

Phame® - phase measurements on 45nm node phase shift features

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ABSTRACT

The extension of optical lithography to the 45nm node and beyond goes along with increased mask complexity and tightening of specifications. The proper use of PSM becomes more and more important and the phase shift needs to be quantified exactly in order to achieve accurate CD printing results during wafer processing. The methods currently available run into limitations because they are not able to consider diffraction limitations caused by scanner NA and mask pitch, as well as 3D mask effects. In the transition to the 45nm node and beyond, these effects play an important role and need to be considered. Zeiss' new phase metrology system Phame® captures diffraction limitations, rigorous effects (i.e., a failure of the Kirchhoff approximation), and polarization effects. The new phase metrology system measures the phase shift in any in-die feature of the active mask area for on- and off-axis applications with high spatial resolution.

This paper is focused on through pitch and through duty cycle measurements on an alternating PSM. Phame® measurements will be compared to AFM measurements. Additionally rigorous 3D simulations have been performed for different CD, varying pitch and varying duty cycle using coherent illumination with polarization. The simulation results will be compared to Phame® measurement results.

Keywords: Phame, phase shift, phase metrology, scanner phase, alt. PSM

1. INTRODUCTION

Lithography has moved into 45nm node and will soon go into 32nm node. The industry faces the challenge that mask complexity increases steadily, mask specifications tighten and process control becomes extremely important. The use of PSM (Phase Shift Mask) is essential. Both alternating and attenuated PSM require accurate and precise phase control to ensure best CD printing performance at wafer lithography steps.

Phase shift measurements have so far been limited to either 1) measuring etch depth using AFMs, or 2) measuring large-feature phase using interferometer-based metrology tools. With CD going down to 45nm feature imaging effects and feature profile impact the phase shift in the image plane. This effect is increasing with smaller feature sizes. Therefore currently available phase shift measurement methods run more and more into limitations because they are not able to capture these effects.

Carl Zeiss SMS has developed a new phase metrology system – Phame® that overcomes the limitations of currently existing tools. Phame® measures the phase shift with high spatial resolution in any kind of production feature down to 120nm at mask for on- or off-axis application.

This paper reports phase shift measurements through pitch and through duty cycle and compares the measurement results to AFM measurements and to rigorous simulation.

2. PHAME[®] - TOOL SET-UP

The optical beam path (Figure 1) of the new metrology system allows actinic phase measurements of 193nm photomasks with a mask side NA up to 0.4, which is 1.6NA scanner equivalent at the wafer. This enables full compatibility to future 193nm immersion scanners down to the 32nm node.

The 193nm laser is combined with a low sigma illumination unit which generates a coherent illumination (i.e. single source point) of the mask. The mask is handled face down similar to the scanner. 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. 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) [1]. The phase shift can be measured laterally resolved in any kind of production feature inside the active mask area (Figure 2). In addition to in-die phase shift, the tool also measures in-die transmission.

The tool has full 45nm node and beyond production process capability. The operator GUI allows easy production use. Furthermore the tool has full automation capability including SECS/GEM and SMIF.

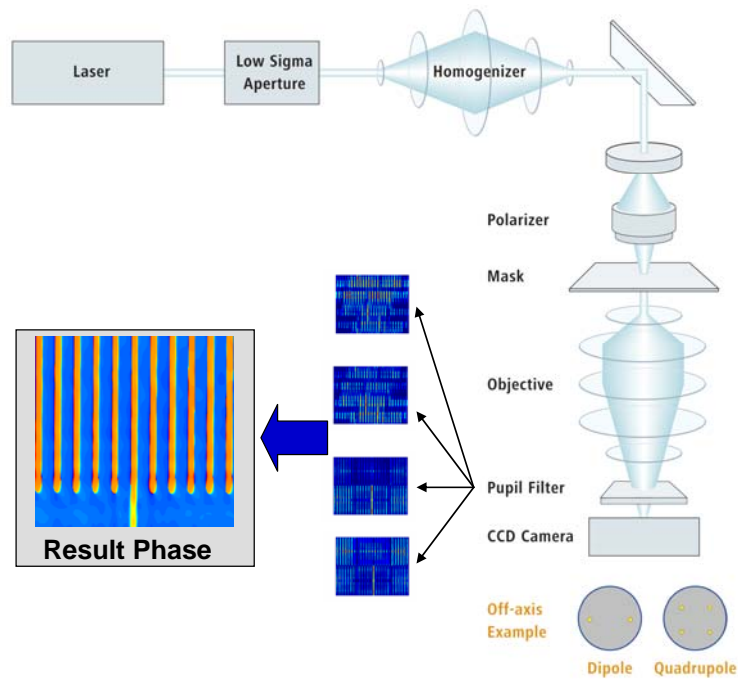


Figure 1: Optical beam path of Phase Metrology System – Phame[®]

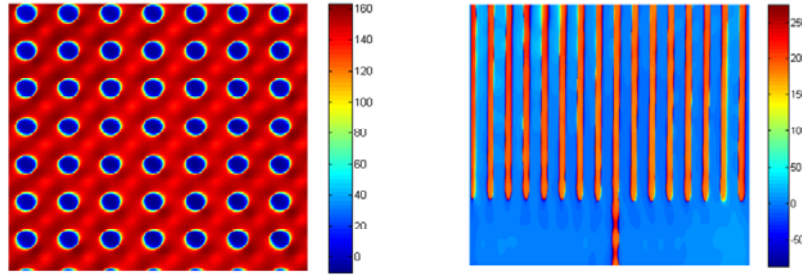


Figure 2: Laterally resolved Phase Images: (a) contact hole array, (b) 45nm lines/spaces

3. SIMULATION

For a comparison to the Phame[®] measurement rigorous 3D simulations have been performed using the simulator EM-suite of Panoramic Technology Inc., which is based on the Finite-Difference Time-Domain method. For this, coherent illumination (193nm) with a single source point and y-polarization (along the mask structure) 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 particular measurement. A fixed pi-space bias (20nm on wafer) accounts for balancing during wafer printing as reported in [3]. Moreover, the etch depth used as input in the simulator has been obtained by extrapolating AFM data, measured on 10 CDs and 11 monitoring sites to all necessary CDs (Figure 3).

Since a phase measurement shows extremely sensitive focus dependencies, it was necessary to use the same best-focus algorithm as implemented in the Phame[®] tool to determine the best-focus plane in the simulation.

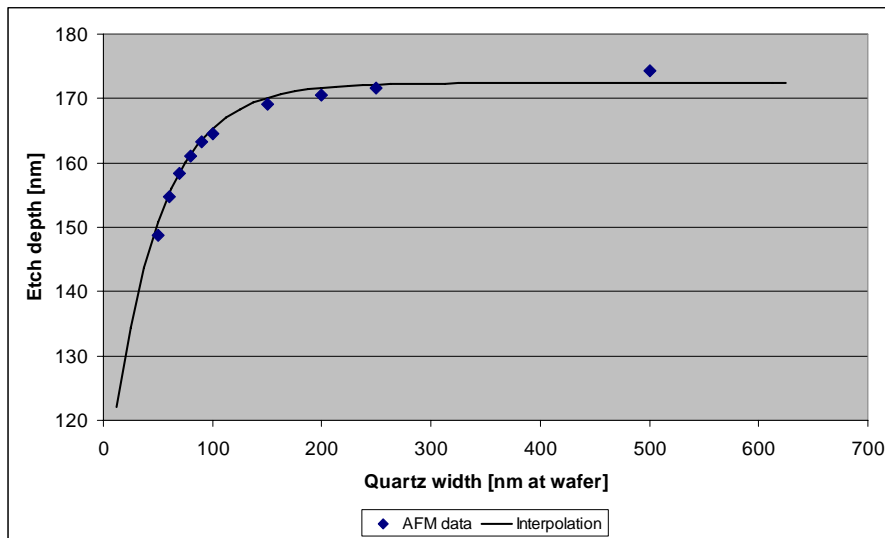


Figure 3: AFM data for etch depth through CD for a 1:1 structure. The data has been averaged over 11 monitoring sites. For the interpolation, the function $f(x) = a_1 - a_2 \exp(-a_3 x)$ has been used, which results in the parameters $a_1 = 0.1724$, $a_2 = 0.0668$ and $a_3 = 5.6279$. This yield all etch depths used as input for the simulations.

4. RESULTS AND DISCUSSION

4.1. Test mask

For investigation of phase shift behavior an alt. PSM was used which was provided by IMEC. The test mask contains a variety of different test modules and feature types. For investigation of phase shift behavior test modules have been used containing lines/spaces features going down to 37.5nm CD at wafer level. The pitch varies from 90nm up to 2 μ m (wafer scale). This matrix allows the combination of different CD's, different pitches and different duty cycles. Throughout this paper, duty cycle is defined as line width (Cr) divided by print pitch. In addition to that different etch biases for the pi space can be chosen.

Additionally to the lines/spaces module a so called etch depth monitor cell is available, which contains 1:1 lines/spaces with a CD starting from 40nm in steps of 10nm to 100nm, then in steps of 50nm to 250nm, and 500nm (wafer scale). These etch monitors are used to measure the etch depth by AFM.

4.2. Comparison of Phame[®] measurement to AFM measurement through pitch at constant duty cycle

In a first step phase shift measurements have been performed in the etch depth monitor, using maximum NA of 1.6 at the Phame[®]. The measurement results have been compared to phase shift results generated from AFM depth measurements according to equation:

$$\Phi = 2\pi d(n-1)/\lambda,$$

where Φ is the phase angle, d the thickness measured by AFM, n the refractive index of the quartz material and λ the lithography wavelength. The AFM depth measurements have been provided by Toppan Printing.

Figure 4 shows the comparison between Phame[®] and AFM measurement. In this plot the averaged values over 11 depth monitors for each CD are plotted. An excellent correlation is found with differences below 2° for line width going down to 80nm at wafer level. As expected the deviation in-between the two measurements is increasing up to 5° for line width below 80nm. At these feature sizes 3D mask effects are becoming important, which can not be captured by AFM measurements. This shows impressively that Phame[®] can measure the phase shift optically and captures additionally the rigorous mask effects.

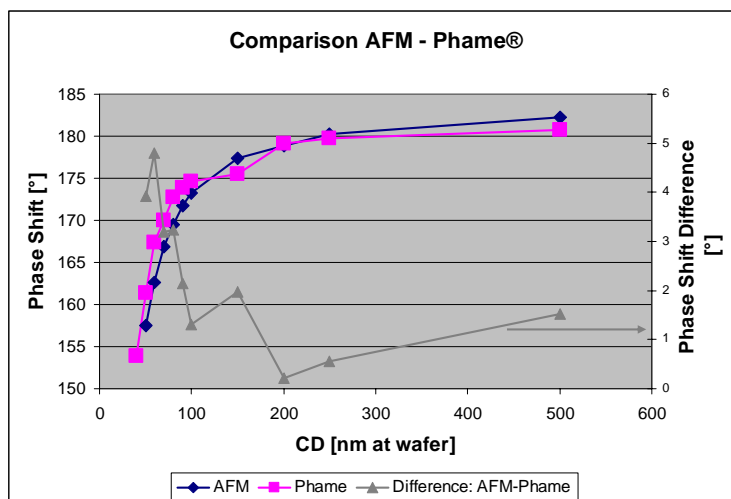


Figure 4: Comparison between phase results measured by Phame[®] and calculated from AFM etch depth measurements

4.3. Phase behavior through pitch at constant CD

Next, the image phase behavior through pitch at constant CD was measured with the Phame[®] tool and compared to rigorous simulations. A NA of 1.2 and y-polarization has been used for simulation and measurement. For the 45nm node the result is shown in Figure 5. The image phase shift is plotted against the print pitch at wafer. In the regime of small pitches the phase shift differs from 180° as expected from the AFM etch depth data, for larger pitches it converges to 180°. The difference between the measurement and the rigorous simulation is less than 2° for pitches larger than 120nm at wafer. The phase signature in this regime shows an impressive agreement. However, for smaller pitches the difference increases up to 6°, which is likely due to the insufficient knowledge of all input parameters in the rigorous simulation. A simple etch depth based simulation of the image phase seems not to cover all rigorous effects of the mask, as measured by Phame[®].

To illustrate NA effects, the pitches where new diffraction orders enter the pupil have been marked by triangles in Figure 5. Since an alt. PSM has strongly suppressed even diffraction orders, those are shown as open triangles.

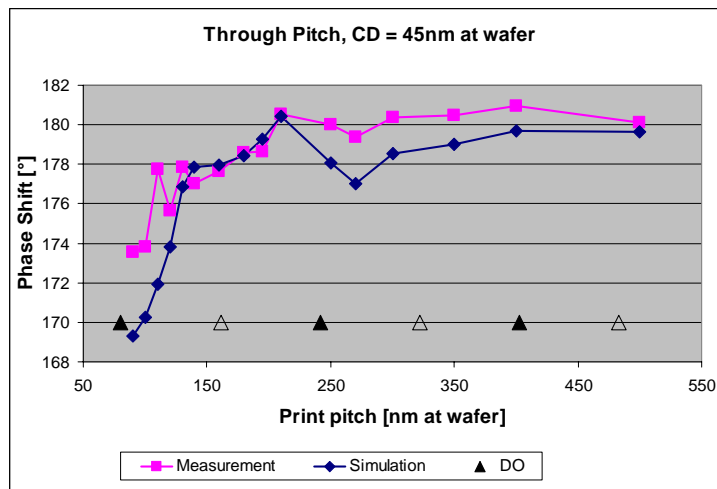


Figure 5: Image phase shift through print pitch for a constant line width of 45nm at wafer. The triangles mark the pitches which introduce new diffraction orders (DO) in the pupil (filled triangle: even DO, open triangle: odd DO).

For an alt. PSM, a phase value off 180° is combined with increasing amplitude of the 0th diffraction order. This has consequences to the printing process: depth of focus decreases and the process window becomes smaller [2]. Note that the image phase signal provides this kind of information for the whole field of view simultaneously.

A similar result is obtained when considering a larger CD of 110nm at wafer through pitch (Figure 6). Again, the phase signatures of measurement and simulation agree and the difference is below 2° for pitches larger than 200nm at wafer. For quartz line width above 80nm the deviation corresponds to the same order of magnitude as in the 45nm case. For pitches below this value one enters the rigorous regime and the difference between measurement and simulation increases up to 6° due to insufficient knowledge of all mask parameters.

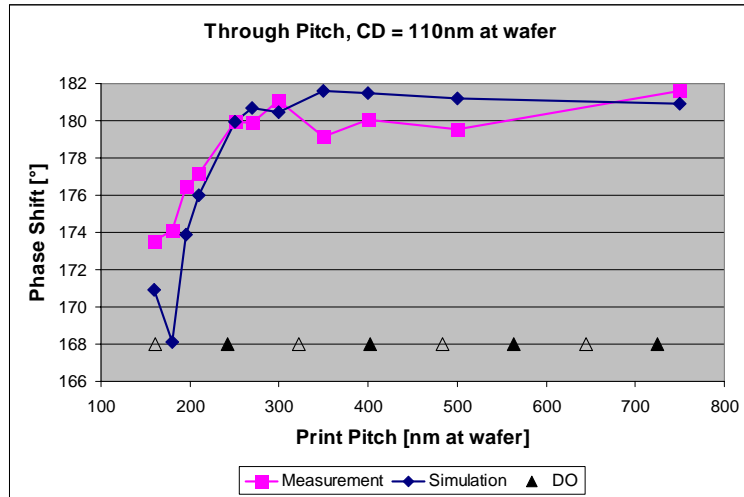


Figure 6: Image phase shift through print pitch for a constant line width of 110nm at wafer. The triangles mark the pitches which introduce new diffraction orders (DO) in the pupil (filled triangle: even DO, open triangle: odd DO).

4.4. Phase behavior through duty cycle at constant pitch

To complement a systematic phase evaluation of an alt. PSM, the image phase shift through duty cycle for two constant pitches have been measured. Again, a NA of 1.2 has been used. Figure 7 shows the result for a print pitch of 90nm at wafer for duty cycles from 0.42 up to 0.72. Moreover, in this measurement the polarization has been switched from y-polarization (Figure 7a) to x-polarization (Figure 7b). In both plots, the image phase decreases for increasing duty cycle and this signature is perfectly reproduced by the rigorous simulation. However, there is a constant offset of $\sim 5^\circ$ between the y-polarization measurement and simulation. Since the 90nm pitch is in the regime of strong rigorous effects, the order of magnitude of this offset agrees with the through-pitch measurements shown above and it is again due to insufficient knowledge of mask parameters. For x-polarization, stronger rigorous effects are expected since the electrical field oscillates perpendicular to mask structures, and this may explain the slightly larger differences between measurement and simulation in Figure 7b.

In comparing y-polarization and x-polarization measurements, a phase shift difference of up to 5° is observed that is reproduced both in the simulations and in the measurements. Thus, it becomes obvious that Phame[®] correctly measures polarization effects and the corresponding signatures.

For a duty cycle of 0.45, the phase difference to 180° becomes minimal. As a consequence, we expect the best printing behavior for this duty cycle [2]. Further analysis and comparison to wafer print data will be performed in the near future to prove this. For larger duty cycles, the phase shift differs considerably from 180° , thus the 0th diffraction order becomes significant and depth of focus decreases.

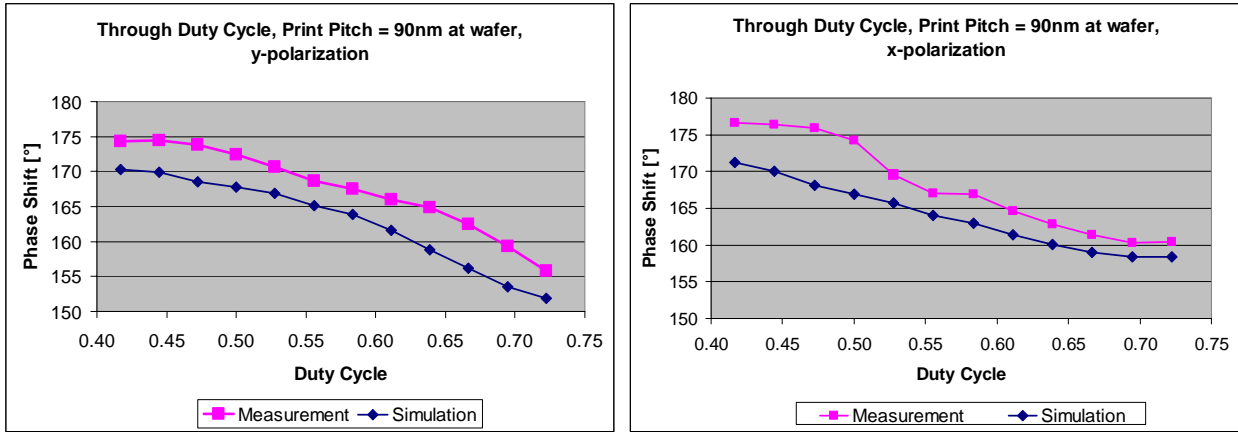


Figure 7: Image phase shift through duty cycle for a constant print pitch of 90nm at wafer. (a) y-polarization (b) x-polarization

For a larger pitch of 250nm at wafer, we expect from the through-pitch evaluations a tighter agreement with the simulation since rigorous effects are not as dominant as for small features. The result for a duty cycle variation from 0.15 up to 0.45 is shown in Figure 8. Indeed, the Phame[®] measurement shows a difference of less than 1° to the rigorous simulation. Both signatures exhibit an oscillating behavior through duty cycle, in which maxima and minima are slightly shifted. For this print pitch of 250nm, the image phase variation is less than 1.5° over all measured duty cycles, indicating a much better printing behavior through duty cycle than for the small pitch. Again, the data point for duty cycle = 0.18 in Figure 8 has been also measured in the through-pitch evaluation for the 45nm node and both measurements agree up to 0.1°.

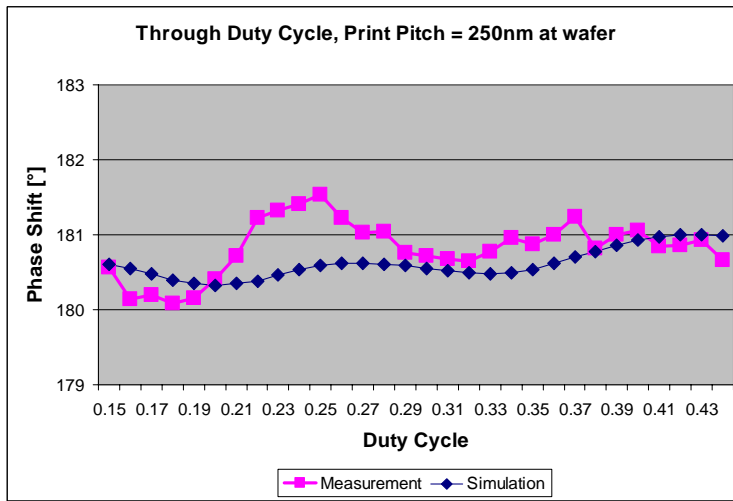


Figure 8: Image phase shift through duty cycle for a constant print pitch of 250nm at wafer.

5. SUMMARY

The extension of optical lithography to the 45nm node and beyond requires the use of PSM. The mask complexity increases steadily, which goes along with much tighter mask specifications. The phase shift needs to be quantified exactly in order to get accurate printing results during wafer processing. The methods currently available run into limitations because they are not able to consider diffraction limitations caused by scanner NA and mask pitch, as well as 3D mask effects. These effects become especially important for smaller feature sizes. The new phase metrology system Phame[®] captures diffraction limitations, rigorous effects as well as polarization effects.

In this paper phase dependencies from pitch and duty cycle have been demonstrated. For large pitches the phase shift is close to 180° whereas for smaller pitches the phase is significantly dropping down. This goes along with a smaller process window for the small pitches.

For large features Phame[®] phase shift measurement results show an excellent correlation between AFM measurement results as well as simulation results, as expected. For small features rigorous effects significantly impact the phase shift. Here the AFM method runs into limitations because it relies on an etch depth measurement only which does not capture 3D mask effects and polarization. Also for the simulation results a larger deviation to Phame[®] measurements was found for small feature sizes. The simulation is restricted to the quality and the limitation of the input parameter used, whereas the Phame[®] captures the rigorous effects directly.

Additionally the comparison between y- and x-polarization measurements shows phase differences up to 5° which is found for simulation and Phame[®] measurement. This shows impressively that the Phame[®] considers also polarization effects exactly.

Phame[®] captures the imaging effects as well as the rigorous 3D mask effects and enables the industry to measure the phase shift with high spatial resolution in any kind of production features.

In a next step the reported measurements will be compared to waferprints. Additionally similar investigations will be performed on att. PSM.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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