Development of a Laboratory Extreme-Ultraviolet Lithography Tool

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ABSTRACT

The development of a laboratory EUV lithography tool based on a laser plasma source, a 10x Schwarzschild camera, and a magnetically levitated wafer stage is presented. Interferometric measurements of the camera aberrations are incorporated into physical-optics simulations to estimate the EUV imaging performance of the camera. Experimental results demonstrate the successful matching of five multilayer reflecting surfaces, coated to specification for a wide range of figure and incidence angle requirements. High-resolution, 10x-reduction images of a reflection mask are shown.

1. INTRODUCTION

High-resolution extreme-ultraviolet (EUV) images have been obtained using multilayer-coated Schwarzschild imaging objectives.¹⁻² In our previous work,³ a 20x reduction Schwarzschild camera served as a useful tool for studying the mounting and alignment of EUV optical elements

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and the quality and alignment of the condensing optics. However, the field of view, 25 μm by 50 μm , was too small for the development of EUV lithography tools.

We have optimized a 10x-reduction Schwarzschild camera to maximize the field of view that is corrected to a resolution of 0.1 μm^4 . A laboratory EUV lithography tool, based on this camera, is being developed for device fabrication experiments. This laboratory tool is the initial step in the development of more advanced tools, that will incorporate the results of parallel efforts to improve the camera, condenser, and source.

In this paper, the development of the 10x-reduction Schwarzschild camera is described. Simulations of the combined camera and condenser system using optically measured wave-front errors are shown. An LPS-based system for characterization of the Schwarzschild camera is described, and the results of initial imaging experiments are presented. Finally, we describe the 10x-reduction laboratory tool, currently under development.

2. SCHWARZSCHILD CAMERA

We have optimized a Schwarzschild camera to achieve a 0.4 mm diameter field of view corrected to a resolution of 0.1 μm . The increased field of view, although not large enough for a practical lithography tool, approximates the ring width in practical ring-field designs. This camera also covers enough area on the wafer to perform device fabrication experiments, while more advanced aspheric systems are being developed. The convex primary and concave secondary are reasonably small spherical mirrors having clear apertures of 14.8 mm and 82 mm, respectively. An aperture is located immediately in front of the primary mirror to provide a decentered, unobscured, numerical aperture (NA) of 0.08, resulting in a design depth of field of $\pm 1.0 \mu\text{m}$. The effective focal length is 26 mm, and the object-to-image distance is 315 mm.

In the housing, developed by Talandic Research Corporation, the secondary mirror is kinematically front-surface mounted. An epoxy-mounted primary mirror is adjustable in two lateral directions by means of adjustment screws and mechanical motion amplifiers. The separation between the two elements is controlled by shimming or lapping surfaces that support the primary. The alignment of the primary and secondary must be achieved to tolerances of $\pm 9 \mu\text{m}$ in separation and $\pm 2.5 \mu\text{m}$ in decentration. A photo of the 10x Schwarzschild is shown in Figure 1.

A matching and clocking procedure was used to minimize wave-front error due to figure errors in the Schwarzschild elements⁴. Multiple sets of mirror substrates were fabricated and measured using a Zygo Mark IV xp interferometer. Figure errors were observed in the primaries ranging from 1 to 4 nm rms and in the secondaries ranging from 4 to 6 nm rms. These magnitudes are very small at visible wavelengths but sufficient to cause significant degradation in the image resolution at the 13.4 nm design wavelength of this camera. Both circularly symmetric (zonal) errors and asymmetric errors of low spatial frequency were observed in the substrates. Primary and secondary substrates were matched and clocked using Code V to minimize the rms wave-front error in the EUV sub aperture. Aberrations in the remainder of the full aperture do not affect EUV imaging performance, and, therefore, do not constrain the clocking results. Four sets of elements were found that approach the design wave front error to within a factor of two. The third best set of elements, selected for the existing camera, produce a measured wave-front error in the EUV sub aperture of 2 nm rms. While this value is about twice the design wave-front error of 1 nm rms, it is about half that measured in our earlier work using the 20x Schwarzschild. When measuring wave-front errors at these levels, the uncertainty in the interferometric data is significant. Efforts are under way to improve the interferometric measurements and clock elements to more closely approach the design wave-front error.

Figure 1. Photograph of 10x Schwarzschild housing and optical elements.

3. SIMULATIONS OF IMAGING PERFORMANCE

We simulated the formation of EUV images using the physical optics code GLAD^{5,6} to estimate the effect of small wave-front errors on resolution. The measured wave-front error was placed in the entrance pupil of the Schwarzschild, and a pattern containing features as small as $1\text{ }\mu\text{m}$ ($0.1\text{ }\mu\text{m}$ in the image) were introduced into the mask plane (See Figure 2a). The mask was illuminated in such a way that undiffracted rays fill half of the entrance pupil diameter, i.e. the coherency factor is 0.5.

Line scans through the simulated image are shown in Figure 2b and 2c. Also shown are simulated images of the same mask under the same illumination conditions but assuming perfect spherical elements in good alignment. The line scans are in good agreement for features in the x direction, but show significant reduction in contrast for features in the y direction. Greater fluctuations in the wave-front error along the y axis reduced the sharpness of the image. These results, however, represent a significant improvement over the 20x Schwarzschild in which the wave-front error was larger and fluctuated on a finer spatial scale.

Figure 2. GLAD simulations of 10x Schwarzschild imaging using the measured wave-front error (solid line) compared to the unaberrated camera (dashed line). a) the test pattern, b) line scan in the x direction. c) line scan in the y direction (in the plane of the decentered aperture).

4. LPS-BASED EUV SYSTEM

4.1. Laser plasma source

A laser plasma source has been configured for imaging experiments using the 10x Schwarzschild camera (See Figure 3). The LPS is driven by a Lambda Physik LPX 250 KrF excimer laser emitting 0.6 Joule, 20 ns pulses at repetition rates as high as 200 Hz. Various targets have been explored including mass limited targets of gold and tin on mylar tape.⁷ Atomic-scale debris is effectively stopped by using a He pressure of 200 milliTorr.

Figure 3. Sketch of LPS-based system for characterization of the 10x Schwarzschild.

Measurements of the source size indicate that the full-width-half-maximum diameter is less than $100\text{ }\mu\text{m}$. The source size can be approximately doubled, to adjust the coherency factor, by defocusing the laser beam.

4.2. Condenser

The condenser in this system has an ellipsoidal figure. It is positioned so that one focal point, f_1 , is located on the LPS 112.5 mm from the ellipsoidal surface and the other focal point, f_2 , is located 1.5 m from the ellipsoidal surface in the extension tube to the right of the camera chamber (See Figure 3). The resulting image of the source at f_2 is magnified by 13.3 times. When the source image is projected into the 4 mm entrance pupil of the Schwarzschild, a coherence factor of about 0.5 can be achieved. A 50 mm diameter aperture is placed in front of the condenser to protect the unused portion of the ellipsoid from debris. EUV rays within a 0.155 steradian solid angle (2.5% of the available 2π steradians) are collected through this aperture to provide a 5 mm Kohler-illuminated spot on the mask.

4.3. Camera assembly

The camera chamber is adjustable in the vertical and horizontal directions (out of the plane of Figure 3) by means of adjustment screws and a gimbaled bellows located in the transport tube between the target and camera chambers. These adjustments are used to place the turning mirror in

the center of the EUV beam. The beam then reflects downward at near-normal incidence onto a flat multilayer-coated reflector, identical in dimensions to the reflection mask. Small adjustments are made in the turning mirror to center the plasma image in the aperture of the Schwarzschild. The near-normal mirror is replaced by the mask for making EUV exposures.

The Schwarzschild camera housing is designed with three ball bearings defining the image plane. The resist coated wafer is placed on these ball bearings and focus is achieved by vertical motion of the mask carrier. A two-dimensional array of exposures can be made on a wafer using an in-vacuum wafer pusher that translates the wafer in the image plane.

4.4. Multilayer coatings

Five multilayer reflections are required to collect the EUV radiation from the LPS, direct it onto the mask, produce a pattern and form an image of the pattern on a resist-coated wafer. These reflections include flat surfaces at near normal incidence and at large incidence angle. They include spheres and an asphere (See Table 1). The turning mirror, mask, and Schwarzschild secondary mirror have nearly constant angles of incidence, while the condenser and Schwarzschild primary mirror experience an incidence angle that varies with location on the surface. The later cases require that the multilayer period (d spacing) be varied spatially to maintain a constant center wavelength. In all cases the surfaces must be coated to precise specification to achieve a center wavelength of 13.4 nm in this application. The demands of this system provide a realistic test of the ability of state-of-the-art multilayer technology to meet the d-spacing requirements of EUV lithography.

Table 1. Multilayer requirements

	Element	Figure	Incidence Angle	d spacing
1	Condenser	Ellipsoidal	$1.2^{\circ} - 12.6^{\circ}$	Tapered
2	Turning Mirror	Flat	45°	Uniform
3	Mask	Flat	1.2°	Uniform
4	Primary	Spherical	$6.1^{\circ} - 13.6^{\circ}$	Tapered
5	Secondary	Spherical	$2.0^{\circ} - 4.3^{\circ}$	Uniform

One of the most difficult surfaces to coat is the Schwarzschild primary. Figure 4 shows the desired d spacing as a function of radius from the center of the primary. The clear aperture is located between radii of 3.3 mm and 7.3 mm. The average d spacing in the 40 pairs of Mo/Si layers must taper from 68 Å at the smaller radius to 70 Å at the larger radius, following the profile of the dashed line. Dotted lines indicate a $\pm 1\%$ tolerance band. The measured data points show that the d spacing was maintained within the specified band. Similar results were obtained for all five surfaces in this system. Imaging results, described below, demonstrate that the wide range of multilayer specifications required for this system have been satisfied.

Figure 4. Multilayer d spacing on Schwarzschild primary as a function of radial position.

5. INITIAL IMAGING EXPERIMENTS

In our initial experiments, images of a reflection mask were recorded in PMMA resist. The mask comprises a fused silica substrate coated with a Mo/Si multilayer and patterned using an absorber consisting of a 30 nm Ge layer over a 60 nm layer of hard-baked resist.⁸ A variety of features are contained on the mask including lines and spaces of various pitches and orientations, star patterns, isolated lines, FET device gate lines, etc.

A 70 nm layer of PMMA was spun onto silicon wafers which were placed on the ball bearings that define the image plane. Exposures were controlled by counting the laser pulses and monitoring the LPS output using an EUV sensitive photo diode. Using a pristine condenser, exposures of 500 laser pulses were sufficient to clear the resist. In some experiments, a 0.5 μm silicon membrane was used in the EUV beam to eliminate radiation outside the wavelength band of interest. The exposed wafers were developed for one minute in a 1:1 solution of MIBK and isopropanol. The developed wafers were coated with Au Pd and observed in a scanning electron microscope, producing the images shown in Figure 5. Modulation was observed in two orthogonal directions down to 0.1 μm . High resolution images were observed over a 0.4 mm region on the wafer. We are preparing a second camera, containing slightly higher quality elements, for our next imaging experiments.

Figure 5. Scanning electron micrographs of 10x reduction images in PMMA resist. The upper photograph is an image of one mask cell, measuring 0.1 mm square. The lower photograph is an enlargement showing lines and spaces from 0.5 μm to 0.1 μm .

6. DESIGN OF LABORATORY EUV TOOL

6.1 Camera chamber design

We are designing a laboratory EUV lithography tool based on the 10x Schwarzschild camera (See Figure 6). The target transport and condenser assembly will remain very similar to the existing system described above. Major changes are required in the camera chamber to include a mask and wafer stage.

Figure 6. Sketch of laboratory EUV lithography tool based on a laser plasma source, a 10x reduction Schwarzschild camera and a magnetically levitated fine stage.

The system cannot accommodate adjustments between the target and camera chamber to facilitate alignment of the EUV beam. The ability to place the condenser precisely in the desired location has been demonstrated on the current system and can be achieved with a fixed camera chamber.

The wafer stage requires that the Schwarzschild camera be inverted relative to the current arrangement. EUV radiation reflects upward off of the turning mirror onto a reflection mask. Two in-vacuum tilt adjustments of the turning mirror are provided to align the EUV beam. The mask is placed face down against three ball bearings. The mask stage provides 6 degrees of freedom for positioning and orienting the mask in the well corrected field of view of the Schwarzschild. The camera has been redesigned to accept the mask stage and to interface with the bridge structure that

supports the camera above the wafer stage. The wafer end of the camera has been modified to provide clearance between the camera and the wafer stage. Interfaces are provided for a focus system, mask-to-wafer alignment system and reference mirrors for the position measuring interferometers required for the stage controllers.

The wafer stage comprises a coarse x-y stage carrying a magnetically levitated 6-axis fine stage. The fine stage is a vacuum-compatible version of a magnetically levitated stage developed jointly by Sandia National Laboratories and the former GCA Corporation.⁹ The fine stage is being modified to support an electrostatic chuck capable of carrying 5 inch wafers. A digital feedback control system maintains the desired wafer position using data acquired from capacitive and interferometric position sensors. The interferometer system measures tilt of the wafer stage in three axes and the in-plane displacement of the wafer stage relative to reference mirrors located on the camera. In-plane stability of 20 nm has been demonstrated. A vacuum load lock is being designed to change wafers without breaking vacuum.

6.2. Mask-to-wafer alignment

Two systems will be implemented for mask-to-wafer alignment. The first system is a visible Moiré technique in which 2 gratings of slightly different pitch are etched into the wafer in each of the 2 in-plane directions. Similar gratings are written on the mask such that the projected image of the mask will cause gratings of different pitch to overlay. A Moiré pattern, sensitive to in-plane wafer displacement, is formed at each grating site. The relative phase of the Moiré patterns provides an absolute reference for mask-to-wafer alignment. This process must be carried out using visible light. We plan to use gratings of about 10 μm pitch.

7. CONCLUSION

We have developed a 10x Schwarzschild camera that produces EUV images over a 0.4 mm field of view on the wafer. This field of view is on the order of the ring width in advanced camera designs and provides sufficient coverage on the wafer for device fabrication experiments. Using a laser plasma source, we have demonstrated high resolution images of a reflection mask in PMMA resist. These results further demonstrate the use of five multilayer-coated surfaces in the EUV path. These surfaces include flats, spheres and an asphere and require both uniform and tapered coatings. The throughput achieved in these experiments demonstrates the ability of multilayer technology to meet the d-spacing requirements of EUV lithography.

We are proceeding with the design of a laboratory EUV lithography tool based on a laser plasma source, the 10x Schwarzschild camera and a magnetically levitated fine stage for positioning the wafer. This system will provide the capability to perform device fabrication experiments and serve as the initial step in the development of more advanced EUV lithography tools.

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