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**Characterization of an expanded-field Schwarzschild objective
for extreme ultraviolet lithography**

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Abstract

The performance of a new 10x-reduction Schwarzschild system for projection imaging at 13.4 nm wavelength is reported. The optical design is optimized to achieve 0.1 μm resolution over a 0.4 mm image field of view, an increase in area of a factor of 100 over previous designs. An off-set aperture, located on the convex primary, defines an unobscured 0.08 numerical aperture. The system is illuminated using extreme ultraviolet (EUV) radiation emitted from a laser plasma source and collected by an ellipsoidal condenser. A 45° turning mirror is used to relay the collected EUV radiation onto a near-normal reflecting mask. Multiple sets of primary and secondary elements were fabricated, matched and clocked to minimize the effects of small figure errors on imaging performance. Optical metrology indicates that the wave-front error within the subaperture used is within a factor of two of the design value. Images recorded in PMMA and ZEP 520 resists reveal good imaging fidelity over much of the 0.4 mm field with equal line/space gratings being resolved to 0.1 μm .

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I. INTRODUCTION

Laboratory optical systems for use in Extreme Ultraviolet Lithography (EUVL) are being fabricated to experimentally establish the design and performance criteria of eventual commercial EUVL systems[1-6]. Such criteria include data regarding EUV source flux and debris control, condenser efficiency and lifetime, optical fabrication and alignment tolerances, multilayer reflective coating precision and efficiency, mask performance and repair, and resist sensitivity and thickness. The exposure fields achieved in the proof-of-principle imaging systems used to date have been small, ranging from 0.025 mm x 0.050 mm [7-10] to 2 mm x 0.6 mm [11]. While these optical systems have been very useful for EUVL imaging and resist studies, the exposure fields or imaging quality have been marginal for initial 0.1 μm device fabrication by EUVL.

In this work, we report the characterization of an expanded-field Schwarzschild objective, optimized to achieve 0.1 μm resolution with a 10x reduction factor over a 0.4 mm diameter exposure field. A laboratory EUVL tool employing this camera and illuminated by a laser plasma source (LPS) has been constructed to perform imaging, source, mask, and resist experiments and to fabricate simple devices. This tool represents an intermediate step in the development of more advanced tools that will incorporate the results of parallel efforts to improve the camera, condenser and source. The integrated 10x system and all of its constituent subsystems have already been described in detail [1,2,12]; the focus of this paper will thus be to describe system performance. A brief overview of the 10x system will be presented in section 2, followed in section 3 by a description of the overall system performance and the results of imaging experiments at a wavelength of 13.4 nm.

II. LABORATORY EUV SYSTEM

A schematic diagram of the overall 10x EUVL system is shown in Fig. 1. It comprises a laser-produced plasma source, an illumination system, a translating reflective object mask, the

Schwarzschild camera, a wafer stage, and the associated vacuum apparatus. The individual subsystems are described below.

II.a. Laser Plasma Source

The EUV illumination source is a laser-produced plasma, irradiated by a 120 W KrF excimer laser operating at 248 nm. The laser produces 0.6 Joule pulses having 25 ns duration at a maximum repetition rate of 200 Hz, and is focused to achieve an intensity of $1\text{--}2 \times 10^{11}$ Watts/cm² on the target. The target consists of a continuous narrow metal strip, transported on a high-speed tape delivery system, previously described[13]. To date, Au, Cu, Ta, W, and Sn have been employed as target media. Tungsten targets have been found to be somewhat brighter near 13.4 nm than Cu and to emit less debris than both Cu and Au[14], but are difficult to operate reliably over extended periods due to brittle fracture and flaking. Each reel of target yields at least 14 hours of uninterrupted operation at 20 Hz laser repetition rate.

The deposition rate of laser plasma debris onto nearby optical surfaces is reduced in several ways. First, the target geometry has been selected to minimize the production rate of particulate debris. Second, 200 mTorr of flowing He is circulated through the laser plasma region to reduce the deposition rate of atomic vapor. Third, a rotary chopper is used to intercept particulate ejecta moving toward the condenser with velocities $\leq 1.5 \times 10^4$ cm/sec. These mitigation measures result in a condenser mirror reflectance 1/e lifetime of $\sim 10^5$ plasma pulses. We have recently implemented a more aggressive intervention approach which employs a 5x5 array of 1 cm square, 0.5 μm -thick crystalline Si windows to shield the condenser from all target ejecta. Placed 5 cm from the plasma, these membranes have survived exposures of up to 60,000 pulses without rupture. Due to the existing geometry of the plasma source and condenser, the 13.4 nm illumination beam is constrained to pass twice through these windows, yielding an overall transmittance of 20% when the windows are clean and significantly less as they become coated with target ejecta. The ultimate lifetimes of such Si windows and the effects of

illumination nonuniformity caused by the shadows of their support grids are presently being investigated.

II.b. Ellipsoidal Illuminator

The illumination system is based on an ellipsoidal condenser and a simple turning mirror. The condenser 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 1). 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.

Illumination alignment is achieved by first removing the turning mirror and placing a phosphor-coated (P1) glass plate at a focal plane equivalent to the entrance pupil of the camera (labeled f_2 in Fig. 1) to obtain the best focused image of the plasma. Then the turning mirror is restored and a surrogate optic, also with a phosphor plate, is placed in the position that the camera would normally occupy. The phosphor plate lies in the plane of the camera pupil and is marked with fiducials that represent the boundaries of the entrance pupil. In-vacuum tilt and rotation adjustments on the turning mirror allow the illumination spot to then be brought into precise alignment with respect to the pupil.

II.c. Schwarzschild 10x Camera

The Schwarzschild camera used in the present system has been optimized to achieve 0.1 μm resolution over a 0.4 mm diameter field of view. This dimension is comparable to the ring width of candidate ring-field commercial camera designs and is adequate to allow simple devices

to be fabricated while more advanced aspheric systems are being developed. The two spherical mirrors have modest clear apertures of 14.8 mm and 82 mm for the primary and secondary mirrors, respectively. A decentered, unobscured numerical aperture (NA) of 0.08 is selected by rotating an aperture plate immediately in front of the primary mirror, resulting in a design depth-of-focus of $\pm 1.0 \mu\text{m}$. The distance between object and image planes is 315 mm.

A procedure of matching and clocking, described in more detail in Ref. 12, was used to minimize contributions to the overall wave-front error (WFE) from figure errors in the Schwarzschild elements. Multiple sets of mirror substrates were fabricated and their surface figures measured with a Zygo Mark IV xp interferometer. Mirror elements and their joint azimuthal orientation were then selected to minimize the composite WFE. Assembly and alignment of the resulting "clocked" mirror pair within the camera housing was then performed with optical interferometry. The alignment of the primary and secondary mirrors must be performed to tolerances of $\pm 9 \mu\text{m}$ in separation and $\pm 2.5 \mu\text{m}$ in decentration. The mirror pair used for the present experiments exhibited a WFE of 2 nm rms within the relevant subaperture after final alignment. This represents an improvement of a factor of two over the WFE value measured in our previous work with the 20x Schwarzschild[9], but is still a factor of two larger than the design value of 1 nm[1]. Another improvement of the present camera is that the WFE exhibits only a very slow variation across the subaperture, in contrast to the rapidly varying WFE seen earlier in the 20x system. Finally, camera alignment has remained stable over a period of several months.

II.d. Multilayer coatings

A total of five mirror surfaces must be coated with precisely matched multilayer Bragg reflective coatings: condenser, turning mirror, mask, camera primary, and camera secondary. Two of these coatings intercept a wide enough range of incident angles as a function of position on the optic that the multilayer period (d) must be varied across the aperture: on the condenser and on the Schwarzschild primary. Spectral reflectance measurements as a function of position

on both the tapered and uniform mirror coatings demonstrate that the multilayer period remains constant to within 1% for all positions inspected on all 5 mirrors[15].

III. RESULTS

III.a. Source Stability and Uniformity

Optimal imaging quality requires precise control of the illumination beam on the mask and in the camera entrance pupil. Plasma source motion can cause an increase in the illumination partial coherence factor from its desired value of 0.5, yielding reduced sidewall slope in the resulting image. Measurements of the short- and long-term spatial stability of the plasma source reveal that the emission centroid remains fixed to within 10 μm over a 20 pulse burst, but that a drift of $\sim 80 \mu\text{m}$ occurs over a time scale of a few minutes (several exposures). This motion is roughly equivalent to a 15 μRadian pointing error in the laser cavity, and is attributed both to thermal gradients in the focusing lens and laser cavity distortions caused by heating during prolonged operation. These effects can be reduced by allowing the laser to achieve steady state before performing EUV exposures. Active stabilization of the laser focal position will be implemented to further reduce source motion. Amplitude stability of the source at 13.4 nm is $\sim 10\%$ RMS and represents a small contribution to resist dose uncertainty due to the large number of pulses required to fully expose all resists used in this work.

The illumination uniformity on the object mask is approximately $\pm 10\%$ over the 4 mm object field when a pristine condenser is used. This variation is caused by the combined effects of a source-condenser distance variation and the weak variation in plasma EUV emission intensity as a function of viewing angle across the 50 mm condenser subaperture[16]. As target debris is deposited on the condenser, the illumination uniformity worsens significantly. This is caused principally by the strong angular dependence of the debris flux from the target over the range of ejection angles subtended by the condenser subaperture. For qualification of the optical system, the illumination uniformity now achieved with a pristine condenser is adequate. For

eventual device fabrication, however, improvements will be necessary. Incorporating a graded transmittance across a debris shield is one possible approach to compensate for nonuniformity.

Cleaning procedures have been developed to remove Sn, Ta, or Cu debris deposits from the condenser after its reflectance has been reduced to ~30% of the original value, restoring up to ~90% of the original reflectance. Examination of the optic in a scanning electron microscope after debris removal does not reveal fractured or crazed regions of the multilayer coating, in contrast to earlier observations made when debris from bulk Au targets was chemically removed from Mo/Si multilayers[14]. These earlier observations revealed that obvious multilayer fracture occurred only in regions where debris particulates $\geq 10\text{ }\mu\text{m}$ diameter were deposited. The present target has been designed to produce very few of these large particulates, which, in tandem with the rotary chopper, reduces multilayer fracture damage. While the present level of debris control and condenser cleaning is adequate for characterization of experimental optical systems, further development of cryogenic[14] or "zero-debris" EUV sources are needed for a production-worthy EUVL tool.

III.b. Resist Imaging

Imaging performance of the Schwarzschild camera was established with a reflective mask containing various test patterns to produce printed features ranging in size from $5\text{ }\mu\text{m}$ to $0.05\text{ }\mu\text{m}$. The mask is a Mo/Si multilayer-coated fused silica flat patterned with a bilayer absorber having 60 nm of hard baked resist and 30 nm of Ge[17]. Figs. 2-4 show scanning electron micrographs (SEMs) of selected test structures located on the mask. Fig. 2(b) shows a spoke-pattern resolution target used to reveal astigmatism, Fig. 3(b) shows equal line/space gratings with pitch of $3\text{ }\mu\text{m}$ and $2\text{ }\mu\text{m}$, Fig. 4(b) shows gate/pad structures with gate widths of $1.5\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$, and Fig. 4(d) shows gratings with pitch ranging from $6 - 2\text{ }\mu\text{m}$. Masks have been fabricated in both light- and dark-field tones; all results presented here were obtained with the light-field mask.

Exposures were performed in the positive-tone resists poly(methyl methacrylate) (PMMA) (OCG Microelectronics) and ZEP 520 (Nippon Zeon). PMMA patterns were developed for 1 min. in a 1:1 mixture of methyl isobutyl ketone and isopropanol, while ZEP patterns were developed in xylenes for 5 minutes. Approximately 10 nm of unexposed resist was removed from ZEP films developed in this manner. The resulting surfaces were found to be significantly rougher than those of PMMA exposed under similar conditions; an acceptable compromise for the present application when weighed against the three-fold reduction in required exposure dose.

Initial resist exposures were performed with no additional spectral filtering. In this case, ~500 laser pulses were required to clear 70 nm of PMMA, yielding strong modulation at 0.1 μm . Imaging artifacts caused by the presence of unwanted long-wavelength radiation grew increasingly noticeable over the course of many exposures, especially in ZEP. We attribute this to a reduction in the spectral contrast at 13.4 nm caused by the deposition of plasma source debris on the condenser. Si membranes 0.38 μm thick were used to remove unwanted spectral components, increasing the necessary exposure time by a factor of 2 but sharply increasing printed image contrast, as expected. Spectral purity was not an issue in our earlier 20x system because a transmissive Si membrane mask was used, providing adequate filtering of long-wavelength components for all but the most visible-light-sensitive resists.

Typical images recorded in ZEP are shown in the SEMs of Figs. 2-4. These images and others recorded in PMMA exhibit reasonable two-dimensional image fidelity across the full design exposure field of 0.4 mm to a resolution of ~0.2 μm , although image contrast decreases sharply for smaller structures. For example, Fig. 2(a) shows no discernable astigmatism down to 0.2 μm , while the 0.1 μm lines and spaces shown on the right in Fig. 3(a) are marginally resolved in ZEP and are only slightly better in PMMA. Imaging artifacts associated with highly coherent illumination, such as speckle and ringing, are not observed. These images are consistent with the 2 nm WFE measured for the camera after final alignment and are substantially improved over images produced with the 20x Schwarzschild[18], which exhibited significant astigmatism caused

by zonal errors. Further improvements in image quality are expected from other mirror pairs which were fabricated at the same time as the pair used in this work but which have slightly improved figure. These optics are to be incorporated in a laboratory EUVL tool based on the 10x Schwarzschild camera and a magnetically levitated fine-control stage for precise wafer positioning. This system is currently under construction and will provide the capability for future device fabrication.

IV. CONCLUSIONS

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 illumination source and a near-normal incidence reflection mask, we have printed 0.1 μm images in PMMA and ZEP 520 resists. Source brightness and debris control are shown to be sufficient for the qualification of experimental EUVL optical systems, but also show that further progress in source debris control will be needed for a production-worthy EUVL tool. 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 exposure times achieved in these experiments demonstrate the ability of multilayer technology to meet the multilayer period precision requirements of EUV lithography.

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VI. FIGURE CAPTIONS

Figure 1. Schematic diagram of the 10x Schwarzschild system for projection imaging at 13.4 nm wavelength.

Figure 2. Scanning electron micrographs (SEMs) of a star resolution target on the reflective mask (b), and its resulting image printed at 13.4 nm in ZEP 520 (a). The SEM of the resist pattern in the top panel was obtained with the sample rotated 26° with respect to the electron beam to improve SEM contrast. No rotation was applied to obtain the SEM of the mask.

Figure 3. SEMs of 1.5 μm (left) and 1.0 μm (right) line/space grating resolution targets on the reflective mask (b), and their corresponding images printed at 13.4 nm in ZEP 520 (a). The nominal printed resist linewidths are 0.15 μm (left) and 0.1 μm (right). The SEM of the resist pattern in the bottom panel was obtained with the sample rotated 26° with respect to the electron beam to improve SEM contrast. No rotation was applied to obtain the SEM of the mask.

Figure 4. SEMs of 1.0 μm and 1.5 μm gate resolution targets (b) and equal line/space gratings (d) on the reflective mask and their corresponding images printed at 13.4 nm in ZEP 520, (a) and (c). SEMs of the resist patterns in (a) and (c) were obtained with the samples rotated 26° with respect to the electron beam to improve SEM contrast. No rotation was applied to obtain the SEMs of the mask.

TARGET
TRANSPORT

LPS (f_1)

SECONDARY

WAFER

PRIMARY

TURNING MIRROR

MASK

f_2

CONDENSER

Fig. 1

Fig. 2

(a)

(b)

(a)

(b)

(c)

(d)

DATE

FILMED

10/12/94

END