Actinic Review of EUV Masks: Performance Data and Status of the AIMS™ EUV System

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ABSTRACT

The EUV mask infrastructure is of key importance for the successful introduction of EUV lithography into volume production. In particular, for the production of defect free masks an actinic review of potential defect sites is required. ZEISS and the SUNY POLY SEMATECH EUVL Mask Infrastructure consortium have developed such an EUV aerial image metrology system, the AIMS™ EUV, with the prototype tool regularly being used for customer measurement campaigns and the first system shipped to customer end of last year. In this paper, we provide an update on the system performance and present quantitative measurements of the impact of mask surface roughness on the aerial image. We show that an increasing amount of effects is only visible in actinic aerial imaging and discuss potential benefits of aerial image based mask qualification.

Keywords: Mask metrology, AIMS™, Aerial image review, EUV, scanner emulation, defect review, EUV optics

1. INTRODUCTION

The introduction of EUV lithography into volume manufacturing is a major step in advancing to smaller design nodes such as the 7nm and 5nm node. Several ASML NXE:33x0 tools are running at chip manufacturers and shipment of the next generation NXE:3400B has already started [1]. The introduction of EUV lithography into volume manufacturing poses challenges on the infrastructure for manufacturing EUV masks. In particular, the production of defect free photomasks requires the review of potential defect sites. The AIMS™ EUV is closing this gap in the mask infrastructure.

The increased complexity of the EUV photomask structure introduces new defect classes, which have not been existing for 193nm systems. In addition to the absorber defects and particle adders directly on the mask surface, defects buried within the structure of the EUV mask are critical to EUV-imaging. Such phase defects even though invisible to SEM can cause defective wafer prints. By analyzing AIMS™ EUV aerial images of such phase defects and comparing them to wafer prints, Verduijn et al. have shown that the actinic review of AIMS™ EUV captures these defects and accurately predicts their imaging [2].

The mask structure is transferred to the wafer by imaging with the wafer fab scanner exposure system, i.e. in case of EUV masks the ASML NXE system. Therefore, it is the mask image and not the physical structure of the mask, which directly matters for the wafer printing process. The AIMS™ EUV measures the mask image under the conditions used in the NXE scanner system. These imaging conditions together with the 3D-structure of the reflective EUV photomask introduces EUV-specific mask effects like scanner-slit dependent CD-changes (“shadowing”) [3] or best focus separations of e.g. 2-bar structures [4]. These mask 3D-effects can be taken into account by OPC and source mask optimization. However, the accuracy is limited by uncertainties in the physical mask parameters and approximations used in the models. In this paper we show measurements on an EUV-specific phase effect, namely the aerial image effect of mask surface roughness and discuss its impact on line width roughness (LWR). The measurement of these “actinic” effects and OPC/SMO model calibration and verification needs scanner matching actinic aerial imaging such as provided by the AIMS™ EUV.

Figure 1 shows images of the currently four AIMS™ EUV tools. On the prototype tool, we have been able to run customer measurement campaigns for members of the SUNY POLY SEMATECH EUVL Mask Infrastructure consortium (EMI) on a regular basis since about two years. Recently the shipment of the first customer tool was achieved which is now being installed at the customer site. Beginning of this year, we have been able to achieve first light on the last customer tool, i.e. basic imaging capability is established and demonstrated on all tools.

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Figure 1: Images of the AIMSTM EUV tools in the ZEISS cleanroom. The prototype tool is used for customer measurement campaigns on a regular basis. We have achieved shipment of the first customer tool. The photographs at the right bottom show the empty bay after shipment and one of the transport containers loaded on a truck.

2. AERIAL IMAGE REVIEW OF EUV MASKS

EUV mask manufacture introduces new classes of defects for which a through focus characterization is necessary for the correct classification of the defect and for the determination of its repair process. For example, it has been shown that for topological or phase defects in spite of little CD variation in the nominal focus plane, a defect may be significant when the reticle or wafer is slightly defocused [5]. The AIMSTM EUV actinic mask review tool provides the mask shop with the capability of imaging defects on EUV masks within a focus range which can span several Rayleigh lengths (Figure 2, right panel) and thereby allows to measure process windows. Within this given focus range, a mapping of the defect through focus behavior can be set as dense as required by the particular application (i.e. number of focus planes), providing therefore a very flexible platform for the disposition and investigation of different defect types/sizes.

The full emulation capability of the ASML NXE:33x0 EUV scanner imaging provided by the AIMSTM EUV tool is of fundamental importance for the mask manufacturing flow. The AIMSTM EUV uses the same wavelength, illumination setting (see left panel of Figure 2 for exemplary illumination pupils), NA, chief ray angle (CRA) as the scanner and delivers imaging quality on scanner optics performance level. The scanner illuminates the mask through a thin arc shaped slit (see left panel of Figure 2) which introduces a field dependence of the illumination angles (theta CRA fixed to 6 degrees, variable azimuthal angle through the scanner slit) that generates 3D effects typical of the EUV lithographic process, e.g. shadowing effects. This complex illumination scheme is fully provided by AIMSTM EUV.
The contribution of the AIMS™ platform within the mask production process flow can be described as two folded: defect disposition, which traces the actual through focus printing behavior of a defect and repair verification, which certifies that a printing defect was repaired successfully. Figure 3 shows SEM images of a wafer print in which two 80nm diameter pin dots of absorber material on the mask are imaged as defects on wafer. As the two pin dots are classified as defects and repaired (etched from mask), a post repair review measurement is performed with AIMS™ EUV in order to verify the repair, before delivering the mask to production.

![Figure 2: Left. AIMS™ EUV schematics of NXE:3300 scanner emulation. Five pupil images as taken with the prototype tool, whereas the bottom line shows how the through field scanner slit illumination is emulated by the AIMS™ EUV tool. Right: AIMS™ EUV through focus stack of lines and spaces structure with defects. The bottom line shows the cornerstones of the AutoAnalysis software solution: reference and defect image analysis, defect identification and multi slice analysis.](image)

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![Figure 3: Exemplary selection of SEM images of pre and post defect repair. In this example two 80nm pin dots of absorber material have been repaired. An AIMS™ EUV image is shown here as post repair verification step, therefore enabling defect free mask production.](image)

ZEISS provides all AIMSTM actinic mask review tools with an analysis software, capable of performing the analysis on acquired AIMS™ images according to already established process of records and internal specifications. In addition, in 2015 the FAVOR® (Fast Analysis and Verification for Optimized Results), a powerful platform capable of hosting multiple applications and interfacing to multiple mask shop systems, was launched in order to provide customers with a higher level of productivity. The first FAVOR® solution available was AIMS™ AutoAnalysis [6] which allows mask shops to fully automate the evaluation of AIMS™ images in parallel to the image capturing sequence via direct tool connection, enabling flexible and reliable, operator independent image evaluation of even the smallest variations of the most complex structures. Full AutoAnalysis functionality will be available for the AIMS™ EUV platform by the finalized field acceptance of the first customer tool (engineering tool already in place, see right panel in Figure 2).

3. PERFORMANCE UPDATE

Previous publications have already shown promising data obtained from the AIMS™ EUV tool. In particular the high image quality and the ability to resolve target node features have been shown [7][8]. Key application of the AIMS™ EUV is the review of defects. E. Verduijn et al. have used customer access slots on the prototype tool to analyze...
several classes of native defects and compare AIMS™ EUV results with those of wafer prints obtained from an EUV scanner system [9]. The authors concluded that the AIMS™ EUV was able to detect all defects. In last year’s conference, we have reported the tool performance measured on the prototype tool with final acceptance test procedures [3]. We have shown, that the AIMS™ EUV reaches its main ATP specifications in terms of imaging, optics, defect location accuracy, CD-reproducibility, productivity of the most relevant settings and particles. All ATP tests have now also been performed on the first customer tool and some of these tests have already been done on the second customer tool. In this section, we will show that these tests indicate process stability of the AIMS™ EUV platform.

In April 2015, the AIMS™ EUV project reached an important milestone, which grants regular access to the prototype tool to the five members of the EMI consortium. Over the last approximately two years, participants have benefit of a constantly increasing level of automation and machine stability with the tool assuring through each measurement campaign a productive time above 60%, in some slots reaching peaks above 90%. These values are representative for a prepared tool operation over a few days, but it should be noted that they do not represent uptime measured over longer periods of time. They do not include time needed for preventive maintenance operations, which are executed in preparation of the access or the impact of component failures in between of the customer access slots. Also in terms of core performance, the AIMS™ EUV is already meeting final specification. Figure 4 shows the average throughput (sites/hour) reached by the prototype system in each of the 12 measurement campaigns executed to date. The graph shows a significant increasing trend, which benefited through the past months from the optimization of the image acquisition sequence and software stabilization. In customer access the measurement sequences are defined for the specific measurement purposes, i.e. they can vary e.g. in terms of number of focal plane, distribution of measurement sites on the mask and pupil fill. Despite the non-standardized measurement conditions the figure shows that the throughput does constantly reach values above spec (27.5 sites/hour for a 38.5% pupil fill). During both preliminary tests as well as source acceptance test, the first customer tool successfully met the throughput target specification. Besides, standardized throughput tests have been successfully executed also on the second customer tool, demonstrating overall process stability and through platform stability.

Figure 4: Left: Throughput achieved by the AIMS™ EUV prototype tool during the 12 customer access campaigns executed since April 2015. The red dashed line represent the specification performance of 27.5 sites/h for a 38.5% pupil fill (for example dipole sigma aperture). Right: Optics aberration performance RMS (Z5-Z37) as measured on AIMS™ EUV prototype tool and first two customer tools.

Also for optics performance the AIMS™ EUV total aberrations level has been measured to reach a result significantly better than target specification, providing the customer with an excellent scanner optics performance level. Qualification of the aberration level and alignment of the projection optics is executed through internal system wavefront metrology. The right panel of Figure 4 shows the aberration level measured in terms of total wavefront root mean square (RMS Z5-Z37) for the prototype tool together with the first two customer tools. As can be seen, an excellent and reproducible performance is achieved through platform.
As a performance test to quantitatively establish the repeatability of a measurement, the critical dimension (CD) value of a reference structure is measured and compared to a second equal one in which a defect introduces a change of recorded light intensity and therefore CD.

![CD repeatability of reference-defect pair as measured on the AIMSTM EUV prototype and first two customer tools (color code), where the mean difference in each of the three measurement series is set to zero. The gray dashed line represent the target specification, whereas the black dashed line represents the typical defect disposition tolerance band (10% of CD)](image)

Figure 5 shows the result of such an investigation performed on the prototype tool as well as the first two customer tools (three colors in the plot). The test consists of 30 repetitions of the reference-defect images acquisition, for each one of which the difference in CD is measured for a predetermined structure/region of interest. The measurements were carried out on a different reference-defect pair for each of the three systems, the mean difference in each of the three measurement series is set to zero. The target specification, the required tool performance for quantification, is defined in terms of standard deviation of the 30 difference values recorded and displayed by the grey dashed line in the Figure 5. The black dashed lines therein represent in comparison the 10% CD difference tolerance band criterion typically used for defect disposition. Both the prototype tool and first two customer tools reliably meet target specification also in terms of CD repeatability, demonstrating and assuring the achievement of the core performance specification of the AIMSTM EUV system through the series platform production.

4. AERIAL IMAGE QUALIFICATION OF EUV MASKS

At last year’s SPIE advanced lithography conference, we have shown quantitative measurements on the CD-variations through scanner slit [3]. This is an example of mask 3D-effects, which can only be measured with actinic aerial imaging. Another group of effects requiring actinic imaging are phase effects. In the following section, we present quantitative measurements on such a phase effect, namely the impact of mask surface roughness on the aerial image. We discuss consequences of these “actinic” effects on EUV mask qualification in the last part of this section.

4.1 Speckles caused by mask surface roughness

The surface roughness of an EUV-mask causes phase variations of the incoming wave fronts. These lead to intensity variations in the aerial image i.e. speckles [10]. Due to the reflective nature of EUV-masks and the smaller wavelength, the speckles contrast (3 sigma of intensity) is significantly higher than for DUV-masks and can reach several percent of the mean signal level. It can thus have an impact on the wafer print behavior of the mask for example on the line width roughness (LWR) ([11], [12]).
In this section, we demonstrate that AIMS™ EUV can directly measure and quantify the impact of speckles on the aerial image. We show that the observed variation of the speckle contrast with the illumination setting matches well with theoretical predictions. Based on these measurements, we predict the impact of speckles on the aerial image LWR for different realistic illumination settings. For aggressive NXE:3400 settings with low pupil fill and large defocus, speckles can have a significant impact on the LWR. AIMS™ EUV allows to quantify the mask surface roughness. We demonstrate this by evaluating the surface roughness of different masks that were qualified during the AIMS™ EUV access campaigns in the last year.

Observation of Speckles and Speckle Sensitivity

Figure 6 shows an aerial image focus stack acquired with the AIMS™ EUV and an annular illumination setting at a purely reflecting site. We observe stationary intensity variations whose amplitude increases up to 4% in the defocus. These speckles are not a measurement artefact, but they are direct consequence of mask surface roughness. They will also be present in the aerial image of a scanner and thus affect wafer printing. Speckles due to mask surface roughness have also been observed at the Sharp tool [13].

We have performed additional measurements with different illumination settings (cf. Figure 7). In all cases, an asymptotic linear increase of the speckle contrast with the defocus was observed. The constant of proportionality, the speckle sensitivity, depends strongly on illumination setting as shown in Figure 7. The smaller the pupil fill, the higher the sensitivity. A quantitative theoretical prediction of the speckle sensitivity can be made using the weak object transfer function approach to model the impact of mask surface roughness on the aerial image [14]. The calculated theoretical sensitivities, also shown in Figure 7, match well with our measurements.

This good agreement between measurements and model allows us to predict the speckle sensitivity for future NXE:3400 illumination settings. As shown in Figure 7 the sensitivity will increase by up to a factor seven compared to the conventional NXE:3300 setting. Therefore, the impact of mask surface roughness on the aerial image and consequently on wafer print is expected to increase in next generation EUV scanners.
Mask Surface Roughness Impact on Line Width Roughness

The LWR of a structure printed on a wafer is affected by the LWR of the aerial image, which can be qualified with AIMS™ EUV, and additional effects due to photoresist exposure and etching. As noted previously ([10], [11], [12]), the local intensity variations in the aerial image caused by speckles are one contribution to the linewidth roughness of the aerial image.

Figure 8 shows quantitative predictions for the impact of speckles on the aerial-image LWR based on the measured speckle contrasts. Predictions are shown for different realistic illumination settings of current and future EUV scanners for structures with NILS=2 at a defocus of 990 nm. For these predictions, we assume that the contribution of the mask to aerial-image linewidth roughness can be written as the sum of two statistically independent contributions:

\[
LWR_{\text{abs}} = LWR_{\text{mask}} + LWR_{\text{speckle}}
\]

\( LWR_{\text{mask}} \) is the linewidth roughness of the absorber caused by the mask patterning and manufacturing process. \( LWR_{\text{speckle}} \) is the illumination setting dependent contribution of speckles to the line width roughness. We estimate its magnitude using the following approximation formula:

\[
LWR_{\text{speckle}} \approx w \frac{\Delta I}{N\text{ILS}}
\]

\( \Delta I \) is the speckle contrast. For NXE:3300 illumination settings, it is measured directly as described in the previous paragraph. For NXE:3400 scanner settings, it is calculated using the model for the speckle sensitivity described in the
previous paragraph. \( w \) is a factor between 0 and 2 that describes how the speckle intensities on both sides of the line are correlated. A value of two corresponds to identical intensity variations on both sides of the line, whereas \( \sqrt{2} \) corresponds to statistically independent variations. In simulations, an intermediate value of 1.8 has shown to yield good agreement between the observed line width roughness and the above approximation.

Whereas for the NXE:3300 scanner the mask contribution to LWR is dominated by the absorber contribution, the situation changes for NXE:3400 settings. Due to the higher speckle sensitivity, the speckle contribution to the LWR of the aerial image surpasses the typical absorber LWR significantly and becomes the dominant contribution. A total LWR of up to 8 nm at mask level, i.e. 2 nm at wafer level, is predicted at a defocus of 60nm (wafer level). This approaches the state-of-the-art wafer LWR of about 4.5 nm [15]. Thus, the mask contribution to the wafer LWR might no longer be negligible.

**Figure 8:** Projected impact of speckles on linewidth roughness (at mask level) for different illumination settings and two different absorber linewidth roughness (2 and 4 nm) at a defocus of 990 nm (mask surface roughness 65nm). For NXE:3400 the speckle contribution is expected to dominate over typical mask absorber linewidth roughness of about 2-4 nm.

**Measurement of Mask Surface Roughness**

As shown in the last paragraph, speckles due to mask surface roughness can become a significant contribution to the aerial-image LWR in next generation scanners. AIMS™ EUV can be used to measure and quantify the mask surface roughness of EUV masks. In contrast to measurements with an atomic force microscope [11], AIMS™ EUV is only sensitive to the optical effect of the roughness within the relevant spatial frequency range defined by the NA of the scanner.

Figure 9 shows the measured root means square (RMS) of the surface roughness of different customer masks that were qualified during previous customer access campaigns. We observe variations of the mask surface roughness between 0.05 nm and 0.07 nm much higher than the experimental reproducibility. As the expected LWR is proportional to the mask surface roughness, this corresponds to up to 40% variations of the speckle contribution to line width roughness for these different masks.
Figure 9: AIMS™ EUV is capable of measuring the optical relevant mask surface roughness of EUV masks. We show measurement results of different masks that were qualified during the customer access campaigns on the prototype tool. Reproducible mask-to-mask roughness variations of up to 40% are observed. On the right hand side, we show the expected impact on the line width roughness at defocus for different illumination settings. Reducing the mask surface roughness leads to an improved line width roughness in particular for NXE:3400 settings with low pupil fill.

4.2 Qualification of EUV masks

In the previous section we have shown that mask surface roughness produces local intensity inhomogeneities ("speckles"). These speckles increase the aerial image LWR. With smaller pupil fill ratios used in the future, they will become an increasingly important and relevant contribution to the mask LWR. This is an example of a contribution invisible to the current SEM based qualification process. A SEM based CD-qualification measures the absorber structures on the mask, whereas an aerial image based CD-qualification measures the optical mask effect in the wafer exposure process. It is this aerial image, which transfers the mask pattern to the wafer. In this section we will briefly discuss differences of these two approaches.

As shown in Figure 10, even for DUV masks using assist features, strong OPC or inverse lithography patterns the structure on the mask is significantly different from that in the aerial image. Furthermore, the transfer of CD-errors on the mask structure, characterized by the MEEF, depends on the structure and imaging conditions. Mask process variations may lead to printing failures especially for high MEEF pattern and mask characterization by CD-SEM only might not be sufficient anymore. These facts led to the development of the WLCD platform that allows for measuring the aerial image CD of DUV masks capturing OPC, MEEF and 3D mask effects [16]. For EUV lithography, 3D mask effects become even more pronounced and dependent on position within the exposure field ("shadowing"). Additionally phase effects influence wafer printing but are not visible in the mask absorber structure. I.e. the amount of effects only visible to actinic aerial imaging is further increasing for EUV lithography (see Figure 10).

It is also important to notice that aerial image qualifies a higher budget level than SEM based mask CD qualification does. The absorber structures are sub-budget contributions to the aerial image. They are by far not the only contributions (e.g. phase errors, mask material constant variations/uncertainties and accuracy of OPC are also contributions) and they do not contain the transfer function to the aerial image (e.g. MEEF for CD-errors or the spatial frequency transmittance for LER/LWR). The higher budget level of the aerial image has two potential advantages for the qualification:

(i) It is significantly more complete, i.e. reduces the risk of not noticing potential deviations in contributions invisible to SEM and uses the chance of balancing effects of individual contributions. A sub-budget qualification needs to assume, that individual effects add in a rather worst-case manner. For example, scanner-slit dependent OPC error and mask structure CDU error due to mask processing may in some...
instances even partially balance. As a consequence masks suitable for printing may be revised because of deviations in a sub-budget, i.e. mask yield might be affected.

(ii) The aerial image CD can be qualified against significantly higher specification values compared to the mask structure CD, because it contains (a) all mask effects contributing to the wafer exposure, thereby aggregating all the corresponding sub-budgets, and (b) the structure CD-error amplification by optical MEEF. The impact of this error amplification is e.g. taken into account in the ITRS roadmap [17]. It assumes a total CDU requirement of 10% of the target CD, the same contribution of 10% / sqrt(2) is attributed to mask and process, respectively. I.e. for a target CD of 40nm, as anticipated for 2021 in the ITRS tables, 2.8nm mask CDU contribution is acceptable. Assuming a MEEF of 3, a mask structure CDU requirement of only 0.9nm is derived.

Litho performance is driven by the edge placement error (EPE) budget [18]. Important contributions are overlay, CDU, LER and OPC. With aerial imaging, the mask EPE contribution of CDU, LER and OPC errors can be qualified on a high budget level in an integrated way. Due to its actinic aerial imaging, the AIMS™ EUV is capturing all relevant mask effects contributing to the wafer exposure. Currently the AIMS™ EUV system processes are optimized for defect review. With the development of options dedicated to the purpose of aerial image metrology, the AIMS™ EUV system could support aerial image qualification in an optimized way.

Figure 10: For EUV masks, an increasing amount of effects is only visible in actinic aerial imaging. Top: SEM image of a particle defect (left) and corresponding AIMS™ EUV aerial image (middle) and wafer print (right). The aerial image much closer resembles the wafer printing effect compared to SEM. Center: exemplary inverse lithography mask layout (left) compared to the corresponding aerial image (middle) and wafer print (right). Bottom: Illustration of EUV-specific effects not visible in SEM. These are namely phase effects like mask surface roughness induced LWR and mask 3D-effects like scanner slit dependent shadowing.
5. CONCLUSION

With the shipment of the first customer tool end of 2016 and first light on all currently integrated tools beginning of 2017, we have achieved important milestones of the AIMSTM EUV programme. In last year SPIE conference, we were able to show that the prototype system is reaching all core specifications. This year we show data indicating process stability, i.e. stable performance over the various AIMSTM EUV tools. Examples of repair verifications and customer studies ([2],[9]) using data from EMI member customer access show, that the AIMSTM EUV is capable of its main application, the review of potential defect sites. In this paper, we have presented quantitative measurements of mask surface roughness and its effect on aerial images. We have made a model-based prediction that this contribution to LWR will be increasingly important for the future. Based on the observation that for EUV masks the amount of effects only visible in actinic imaging is increasing we discussed the possibility of mask qualification based on aerial images.

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