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 started a development program for such an EUV aerial image metrology system, the AIMS™ EUV. In this paper, we provide measurement data on the system’s key specifications and discuss its performance and capability status.

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 while keeping the process complexity, i.e. the number of process steps on a level comparable to nowadays products. Several NXE:3300 tools are running at chip manufacturers, and the insertion of EUV lithography for the 7nm node is discussed. This introduction 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 being developed to close this gap in the mask infrastructure.

The increased complexity of the EUV photomask structure introduces new defect classes, which make defect inspection and review more challenging than for 193 nm 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. The substrate of the EUV mask is coated with a reflective multilayer structure and the EUV light is penetrating into this structure. Bumps and pits on the substrate or defects in the multilayer itself can penetrate and spread through the multilayer changing the amplitude and phase of the reflected light.

Since the penetration depth into the material and the multilayer reflection heavily depends on wavelength, the imaging effect of these defects critically depends on the wavelength. Thus, the review needs to be actinic in particular for these phase defects. Furthermore, the repair strategy for these defects is different from that for absorber defects [1]. As of today, the defects inside the EUV masks cannot be repaired directly, they can either be covered by the absorber structure using pattern shift or they can be compensated for. I.e. the absorber is modified such that it counterbalances the effect of a defect inside the mask structure under the imaging conditions used for printing this mask. Such repairs can be done in closed loop of the AIMS™ EUV and MeRiT® repair tool. The information needed for determination of the repair shape can be extracted from the AIMS™ EUV measurements and after the repair its success can be verified with the AIMS™ EUV.

The AIMS™ EUV measures the aerial image under the conditions used on the scanner system, e.g. the NXE:3300. This means that it uses the same wavelength, numerical aperture, illumination setting and chief ray angle as the scanner system. Thereby it measures the effect of potential defects as they will appear in the aerial image of the scanner system used for wafer printing, i.e. it fully emulates the scanner imaging process. By measuring through focus and by the ability to vary the threshold in the analysis (corresponds to exposure dose on the scanner system), the AIMS™ EUV can be used for determining the process window reduction caused by potential defects.

ZEISS and the SUNY POLY SEMATECH EUVL Mask Infrastructure consortium (EMI) are pursuing a development program for the AIMS™ EUV which includes the realization of a prototype tool. For a discussion of the tool concept see [2]. In addition to the prototype tool, ZEISS is currently building three customer tools, see Figure 1. All four tools are assembled, EUV imaging capability has been achieved on three of the tools. For the prototype tool application automation including the mask and aperture handling process and the measurement sequence has been reached. Remaining tasks include machine automation and stabilization packages, e.g. for start-up and service. On the prototype tool customer measurements for EMI program participants are running on a regular basis with already seven measurement campaigns finished.

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2. ACHIEVED TOOL CAPABILITIES

In the last year several tool capabilities including automated handling, alignment and measurement sequences have been launched. The handling system is now able to automatically handle masks from the load port to the reticle stage and back and to automatically exchange illumination sigma apertures from the optical path with those stored in the in-vacuum library. Figure 2 shows pupil images of apertures used in the EMI access program on the prototype tool.

Furthermore, the alignment sequences for masks and apertures have been taken into operation. Details on the accuracy of the mask alignment are given in section 3.3. The measurement sequence is now fully automated. It involves that the system navigates to a number of measurement sites on the mask, emulates the chief ray angle, focusses the mask, acquires focus stacks consisting of a number of predefined focus levels and applies the required normalizations.

The pupil images in Figure 3 show the movement of the illumination pupil with the automated emulation of the chief ray angle rotation. For the various chief ray angles images of an elbow structure have been taken. Even though the images look visually the same, the effect of the chief ray angle rotation becomes visible in the CD analysis. The CD of the vertical structures is increased if the chief ray angle is moved from the central position, the CD of the horizontal structures is decreased. The HV-difference of the CD changes by more than 5nm over the scanner field. The significant CD-variation demonstrates the need to emulate the chief ray angle rotation by using the same chief ray as the structure is exposed with in its position in the scanner slit.

Figure 1: Four AIMSTM EUV tools are currently integrated in the ZEISS cleanroom. We have been able to conduct several customer measurement campaigns for the EMI program participants on the prototype tool.

Figure 2: Pupil images of apertures used during the EMI access program. The AIMSTM EUV is able to automatically exchange these apertures and align them.
3. TOOL PERFORMANCE DATA

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 [3][4]. 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 [5]. The conclusion was, that the AIMS™ EUV was able to detect all defects.

In a recent measurement campaign done in the framework of a SEMATECH milestone, the tool performance status with respect to its key specifications has been tested, using final acceptance test procedures. This section shows these qualification results obtained on the prototype tool.

3.1 Imaging performance

The excellent visual impression of the AIMS™ EUV images could be already observed by the first light images [3] and the low noise level of the images was noted in [5]. The tool acceptance test contains a measurement of the image contrast. This contrast defined as (max- min) / (max + min) of a line profile is evaluated at the center and the four corners of the AIMS™ EUV quality field of ±2µm. The specified structures are 88nm lines with a pitch of 528nm with NA=0.33/4 and conventional illumination sigma=0.2 – 0.9. The analysis is done at best focus with the line profiles averaged over 200nm. As shown in Figure 4 the measured contrast of about 90% is close to the ideal imaging contrast determined by 3D aerial image simulations and clearly fulfills the specification of ≥64%. The AIMS™ EUV delivers high quality images of target node structures.

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3.2 Optics performance

We have used the tool internal wavefront metrology for qualification of the aberration level and alignment of the projection optics system. Figure 5 shows the aberration level measured after adjustment in terms of total wavefront root mean square (RMS Z5-Z37) and grouped RMS in comparison to the specification. The AIMS™ EUV clearly reaches its specification with an excellent aberration performance on scanner optics quality level. In a previous publication [4] a flare-level <1% has been shown, clearly meeting the specification. The illumination optics has been qualified in terms of the illumination pupil performance, see Figure 6. The pupil performance has to be achieved for all chief ray angles used for scanner emulation and is specified in terms of ellipticity and pole balance. For determining ellipticity and pole balance the pupil is cut into 4 quadrants and the integrated energies (E_{left}, E_{right}, E_{up}, E_{down}) in these quadrants are determined. Pole balance x is defined as (E_{left} - E_{right}) / (E_{left} + E_{right}), pole balance y as (E_{up} - E_{down}) / (E_{up} + E_{down}). Ellipticity is defined as (SUM X - SUM Y) / (SUM X + SUM Y) with SUM X = E_{left} + E_{right} and SUM Y = E_{up} + E_{down}. It is relevant for HV differences of the CD. It can be seen, that all values fulfill the specifications. In summary, the AIMS™ EUV optics has been qualified and reaches an excellent performance level.

![Figure 5](image)

**Figure 5.** Measured aberration performance of the projection optics in comparison to the specification. The specification is clearly reached.

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3.3 Positioning performance

The positioning performance describes how precisely the AIMS™ EUV can go to a given structure on the mask. It is measured by the defect location accuracy test. The procedure is such that automatic mask alignment is done with 3 alignment markers and then the AIMS™ EUV acquires images of 5 position markers distributed over the mask approached from 4 directions, respectively. Ideally, the position markers would be exactly in the center of the 8x8µm field of view. The deviation ($\Delta x_i$, $\Delta y_i$) from this position is measured. In the test the maximum of these 20 deviations was $\Delta x_{\text{max}} = 64.9\text{nm}$ and $\Delta y_{\text{max}} = 44.1\text{nm}$. This means, the specification of $\leq 200\text{nm}$ is reached. The AIMS™ EUV positions each review site directly in the center region of the AIMSTM image.

3.4 CD reproducibility

A defect is characterized by its CD-change, i.e. by the structure size error it introduces. The tolerance with respect to such CD-changes depends on the layer and the process. As rule of a thumb CD-changes of 10% or greater are regarded as defects. In repeated measurements of the same structure, ideally always the same structure size is measured. The reproducibility of the measurement result is crucial for the quality of the AIMS™ EUV measurement and is characterized by the CD-reproducibility. The test procedure is graphically illustrated in Figure 7. Focus stacks with three levels (best focus, ±990nm defocus) are taken at three positions on the mask (left: x=-49mm, center: x=-1mm and right x=+47mm). The underlying idea of the procedure is, that the CD-reproducibility is tested through a typical focus range of a Rayleigh unit of defocus= 0.5 * $\lambda$ / NA$^2$ = 992nm and for the extreme positions of the exposure tool scanner slit of ±52mm, i.e. for the extreme chief ray angle rotations. The AIMS™ EUV was used in the ASML NXE:3300 emulation mode, i.e. a numerical aperture of NA = 0.33 /4 (reticle level coordinates) and the chief ray angle rotation of that exposure tool were used. In the described sequence the measurement position on the mask is changed from left to center to right and then it is repeated 10 times. This results in 10 repeated measurements at each position with stage- and aperture movement in between. This test has been done with a vertical dense line structure of CD=64nm with a dipole-x sigma=0.2-0.9 illumination and a dense contact pattern with CD=80nm and quasar sigma=0.2-0.9 illumination. All CD-values refer to mask level, i.e. the structure size on the wafer will be a factor of four smaller. For each feature and each reticle position, the first measurement was used to determine the threshold that yields the target CD. For the following measurements the same threshold was used for the CD evaluation. The CD-reproducibility is specified as 3 times the standard deviation of the 10 repetitions. For readers familiar with current AIMS™ tools for 193nm, we note, that this definition is different from that used in these tools and results in about a factor of 2 higher values. Figure 7 shows the result of this CD-reproducibility test and compares it to the specifications. It shows, that CD-reproducibility values on the order of 1nm are reached with all values fulfilling this key specification of the AIMS™ EUV.
3.5 Productivity

The productivity of the AIMS™ EUV is quantified by the run-rate, which gives the number of sites measured per hour. The run-rate test uses a number of sites distributed over the mask and 7 focus planes per site. It therefore includes reticle stage- and aperture-movement as well as clear calibrations, i.e. resembles a realistic measurement job. The test performed for the SEMATECH milestone is done with 28 sites distributed over the mask. A vertical dense lines structure with CD=64nm was used and imaged with an NA=0.33/4 and dipole-x, sigma=0.2-0.9 illumination having a pupil fill of 38.5%. The time the sequence has taken, was extracted from the log-files and results in a run-rate of 45 sites per hour significantly exceeding the specification of 27.5 sites per hour. Figure 8 shows the run-rate specification table presented in previous publications [3] with a column for currently measured tool performance added. For the setting using high pupil fill of 77% corresponding to a large conventional setting with sigma 0.2 – 0.9 the specification is not yet reached. It is also anticipated to develop a fast mode which compromises measurement accuracy in favor of a faster run-rate. Since we currently concentrate on the standard measurement mode, this mode is not yet implemented. It should be noted, that from application point of view the settings with smaller pupil fill are expected to be the most relevant. Therefore, it is a positive result, that for these settings the AIMS™ EUV already exceeds the specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Measured</th>
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<tbody>
<tr>
<td>Run Rate standard</td>
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<tr>
<td>7 focus planes per site</td>
<td>≥ 27.5/hr</td>
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<td></td>
<td>≥ 51/hr</td>
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<td></td>
<td>45/hr</td>
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<tr>
<td></td>
<td>&gt; 38.5% pupil fill</td>
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<tr>
<td></td>
<td>&gt; 77% pupil fill</td>
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<tr>
<td>Run Rate fast mode*</td>
<td></td>
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<tr>
<td>7 focus planes per site</td>
<td>≥ 55/hr</td>
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<tr>
<td>*CD-repro = 1.8 nm (3σ)</td>
<td>Not yet implemented</td>
</tr>
<tr>
<td></td>
<td>&gt;38.5% pupil fill</td>
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Figure 7. CD-reproducibility test. Top: measurement procedure. Focus stacks are taken for three positions within the scanner slit of the exposure tool (left → center → right). This sequence is repeated 10 times resulting in 10 repeated measurements at each position with stage- and aperture-movement in between. Bottom: measured CD-reproducibility compared to specifications. All values are 3 times the standard deviation at mask level.

Figure 8: Run-rate measurement. 28 sites distributed over the mask are measured with 7 focus levels. The table shows the current tool performance with compared to its specifications.
3.6 Cleanliness: Particle adder

Our strategy for particle mitigation included implementing best engineering practices and cleanliness specifications for the individual components and processes. These specifications have been tested on component level and individual contributions have been tested on the prototype tool. We were now able to perform a full particle acceptance test procedure sequence on the prototype tool. This sequence includes the full reticle path from the outer handling load port to the reticle stage, an exchange of the sigma-aperture, a measurement of 9 sites distributed over the mask and the reticle path back from stage to load lock. I.e. it also includes reticle stage movement and operation of the EUV light source. This sequence has been repeated 25 times (final ATP test has 40 cycles) and the number of particle adders on the mask frontside and backside has been measured. For the frontside the quality area of 142x142mm is evaluated, i.e. excluding the handling zones. Figure 9 shows the results of this particle test. On the mask frontside quality area 9 adders ≥ 100nm have been measured, on the backside 6 adders ≥ 100nm with 1 of them ≥1µm. This corresponds to 0.36 adder/cycle ≥ 100nm for the frontside and 0.04 adder/cycle ≥1µm for the backside; both values without subtracting any offset for the test procedure. The particle measurement is done with a ZEISS in-house tool and contains manual handling of the mask causing a low number of particle adders. The acceptance test procedure therefore allows the subtraction of this offset which has to be previously qualified. These test results show an encouraging particle performance.

**Frontside:**

**Backside:**

![Figure 9: Particle measurement results of 25 cycles of the acceptance test procedure sequence. Left: particle adder in frontside quality area, Right: backside. For the frontside adder ≥100nm in the quality area are specified, for the backside ≥1µm. The measured values correspond to 0.36 and 0.04 adder/cycle, respectively.](image)

4. CONCLUSION

Automated handling and measurement capability has been launched including emulation of the scanner chief ray angle. Accordingly, customer measurements can now be run automatically by predefined jobs. Further tool functionality will be added for e.g. automated start-up, error-handling and service. The EMI program participant access on the prototype tool is running with already 7 campaigns performed. The tool performance has been tested in the context of a SEMATECH milestone using final acceptance test procedures. The AIMS™ EUV already reaches its main ATP specifications in terms of imaging, optics, defect location accuracy, CD-reproducibility, productivity of the most relevant settings and particles. The data show that the AIMS™ EUV is capable of fulfilling the application needs and will close an important gap in the infrastructure for EUV volume production.
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