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Performance of a Two-Mirror, Four-Reflection, Ring-Field Optical System Operating at $\lambda=13\text{nm}$

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Abstract

The performance of an Extreme Ultraviolet Lithography (EUVL) imaging optic was characterized by printing resolution test images in resist. While features as small as 0.137μm were successfully printed, a resolution of 0.175μm better represents the performance of the system over the full 0.9mm$^2$ image field. The contrast of the aerial image was estimated to be approximately 40% or less for the fine features printed. This low contrast value is attributed to a degradation of the modulation transfer function (MTF) due to the presence of scattered light in the image.

Keywords: Microlithography, Imaging systems, Image quality assessment

Introduction

Extreme ultraviolet (EUV) lithography is considered as one of the possible technologies for producing microdevices with critical dimensions of 0.13μm and smaller. Several lithography system prototypes have been built to this date. [1-5] The first demonstrations showed that a resolution better than 0.1μm was attainable using a wavelength $\lambda=13\text{nm}$ and numerical aperture NA<0.1 [6]. However, these results were obtained over a very limited image field ($\sim 1\times10^{-3}\text{mm}^2$) and used a very small area of the mirrors in the optical system. Since then, a lot of attention has been devoted to reducing the wavefront error of the optical systems and increasing the image field size.

In this paper, we report results obtained with a lithography system designed to print over a 0.9mm$^2$ image field with a resolution of 0.14μm. One of the distinctive characteristics of this system is its well characterized illumination system, providing better than 10% uniformity at the reticle plane [7] and controlled spatial coherence over the full field.

Our goal was to characterize the performance of the lithography system by printing resolution test images in resist, over the full field.

Experimental arrangement

A schematic of the LLNL experimental EUV lithography station is shown in figure 1. The front end consists of a high average-power laser [8] producing a plasma that emits EUV radiation and a Mo/Si multilayer-coated condenser providing Köhler illumination.

Figure 1. Schematic of the experimental set-up.

The laser operates with a pulselength of 14ns, an energy of 250mJ per pulse, at a repetition rate of 100Hz. The laser beam is focused onto a solid tungsten (W) rod producing a 0.01mm$^2$ spot (100μm X 100μm FWHM), at an average irradiance of $2.5 \times 10^{14} \text{W/cm}^2$. The total angularly integrated EUV yield in a 3% bandwidth around $\lambda=13\text{nm}$ is about 0.7% [9]. The laser
strikes the target rod at an incidence angle of 20° from the target normal and the EUV light is collected by the condenser at an angle of 45° on the other side of the target normal. This geometry was chosen so as to optimize the amount of EUV light collected by the condenser while minimizing the amount of debris emitted in the direction of the condenser. In order to protect the condenser optic, a debris shield is placed between the plasma and the first condenser mirror. This debris shield is a thin film of Si (0.5μm thick) with a diameter of 1cm, that has a transmission of 41% at λ = 13.2nm.

The condenser system is composed of three reflectors coated with a molybdenum-silicon multilayer to reflect light at λ=13.2nm. This condenser collects 0.12 steradian of the EUV light emitted by the plasma and illuminates the mask uniformly with 4μJ/cm² of EUV light per laser pulse, as measured with a calibrated silicon photodiode. It operates in a Köhler configuration, where the source is imaged onto the entrance pupil of the imaging optic with a magnification of 26.5 and the first mirror of the condenser is imaged onto the reticle. This allows for a uniform illumination of the reticle to better than 10%.[7]

The imaging part of the system is composed of a mask/reticle, the imaging optics and a resist coated wafer.

The reticle was fabricated using a deep ultraviolet stepper with a resolution of 0.35μm. The patterns were etched in a 850Å thick aluminium absorber containing 1% silicon, providing a 100:1 contrast at λ=13.2nm. The reticle is used at an incidence angle of 10°. Its reflectance before patterning was 55%. The mask comprises both reflective features in a dark field and dark features in a bright reflective field. It is divided in a 4 X 6 array of smaller cells, separated with vertical lines. Four of these fields can be illuminated by the condenser. Each of these cells is composed of various features (lines and spaces, contact holes, star patterns, etc.). The size of these features range from 3.4μm down to 0.34μm, corresponding to 1 to 0.1μm at the image plane.

The imaging optic itself has been described in a previous paper.[5] It is a two-mirror, four-reflection ring field optic with a reduction factor of 3.4:1 and a numerical aperture of 0.06. The best focus aerial image is formed 1.4 mm above the top imaging mirror. A precisely polished ceramic ring spacer is used to position the resist in that plane. The optic is coated with molybdenum-silicon multilayers for high reflectance at λ=13.1nm.

Its wavefront was measured using a phase shifting interferometer that was recently developed at LLNL.[10] A 36-term Zernike polynomial representation of the wavefront, shown in figure 2, indicates a root-mean-square error of 1.4nm. The modulation transfer function (MTF) of the imaging optic is plotted in figure 3, where the different curves represent an average value for sagittal and tangential directions in the center of the field. The dashed curve is the diffraction-limit MTF of the system, the dotted curve shows its design performance and the solid line illustrates the performance of the assembled system as calculated from individual mirror characterization. Depending on the resist and processing used, the resolution limit of a lithography printing system is defined by a certain modulation value of the aerial image. Typically, a modulation of 50% is considered sufficient for printability. In that case, the resolution limit, for incoherent illumination, would be 0.14μm for the designed system and 0.20μm for the assembled system.

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Figure 2. Wavefront map of the imaging optic. Each contour represents a tenth of a wave, at λ=13nm.

Figure 3. Modulation transfer function of the imaging optic. Plotted are the average MTF curves for tangential and sagittal orientations, for the diffraction-limit, the original design and the assembled system.
A negative-tone chemically-amplified resist, Shipley's SAL 605, was used to record the images. The dose required to expose this resist is \((1.3\pm0.3)\,\text{mJ/cm}^2\) and its contrast is described by a gamma value of \(\gamma = 1.6\) to 4, depending on the processing conditions. [11]

Results and discussion

Lithographic exposures were carried out under the conditions described above. Figure 4 shows a low-magnification optical micrograph of a typical exposure at best focus. The total area exposed is \(0.9\,\text{mm}^2\). The image contains both dark and bright regions. The exposure dose is \((1.3\pm0.3)\,\text{mJ/cm}^2\) and the resist was developed for 120s in tetramethyl ammonium hydroxide (TMAH), with a normality of \(N=0.27\). This development procedure yields a high resist contrast of \(\gamma=4\).

Figure 4. Typical image recorded in SAL605. The total area printed is \(0.9\,\text{mm}^2\).

Figure 5 shows a scanning electron microscope (SEM) image of a mainly dark area (no resist) with lines and spaces and checkerboard patterns ranging from 0.4µm to 0.15µm, with a zoom of the 0.20µm, 0.175µm and 0.15µm lines and spaces. There is clearly modulation down to 0.15µm lines and spaces, although the number of defects in the image of the 0.15µm features indicate that the modulation of the aerial image is plummeting for features smaller than 0.15-0.175µm. This type of result is typical of the entire image field.

Measurements of the resist profiles were made with an atomic force microscope (AFM). Figure 6 shows the best resolution results obtained within the image field. Scans of 0.137µm and 0.15µm lines and spaces on a dark background are presented. The scans of 0.175µm and 0.2µm lines and spaces presented in figure 7 better represent the typical resolution achievable with this system. The patterns are printed both on bright and dark backgrounds, in orthogonal directions. For all these patterns, the resist sidewall angles were measured to be \((70\pm5)^\circ\).

The contrast of the aerial image was estimated by using a using a process yielding a more linear response of SAL 605. Exposures were made at \((0.6\pm0.2)\,\text{mJ/cm}^2\) and the resist was developed for 15s, giving a resist contrast of \(\gamma=1.6\). Figure 8 illustrates the results. AFM scans of 0.25µm, 0.175µm and 0.15µm lines and spaces on a bright background are shown. The resist height clearly decreases with the size of the features, indicating a drop in the modulation of the aerial image. These measurements reveal sidewall angles ranging from \((35\pm4)^\circ\) for the 0.25µm features to \((24\pm3)^\circ\) for the 0.15µm ones. By simulating these profiles with Prolith/2 [12], the contrast of the aerial image was inferred to be less than 40%. This result indicates that the MTF of the imaging optic is less than what is expected from the interferometric measurements alone. This degradation is consistent with the observation of scattered light in the image plane. [13]
Figure 6. AFM scans of (a) 0.137µm, (b) 0.15µm and (c) 0.165µm lines and spaces on a dark background. These are representative of the best resolution achievable with this system.

Figure 7. AFM scans of 0.175µm and 0.2µm lines and spaces on both (a) bright and (b) dark backgrounds.

Conclusions

A two-mirror, four-reflection, ring-field lithography system was tested and features as small as 0.137µm were printed. However, only the features larger than 0.175µm could be reproduced with fidelity over the full 0.9mm² image field, on bright and dark background for different orientations. A low resist contrast process was used to estimate the contrast of the aerial image. The results indicate a loss of contrast that cannot be attributed to wavefront errors alone.

This is very important for the specification of optics substrates for EUVL systems. In the past, a number was given to characterize the figure accuracy of the optic, e.g. a wavefront error < λ/14, and another number described the maximum roughness of the substrate necessary for high multilayer reflectance. From the results reported here, it appears that the characteristics of the optics need to be specified more fully to include the effects of light scattered in the image plane.
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References


Figure 8. AFM scans of resist profiles obtained with a low contrast process. (a) 0.25μm, (b) 0.175μm and (c) 0.15μm.


11. B. La Fontaine, D. Ciarlo, D. P. Gaines, and D. R. Kania, "Characterization of SAL605 at λ=13nm," these Proceedings

12. Prolith/2 is a lithography simulator software available from FINLE technologies, P.O. Box 162712, Austin, Texas 78716 USA.