Aerial image measurement system for 157nm lithography masks

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Abstract

The first Aerial Image Measurement System (AIMS™) [1] for 157 nm lithography worldwide has been brought into operation successfully. Due to the wavelength in the vacuum ultraviolet (VUV) spectrum major efforts had been required for the illumination and imaging part of the optical components as well as for the purging of the system which will be discussed. The system's performance will be demonstrated by AIMS™ measurements at 157 nm wavelength on binary chrome photomasks. Several through focus series have been measured in order to evaluate transmission, linewidth (CD) results, Bossung curves and to calculate the exposure-defocus windows. Detailed results of short-term and long-term CD repeatability measurements are discussed which prove the usage of the system for mask evaluation for 157nm lithography. Measurements of mask structures with feature sizes at mask level of 240 nm will be presented and discussed.

Introduction

The AIMS™ is an optical system for evaluating reticles under specific exposure tool conditions of numerical aperture (NA), sigma, wavelength and illumination type. By adjustment of illumination type, numerical aperture and partial coherence to match the conditions in 157 nm exposure tools, it can emulate any type of reticles like binary, OPC and phase shift, designed for 157 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 a reticle without the need to do real wafer prints using the exposure tool and following SEM measurement of the printed features [2,3].

For DUV (deep ultraviolet: 248, 193 nm) these kinds of tools are commercially available as AIMS™ fab and AIMS™ fab 193. They are state-of-the-art in the photo mask industry for development, quality control, repair verification and defect classification of photomasks and reticles. International SEMATECH, Infineon and Selete are currently engaged in a project with Carl Zeiss Microelectronic Systems GmbH to develop such an AIMS™ tool for direct optical simulation of 157 nm lithography [4].

The project consists of two phases: an alpha tool and a beta tool phase. Figure 1 shows a picture of the first beta tool. The alpha tool is a fully functional 157 nm AIMS™ tool with minor limitations in terms of mask handling and throughput comparing to the beta and production tools. The value of the tool for mask evaluations and lithographic assessments is not affected by these limitations. The purpose of the alpha tool is to test and prove out technical concepts for an 157 nm AIMS™ tool [5,6,7].

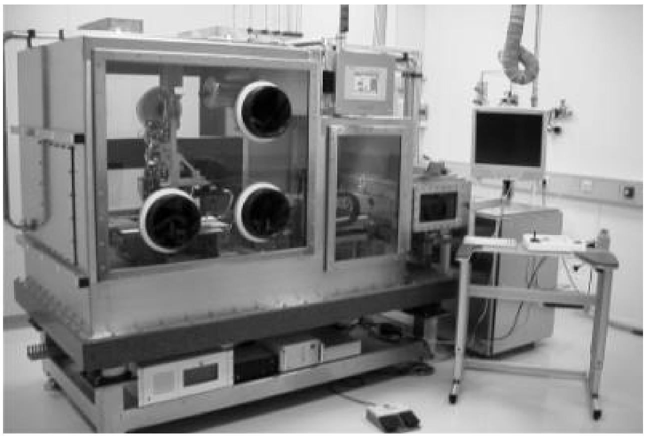

Figure 1. View of the AIMS™ fab 157 beta tool.

Tool Setup and Technological Challenges

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 coherence of light, i.e. the adjustment of sigma (σ). The imaging part contains changeable pinholes to realize the stepper equivalent setting of numerical aperture (NA). Both the σ and the NA have to cover a wide range of values in quasi-continuous steps and be able to adjust to different exposure tool settings with minimal effort at one and the same system. An F_2 excimer laser and beam homogenizer are used as illuminator. Bandwidth value is 10pm for 157nm (FWHM). Therefore the beam homogenizer is needed to reduce the speckles in the laser beam and ensure a similar illumination uniformity as the longer wavelength systems, 248nm and longer, using an arc source. To minimize vibrations the optical components are mounted to a granite stand, and the optical table is installed on an active vibration damping system. For recording the

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AIMS™ images a VUV CCD camera with 14 µm x 14 µm pixel size is in use. For overviewing and alignment purposes a reflected light optical system working in the VIS is provided.

In order to overcome the absorption of 157nm irradiation in air an inert gas compartment has been realized, consisting of a two level purging: An outer compartment is realized by a glovebox housing an atmosphere of purified nitrogen. In addition the illumination and the imaging beam path are completely housed and separately purged with nitrogen purified by dedicated filters.

The photomasks are loaded into the system via a load port. The beta tool is equipped with an automated mask handler to bring the reticle from the load port to the stage and back. The tool is equipped for reticles in 5", 6" and 9" format.

Item	Specification
Mask size	6" square, 0.250" thick, 9" square, 9 mm thick
Mask types	Binary, OPC, PSM
Objective working distance	~7.5 mm
Exposure wavelength	157.6 nm
Mask reduction	4x, 5x
Illumination type	Conventional, annular, dipole, quadrupole
NA range	0.6 to 0.92, $\Delta NA = 0.01$
σ range	0.25 to 1.0, $\Delta\sigma = 0.01$
Scanning stage	< ± 2 µm with CAA, precision < 2 µm
Z focus step	50 nm, repeatability = ± 50 nm
Resolution	180nm (incl. off-axis illumination)
Measuring range	180 nm – 5000 nm
Field illumination stability over 1h	< ± 2.5 % of normalized clear reference value
Field illumination uniformity, normalized	< ± 1.5 % of normalized clear reference value
CD repeatability over 1h	< ± 16 nm on wafer level
CD uniformity	< ± 6 nm on wafer level

Table 1. Summary of current specifications and measurement results of alpha-tool.

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.

All applied optical and mechanical materials have been carefully selected and tested for 157 nm compatibility. A full CaF_2 – optics has been established. Various technological challenges are inherent with a development of an optical system operating at 157nm (VUV). Below are listed the key critical items which are overcome:

- Most critical field illumination uniformity and speckle reduction of the 157 nm laser that shows a much larger coherence length than a 193 nm table top laser,
- system purging and housing,
- CaF_2 tolerances and availability,
- chromatic correction of the optical system with only very few optical materials suitable for 157 nm,
- development of high reflection and anti reflection optical coatings,
- new test tools as well as alignment concepts for VUV,
- high performance CCD camera had to be found and evaluated that combined spatial resolution, high quantum efficiency and sufficient irradiation stability.

Measurements from Alpha-tool and Discussion

In figure 2 an aerial image is shown acquired on a 720nm pitch lines and spaces, 1:1 ratio, on a chrome on glass binary mask. The intensity profile which is obtained with a horizontal slice allows to extract maximum peak intensities of individual lines and provides an indication about the contrast of the features.

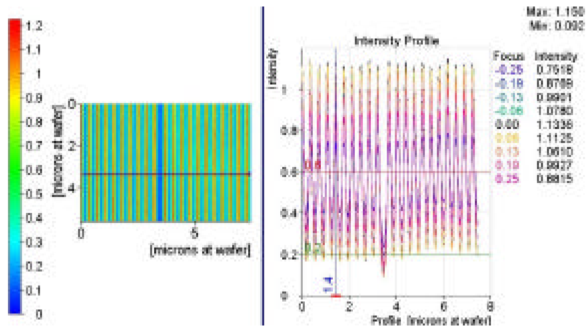

Figure 2. CCD image at best focus of a 720nm pitch lines and spaces and horizontal intensity profile of the through focus series.

In the profile plot shown in figure 2 one of the lines is selected for further analysis to extract the linewidth (CD) at

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the Pivot point where the CD value is independent from the selected focus level. Figure 3 shows the linewidth versus threshold. Taking the mask reduction 1:4 into account a CD value of 84 nm feature size on wafer level is found.

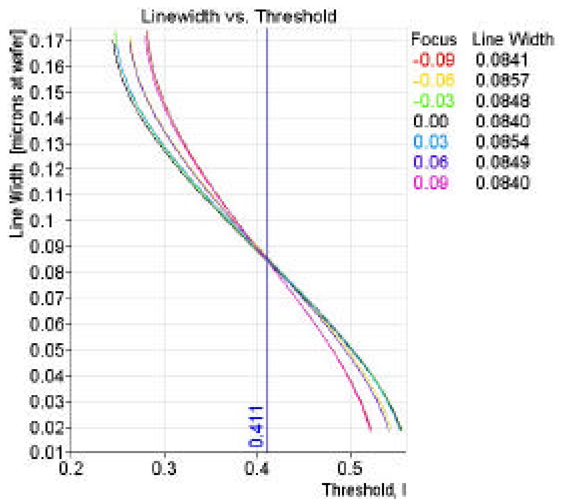

Figure 3. Linewidth versus threshold plot of the selected feature of the 720 nm pitch measurement shown in figure 2.

After determination of the best focus, the measurement at best focus level has been repeated 12 times in succession, 5 min between each image and normalized to the same clear field. For data extraction again the Pivot point is used as threshold. As shown in figure 4 the variation is < ±16nm on wafer level. The mean value for the CD of the structure is 84.1 nm. Figure 5 shows similar measurement results, where repeatability was measured over the duration of 14 days. The variation is < ± 7nm on wafer level. The different variations which are found are influenced by thermal effects and cleaning effects on the mask surface. Latter especially occurs for aerial imaging with 157nm irradiation.

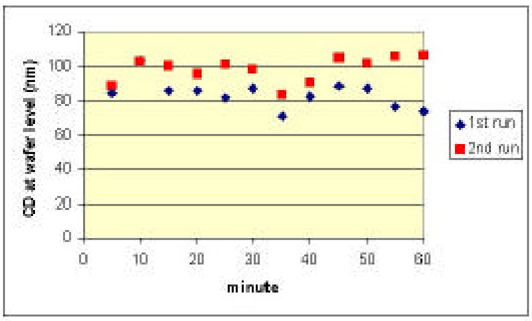

Figure 4. Repeatability results of CD measurement of the lines and spaces features shown in figure 2.

The analysis of aerial images for peak intensity, transmission loss between neighbored features and for CD variation are typical applications for the AIMS™ systems in the mask shop to decide about the need for repairs of mask defects, ensure repair success and to do outgoing quality control.

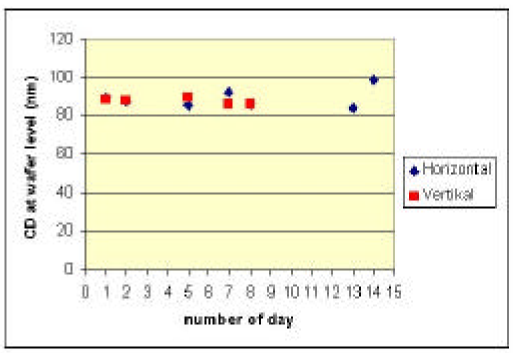

Figure 5. Repeatability results of CD measurement of the lines and spaces features shown in figure 2.

With smaller nodes, where design rules are 65nm or even below, it is expected that smaller defects on reticles will occur in increasing numbers in the wafer fab. The smaller mask defects will become a serious problem for the yield in the wafer fab. With increasing mask prices and number of defects on reticles it will become cost beneficial to do defect disposition on the reticles of masks in production. The AIMS™ can be used for such application using the information about printability of defects, repairs or critical features based on the analysis of transmission loss, linewidth changes or tilts of Bossung plot curves (figure 6) from the aerial image stack. Beyond that figure 6 shows also the exposure-defocus window (process window) which can be obtained with the AIMS™ measurements rapidly from mask features. Due to a very high flexibility to adjust to different exposure tool settings, fast succession of image acquisitions various process windows can be obtained and analyzed to see how they overlap for different features or different setting. It is very helpful in the field of lithographic engineering [8]. Figure 6 shows that for 84 nm feature size on wafer level and ±10% linewidth tolerance and 10% exposure tolerance a 130nm defocus tolerance can be found.

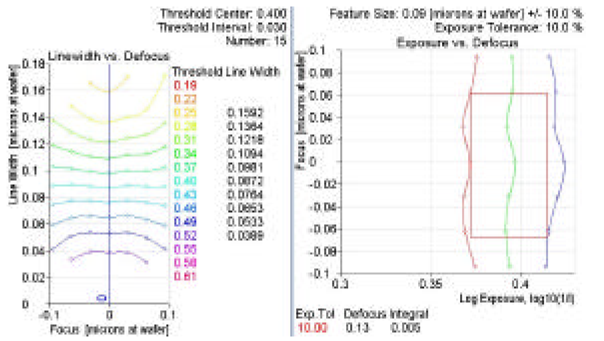

Figure 6. Bossung Plot and Defocus-Exposure Matrix of the 720nm pitch lines and spaces.

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Figure 7 shows an aerial image of 480 nm pitch, 1:1, lines and spaces on chrome on glass binary mask. At a threshold selected at the pivot point a feature size of 62 nm on wafer level was determined. The intensity profile which is obtained with a horizontal slice shows that the contrast is lowered significantly which can be shown by less modulation between minimum and maximum intensities.

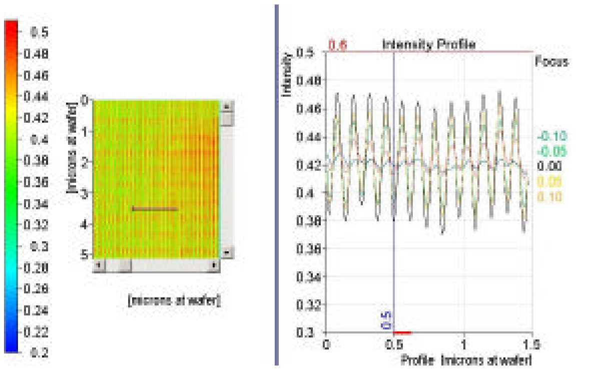

Figure 7. CCD image at best focus of a 240nm pitch lines and spaces and horizontal intensity profile of the through focus series.

The smallest feature size to which an exposure tool can print to is determined by

$$feature.size = k_1 * \frac{\lambda}{NA}$$

with λ the exposure wavelength and NA the numerical aperture of the exposure system. The numerical aperture (NA) which was used for this measurement was set equivalent to NA = 0.92 and the degree of coherence of light (σ) value was chosen to be σ = 0.95. For 157 nm wavelength, 62 nm printable feature size and NA = 0.92 this measurement reflects with k_1 = 0.36 on the one side the proximity to the resolution as well as to the printability limit of 157 nm exposure technique. On the other side it also shows the performance capability of such an early 157 nm AIMS™ tool.

Measurements from Beta-tool and Discussion

In figure 8 the first measurements from the beta tool are shown. An aerial image of L-bars is shown acquired on a 3 µm pitch lines and spaces, 1:1 ratio, on a chrome on glass binary mask. The lower left part of the picture shows the intensity profile of the through-focus measurement by selecting a vertical slice. The highest peak intensities are achieved for the best focus image. On the right side of figure 8 a comparison can be seen for the intensity profile of best focus measurement for the vertical and the horizontal slice. Whereas the maximum peak intensities for every feature in one direction are changing only slightly, a difference of about 10% can be seen between vertical and horizontal direction. The valley intensities are very close between x and y direction.

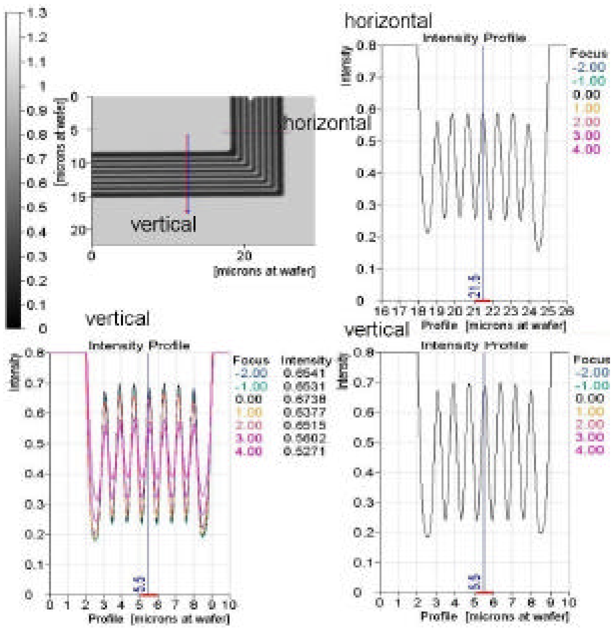

Figure 8. CCD image at best focus of 3mm pitch lines and spaces. The intensity profile of a through focus measurement is shown for a vertical slice. The intensity profile of the best focus curve can be seen for x and y direction.

Future Work

The performance criteria of the alpha-tool will be tested on the beta-tool. A focus will be put to the system's stability to achieve tight specifications for field illumination stability over time and for CD repeatability values for short and long term behavior. In a next step the tool will be qualified for aerial imaging of mask features with several feature sizes down to the 45nm node.

Conclusions

Experimental results on AIMS™ 157nm systems have been obtained and evaluated. Long-term and short-term CD repeatability measurements show that the technological difficulties have been successfully managed. The alpha tool is capable of speeding up mask development work for 157 nm photolithography masks. The first AIMS™ fab 157 beta-tool has been brought into operation successfully.

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