Phame® - high resolution off-axis phase shift measurements on 45nm node features

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ABSTRACT

The extension of optical lithography to 45nm and beyond goes along with an increased mask complexity and tighter specifications. Both attenuated and alternating phase shift masks (PSMs) require precise control of the phase shift as a function of both pitch and target sizes. Simulations show that the phase shift in the image plane of a microlithography scanner is strongly impacted by numerical aperture (NA), mask pitch, 3D mask effects, and polarization, especially if the feature sizes come close to the imaging wavelength. Carl Zeiss SMS has developed a new phase metrology system that overcomes the limitations of currently existing tools.

The new optical metrology tool – Phame® – enables the industry to perform in-die phase measurements on alternating PSM (altPSM), attenuated PSM (attPSM), and CPL (chromeless phase lithography) masks down to 120nm half pitch at the mask.

The optical beam path 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.

Off-axis phase measurement is realized by applying consecutive measurements of single source points according to the scanner relevant illumination settings. Phame® measures the scanner equivalent phase and amplitude in the image plane for each coherent source point. For off-axis phase shift extraction Zeiss has developed a new concept called high resolution phase. This high resolution phase is sensitive to the diffraction spectrum and to mask phase errors. In this paper we will explain the off-axis high resolution concept in detail.

First measurements have been performed on attPSM with 45nm node test features. The results show strong deviations of the high resolution phase shift depending on the pitch. Isolated features combined with dense features have been investigated. The measurement results will be presented in the paper.

Keywords: Phame, phase, phase metrology, scanner phase, off axis illumination, PSM

1. INTRODUCTION

The use of PSM (Phase Shift Mask) combined with high NA (Numerical Aperture) and special adapted illumination settings drives 193nm lithography further down to 45nm and 32nm node. This goes along with increased mask complexity and tighter specifications. For example, the ITRS roadmap specifies the phase error of alternating phase shifting masks with +/- 1 degree in 2008. Process control becomes extremely important. Phase shift needs to be quantified exactly in order to achieve accurate CD printing during the wafer lithography process.

Currently available phase shift measurement methods, like interferometer based methods or high resolution AFM (Atomic Force Microscope), measure the etch depth equivalent phase accounting for refractive index of the material, the etch depth of the feature and the lithography wavelength. These methods are not able to consider diffraction limitations caused by the actual scanner NA, pitch dependencies by the mask, 3D mask effects or polarization. In the transition to the 45nm and beyond, these effects play an important role and need to be considered. [1]

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

2. PHAME® - 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 combined with a low sigma illumination unit generates a coherent illumination (i.e. single source point) of the mask. The mask is handled face down similar to the scanner. On-axis or off-axis illumination including polarization can be applied depending on the PSM type. Partial coherent illumination settings of a scanner can be sampled in consecutive measurements of adjustable intervals allowing phase control under scanner relevant illumination settings. [2] The CCD-camera is in the same position as the wafer in the actual scanner. A stack of intensity images is captured during measurement where for each image the phase is manipulated by pupil filter. Phase information is obtained using iterative software algorithms. In addition to in-die phase shift, the tool also measures in-die transmission.

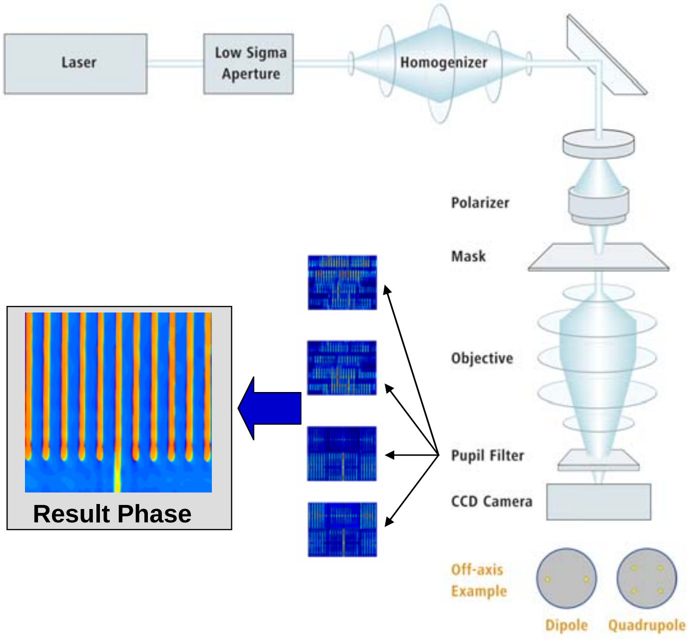

Figure 1: Optical beam path of Phase Metrology System – Phame®

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.

3. OFF-AXIS MEASUREMENT PROCEDURE

Phame® allows on- and off-axis illumination. Off-axis phase measurement is realized by applying consecutive measurements of single source points according to the scanner relevant illumination setting (e.g., dipole illumination is the measurement of two opposite source points). For each coherent source point Phame® measures the scanner equivalent phase and amplitude in the image plane (Figure 2). Due to off-axis illumination the phase in the image plane shows strong tilts depending on the diffraction spectrum.

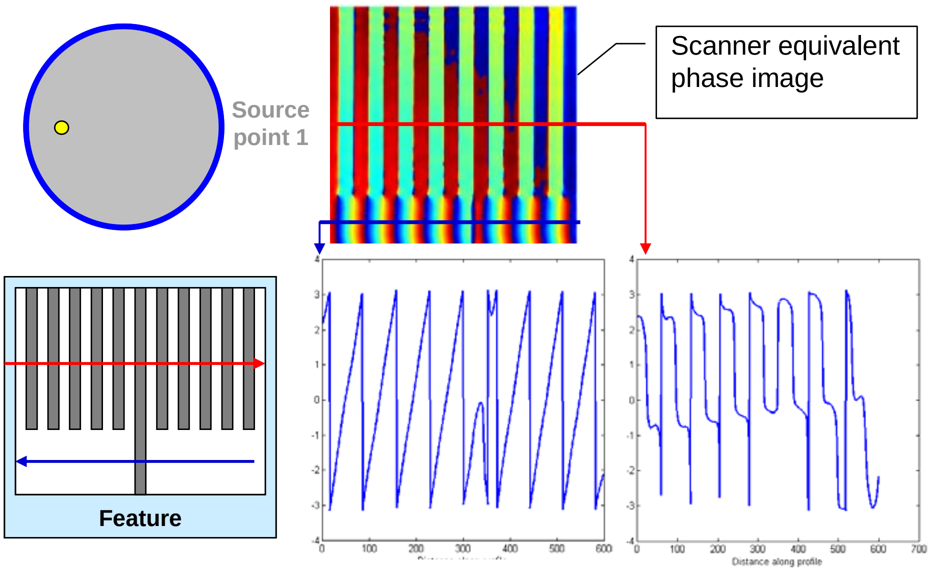

Figure 2: Scanner equivalent phase shift image for a single off-axis source point measured with Phame®

Comparing the diffraction spectrum, in particular, the 0th and 1st, -1st diffraction orders for an altPSM and an attPSM, the following applies. For an altPSM using on-axis illumination, the -1st and 1st diffraction order is captured in the scanner NA and ideal two-beam interference applies. The diffraction spectrum lies perfectly symmetrical in the pupil. To achieve the same printing information with an attPSM or CPL mask with the same scanner NA, off-axis illumination is required.

Therefore, for an attPSM the 1st, respectively -1st, and 0th diffraction orders (i.e., the combination is 1 and 0, or -1 and 0) are captured in the pupil. Generally the diffraction spectrum for off-axis illumination might be asymmetrical in the pupil depending on the feature pitch. This asymmetry in the diffraction spectrum causes large phase tilts in the image plane which makes a phase shift value extraction impossible. Simulation and measurement results show that the symmetry of the diffraction spectrum depends on the pitch. The diffraction symmetry determines the phase tilts in the image plane [3]. In order to get rid of the tilts, a symmetric diffraction spectrum is required to extract phase shift value information. Zeiss has developed a new method for off-axis phase shift value extraction which is called high-resolution phase.

The diffraction spectrum of each single source point is measured in the new phase metrology system. The 0th diffraction order for each source point is shifted in the pupil with respect to the optical axis due to off-axis illumination. For each source point, the electrical field is determined in the Phame®. The zero diffraction orders of each source point are algorithmically shifted in such a way that they fall together in the optical axis of a fictive pupil and the resulting electrical fields are coherently merged (Figure 3). By applying this procedure, a symmetric diffraction spectrum of the mask is obtained and at the same time, the original mask side NA is enlarged by the off-axis angle.

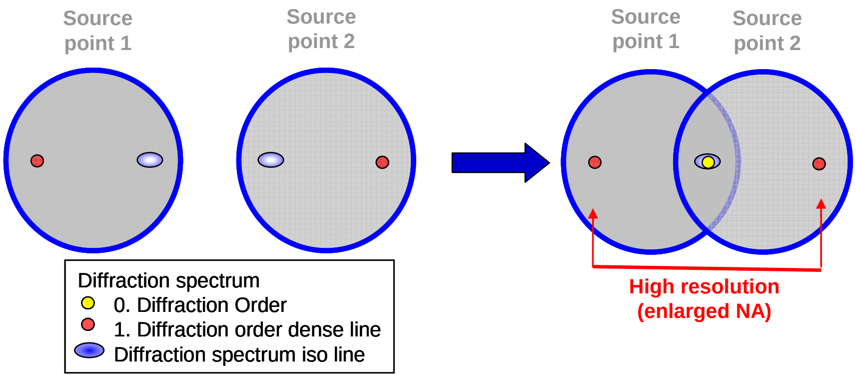

Figure 3: Diffraction spectrum and coherent merge of the diffraction spectrum

The so achieved symmetric diffraction spectrum is now propagated into the image plane and a high-resolution phase image and a high-resolution intensity image is obtained. Figure 4 shows that all tilts are removed. This off-axis high-resolution phase shift is sensitive to the diffraction spectrum and mask phase errors. It can be used for process control, design verification and defect analysis.

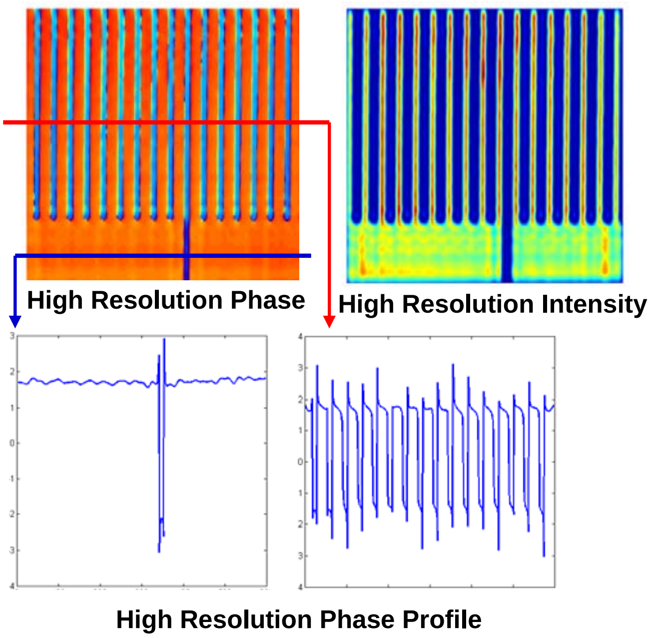

Figure 4: High resolution phase image and corresponding phase shift profile and high resolution intensity

4. OFF-AXIS MEASUREMENT RESULTS

For off-axis measurement a MoSi test mask was used containing 45nm lines/space features at waferlevel. The pitch for the lines/spaces did vary from 1:1, 1:2 to 1:3. Additional an isolated line was combined with the dense features. Dipole illumination was applied for all measurements. Figure 5 shows the high resolution phase shift images for the different pitches.

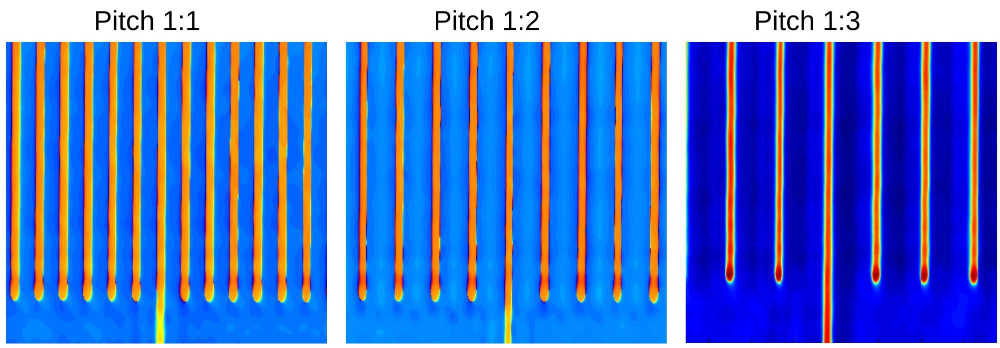

Figure 5: High Resolution Phase shift images on 45nm test features (wafer) for different pitch

To investigate the impact of phase over pitch the high resolution phase shift value was evaluated using histogram analysis. Due to fact that different pitches are in the field of view ROI (Region of Interest) have been defined over dense lines and over the isolated line as shown in Figure 6.

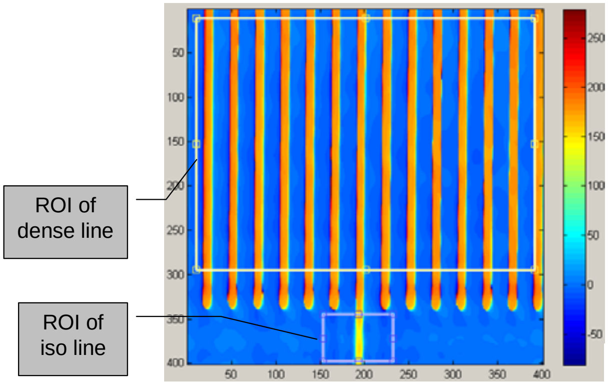

Figure 6: Definition of ROI (Region of Interest) for different pitches

For each ROI histogram analysis was applied. A Gaussian is fitted into the measurement data to account for statistical variations. The centre of gravity for each peak is algorithmically determined. The phase shift value equals the difference in-between these two points as shown in Figure 7.

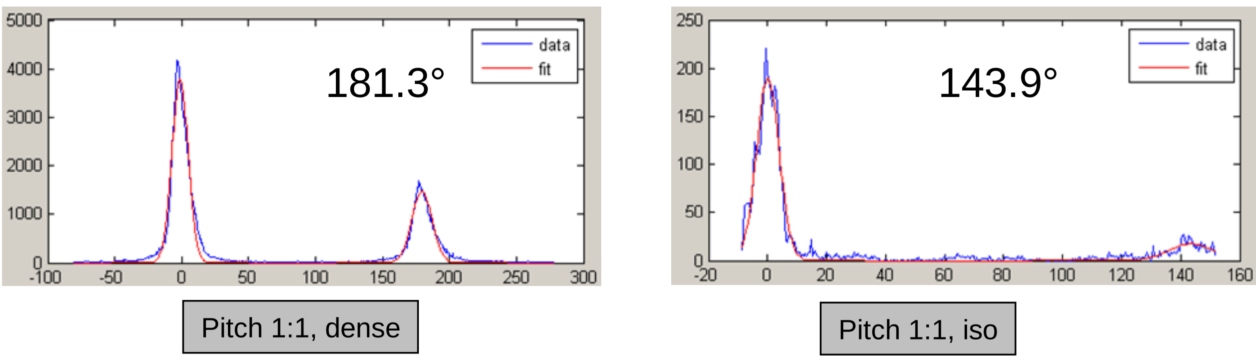

Figure 7: Histogram analysis for dense and iso line for 45nm feature pitch 1:1 at wafer

Figure 8 shows that for the dense lines/spaces the phase shift value is close to 180° for pitch 1:1 and pitch 1:2. However the phase shift value drops down by approximately 10° to 170° for pitch 1:3. This behavior can easily be explained in terms of the corresponding diffraction order amplitudes. For pitch 1:1 one expects a perfect two-beam interference with equal amplitudes of the 0^{th} and the 1^{st} diffraction orders. This is reproduced by a phase value close to 180°. However, with a decreasing duty cycle, the amplitude of the 0^{th} order becomes smaller than the corresponding amplitudes of the 1^{st} orders and this can be shown to result in a loss of contrast. As a consequence, the image phase drops down to values below 180° for a duty cycle of 1:3.

The evaluation of phase shift for the isolated line shows a significant deviation of up to 40° if the isolated is combined with dense lines/spaces of pitch 1:1. This reflects the different printing behavior of dense and isolated lines. The phase deviation is decreasing as the pitch increases. There is almost no deviation in phase shift in-between isolated line and dense lines/spaces for pitch 1:3 (see Figure 8, purple line) – an indication that the printing behavior of 1:3 lines is comparable with the printing of an isolated line. These effects will be further investigated.

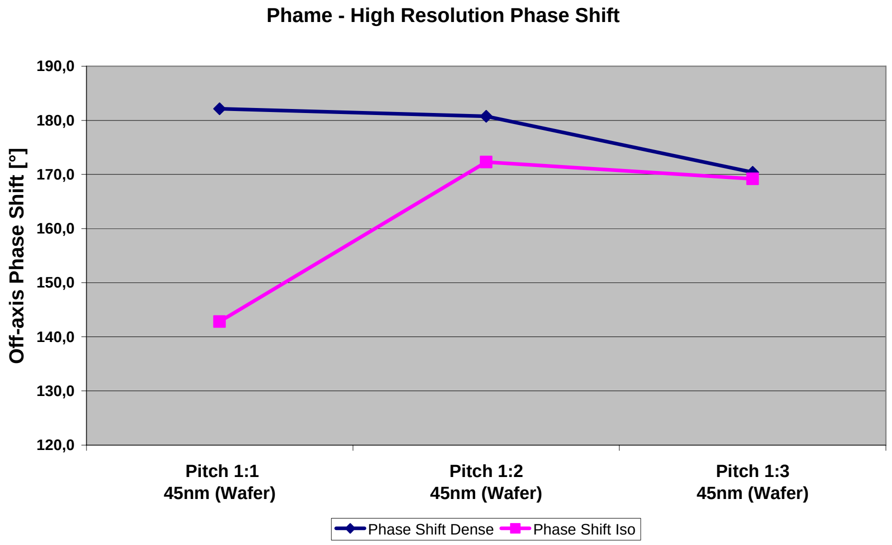

Figure 8: High Resolution Phase shift over pitch for dense lines/spaces vs. isolated on 45nm test features (wafer)

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. Simulation and measurement results show that in the transition to the 45nm node and beyond, these effects play an important role and need to be considered. The new phase metrology system Phame® captures diffraction limitations, rigorous effects as well as polarization effects. Phame® measures the phase shift in any production feature within the active mask area for on- and off-axis applications.

Beside the large feature measurement capability and on-axis in-die measurement capability, Zeiss has developed a high-resolution phase concept for off-axis illumination. First high-resolution phase shift measurements on 45nm (wafer level) MoSi test features showed strong variations of phase shift over pitch. Additionally, significant variations in phase shift up to 40° were observed for dense lines vs. isolated lines. This effect is decreasing with increasing pitch and can be related to the difference in printing behavior of dense structures and isolated structures. Further investigation on this effect will be applied, including comparison of measured phase shifts with corresponding process window.

In General, the high resolution phase is sensitive to the diffraction spectrum and mask phase errors. Thus, the Phame® can be used for process control, repair verification as well as for R&D processes especially in terms of design and OPC verification.

6. REFERENCES

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