Development of compact extreme ultraviolet interferometry for on-line testing of lithography cameras.

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ABSTRACT

When characterizing an extreme ultraviolet (EUV) lithographic optical system, visible light interferometry is limited to measuring wavefront aberration caused by surface figure error while failing to measure wavefront errors induced by the multilayer coatings. This fact has generated interest in developing interferometry at an EUV camera's operational wavelength (at-wavelength testing), which is typically around 13 nm. While a laser plasma source (LPS) is being developed as a lithography production source, it has generally been considered that only an undulator located at a synchrotron facility can provide the necessary laser-like point source for EUV interferometry. Although an undulator-based approach has been successfully demonstrated, it would be advantageous to test a camera in its operational configuration. We are developing the latter approach by utilizing extended source size schemes to provide usable flux throughput. A slit or a grating mounted in front of the source can provide the necessary spatial coherence for Ronchi interferometry. The usable source size is limited only by the well-corrected field of view of the camera under test. The development of this interferometer will be presented.

Keywords: extreme ultraviolet interferometry, extreme ultraviolet lithography, soft X-ray projection lithography, soft X-ray interferometry, laser plasma source, Ronchi interferometry, Mo-Si multilayers

1. INTRODUCTION

Extreme ultraviolet lithography (EUVL) is a candidate technology for the microelectronics industry with design rules for 0.1 μm features and beyond[1, 2]. The basic concept of EUVL is to utilize near-normal incidence multilayer-coated reflective optics operating at a typical wavelength of λ_{EUV}=13 nm. A major challenge for this technology is the fabrication of optical systems with unprecedented requirements for wavefront aberration control. To meet diffraction-limited imaging performance, Maréchal's criterion stipulates that an EUV optical system's RMS wavefront error can be no greater than 0.07 λ_{EUV}. In terms of conventional visible light interferometry carried out with 632.8 nm radiation (λ_{HeNe}), this requires the capability of measuring RMS wavefront errors less than $\lambda_{HeNe}/695$. Such a requirement is beyond the capability of current visible light metrology.

A more fundamental limitation of visible light techniques is that they can only measure the *surface* wavefront error generated by an optical system, whereas a multilayer-coated optical system has effects that depend on the buried interfaces. Because the reflectivity and phase shift upon reflection from a multilayer coating vary with the incident angle and layer spacing; a departure from either the ideal figure or multilayer coating specification can induce unwanted apodization as well as wavefront error[3]. These theoretical effects can be readily calculated [4] .

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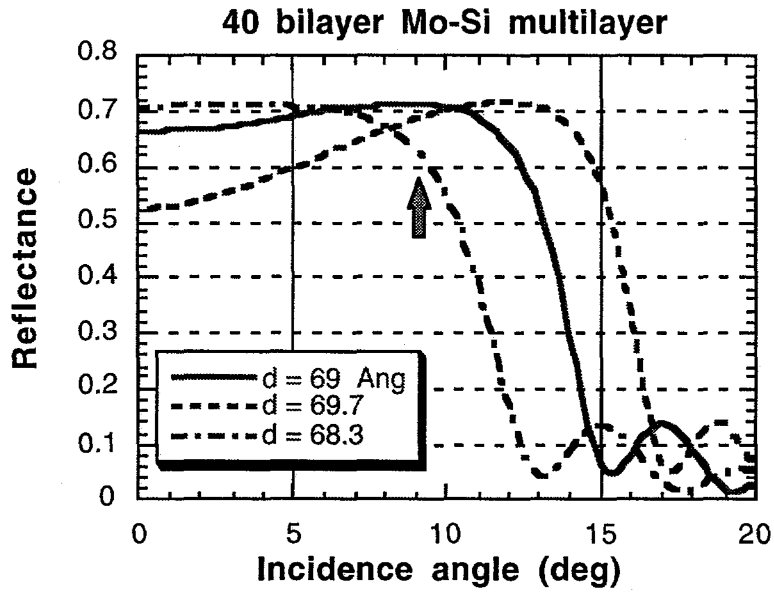

Figure 1. Effect of ± 1% multilayer period error on reflectance.

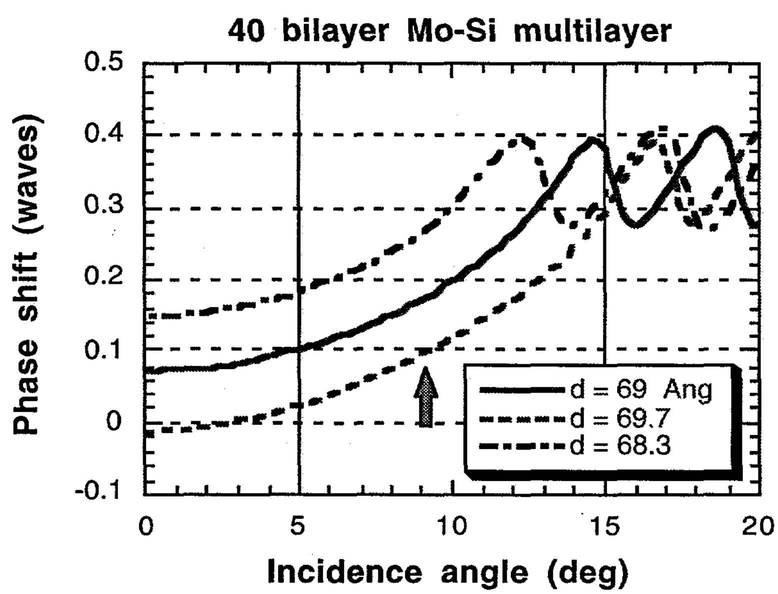

Figure 2. Effect of ± 1% multilayer period error on phase shift upon reflection.

Figures 1 and 2 are plots of reflectance and phase shift respectively at a wavelength of 13.4 nm versus incident angle. The period of a multilayer optimized for peak reflectance at 9 degree incident angle (highlighted in Figs. 1 and 2) is varied by ±1%. This angle represents the chief ray on the first mirror of an EUV Schwarzschild camera operating at Sandia. Up to an 8% drop in reflectance and a phase shift of 0.08 waves could be expected for this coating error. The detection of these and other wavelength-dependent effects can only be carried out with optical tests that are performed at the functional wavelength of the optical system under test ("at-wavelength"[5]).

2. EXPERIMENTAL APPROACH

In visible light interferometry, a high brightness (photons/sec/unit solid angle/unit source area) HeNe laser typically provides a point source that is both spatially and temporally coherent. Analogously, researchers have utilized an undulator located at a synchrotron facility to provide the laser-like point source for EUV interferometry. Although such an approach has been successful[6] , the high cost and the limited availability of an undulator are impediments to widespread use. Our approach is to realize that one can select a metrology technique which can utilize either a slit source or even a grating source and still provide the necessary spatial coherence requirements of the technique while increasing the delivered flux (photons/sec) by several orders of magnitude. In this way, more compact and less expensive sources can be utilized despite lowered brightness.

2.1 Extended source Ronchi interferometry

Two points on a wavefront located at the optic's pupil plane, emanating from a source a distance r_S away, are considered to have a high degree of mutual coherence if they are capable of producing high contrast interference fringes. For a pinhole source, this condition is satisfied by two points on the wavefront oriented in any lateral direction. Their separation (Δx) can be a continuous range of values. As Δx increases, the interference contrast decreases. For a slit source, high contrast interference fringes are now limited to two points on a wavefront oriented in one lateral dimension, but Δx can still be varied. In the case of a grating source with period d_S, only two points on a wavefront along one dimension with a lateral separation very close to the value $\Delta x = \lambda r_S / d_S$ are capable of producing high contrast fringes. Ronchi interferometry[7] alternatively known as lateral shear interferometry, is unique in that it can utilize a grating source. In this test, a second transmission grating (Ronchi ruling) with period d_i is placed at or near the image plane at a distance r_i from the optic's pupil plane. The various diffraction orders will be laterally displaced or sheared. The shear distance (S) is given by $S = \lambda r_i / d_i$. By tailoring the two ruling such that $S = \Delta x$, high contrast interference fringes from overlapping orders can be obtained. Additional high contrast interference modes are also obtained through self-imaging of the ruling [8] .

Ideally, the phase difference between two overlapping orders will vary linearly with small shear; producing straight, equal-spaced fringes. For small shear values, each fringe is a contour of the first derivative of the wavefront aberration. Quantitative wavefront information can be obtained by utilizing phase shifting techniques on small shear interferograms [9, 10]. By stepping both rulings laterally and in phase, a periodic phase shift in the Ronchigram is introduced for synchronous phase detection. Two separate measurements in orthogonal directions are required to completely analyze the optical system. A more accurate technique involving large shear interferograms has been also been developed in conjunction with this work[11] .

EUV Ronchi interferometry has the practical advantage of a large dynamic operational range. This can be obtained by using rulings of different pitch. This property is extremely important for enabling mechanical designs with *in situ* adjustments that can utilize an at-wavelength technique for the complete alignment. As the alignment is improved, a higher frequency ruling provides higher sensitivity. An additional advantage of this technique is the common path design; no EUV reference optics are required to test the optical system.

3. EXPERIMENTAL DESIGN

Figure 3 is a schematic of the interferometer setup installed on a 5 multilayer mirror, laboratory EUV exposure system located at Sandia National Labs in Livermore, CA. All multilayer mirrors are optimized for peak EUV reflectance at a wavelength of 13.4 nm. A Nd:YAG (1.06 μm) laser capable of 800mJ, 9 nsec pulses at a 20 Hz repetition rate is targeted on a metal target. The extremely hot plasma that is created has a continuous radiation spectrum that extends into the EUV regime. An ellipsoidal condenser mirror magnifies the source by 13.3 times and projects the image to the entrance pupil of a 10x-reduction Schwarzschild camera. The entrance pupil is located off-axis to avoid the central obscuration. Under normal operation, the pupil fill factor is approximately 0.5. The condenser can be adjusted to illuminate and test the entire pupil.

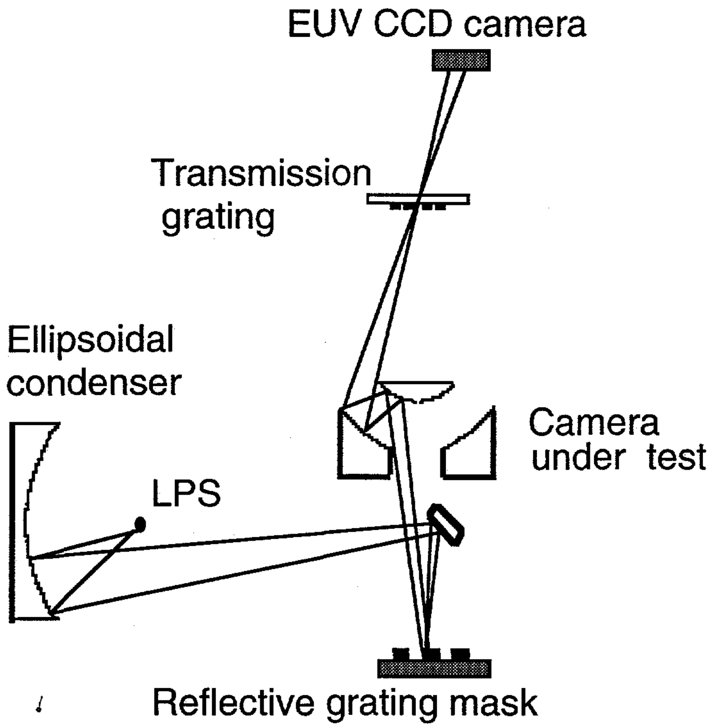

Figure 3. Schematic of experimental setup.

A turning mirror deflects the condenser illumination on to a reflective multilayer mask. The camera's well-corrected field size is 0.4 mm in diameter. To define the grating source, absorber lines were lithographically patterned by contact printing of resist and 100 nm Au lift-off. The reflectance of the multilayer was measured after patterning to ensure that no degradation occured. The quality of the periodic source mask was verified by recording the grating image produced by the Schwarzschild camera in 90 nm of SAL 603 photoresist. A scanning electron micrograph of the developed 0.5 μm features is presented in Figure 4.

A 10x reduction transmission ruling is patterned on a 0.5 μm thick Si support membrane by electron beam lithography and Au lift off. The Si membrane provides approximately 44% transmission at 13.4 nm. A scanning electron micrograph of a ruling with 0.5 μm features is presented in Figure 5. The Si membrane exhibits some surface roughness, however any aperiodic features will be averaged out and not appear in an interferogram produced with an extended source.

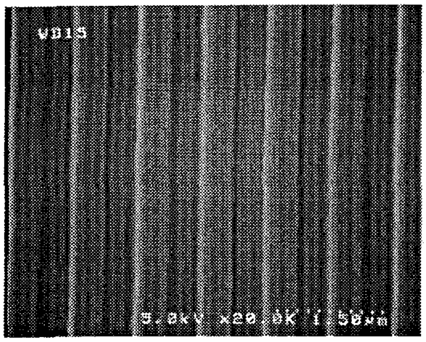

Figure 4. Reflective grating mask imaged by Schwarzschild canera into SAL 603 reist.

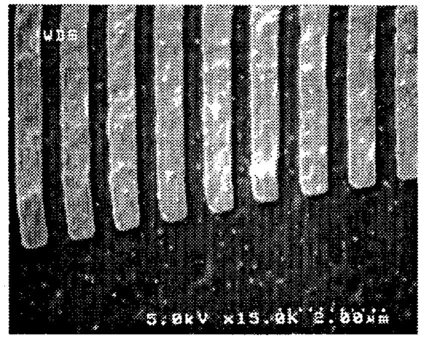

Figure 5. EUV transmission ruling with 1.0 μm pitch.

To enable alignment, the reflective mask is mounted on a vacuum compatible, x-y-z-θ crossed roller bearing stage with New Focus Picomotors* actuating the coarse motion. The transmission ruling is mounted on an x-y stage of similar design. A photodiode can measure the transmitted signal as the rulings are brought into alignment. For the fine translation during phase shifting analysis, Queensgate* piezoelectric stacks with capacitive position feedback actuate both rulings.

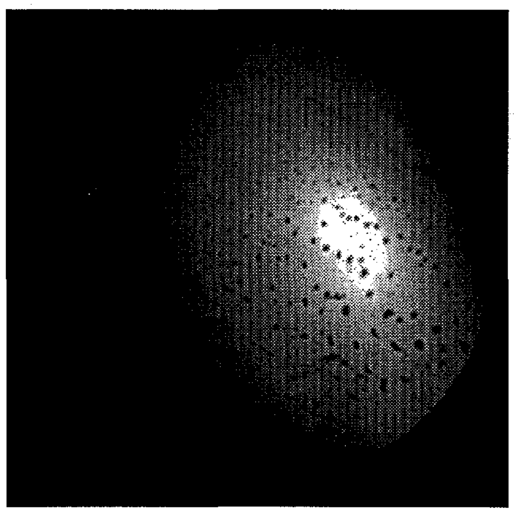

Figure 6. Far field image of Schwarzschild camera obtained with EUV CCD camera.

The EUV detector is a Peltier-cooled CCD camera containing a Tektronix* 1024 x 1024 pixel, back-illuminated CCD. Each pixel is 25 x 25 μm in size. A 1 μm Be membrane is utilized to filter out unwanted radiation. The transmission at 13.4 nm is approximately 18% for this filter. Figure 6 is an EUV image acquired by the camera when positioned in the far field of the Schwarzschild camera at a distance of 10 cm from focus. The image was acquired with the periodic source and no transmission ruling in place. The recording duration for this low noise image was 6 laser pulses. This result confirms that there is sufficient flux for performing interferometry in a reasonable period of time. Interestingly, one can observe spots where the reflectance has decreased by 20-50%. The pattern appears to indicate that some type of droplet contamination has occured for this set of optics during either fabrication or subsequent handling.

4. SUMMARY

A method for performing EUV interferometry with a laser plasma source is currently under development. To make use of the relatively low brightness in comparison to an undulator, an extended source Ronchi technique is proposed. This will enable the on-line alignment of an EUV lithographic optical system as well as make EUV interferometry more readily available to optical manufacturers. Preliminary results indicate that sufficient flux is available.Obtaining an interferogram in a single shot may be possible with additional optimization. This would be a tremendous advantage in terms of eliminating apparent vibration.

5. ACKNOWLEDGMENTS

We gratefully acknowledge D.A. Tichenor and G.D. Kubiak for helpful discussions. This work is supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

*The mention of trade names in this paper is for information purposes only and does not represent endorsement of the products by the authors or their institutions.

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