CD SEM measurements were held out on the test features generating more realistic 3D mask topographies as simulation input.

Figure 8 shows the image and it's cross section of the coherent intensity and the Phame™ phase of one test feature, indicating, that the used model of an infinite grating used as model in a rigorous coupled waves simulator cannot be applied without errors.

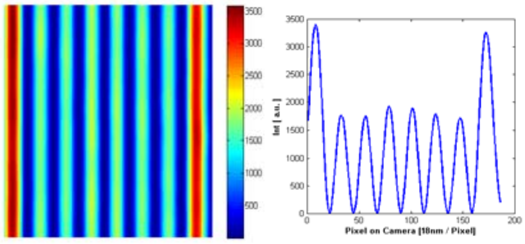

Figure 8 Left: low sigma intensity image of mask test feature; Right: horizontal cross section of intensity image; Outer lines showing increased intensities due to proximity effects

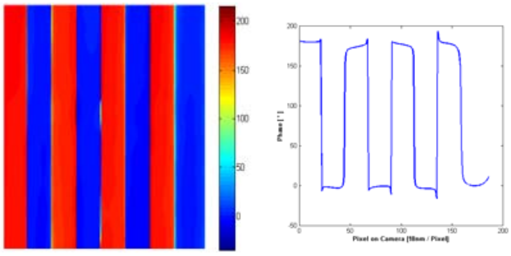

Figure 9 Left: Phame™ phase image of in-die mask test feature; Right: horizontal cross section of phase image; Proximity effects cause deviations of local phase shifts, allowing only the middle line to be evaluated against simulations

Defining the whole mask feature of 8 lines as period of the mask in the simulator model and infinitely extending the period did not correlate with the coherent images of the Phame™ tool. As can be seen in the cross section of the measured phase of the Phame™ (Figure 9), the finite size of the phase grating causes proximity phase effects, which change the phase shift value at the outer lines.

In order to avoid these proximity effects in comparison to a simulated, infinitely extended line space phase grating, only the middle phase shift was evaluated in the Phame™ phase image, accepting deviations caused by asymmetries in the grating topography.

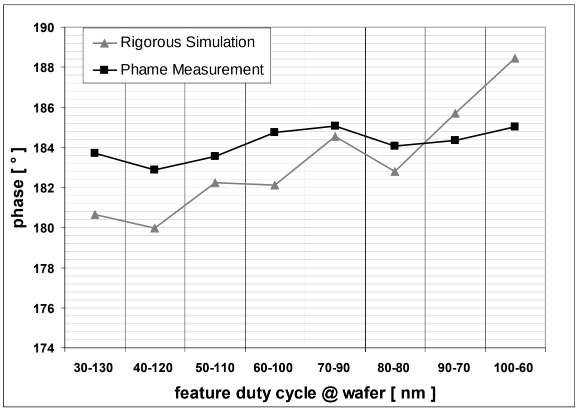

Figure 10 Phame™ phase measurements over duty cycle on in-die mask test features against rigorous simulation; Phase effects up to 3°

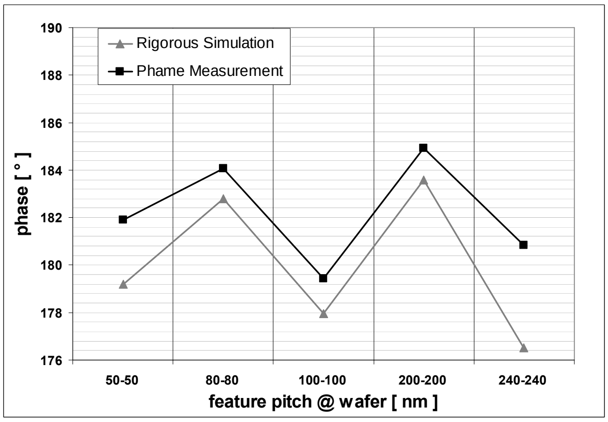

Figure 11 Phame™ phase measurements over pitch on in-die mask test features against rigorous simulation Phase effects up to 7°

The results are stated in Figure 10 for varying duty cycle and in Figure 11 for varying pitch. The measured scanner relevant phase at the Phame™ coincides well with the simulations especially for the through pitch behaviour, indicating up to 7° changes in the phase shift value over pitch and a slightly deviating behaviour from simulations through duty cycle with changing phase shifts in a 3° range. Possible errors are simplified models of the 3D geometries, proximity effects, which cannot be accurately simulated by the RCWA simulator and the alpha tool status of the Phame™ tool, still allowing improvements in imaging and hardware stability.

4. CONCLUSION

This paper explained through simulations the phase behavior in the image field of a scanner, pointing out the strong impact of rigorous effects and effects generated by the imaging aperture on the scanner relevant phase, especially for features close to the resolution limit. In order to use phase measurements for AAPSM mask balancing, rigorous simulations had been performed, showing the larges process window for a scanner relevant phase of 180°. For in-die process control on phase shifting masks, Zeiss, in collaboration with Intel, have developed an optically resolving phase metrology tool Phame™. First in-die phase images were acquired. On varying duty cycle and pitch of the mask feature, the capability of the Phame™ to measure in-die phase was evaluated, proofing good correlation with rigorous simulations, derived from mask topography models according to AFM and CD-SEM measurements. Strongest phase effects were encountered for pitch variations causing phase differences up to 7°.

5. OUTLOOK

In further studies, the use of Phame™ in-die phase measurements as parameter for optimizing mask balancing and consequently mask yield will be evaluated.

The development of the phase metrology tool Phame™ is currently in the process of enabling the hardware capability for measuring in-die phase of varying angle of incidence. Consequently off-axis measurements on CPLs **[4]** and EAPSM will be performed. For these mask types, intentional and non-intentional proximity effects on phase are of greater interest and will be investigated.

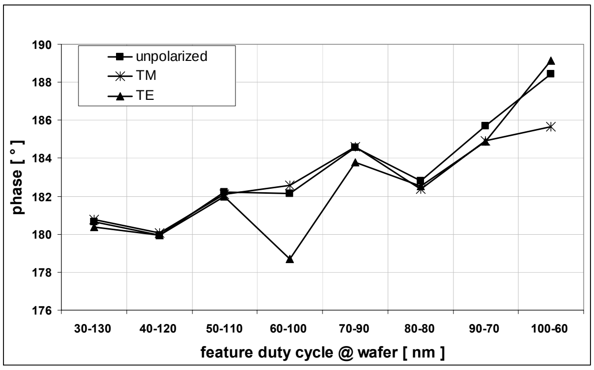

Figure 12 Rigorous simulation of scanner relevant phase over duty cycle with changing illumination polarization; Phase effects of polarization up 4°

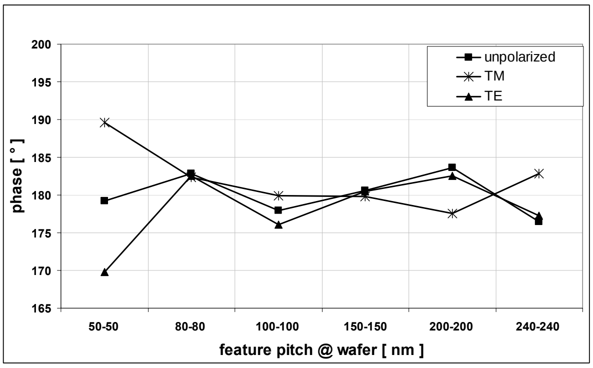

Figure 13 Rigorous simulation of scanner relevant phase over pitch with changing illumination polarization; Phase effects of polarization up 20°

Additionally to varying angles of incidence, the polarization direction of the illuminating light will be adjustable for on- and off-axis measurements. Rigorous simulations on the features described above for changing polarization of the illuminating light as stated in Figure 12 and Figure 13 lead up feature dependant phase shift variations of up to 20°. **[4]**

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