Aerial Image Measurement Technique for fast evaluation of 193 nm lithography masks

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ABSTRACT

The Aerial Image Measurement System (AIMS™)[1] for 193 nm lithography emulation has been brought into operation successfully worldwide. By adjustment of illumination type, numerical aperture and partial coherence to match the conditions in 193 nm steppers or scanners, AIMS™ can emulate for any type of reticles like binary, OPC and phase shift. AIMS™ allows a rapid prediction of wafer printability of critical features, like dense patterns or contacts, defects or repairs on the masks without the need to do real wafer prints using the cost intensive lithography equipment. Therefore, AIMS™ is a mask quality verification standard for high-end masks established in mask shops worldwide. With smaller nodes, where design rules are below 100 nm and low k1 factors are used in the lithography process, the increasing printability of even smaller defects on reticles is becoming a serious problem. The evaluation of defect printability using AIMS™ becomes a significant aid and cost-saving technique to be applied directly in the wafer fab.
The overall measurement capability of the 193 nm AIMS™ system will be demonstrated by measurements at 193 nm wavelength on attenuated phase shift masks. Excellent illumination uniformity is crucial for quantitative analysis of AIMS™ measurements such as CD variation or defect printability. To reduce disturbing speckle formation of the highly coherent ArF excimer laser a new beam homogenizing technique which contains motionless parts only will be presented as well as illumination homogeneity results compared to the current solution using a spinning scattering disk. The latest results on illumination performance exceed the current results especially with respect to illumination uniformity over the field. The improved performance will enable improved measurement capability down to the 65 nm node. An outlook will be given for extension of 193 nm aerial imaging down to the 45 nm node emulating immersion scanners.

Keywords: aerial image, lithography emulation, mask or reticle quality control, immersion, hyper numerical aperture, beam homogenization

1. INTRODUCTION

The AIMS™ is an optical system for evaluating reticles under specific stepper or scanner settings of numerical aperture (NA), partial coherence of illumination or pupil filling (sigma: σ), wavelength and illumination type (like circular, annular, quadrupole or dipole off-axis illumination). By flexible, automated adjustment of any setting to match conditions like in 193 nm exposure tools, it can emulate for 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 a following SEM measurement of the printed features.[2,3]
The AIMS™ tools are commercially available for different wavelengths: 248 nm and longer, 193 nm and 157 nm.[4,5,6]
The 193 nm tool is commercially available as AIMS™ fab 193 including mini-environment and optionally available with mask handling from SMIF pod or from specific reticle boxes. Figure 1 shows the picture of an AIMS™ fab plus, an automated AIMS™ system including mask handling as it is used for 248 nm and equivalent for 193 nm optical emulation of steppers or scanners.
The progress described in this paper will be applicable for both the mask shop AIMS™ users and the wafer fab AIMS™ user. In the next chapter a special focus will be applied for use of AIMS™ in the wafer fab.

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Fig. 1: Picture of an AIMS™ fab plus, an automated AIMS™ system including mask handling as it is used for 248 nm and equivalent for 193 nm optical emulation of steppers or scanners.

2. Cost savings in IC manufacturing by use of AIMS™ in wafer fabs

AIMS™ is de facto a worldwide mask quality verification standard for high-end masks. The systems are in operation in all high-end mask shops. Mask users in wafer fabs strongly benefit from an AIMS™ certification with mask delivery from mask manufacturers to ensure masks free of printing defects enabling a high yield chip production. A strong advantage is given by the fact that AIMS™ allows mask quality assessment for both pelliclelized and unpelliclelized masks.
With smaller nodes, where design rules are below 100 nm, low k1 factors are in use in the lithography and smaller defects on reticles are becoming a serious problem it is expected that critical mask defects will occur in increasing numbers in the wafer fab.[7] Likely defects on the masks are particles, crystal growth, electrostatic damage and irradiation damage due to high radiation dose along with the short exposure wavelength. As repeaters they may cause a catastrophic yield loss. Figure 2 shows the aerial image of a crystal growth defect at best focus. The defect was measured with numerical aperture NA = 0.7 and σ = 0.85 at 193 nm wavelength. A profile plot was selected to show the transmission loss. The loss is 44 % which means that this defect is printing severely.

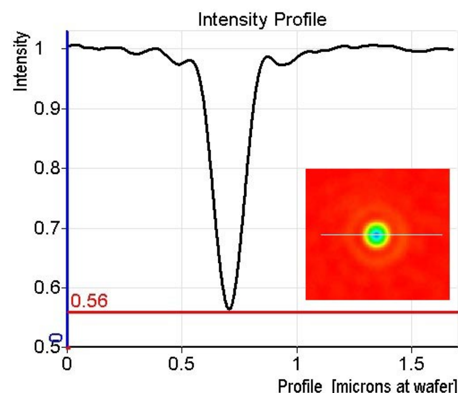

Fig. 2: The aerial image shows a crystal growth defect which can occur during usage of the mask in IC production. The selected profile plot shows the transmission loss caused by this crystal growth defect.

With higher complexity of masks the understanding of such defects can help to decide whether the mask needs to be shipped back to the mask shop or has no influence on the wafer prints or can even be used with a tolerable CD error. Since most of these defects act not fully light blocking, they act like phase defects. A fast method to do the defect disposition without the need for real wafer prints is the AIMS™, where the printability can be determined with actinic measurements under the same exposure tool conditions. This removes also uncertainties from simulation on non-actinic

imaged defects. Defect disposition with AIMS™ is highly cost saving since no valuable stepper time and lithographic processing have to be used.

Figure 3 shows an overview of the key applications of the AIMS™ technique in the wafer fab. In a further step more defect repair efficiency can be obtained if the mask shop and the wafer fab correlate AIMS™ emulation results on both sides.[8] Generally the connectivity between mask shops and wafer fabs and the correlation of the AIMS™ data will improve yields.

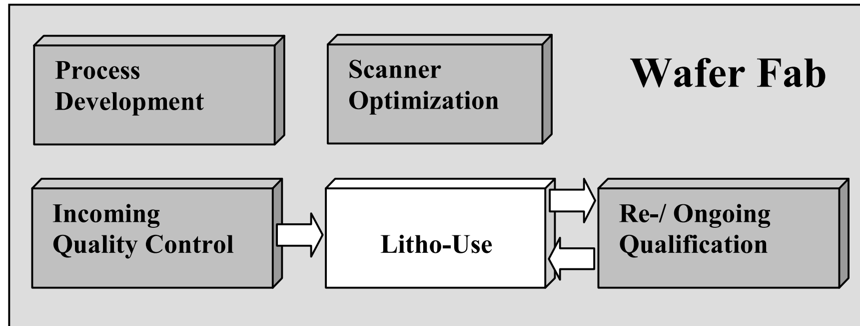

Fig. 3: The dark boxes show were the AIMS™ technique can be applied for mask or reticle quality assessment and stepper or scanner optimization in the wafer fab.

3. Experimental

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 mask region and all measured images are normalized with this reference image. As an example an attenuated phase shift mask with different features was measured to demonstrate mask performance for evaluation down to 65 nm node lithography performance. Figure 4 shows the best focus images of dense lines of 400 nm (left side) and 300 nm (right side), lines and spaces 1:1 on mask level.

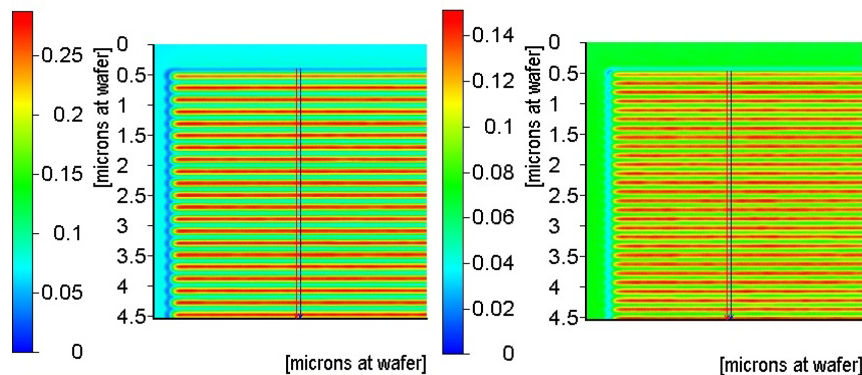

Fig. 4: Dense lines of 400 nm (left side) and 300 nm (right side), lines and spaces 1:1 on mask level. The stepper equivalent settings are wavelength λ = 193 nm, numerical aperture NA = 0.9, partial coherence illumination σ = 0.75 and mask reduction M = 4. The aerial images are shown at best focus.

The stepper equivalent settings are wavelength λ = 193 nm, numerical aperture NA = 0.9, partial coherence illumination σ = 0.75 and mask reduction M = 4. The scale of the images is shown on wafer level. On the left side of each image the grayscale distribution of the intensity values is shown. Instead of a reduction of 1:4 as on the stepper or scanner, the images are taken on a field of view as for example 20 µm x 20 µm on the photomask and magnified 150x between mask and CCD-camera image plane.

Based on the TFS and selection of a profile in the aerial image analyses can be done on intensity variations or transmission losses, linewidths, Bossung curves and focus-exposure matrices. Figure 5 shows the intensity profile plots for various focal planes which were selected on the aerial images of 400 nm and 300 nm shown in Figure 4. The left side shows the 400 nm intensity distribution, the right side the 300 nm distribution, both plotted on the same scale. From 400 nm to 300 nm feature size a significant change can be seen. The maximum normalized peak intensity is dropping strongly from about 0.28 to 0.15. The intensity values in the minima are only slightly changed and about 0.08 for both feature sizes. So the contrast is lowered to about half its value. For such small feature sizes of 300 nm on the mask it is obvious that peak to peak variations are very critical for mask quality. On the one side they can occur from the mask itself and on the other side there is a contribution from the tool itself, the latter one to be kept as small as possible. It means field uniformity has to be optimized to allow the quantitative evaluation of small mask features.

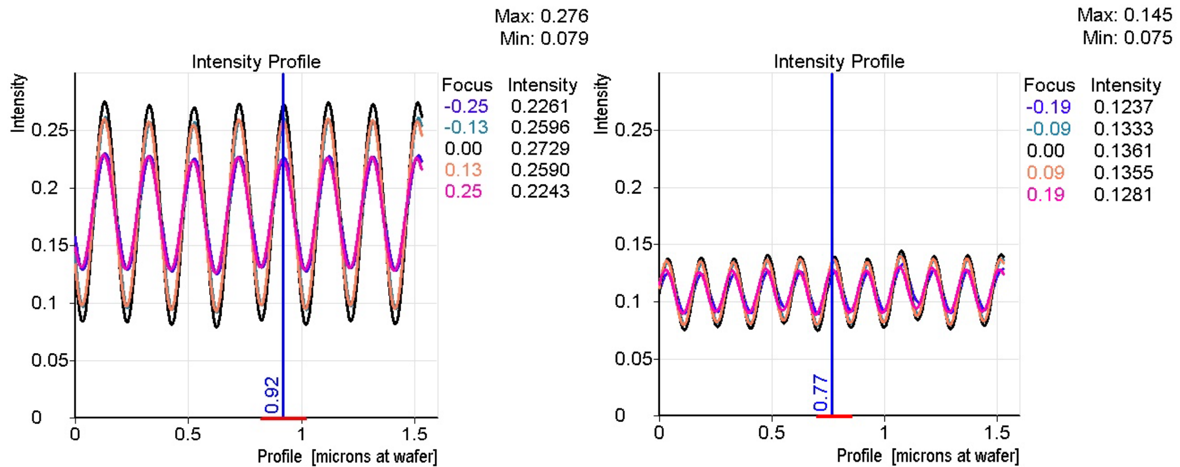

Fig. 5: Intensity profile plots for various focal planes were selected on the aerial images of 400 nm and 300 nm shown in Figure 4. The left side shows the 400 nm intensity distribution, the right side the 300 nm distribution, both plotted on the same scale. In each plot the profile with the most modulation corresponds to the best focus plane.

4. 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 to realize the illumination type and setting of the degree of illumination coherence of light, i.e. the adjustment of sigma (σ). The imaging part contains changeable pinholes to realize the stepper or scanner 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 have to be able to adjust to different exposure tool settings with minimal effort at one and the same system. For AIMS™ fab 193 the numerical aperture range is NA = 0.6 to 0.92 and sigma range σ = 0.25 to 1.0. An ArF excimer laser and a beam homogenizer are used as illuminator. Bandwidth value is 1 nm for 193 nm (FWHM). The beam homogenizer is needed to ensure a sufficient uniformity of the pupil which enables the field uniformity needed for measurements. In the optical beam path the beam homogenizer is placed between laser and illumination unit.

Sufficient tight field uniformity is an important topic to fulfill lithographic evaluation requirements and it even increases with smaller node sizes as it can be seen from the measurement presented above. 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 6 shows a clear image taken on a clear area of the mask which was normalized by a second clear image taken at the same clear area of the mask. Each single image was integrated over 10 ns short laser pulses for 600 ms. A profile plot is selected across the field of view. Modes and a variation of 2.8 % were found.

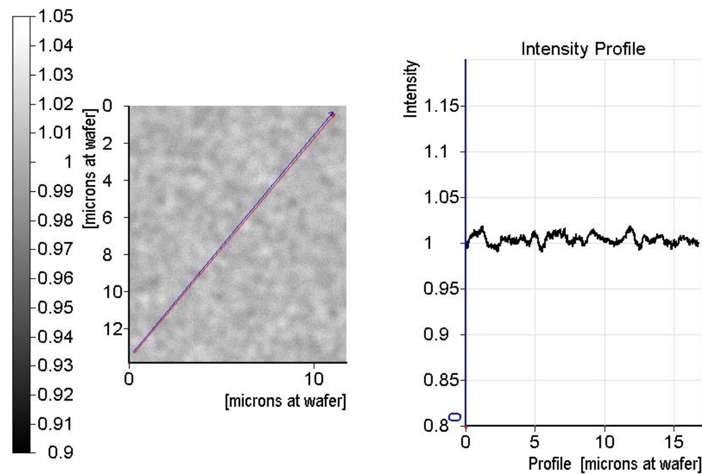

Fig. 6: Normalized clear image acquired with 600 ms integration time and intensity profile plot along the indicated line. Acquisition was done on the system with a fixed and rotating grounded glass setup for beam homogenization.

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, a first stair mirror in vertical direction and a second stair mirror in horizontal direction. 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.[9] The pupil filling (σ) is realized afterwards. Comparable to Figure 6, Figure 7 shows a normalized clear image taken on the system with stair mirrors and a micro lens array for beam homogenization. It can be seen from the intensity profile that the remaining speckle pattern of the homogenizer with moving parts is successfully removed. The newly designed beam homogenizer provides in this test a much smoother field uniformity with < 2% variation. This specification for field uniformity will support significantly such measurements as shown in Figure 5, right side, targeting for the 65 nm node.

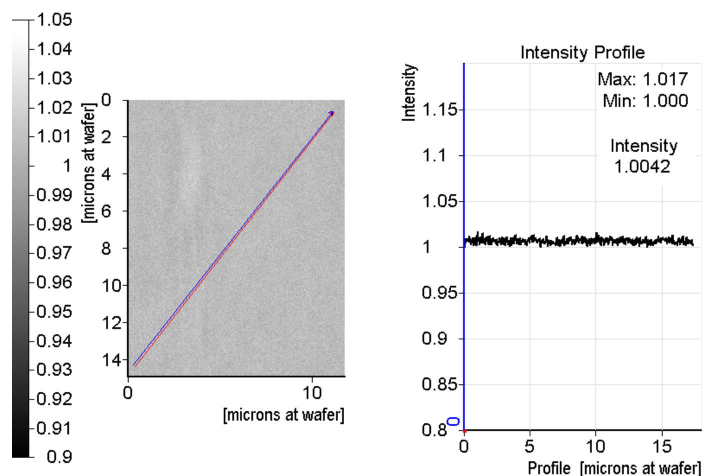

Fig. 7: Normalized clear image acquired with 600 ms integration time, and intensity profile plot along the indicated line. Acquisition was done on the system with stair mirrors and micro lens array for beam homogenization.

5. HIGHER NUMERICAL APERTURE EXPOSURE TOOL EMULATION

Currently, activities are going on to realize 193 nm lithography for smaller nodes even down to 45 nm 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 increase depth of focus just by the use of the immersion liquid instead of air and to print to smaller feature sizes by increasing the numerical aperture by the factor of the refractive index of water, n = 1.47.[10,11]

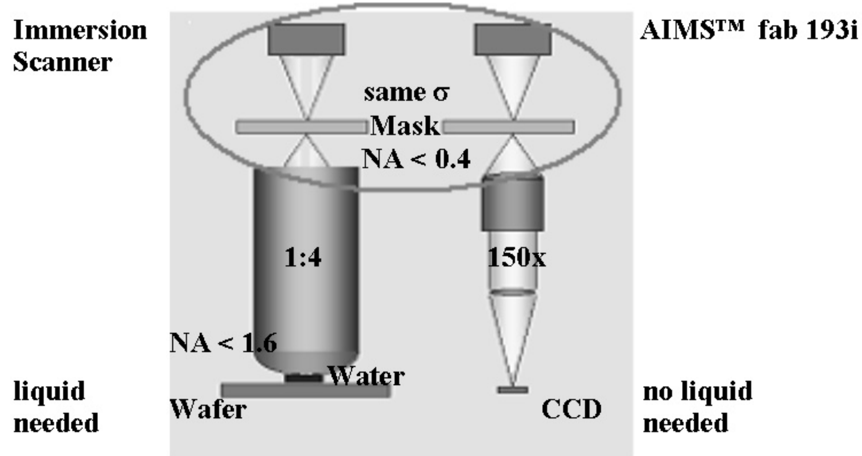

Fig. 8: Comparison of principle of immersion scanner to 193 nm AIMS™ immersion emulator (AIMS™ fab 193i).

For emulation of immersion scanners using 4x masks the upper limit on an AIMS™ tool will be expanded from a common value of up to 0.92 for at least up to 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™ 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. Figure 8 shows a comparison of the principle of an immersion scanner and an emulator for 193 nm lithography. Whereas water is needed to realize the high numerical aperture NA > 1.0 on the scanner side, there is no need to have an immersion liquid on such an AIMS™ system.

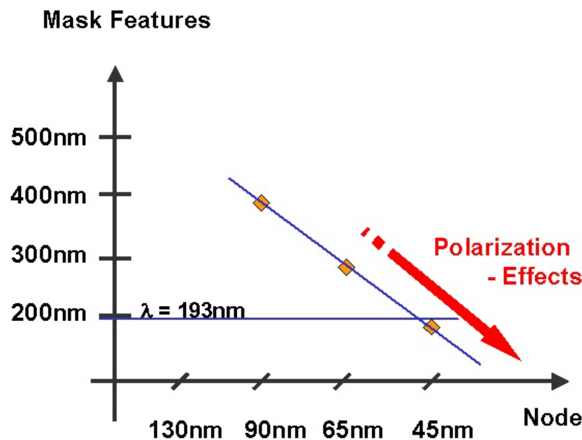

Fig. 9: With mask features at high numerical aperture and in size close to exposure wavelength rigorous polarization effects of the mask will be dominant for the aerial image.

The high NA imaging (immersion or hyper NA range) or equivalent the imaging for nodes of 65 nm and 45 nm 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 the image contrast. Contrast

loss will be found in p-polarization and different defocus behavior for s- and p-polarization. Beyond that rigorous polarization effects from the mask will be dominant when the mask structure size is in the same order as the exposure wavelength. They will also strongly depend on the mask material itself. One can say that a pure phase shift mask introduces the smallest polarization effect. Because of the light metal interaction the choice of the metal and its parameters (thickness etc) the absorbing layer influences how pronounced the polarization effects occur. Figure 9 is indicating this area. It can be seen where mask features in size crossover the wavelength to realize a small node the polarization effects have to be taken into account. Since these imaging and mask effects depend strongly on the wavelength used for the lithographic process it is very important to optically measure printability with the same exposure tool wavelength and scanner equivalent settings and to provide polarization capability in order to interpret the imaging properties of the mask, like printability of optical proximity corrected (OPC) masks, correctly.

Lithographic simulation tools require rigorous simulation capability in order to take the above described effects into account. Even rigorous simulation requires the exact knowledge of the optical constants (n, k), layer thicknesses and geometrical topography, like sidewall angles. The measurements of all these parameters require extremely sophisticated metrology on mask level, like CD, AFM or SEM measurement. Especially the optical constants strongly depend on deposition conditions and exact layer thickness and are mostly unknown or uncertain. Only the AIMS™ technique provides the superior evaluation method to comprise all these issues in kind of one measurement in one tool.

In this hyper NA range or imaging close to the 45 nm node it becomes obvious that the actual layout of the masks is not easily transforming into the aerial image or incident image onto the resist anymore. This is due to heavily loaded OPC, phase shift technology being applied or polarization effects being present. Mask makers and wafer manufactures need to consider a shift of paradigm. Instead of specifying mask critical dimensions in an increased manner, it will be more appropriate and even sufficient to specify, test and certify the aerial image performance instead.

6. SUMMARY

The AIMS™ fab 193 has been brought successfully into the market to evaluate lithographic performance of masks for current 193 nm requirements. A newly developed beam homogenizer has been tested successfully and a drastically improved field uniformity was found. It will significantly improve the performance of investigations of mask features, defects and repairs on masks targeting the 65 nm node. At such smaller nodes below 100 nm the AIMS™ becomes also a significant aid in the wafer fab for cost savings in the IC production. Now an optional mask handling is available to allow a high degree of automation.

With the upcoming immersion lithography for 193 nm an AIMS™ system will be designed for scanner emulation without the need for immersion liquids, and polarization effects will be taken into account with mask features getting equivalent or smaller than the exposure tool wavelength.

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REFERENCES

1. TM: AIMS is a trademark of Carl Zeiss
2. R.A. Budd, D.B. Dove, J.L. Staples, R.M. Martino, R.A. Furguson, J.T. Weed, *Development and application of a new tool for lithographic mask evaluation, the stepper equivalent Aerial Image Measurement System, AIMS,* IBM J. Res. Develop. Vol 41 No.1,2 January/ March, 1997.
3. R.A. Budd, J. Staples and D. B. Dove, *A New Tool for Phase Shift Mask Evaluation, the Stepper Equivalent Aerial Image Measurement System AIMS*, Proceedings of SPIE Vol. 2087, 1993.
4. K. Eisner, P. Kuschnerus, J.P. Urbach, C. Schilz, T. Engel, A. Zibold, T. Yasui, I. Higashikawa, *Aerial Image Measurement System for 157 nm Lithography*, Proceedings of SPIE Vol. 4889, 2002.
5. P. Kuschnerus, T. Engel, A. Zibold, C. Hertfelder, T. Yasui, I. Higashikawa, C.M. Schilz, A. Semmler, *Actinic Aerial Image Measurement Tool for 157 nm Lithography,* Proceedings of SPIE Vol. 5130, 2003.

6. A.M. Zibold, M. Esselbach, P. Kuschnerus, T. Engel, *Aerial image measurement system for 157 nm lithography masks. Technical Symposium: Innovations on Semiconductors*, SEMI 2003.
7. V. Philipsen, R. Jonckhere, S. Kohlpoth, C. Friedrich, A. Torres, *Printability of hard and soft defects in 193 nm Lithography*, Proceedings of SPIE Vol. 4764, 2002.
8. W.Chou, T. Chen, W.Tseng, P. Huang, C.C. Tseng, M. Chung, D. Wang, N. Huang, *Characterization of Repair to KrF 300mm Wafer Printability for 0.13µm Design Rule with Attenuated Phase Shifting Mask*, Proceedings of SPIE Vol. 4889, 2002.
9. Lars Erdmann, Matthias Burkhardt and Robert Brunner, *Coherence management for microlens laser beam homogenizers,* Proceedings of SPIE Vol. 4775, 2003.
10. Harry J. Levinson, *Principle of Lithography*, SPIE, page 257, 2001.
11. E.D. Palik, *Academic Press*, Boston, Vol2, 1991.