Aerial Image Measurement Technique for Today's and Future 193nm Lithography Mask Requirements

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ABSTRACT

The Aerial Image Measurement System (AIMS™ [1]) for 193 nm lithography emulation has been brought into operation worldwide successfully. Adjusting optical equivalent settings to steppers/ scanners the AIMS™ system for 193nm allows to emulate any type of reticles for 193nm lithography. The overall system performance is demonstrated by AIMS™ measurements at 193 nm wavelength on binary chrome masks and phase shift masks. Especially for evaluation of 65nm node lithography performance process window results will be discussed.
An ArF excimer laser is in use for illumination. Therefore a beam homogenizer is needed to reduce the speckles in the laser beam and ensure a similar illumination uniformity as the longer wavelength systems, 248nm and longer, using an arc source. A new beam homogenizing technique will be presented and illumination results compared to the current solution. The latest results on enhanced illumination uniformity exceed the current performance. A newly develop hybrid objective for high resolution imaging is tested for use of high resolution imaging in order to review defects and investigate repairs which do not print under stepper equivalent optical settings. An outlook will be given for extension of 193nm aerial imaging down to the 45nm node. Polarization effects will be discussed.

1. INTRODUCTION

The AIMS™ is an optical system for evaluating reticles under specific stepper/ scanner settings of numerical aperture (NA), partial coherence of illumination (sigma: σ), wavelength and illumination type. By adjustment of illumination type, numerical aperture and partial coherence to match the conditions in 193 nm exposure tools, it can emulate any type of reticles like binary, OPC and phase shift, designed for 193 nm lithography. The image taken with the system is optically equivalent to the latent image incident on the photo resist of the wafer, but magnified and recorded with a CCD camera. Thus, the AIMS™ tool allows a rapid prediction of the wafer printability of critical features, like dense patterns or contacts, defects or repairs on the reticle without the need to do real wafer prints using the exposure tool and following SEM measurement of the printed features [2,3].
The AIMS™ tools are commercially available for different wavelengths: 248nm and longer, 193nm and 157nm [4,5,6]. The 193nm tool is commercially available as AIMS™ fab 193. The AIMS™ tools are state-of-the-art in the photo mask industry for development, quality control, repair verification and defect classification of photomasks and reticles. Figure 1 shows a picture of the AIMS™ fab 193.

Fig. 1. Picture of the AIMS™ fab 193, an automated aerial image measurement system for 193nm wavelength.

Aerial images are recorded either as single images or as a through focus series (TFS) providing a stack of images. A common approach for TFS is to acquire an odd number of images in equidistant focal steps, having one image in best focus position and equivalent extra- and intra-focal images covering the range of depth-of-focus. In actual use a reference image is measured at a clear photomask region and all measured images are normalized with this reference image. Instead of a reduction of 1:4 as on the stepper/ scanner, the image is taken on a field of view like 20 µm x 20 µm on the photomask and magnified 150x between mask and CCD-camera image plane. Based on the TFS analysis can be done on intensity variations or transmission loss, linewidth, Bossung curves and focus-exposure matrix. Figure 2 shows an example of dense lines of 360nm, lines and spaces 1:1 on mask. The aerial image in focus and an intensity profile plot is shown. The profile plot shows curves for measurements taken at best focus (0.00) and out-focus planes (between 0.26 and –0.39 µm at wafer level). The measurement corresponds a typical measurement for 90nm node, thus all values shown in Figure 2 are displayed on wafer level.

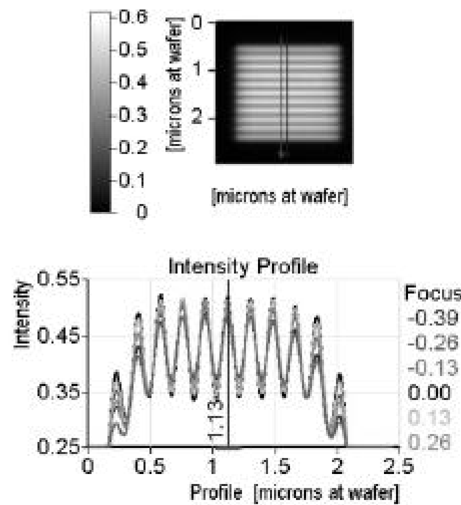

Fig. 2. Dense lines of 360nm, lines and spaces 1:1 on mask. The stepper equivalent settings are wavelength λ=193nm, numerical aperture NA=0.72, partial coherence illumination σ=0.6/0.9, annular setting, and mask reduction M=4. The Figure shows the aerial image at best focus and the intensity profiles along the selected line for different focus planes.

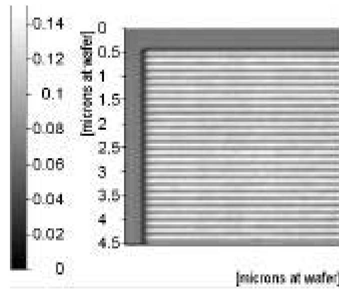

Fig. 3. Dense lines of 300nm, lines and spaces 1:1 on mask level. The stepper equivalent settings are wavelength λ=193nm, numerical aperture NA=0.9, partial coherence illumination σ=0.75 and mask reduction M=4. The aerial image is shown at best focus.

As an example an attenuated phase shift mask was measured to demonstrate mask performance for evaluation of 65nm node lithography performance. Figure 3 shows the aerial image at best focus of a 300nm lines and spaces structure of an attenuated phase shift mask. A through focus measurement was performed by acquiring 5 planes of aerial images with step size 1.5 µm for data analysis. Each of the rectangles in Figure 4 defines a process window: as long as the defocus is not larger than 0.32µm (0.11µm) and the maximum exposure latitude not larger than 4% (8%), the linewidth would not vary by more than 10% from the target size of 300 nm, i.e. 75nm on wafer level.

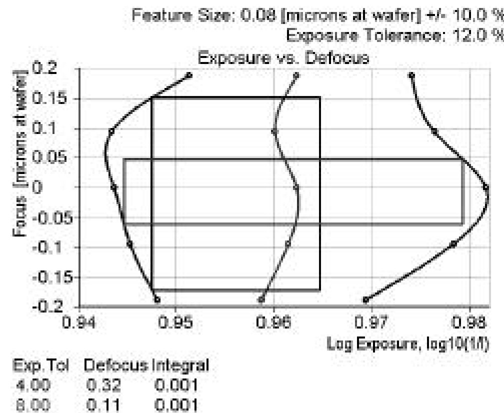

Fig. 4. Process Window analysis of AIMS™ measurement of 300nm lines and spaces 1:1 on mask level.

Such process windows can be used to analyze the lithographic performance of the mask features or used to compare the maximum allowable focus variation for a given specified amount of dose variation of defective and non-defective areas.

2. INVESTIGATIONS ON BEAM HOMOGENIZATION

The optical base elements of an aerial image measurement system are an illumination unit and an imaging unit. The former contains changeable parts like an optical zoom and pinholes to realize the σ setting and the illumination type. The imaging part contains changeable pinholes to realize the stepper equivalent setting of the numerical aperture (NA). Both the σ and the NA have to cover a wide range of values in quasi-continuous steps and be able to adjust to different exposure tool settings with minimal effort at one and the same system.

An ArF excimer laser and beam homogenizer are used as illuminator for 193nm. Bandwidth value is 0.5nm (FWHM). The beam homogenizer is needed to ensure a sufficient uniformity of the pupil which enables the field uniformity needed for measurements. Sufficient tight field uniformity is an important topic to fulfill lithographic evaluation requirements and even increases with smaller node. Up to now, the speckle pattern was reduced by independently mixing light via a fixed and rotating grounded glass setup. As a disadvantage, the speckle pattern still remains to a certain extent and moving

parts, here the spinning disk, are involved. Figure 3 shows a clear image taken on a clear area of the mask and normalized by a second clear image taken at the same clear area of the mask. Each single image was integrated over 10ns short laser pulses for 600ms. A profile plot is selected across the field of view. Modes and a variation of 2.8% were found.

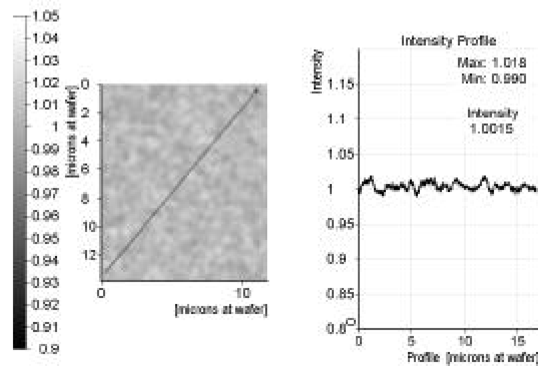

Fig. 5. Normalized clear image acquired with 600ms integration time, and intensity profile plot along the indicated line. Acquisition was done on the system with a fixed and rotating grounded glass setup for beam homogenization.

A different type of beam homogenizer was newly designed and tested for future production. The approach in the newly developed homogenizer is based on mixing sub-apertures of the laser beam that are not able to interfere – either due to a mutual distance larger than the lateral coherence length of the beam or due to a relative time delay of neighboring apertures larger than the temporal coherence length. This delay is realized by two structured mirrors. The structured mirrors are imaged on a micro lens array which provides the mixing and homogenization of the beam which is possible because the coherence of the beams has been modified. Comparable to Figure 5, Figure 6 shows a normalized clear image taken on the system with micro lens array for beam homogenization. It can be seen from the intensity profile that the newly designed beam homogenizer provides in this test a much smoother field uniformity with < 2% variation. In a future project patterned mask measurements will be done to test the specifications of linewidth uniformity and repeatability.

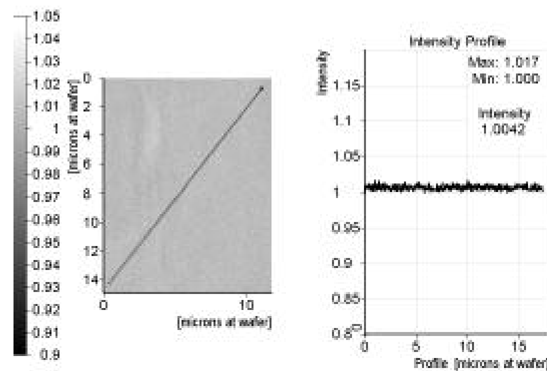

Fig. 6. Normalized clear image acquired with 600ms integration time, and intensity profile plot along the indicated line. Acquisition was done on the system with micro lens array for beam homogenization.

3. HIGH RESOLUTION IMAGING TEST USING HYPRID OBJECTIVE

In order to investigate features and defects with high resolution imaging rich in contrast a newly designed and manufactured objective by Carl Zeiss was tested on the AIMS™ fab 193.

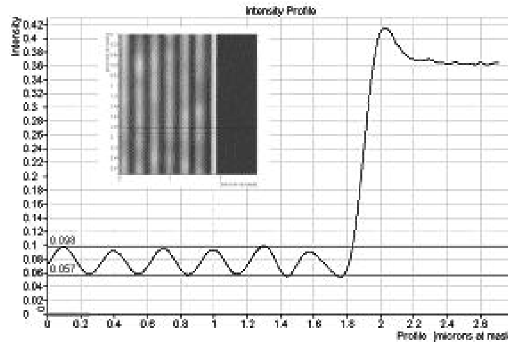

Fig. 7. 150nm lines and spaces on mask imaged at AIMS™ fab 193 and profile plot for horizontal line.

The realized objective is a hybrid objective combining diffractive and refractive lens elements allowing a very compact lens design despite of the complexity of the short wavelength and, material selection and the need for cement-free design [7]. The hybrid objective works at wavelength λ=193nm. It has a magnification of 50x and NA=0.65. The working distance is >7mm and therefore also masks with pellicle s can be investigated. The high resolution is given by the fact that the resolution capability scales with λ/NA. Various measurements have proven that lines and spaces of 150nm half pitch on mask can be resolved [7]. Figure 7 shows a lines and spaces pattern of 150nm on the mask. The profile plot showing normalized intensity distribution reveals an overall modulation between 0.057 and 0.098. Although there is a low intensity found the contrast of 26% is sufficient to resolve the structure.

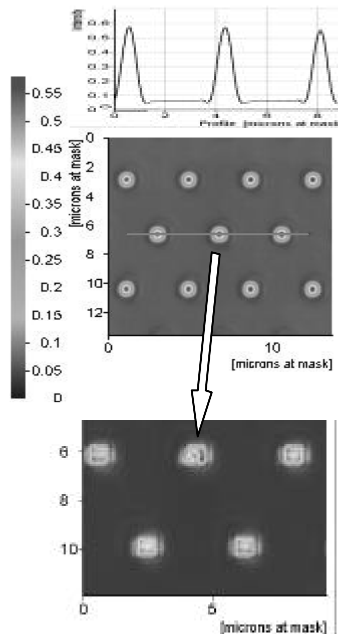

Fig. 8. Contact holes of 800nm on mask. The stepper equivalent settings are wavelength λ=193nm, numerical aperture NA=0.92, partial coherence illumination σ=0.9 and mask reduction M=4. The upper Figure shows the aerial image at best focus and the selected intensity profile. The lower pictures shows the selected contacts in the upper raw imaging at high resolution.

To demonstrate further applications an aerial image was taken of an array of contacts with contact sizes of 800nm on mask. From the aerial image (Figure 8, upper image) and the selected profile we can clearly see that for the selected lithography conditions of NA=0.9, σ=0.9 and 4x mask) the mask can be used for wafer printing of equally sized contacts. In the lower part of Figure 8 we can see the high resolution image of some of the contacts. The arrow shows the printing contact and its high resolution image. Using the hybrid objective the NA on the mask side is 0.65 instead of 0.23 for the aerial imaging and the magnification is 5x larger. Therefore the high resolution image reveals that the center contact of the three selected contacts has some defective corner. From this demonstration we draw the following conclusions:

- The AIMS™ technology using the lithographic conditions determines the printing defects which matter as defects.
- Non-printing defects do not need to be repaired for use under specific lithographic settings, however the hybrid objective can be used to image nuisance defects for more detailed analysis. Such defects are important to know and may matter during the life cycle of the mask at a later time.
- The hybrid objective can be used for high resolution image analysis instead of using a SEM-image.
- The hybrid objective allows to verify that a repair- which is viewed and not printing under lithographic settings- is in the field of view.

4. HIGHER NUMERICAL APERTURE EXPOSURE TOOL EMULATION

Currently a lot of discussions and activities are going on to realize 193nm lithography for smaller nodes even to 45nm by using an immersion liquid, i.e. water, between the lens of the lithography tool and the wafer. Such an immersion lithography approach allows to print to smaller feature sizes by increasing the numerical aperture by the factor of the refractive index of water, n=1.47 [8,9].

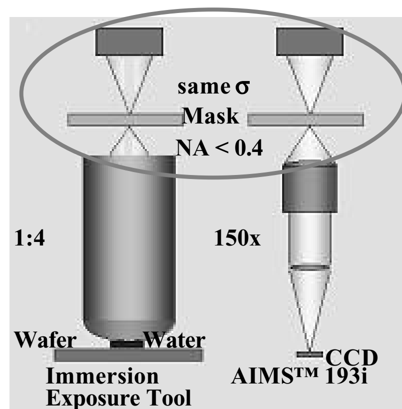

Fig. 9. Comparison of principle of immersion exposure tool to AIMS™ 193nm immersion emulator (AIMS™ 193i).

Common ranges for the numerical apertures (NA) of 4x reticles at 193nm wavelength range from about 0.6 to 0.92 and can also be emulated on an AIMS™ fab 193. For emulation of immersion lithography the upper limit on an AIMS™ tool might have to be realized with at least 1.35. Since the numerical aperture on the mask side is reduced by 1:4, such a high NA can be emulated on an AIMS™ fab system by re-designing the beam path besides general tool improvements and using a microscopic type lens of NA < 0.4 on the imaging side of the mask or reticle. This means there is no need to have an immersion liquid on such an AIMS™ system. The high NA imaging (immersion range) or equivalent the imaging for nodes of 65nm and 45nm will draw the attention to polarization effects which will occur and have not been an issue for the use of AIMS™ fab 193 so far. It is general knowledge, however, that these polarization effects lead to a reduction of contrast of the image when the mask structure size is in the same order as the exposure wavelength. Since this effect depends strongly on the wavelength used for the lithographic process it is very important to optically measure printability with the same exposure tool wavelength and stepper/ scanner equivalent settings in order to interpret the imaging properties of the mask, correctly.

Taking a closer look at the mask effects one finds a strong dependence on the mask material in use. In general one can say that a pure phase shift mask introduces the smallest polarization effect. The choice of the metal in the absorbing layer influences how pronounced the polarization effects occur.
The polarization effects, introduced by the mask, result in differences in intensity and structure that can be found when comparing the s and p polarized images. That means in other words that the s and p polarized images have different light intensity doses which change with the mask structure and size. The dose difference is a negligible amount for example for a pitch gird at 400 nm on the mask, however the dose difference changes to around 40% at 180 nm on mask where mask structure and imaging wavelength are equivalent. In addition there is a difference in the imaging structure between s and p which obeys also different defocusing behavior. Thus for re-designing the beam path for immersion stepper/ scanner emulation the future AIMS™ fab 193i will take such polarization effects into account.

5. SUMMARY

The AIMS™ fab 193 has been brought successfully into the market to evaluate lithographic performance of masks for current 193nm requirements. A newly developed beam homogenizer has been tested successfully. A new hybrid objective allows high resolution imaging for review of features, defects and repairs.
With upcoming immersion lithography for 193nm an AIMS™ systems can be designed for stepper/ scanner emulation without the need for immersion liquids, and polarization effects will be taken into account with mask features getting equivalent or smaller than illumination wavelength.

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