UCRL-JC-123008

CONF-9604150--2

Preliminary Investigation of an Additive Approach to the Fabrication of Precision Aspheres

RECEIVED
AUG 22 1996
OSTI

F. W. Weber, C. Montcalm, S. P. Vernon, D. R. Kania

Lawrence Livermore National Laboratory
Livermore, CA 94551

This paper was prepared for submittal to the
Optical Society of America
Extreme Ultraviolet Lithography
Boston, MA
April 29-May 3, 1996

May 24, 1996

Lawrence Livermore National Laboratory

MASTER

DISCLAIMER

Preliminary investigation of an additive approach to the fabrication of precision aspheres

F.W. Weber, C. Montcalm, S.P. Vernon, and D. R. Kania

Lawrence Livermore National Laboratory, P.O. Box 808, L-395, Livermore, CA, 94551.

Abstract

We report progress in the asphérization of precision optical substrates via deposition of graded period Mo/Si multilayer coatings using a masking technique. These preliminary results show good agreement between the measured and desired thickness profiles over 85% of the sample, however, thickness deviations of up to 7% are observed in the central area. The errors are attributed to misalignments of the mask relative to the substrate during deposition.

Key Words: Optical fabrication, Thin film deposition and fabrication, X-ray mirrors, Microlithography.

Introduction

Extreme-ultraviolet lithography (EUVL) imaging cameras requires multiple aspheric elements with accurate figures and smooth surfaces. High figure accuracy is required to minimize the wavefront error and low surface roughness is required to minimize the adverse effects of scatter. To date, the best aspheric surfaces are fabricated using computer controlled localized polishing techniques. However, these optics exhibit surface roughness in the mid-spatial frequency range, f between 10^1 and 10^4 cm^{-1}, that seriously degrade the imaging properties and make them unsuitable for EUVL imaging applications.[1]

Conventional optical fabrication methods, in combination with state-of-the-art superpolishing techniques, can produce spherical surfaces consistent with the stringent EUVL specifications. The best spheres exhibit mid-spatial frequency roughness values that are one order of magnitude lower than those of the aspheres.[1] In addition, it appears that Mo/Si multilayer coatings do not significantly compromise the imaging properties of an EUVL optic.[2] Indeed, their dominant effect is to increase the surface roughness mainly in the high spatial frequency range ($f > 10^4$ cm^{-1}), which reduces the throughput of the imaging system but not the image contrast. This permits us to envision a strategy for the fabrication of EUVL aspheres using laterally graded multilayer deposition to build up the required aspheric departure on a precision spherical substrate. This additive approach should produce aspheres with superior surface finish than the current state-of-the-art polishing techniques.

Superpolished spherical surfaces are readily available, and the techniques for adding laterally graded multilayer coatings that preserve the surface quality have been demonstrated.[3] The ability to form the surface to the accuracy required for EUVL imaging optics is still in question and this provides a major motivation of our effort. A significant disadvantage of the additive approach, however, is the potential for deformation of the substrate due to intrinsic coating stresses. Nevertheless, this should not limit the utility of the approach since appropriate adjustment of the Mo/Si multilayer deposition conditions can eliminate, or at least minimize, intrinsic stress.[4] The notion of asphérization via thin film deposition is not a new idea and has been employed in the past utilizing mainly single layer coatings; however, the surface roughness of single layer films can be inconsistent with the EUVL specification.[5]

In this paper, we summarize the preliminary results of our attempts to utilize precision multilayer deposition methods to fabricate EUVL aspheres. As a test case we have attempted to reproduce the aspheric departure of the M3 optical element of the 3-mirror ring-field 5× reduction imaging system under development at Sandia National Laboratories.[6] This mirror has a base radius of curvature of ~600 mm and a clear aperture of ~80 mm. The aspheric departure of this concave mirror reaches 0.58 μm at the center and edge, as shown in Fig. 1. We have adopted a sequential approach to the asphérization employing Si wafers as substrates during the initial phases of experimentation and development. At the outset, masks are used to approximate the desired

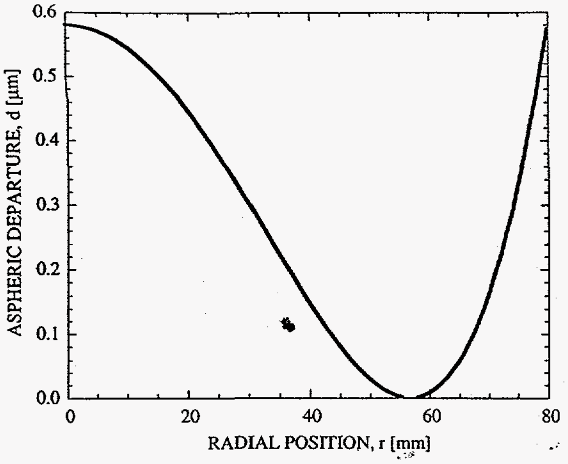

Figure 1. Aspheric departure as a function of radius for the M3 optic of the Sandia 3-mirror ring-field 5× reduction imaging system.

thickness profile of the coating. This work on wafers constitutes the preliminary experiments. Subsequently, an accurate velocity modulation method is used to refine the profile by dynamically varying the transit velocity of the substrate as it passes over each source[7]. Optical flats are used in the final phases of testing prior to generation of the asphere.

Procedure

To date, we have studied the efficacy of shaped apertures (masks) between the deposition source and the substrate to obtain a deposition profile approximating the desired aspheric departure. In the future, we intend to refine the accuracy of the coating profile using the velocity modulation method. In all cases, the substrates were rotated about their centers so that a radially symmetric multilayer coating and, hence, a radially symmetric aspheric departure was produced. The Mo/Si multilayers were deposited in a dc planar-magnetron sputtering system that has been described elsewhere and which is shown in Fig. 2. Briefly, this system contains two rectangular sources with chimneys that limit the deposition to rectangular areas of 12.7 × 25.4 cm. The substrate is held face down on a rotating platter at a distance of 6 cm above the sources. The layer thickness is determined by the time the substrate is exposed to the source which, in turn, depends on the substrate transit velocity. A stationary mask is placed directly below the spinning substrate. The largest part that can be coated with a profile in the present system is 100 mm in diameter. The sputtering chamber was cryo-pumped until the pressure was no greater than 5×10^{-7} Torr before deposition. Ultra-high purity Ar at a pressure of 1.75 mTorr was used to sputter the Si and Mo targets at source powers of 280 W and 110 W, respectively.

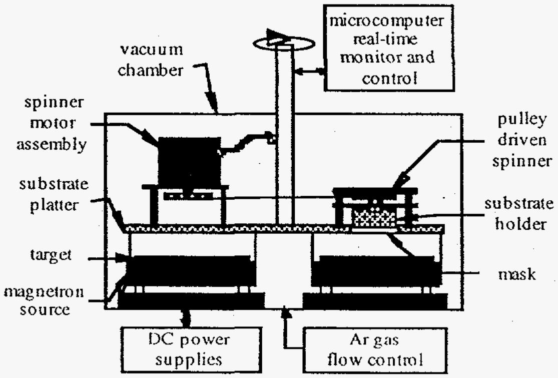

Figure 2. Schematic of the dc magnetron sputtering system used for the deposition of the Mo/Si multilayers.

A high quality multilayer structure must be maintained to accurately replicate the substrate surface. This limits the range of thickness the individual layers may have because they must be thin enough to avoid roughening due to crystallite growth. In addition, it is preferable to have Mo and Si layers of equal thickness since a thickness ratio near 1:1 appears to minimize the intrinsic stress of Mo/Si multilayers.[4] Since an interlayer forms between Mo and Si, the component thickness should be large enough so that the structure is not composed mostly of interlayers. Such a structure would not be amenable to stress control. Therefore, in this study the bilayer thickness was varied from 8 nm in the center to 4.2 nm at the edge, the thickness ratio was maintained at 0.5, and 145 bilayers were deposited to achieve the required 0.55 μm thickness difference between the edge at 55 mm and the center.

A radially varying multilayer thickness profile $t(r)$ is generated from a mask with an angular aperture $\theta(r)$ given by $\theta(r) = \theta_o\ t(r) / t_o$, where t_o is the thickness of the film at the substrate center and θ_o is a normalization factor. The thickness profile $t(r)$ was generated from a fifth order polynomial fit to the aspheric departure shown in Fig. 1. A schematic of the mask employed in the fabrication of samples reported in this study is shown in Fig. 3. Here $\theta_o = 360°$, $t_o = 1.16$ μm, and $\theta(r)$ was divided by 3 to generate the three prongs.

The substrate surface profile is measured before and after deposition with a WYKO 6000 phase shifting

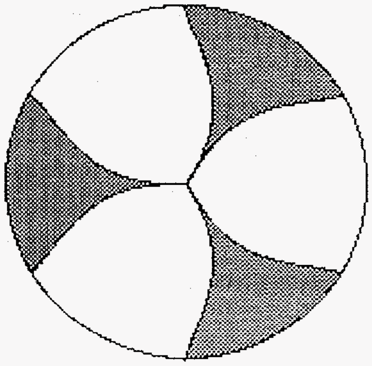

Figure 3. Shape of the mask used to generate the thickness profile of the multilayer samples discussed in this paper.

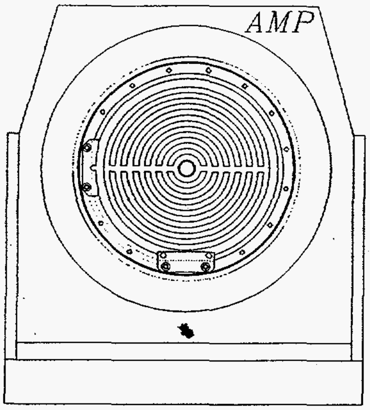

Figure 4. Plan view of the vacuum chuck used to hold the Si substrate flat during the interferometric measurements.

interferometer and the data are subtracted to generate a difference map. A radial thickness profile is then computed by performing an angular average of the difference. The angular average accounts for the radial symmetry of the deposited coating and ignores any residual asymmetry in the coating profile. The analysis technique was sufficient for these preliminary tests, but a more sophisticated characterization method, for example Zernike polynomials, will be required for a thorough analysis.

Electronic grade Si substrates, 100 mm in diameter, were use for the preliminary experiments. A vacuum chuck was used to hold the wafers flat during the interferometric measurements, in part because wafers have too much bow for our measurements. This also allowed us to overcome any residual stress deformation of the multilayer coated wafers and measure the multilayer thickness profile directly. The vacuum chuck, illustrated in Fig. 4, is an optical flat with concentric grooves machined in its surface. Each groove is coupled to a vacuum manifold via a through hole and the manifold fits in a standard optical mount suitable for interferometry. Dowel pins mounted in the manifold provide a reference for locating the major and minor flats on the Si substrates and permit accurate repositioning of the substrate.

Results and Discussion

In Fig. 5a and 5b is shown the thickness profile of a Mo/Si multilayer coating deposited on a Si substrate using the mask shown in Fig. 3. The local irregularities visible on the thickness map of Fig. 5a are caused by particles trapped between the back surface of the wafer and the reference surface of the vacuum chuck. Extreme substrate curvature, a local slope that crowds the interference fringes to their limit of discernability, also occurs at the edges of the sample. The radial thickness profile extracted from the thickness mapping by angular averaging is shown in Fig. 5b. For a radius between 7.5 mm and 37.5 mm, the coating thickness profile agrees with the desired values to within 5 nm.

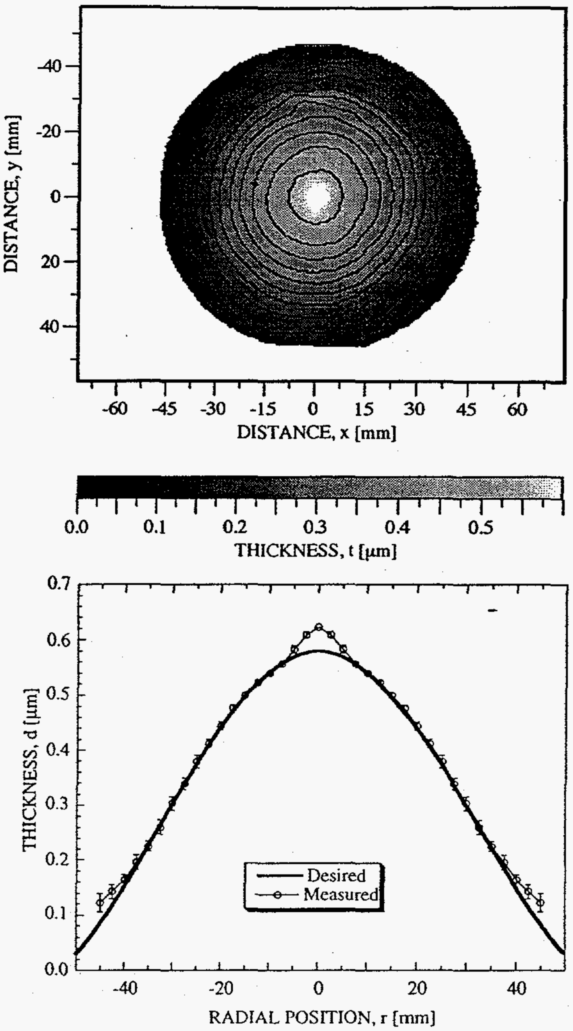

Figure 5. Thickness profile of the multilayer coating obtained using the mask shown in Fig. 4: (a) contour plot of the thickness map obtained from the interferometric difference (contour lines spaced by 0.05 μm) and (b) angular average of the interferometric difference compared to the desired profile.

The error at the wafer edge is an artifact resulting from deficiencies in substrate mount. The central bump, however, is a genuine coating error and is an inherent deficiency of the stationary mask-rotating substrate configuration employed in this study. This configuration is extremely sensitive to misalignment of the mask and substrate, particularly at the center. When misalignment occurs, a portion of the substrate in the vicinity of the substrate center is either always exposed or never exposed to the deposition flux. In the case presented in Fig. 5b, the coating at the substrate center is too thick, indicating overexposure of the substrate center to the deposition sources. Unfortunately, this class of localized error is very difficult to address with velocity profiling because the radial extent of the bump (7.5 mm), translates into only 2.5° of platter rotation.

To confirm that the multilayers did not significantly add to the roughness, 1 µm × 1 µm AFM scans were performed. The bare wafers had an RMS roughness of 0.06 nm, while a coated wafer had an RMS roughness of 0.17 nm.

Conclusions

We have been able to reproduce the aspheric departure of a "real" EUVL imaging optic to better than 10 nm over the radial region between 7 and 40 mm of a 50 mm radius flat substrate using a masking technique. The observed discrepancy at the sample center is a consequence of misalignment of the mask and the rotating substrate. To minimize alignment problems we have recently changed the coating geometry and masked the sources instead of the substrate. This approach directly modifies the coating flux distribution. Preliminary tests have shown that simple apertures over the sources yield thickness profiles that are relatively close to the desired ones with thickness discrepancies that seem easy to correct with the velocity modulation technique. Experiments assessing the potential of this new approach are in progress.

Acknowledgments

We would like to thank W.C. Banyai for helping us establishing the interferometric measurement protocol and P.A. Kearney for enlightening discussions. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-Eng-48. This work was also partially funded by a Cooperative Reasearch and Development Agreement, (CRADA) T-0503-93-C.

References

1. D.P. Gaines, D.W. Sweeney, K.W. DeLong, S.P. Vernon, S.L. Baker, D.A. Tichenor, and R. Kestner, "Surface characterization of optics for EUV lithography," in these proceedings
2. D.L. Windt, W.K. Waskiewicz and J.E. Griffit, "Surface finish requirements for soft x-ray mirrors," Appl. Opt. **33**, 2025-2031 (1994).
3. S.P. Vernon, Lawrence Livermore National Laboratory, Livermore, CA (personal communication).
4. See, for example, M.C.K. Tinone, T. Haga, and H. Kinoshita, "Multilayer sputter deposition stress control," to be published in J. Electron Spectrosc. Relat. Phenom. (1996); D.L. Windt, W.L. Brown, C.A. Volkert, and W.K. Waskiewicz, "Variation in stress with background pressure in sputtered Mo/Si multilayer films," J. Appl. Phys. **78**, 2423-2430 (1995) and D.L. Windt, "Stresses in Mo/Si and W/Si multilayer films," presented at *The 3rd International Conference on the Physics of X-Ray Multilayer Structures*, Breckenridge, Colorado, 3-7 March, 1996; and references therein.
5. See, for example, J. Strong and E. Gaviola, "On the figuring and correcting of mirrors by controlled deposition of aluminum," J. Opt. Soc. Am. **26**, 153-162 (1936); J.R. Kurdock and R.R. Austin, "Correction of optical elements by the addition of evaporated films," Physics of Thin Films **10**, 261-308 (1978); and C.C. Lee, D.S. Wan, C.C. Jaing and C.W. Chu, "Making aspherical mirrors by thin-film deposition," Appl. Opt. **28**, 5535-5540 (1993), and references therein.
6. D.A. Tichenor *et al.*, "Recent results in the development of an integrated EUVL laboratory tool," in *Electron-Beam, X-Ray, EUV and Ion-Beam Submicrometer Lithographies for Manufacturing V*, J.M. Warlaumont, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **2437**, 292-307 (1995).
7. S.P. Vernon, M.J. Carey, D.P. Gaines, and F.J. Weber, "Multilayer coatings for the EUV lithography front-end test bed," in *OSA Proceedings on Extreme Ultraviolet Lithography*, F. Zernike and D.T. Attwood, eds. (Optical Society of America, 1995), Vol. 23, pp. 33-40.
