Aerial image measurement technique for Automated Reticle Defect Disposition (ARDD) in wafer fabs

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ABSTRACT

The Aerial Image Measurement System (AIMS™)* for 193 nm lithography emulation has been brought into operation successfully worldwide. A second generation system comprising 193 nm AIMS™ capability, mini-environment and SMIF, the AIMS™ fab 193 plus is currently introduced into the market. By adjustment of numerical aperture (NA), illumination type and partial illumination coherence to match the conditions in 193 nm steppers or scanners, it can emulate the exposure tool for any type of reticles like binary, OPC and PSM down to the 65 nm node. The system allows a rapid prediction of wafer printability of defects or defect repairs, and critical features, like dense patterns or contacts on the masks without the need to perform expensive image qualification consisting of test wafer exposures followed by SEM measurements. Therefore, AIMS™ is a mask quality verification standard for high-end photo masks and established in mask shops worldwide. The progress on the AIMS™ technology described in this paper will highlight that besides mask shops there will be a very beneficial use of the AIMS™ in the wafer fab and we propose an Automated Reticle Defect Disposition (ARDD) process.

With smaller nodes, where design rules are 65 nm or less, it is expected that smaller defects on reticles will occur in increasing numbers in the wafer fab. These smaller mask defects will matter more and more and become a serious yield limiting factor. With increasing mask prices and increasing number of defects and severability on reticles it will become cost beneficial to perform defect disposition on the reticles in wafer production. Currently ongoing studies demonstrate AIMS™ benefits for wafer fab applications. An outlook will be given for extension of 193 nm aerial imaging down to the 45 nm node based on emulation of immersion scanners.

1. INTRODUCTION

Ten years ago the principle of measuring the aerial image was introduced by Carl Zeiss in a commercially available system to enable what Prof. Harry Levinson of AMD calls the semiconductor industry's 3rd technology wave [1]. Since then a record of continuous system development to keep up with the industries demands for shorter wavelengths has supported the "waves" that came afterwards with their ever smaller design rules. Meanwhile the AIMS™ system is established as an indispensable tool in mask shops worldwide and AIMS™ measurement data of repair sites are provided by mask shops as a quality assurance standard to their customers.

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

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With next generation nodes, where low k1 factors and design rules below 100 nm are utilized in lithography, it is expected that the number of critical mask defects will increase in the wafer fab owing to the fact that the size of critical defects gets smaller and mask designs become more complex. To make the AIMS™ tool suitable for the highly automated and efficiency sensitive production environment of wafer fabs a series of system improvements have been executed and are still ongoing. Since end of 2003 the 248nm AIMS™ system, the AIMS™ fab plus, is available with a robotic reticle handling system and a better than class 10 mini-environment. Figure 1 shows the picture of an AIMS™ fab 193 plus, the automated AIMS™ system including mask handling as it is used for 193 nm optical emulation of steppers or scanners.

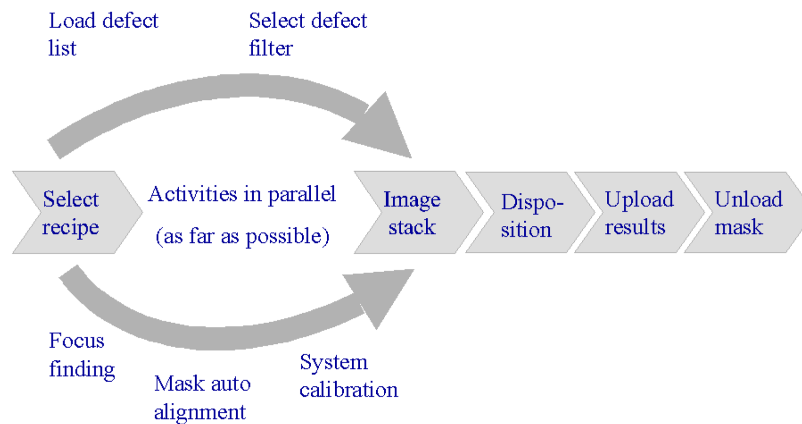

Fig. 2: The diagram shows the automated operation flow supported by the AIMS™ fab 193 plus for wafer fab.

As illustrated in Figure 2 the next generation software features single recipe based operation with a fully automated system set-up. In a next phase automated defect disposition based on printability criteria like transmission loss, CD or process window variations and differences between defect and reference images will be established. Today the reticle defect disposition can be done on the AIMS™ tools by analysis of the aerial image using different image plots like intensity profiles, linewidth versus threshold plots, Bossung curves, contour plots or exposure-defocus matrices. The next generation software, however, will provide the automated reticle defect disposition (ARDD), emphasizing more ease of use and throughput.

By flexible, automated adjustment of any setting to match conditions like in 193 nm exposure tools, the AIMS™ system can emulate for any type of reticles like binary, OPC and PSM. The aerial 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. The field of view is measured as through focus stack with several aerial images to provide full depth-of-focus information.

2. COST SAVINGS IN MANUFACTURING BY USE OF AIMS™ FOR ARDD

The benefits of analyzing all the information that the aerial image provides inherently are valuable at different steps in the wafer fab lithographic process as illustrated in Figure 3. AIMS™ can be used to conduct incoming quality control procedures (e.g. by verifying repairs), image qualification, defect disposition by "reviewing" the aerial image at sites at which defects were detected through other inspection methods, perform design verification like OPC judgement more efficiently and has been suggested for predicting critical issues in low-k1 lithography in process development in order to reduce the necessity of performing expensive wafer prints for this purpose [2].

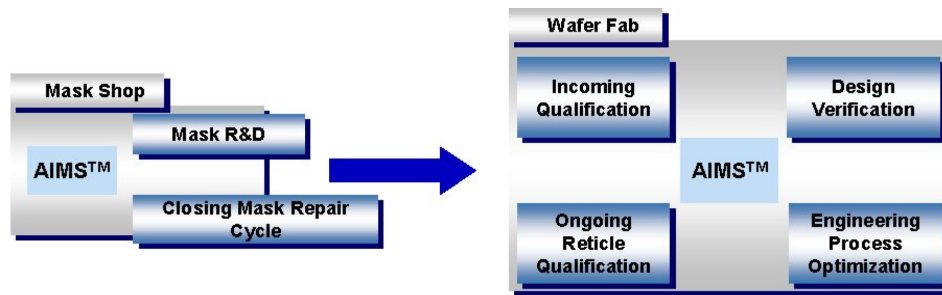

Fig. 3: Different tasks of AIMS™ in the wafer fab where the inherent benefit of the aerial image can be put to use.

Currently reticle surface inspection in brightfield mode is established as a standard method in wafer fabs to monitor the reticles for any new defects added during the manufacturing process on a routine basis. These inspections can be executed in short wavelength high magnification modes to detect defects down to 100 nm and typically use a die-to-database method (mask image is compared to design data) or a die-to-die inspection (comparison of nominally identical dies within a mask) or particle inspection (non-pattern related defects). The frequency of the inspections depends on the specific layers for which the mask is being used (e.g. every 3 days for critical layer reticles). The disposition of the detected defects is either done through predictions of the printability based on software simulations or through more generic disposition criteria like for example particle size, total defect count, or total defect count in clear areas.

The generic criteria are not very accurate and when defined conservatively have an impact in production cost due to either shorter mask life cycles or pose a higher risk of printing killer defects when defined more aggressively. Also there is still a high uncertainty in the printability assessments of the simulation programs in a certain grey area between non-printing and killer defect and whenever there is such an uncertainty in the printability prediction the defect has to be regarded as a "killer" defect. Especially 2D lithographic simulations are known to underestimate the quantitative impact of defect printability even at the 100 nm node [3]. Today the simulation tools are mainly 2D. Therefore the influences of the optical constants (n, k), layer thicknesses and geometrical topography, like side wall angles and trench depths are not taken into account. Even in 3D rigorous simulations where these parameters are taken into account, their exact knowledge is mostly not available, because these parameters require extremely sophisticated metrology on mask level, like CD, AFM or SEM measurement. Only the AIMS™ technique with its through-focus capability at actinic wavelength provides the superior evaluation as ultimate measure, because the AIMS™ method comprises all these issues in one measurement in one tool.

If the critical criteria are met in either case, the mask has to be removed from the wafer manufacturing process and either be exchanged by a replacement or sent back to the mask shop for repair or a cleaning procedure. Only a very limited number of cleaning procedures can be applied to masks of critical layers before they get damaged. Any improvements in reducing this printability uncertainty of defects and thus extending the mask life cycle for production can be directly translated into savings of operational costs of the manufacturing process. Also not having to interrupt the manufacturing process and qualifying an additional mask assures keeping the time line for product deliveries on track and does not turn into financial loss due to a missed time-to-market opportunity.

In order to work with 193nm at the 65nm node a variety of RET techniques like utilization of phase shift effects, off axis illumination, OPC is being applied to reduce the k1 factor. Along these lines the printed image deviates more and more from the actual pattern on the mask and the prediction of the effects on the actual printing of defects on the mask becomes more and more complex. For example the importance of full through focus investigations with an AIMS™ tool of phase defects has been shown and the corresponding simulation would require a rigorous 3D electromagnetic field calculation [4].

Since small defects play an increasing role with these RETs and the detection capabilities of the above mentioned inspection methods have to be maximized to not miss a critical defect, it can be common that a routine reticle inspection results in a number of defects in the magnitude of hundreds to thousands [5]. A printability simulator or a pre-classification of defects in terms of printability can reduce the number of potentially critical defects to about 10 defects which can only be dispositioned on an AIMS™ tool. A principle method of filtering was already demonstrated for the mask shop environment [6]. Likely defects on the masks are crystal growth, particles, pellicle defects, glass side defects, 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, since the reticle patterns are replicated onto hundreds and sometimes thousands of wafers. It is critical to gain absolute certainty about the printability of these remaining “suspects”. The aerial image measurements can remove the bandwidth of uncertainty between defects that don’t print and defects that definitely have an impact. This is especially applicable for defects of the phase shifting type or crystal growth defects and thus either help to extend the life time of the mask or avoid catastrophic printing of killer defects. Figure 4 shows a sketch of the automated defect disposition process and the role of the AIMS™ tool in it. We propose a band of +/- 2% for a 10% CD variation criteria based on common requirements for metrology tools and mask CD qualification. A future task will be the verification of this proposed band.

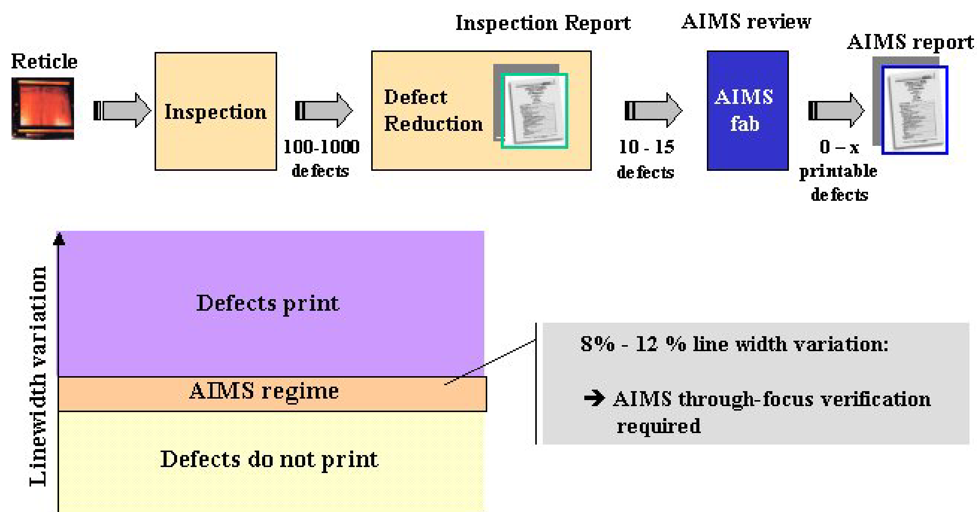

Fig. 4: This diagram shows the process of automated defect disposition based on standard and actinic through-focus inspection.

3. ARDD EXAMPLE CRYSTAL GROWTH

The AIMS™ system loads down mask coordinate information for mask alignment as well as for the remaining detected "suspect" defects from the defect inspection systems, like a TeraStar inspection system, in order to automatically revisit these defects after an automated alignment routine. Figure 5 shows two aerial images of crystal growth defects that occurred on a wafer manufacturing site. The aerial images are at best focus. The defects were measured with numerical aperture NA = 0.7 and partial illumination coherence σ = 0.85 at 193 nm wavelength. The measurements were done as through-focus measurements measuring three extra-focal, the best focus and three intra-focal planes within the range of depth of focus. A profile plot was selected to show the transmission loss. The transmission loss for best focal plane is 48% and 35%, respectively, which means that these defects print severely. For the pin dot defect also the line width versus threshold plot and the Bossung curve is displayed.

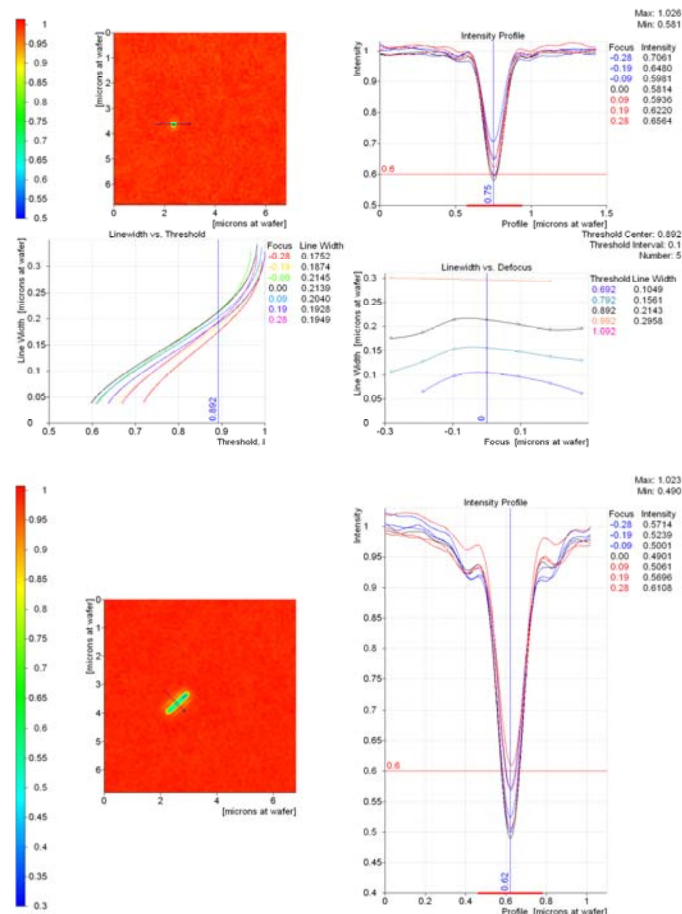

Fig. 5: The aerial image shows crystal growth defects which occurred during usage of the masks in IC production. The selected profile plot shows the transmission loss caused by this crystal growth defect.)

The ability to revisit these defects and investigate their printability by means of evaluating the aerial image at the actinic wavelength adds a cost saving process to the wafer fab environment, since it means no valuable stepper or scanner time and expensive lithographic processing has to be used and the results are obtained in a short turn around time. Based on the successful track record in the mask shops the evaluation of the aerial image ensures a more reliable printability prediction than any other method.

4. ARDD EXAMPLE OF PELLICLE AND BACKSIDE DEFECTS

While re-qualification of masks due to crystal growth and other small progressive defects is one important aspect for the AIMS™ in the wafer fab, recent discussions with customers have revealed another interesting area of mask quality control in wafer fabs, the influence of defects on the pellicle and on the mask backside.

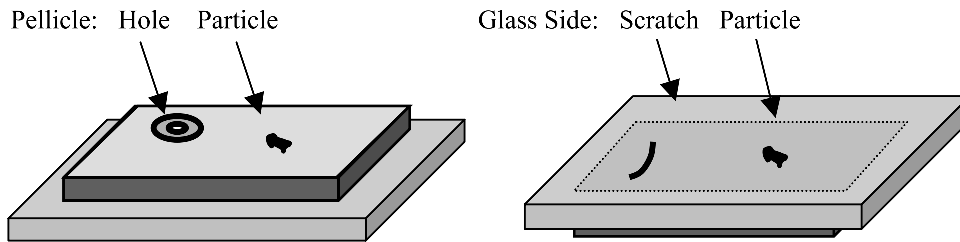

Fig. 6: A sketch showing pellicle and glass backside defects

As for example crystal growth defects are smaller type defects, the defects on the pellicle and the mask backside are big defects away from the chrome and out off the focal plane of the exposure tool. Typical examples of these defects are holes, scratches and big particles in and on the pellicle and scratches and big particles on the glass backside. However, as these defects are big, they can have printing effects on the chrome patterns beneath. Relevant defect sizes range from some 50µm to several millimeter. In the following examples the effects of a big particle on the mask backside (Figure 7) and of a pellicle hole with a few millimeters diameter (Figure 8) are shown. As it can be seen from the intensity profiles, in both cases a significant transmission loss can be observed, i.e. 30% and 15% respectively. Thus, both defects have a severe effect on the printing CD.

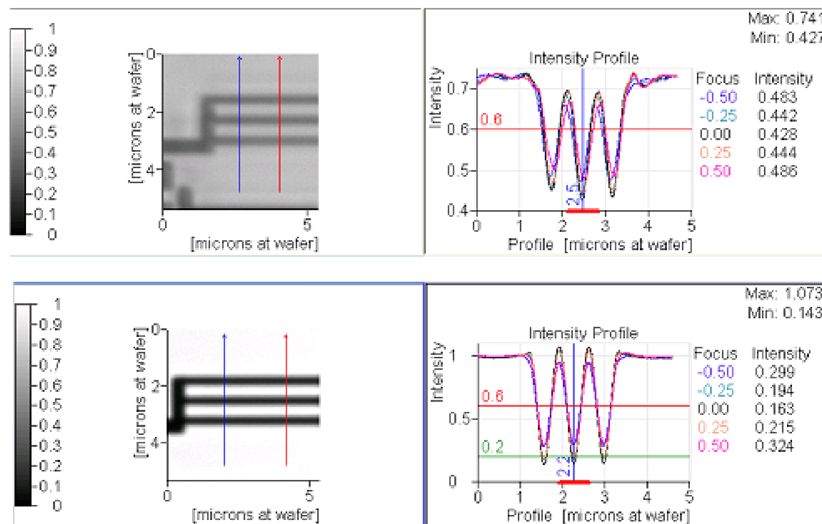

Fig. 7: Pellicle hole defect affecting aerial image (upper image), and defect free structures (lower image). On the left the aerial images are displayed, on the right the selected intensity profile plot.

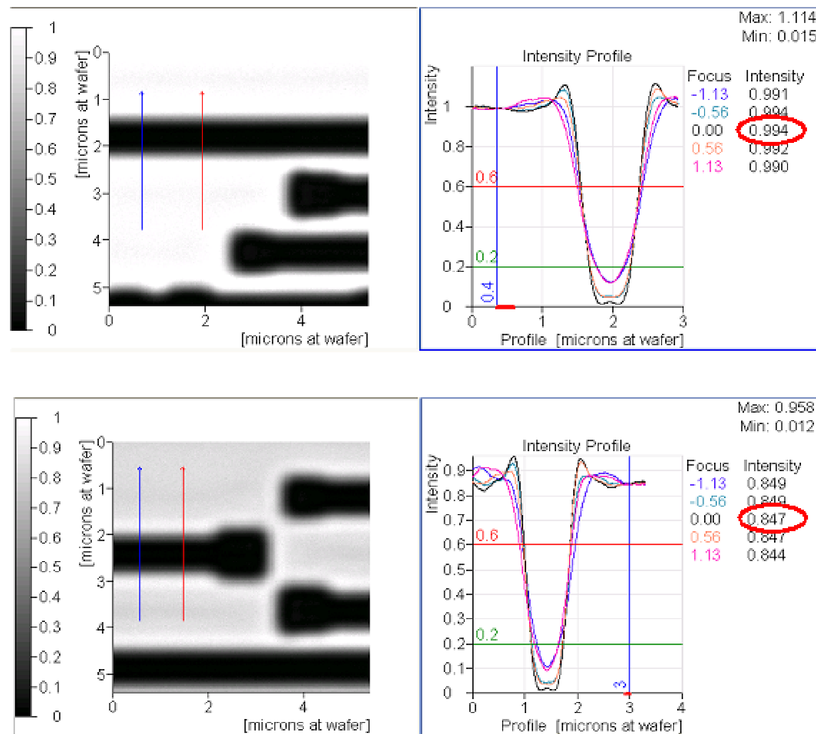

Fig. 8: Glass side particle defect affecting aerial image (upper image), and defect free structures (lower image). On the left the aerial images are displayed, on the right the selected intensity profile plot.

In general, the main question in these cases for wafer fabs is, if the patterns under these big kinds of defects will print properly. To determine this, it is inevitable to analyze the structure at the position, where the effect from the defect is worst. In a first step, the defects have to be inspected and analyzed in an overview mode, imaging the defects on the pellicle or on the backside glass surface. The field of view has to be several millimeters big. The area with the strongest shading, assumed to be the position with the highest transmission loss, can be determined and positioned, before the system is switched back to the aerial image mode in order to analyze the pattern in the selected area. But as the defect surfaces are well out of focus, the pattern under the position with the strongest shading effect is not necessarily the pattern that receives the strongest transmission loss.

In order to determine the pattern with the strongest transmission loss e.g. for a pellicle defect, the cone of light from the pattern through the pellicle to the objective has to be considered. As the pellicle of course is not in focus, not only the pellicle part directly above the chrome structure matters, but the complete area of the pellicle that is in the cone of light (see Figure 9a,b). In Figure 9a a defect directly above a pattern of interest is shown. In Figure 9b there is no defect directly above the pattern of interest. However, there are two different defects in the cone of light, which passes from the pattern through the pellicle to the objective. These take away more light from the aerial image than the single defect in Figure 9a. So it is not only important that the structure in the chrome plane is directly under the defect, it is even more important to look for that structure, which is in the focus of that cone of light, which includes/ passes most defects.
Knowing this, it might be useful to search the area of the cone of light in the overview mode on the monitor so that it is possible to position a maximum portion of the defect in it. Then, at that same position, the pattern can be analyzed by using the aerial image which is most effected by the defect(s). As the diameter of the cone of light on the pellicle is approximately 3.2mm this more complex approach is especially needed for either big defects or defects with very irregular forms.
Despite the complexity of the situation the disposition of such pellicle defects have been done successfully with the AIMS™ tool.

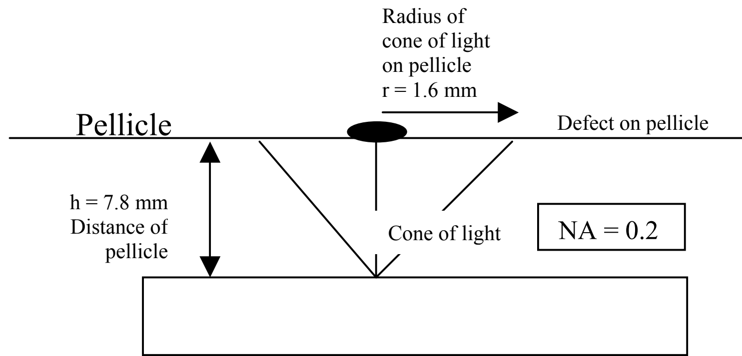

Figure 9a: Pellicle defect directly above structure

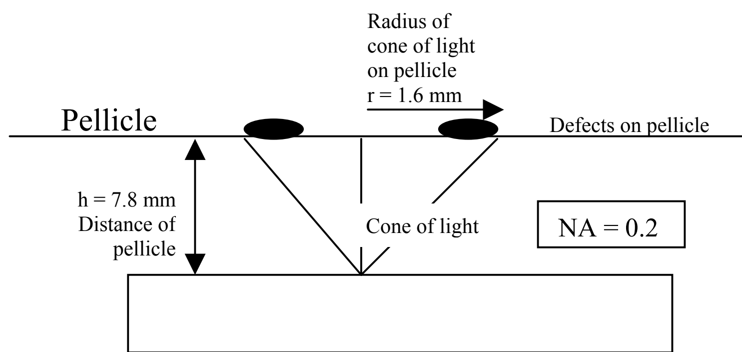

Figure 9b: Pellicle defects at edge of cone of light above structure

5. AIMS™ FOR IMMERSION SCANNER EMULATION

Currently, activities are going on to realize 193 nm lithography for smaller nodes even down to 45 nm. They use an immersion liquid, i.e. water, between the lens of the lithography tool and the wafer realizing a NA larger than 1.0. 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 instead of the current NA < 0.23 on the imaging side of the mask or reticle [7]. On the AIMS™ there will be no need for immersion liquids.
At such a small node automated reticle defect disposition will be even more critical. Not only RET techniques like utilization of phase effects, off axis illumination, OPC is being applied to reduce the k1 however also polarization effects being dominant at higher numerical apertures (hyper NA range: NA >1). Due to these strong rigorous polarization effects from masks and polarization effects from imaging itself actinic through-focus measurements will be needed to ensure the successful defect disposition.
The rigorous polarization effects from the mask 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. Where the size of mask features is equal to or smaller than the exposure wavelength the polarization effects have to be taken into account to realize a small node. 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.

6. SUMMARY

In this paper the aerial image measurement system (AIMS™) which is well establish in the mask shops worldwide was proposed in its wafer fab compatible version for use in wafer fabs. Application examples like crystal growth, pellicle or glass backside defects are shown to illustrate the benefit for integration of an AIMS™ fab 193 plus system in an automated reticle defect disposition (ARDD) process flow.

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