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Multilayer coating and tests of a 10X extreme ultraviolet lithographic camera

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ABSTRACT

A new set of mirrors for the SANDIA 10X microstepper has been fabricated. The optics have been tested by optical profilometry, atomic force microscopy, EUV reflectometry and EUV scattering. These measurments allow one to predict the performance of the camera. Mo/Si multilayer coatings with the required thickness profile were produced by DC magnetron sputtering using shadow masks in front of the rotating substrates. The figure errors of the new mirrors (0.6 nm) are considerably smaller than those obtained previously, while mid-spatial frequency roughness still needs improvement. This roughness reduces mostly the throughput of the system; i. e. most of the scattered light occurs outside the field of the camera and there is only a small reduction of contrast or resolution.

Keywords: EUV lithography, Mo/Si multilayer coatings, power spectral density, EUV scattering, Schwarzschild optics

1. INTRODUCTION

The SANDIA 10X microstepper evolved from Schwarzschild systems that were originally used at AT&T Bell Labs and is presently the main laboratory tool to test exposure and processing steps for EUV lithography [1]. Figure errors of the original mirrors were too large for diffraction limited performance and the resolution of 0.1 µm was only obtained by selecting the best pair from a large number of mirrors and by rotating the mirrors against each other until the best image was found. Recent advances in interferometry and figuring[2, 3] has made it possible to reduce figure errors to below the 1 nm range. We have obtained two sets of mirrors with rms figure errors around 0.6 nm. The mirrors have been fabricated with the same technique that will be used for the aspheric mirrors of future EUV cameras. While the mirrors have excellent figure, they have mid- and high frequency roughness that is considerably higher than that of the best superpolished spherical mirrors. In this paper we will describe the procedure used to coat the mirrors and to characterize the coated optics. The following paper by Gullikson contains a much more detailed discussion of the EUV scattering data.

2. THE OPTICAL SYSTEM

Figure 1 gives the layout of the optical system as described previously [1]. The Schwarzschild camera reduces the mask by a factor 10 and gives 0.1 µm resolution over a 0.4 mm field. Only a decentered part of the imaging and condensor mirrors with 0.1 NA is illuminated. The elliptical condensor mirror has been changed from previous designs in order to adapt the system to a new laser plasma source (see Goldsmith et al., these Proceedings). The condensor projects a 6.6x magnified image of the source into the entrance pupil of the imaging optics. The source at the first focal point of the mirror is $f_1 = 242.8$ mm from the mirror surface, while the entrance pupil of the camera is at the other focal point $f_2 = 1634.2$ mm. The diameter of the condensor mirror is 188 mm.

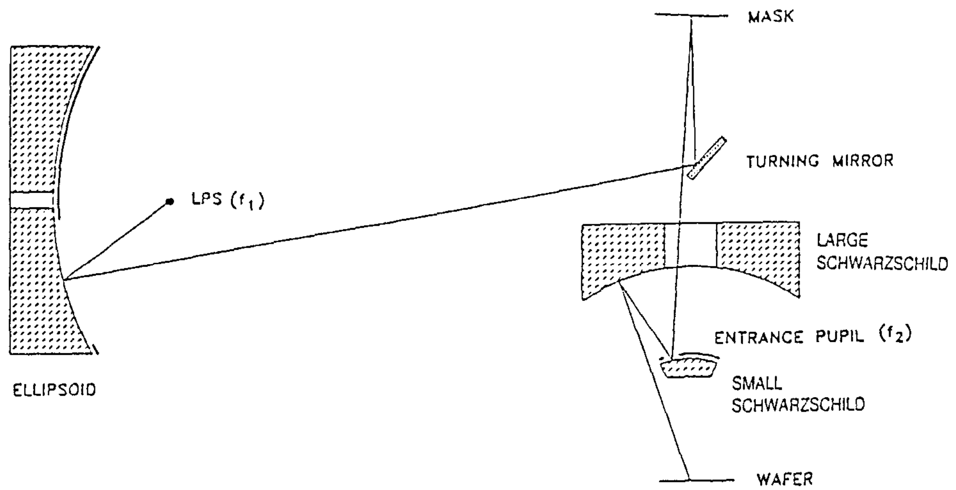

Fig 1. Optical system with source (LPS), condensor mirror, turning mirror, mask, reduction camera and wafer.

3. COATING PROCESS

The incidence angle of rays in the optical system changes over the aperture, and the period Λ of all multilayers has to be graded to reflect the same wavelength with the maximum intensity. The required period of the coatings can be calculated from the generalized Bragg condition

$$\lambda = 2\ \Lambda\ \cos\varphi_0 \sqrt{1 - \frac{2\delta}{\cos^2\varphi_0}}, \tag{1}$$

where φ_0 is the incidence angle measured from normal and δ is the weighted average index of the coating materials. We used $\delta = 0.0272$ as an initial first estimate for the Mo/Si system around $\lambda = 13.4$ nm. The required normalized thickness profiles for all mirrors are given below as the solid curves in Fig. 6. The tolerances for errors in the multilayer period are usually derived from the reflectivity curves (Fig. 2). Mismatch in the reflectivity curves over the surface of one mirror or between mirrors reduces the throughput of the optical system and could produce phase errors that affect the imaging performance. A mismatch of ±0.05 nm in the wavelength of the reflectivity maximum reduces the reflectivity of a mirror by less than 1%. The phase error produced by a mismatch $\Delta\lambda = \pm 0.05$ nm is about 1/20 wave, a factor of two smaller than that by the figure errors of the present optics. The actual effect of the phase errors will even be smaller, because the effect of a phase error centered on the optical axis can be eliminated by a slight change in the mirror spacing. We selected $\Delta\lambda = 0.05$ nm or $\Delta\lambda/\lambda = \Delta\Lambda/\Lambda = 0.4\%$ as the goal for matching the multilayer coatings.

The mirrors were coated in a DC magnetron sputtering system (Fig. 3). Substrates are mounted on spinners and spun about their optical axis. The substrates face downward through the platters on which the spinners are mounted. This platter is then rotated to pass the mirror over each sputtering target. The system usually produces coatings that are thinner at the outside. Shadow masks conforming to the shape of mirror that shadow a larger fraction of the center of each mirror are used to produce the desired profile. The final shape of a mask is found by an iterative process consisting of the following steps:

1. Ray trace the optical system to calculate the incidence angles for all rays on all mirrors of the system and calculate the multilayer period required for each location on each mirror.
2. Fabricate a mock-up of the optical elements.

3. Coat small flat pieces of Si that are mounted on the mock-up and measure the multilayer period for all positions using $\lambda = 0.154$ nm at grazing incidence or a laser plasma source near normal incidence.
4. Produce correcting shadow masks that modify the thickness distribution obtained in 3) to give the desired distribution, assuming that the coating thickness at each distance from the axis is proportional to the unshadowed arc .
5. Iterate steps 3 and 4 until the error in the distribution is at an acceptable level.
6. Coat test optics with the parameters obtained in 5.
7. Map the reflectivity curves of the test optics with synchrotron radiation at the Lawrence Berkeley National Laboratory (LBNL). Go back to step 5 if imperfections are found.
8. Assuming that a perfect coating is obtained in step 7, coat the real optics with the same parameters.
9. Map the reflectivity of the finished optics with synchrotron radiation.

Our method was used by Windt et al. [4] for the coating of the original AT&T mirrors. Windt provided his press to produce masks that conformed to the mirror shapes of the camera.

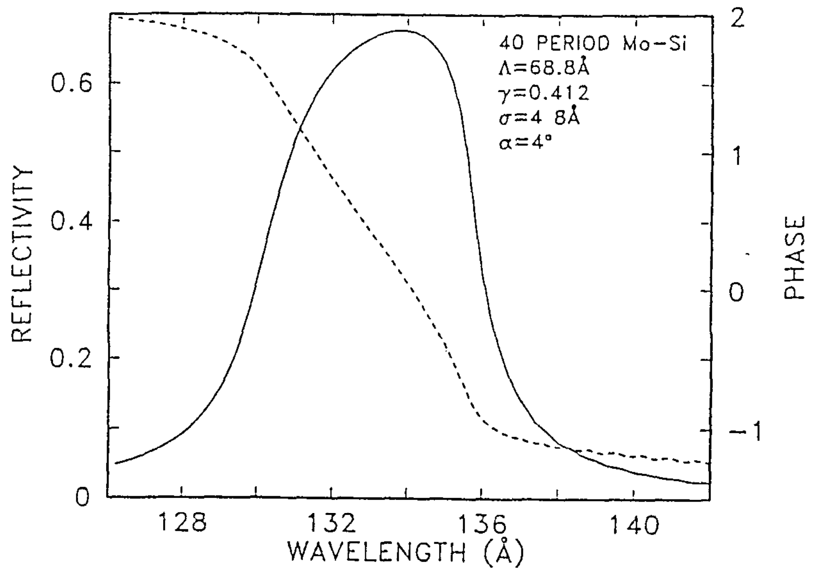

Fig.2 Calculated reflectivity and phase shift for a Mo/Si multilayer mirror on a smooth substrate.

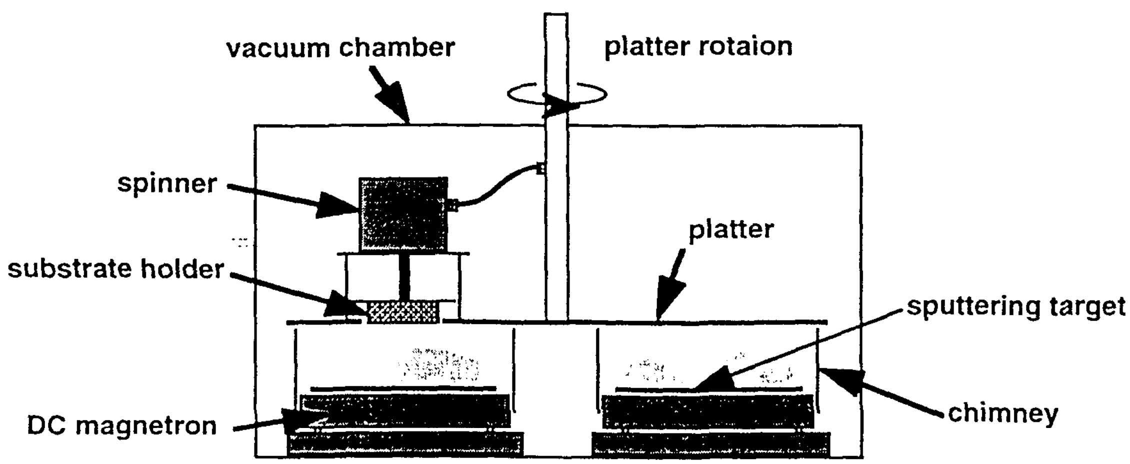

Fig. 3. Sketch of the deposition system.

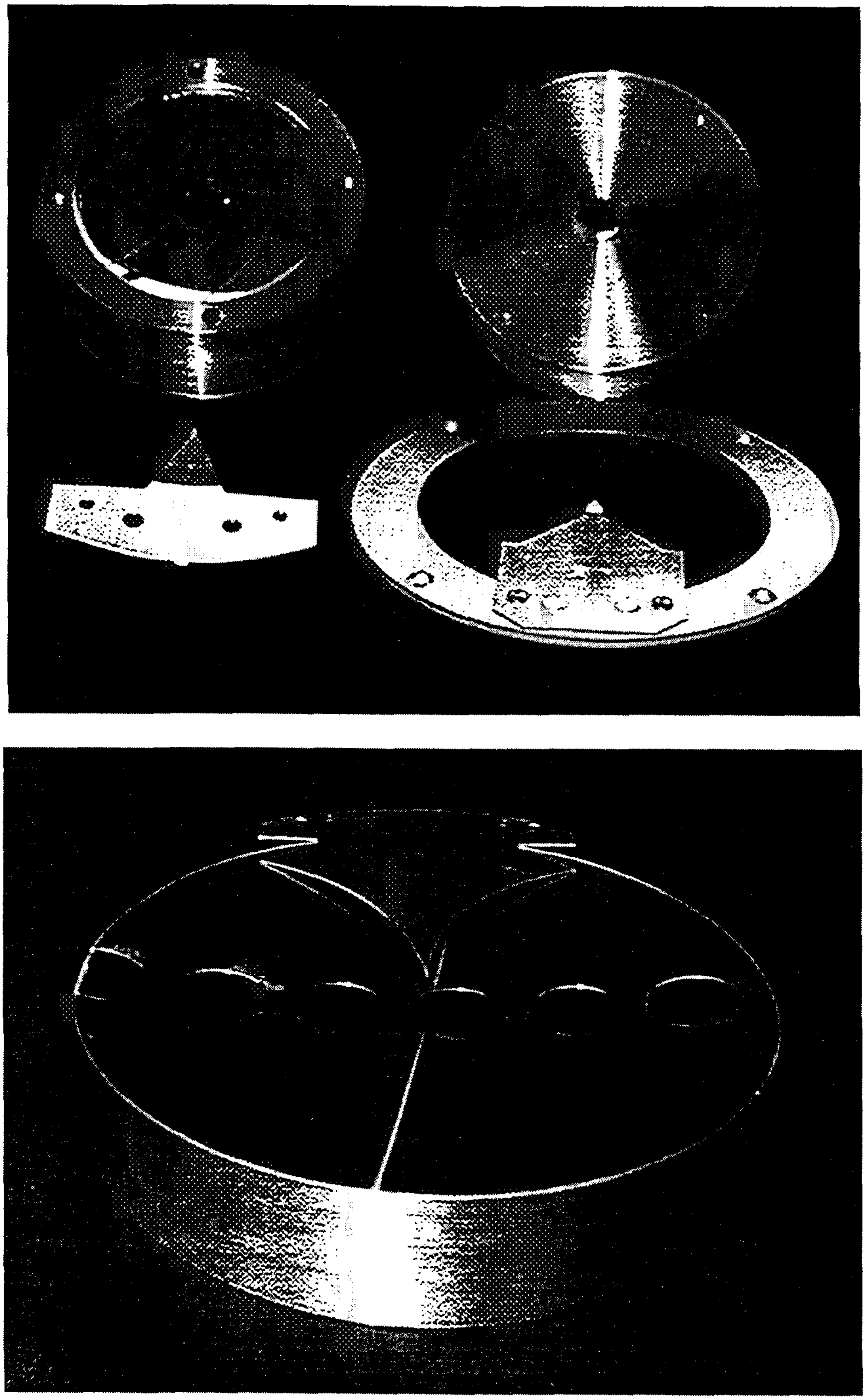

Fig. 4 Photos of the camera mirrors in their mounts for the deposition with their shadow masks (top) and of the mock up for the condenser mirror with its shadow mask (bottom).

The diameter of the condensor mirror is larger than any mirror coated before in our deposition system. It was necessary to mask the magnetrons to avoid coating any of the mirrors during presputtering and to be still able to coat two mirrors in one deposition. These masks shadowed a large fraction of the center of the magnetrons, resulting in an increase in the coating thickness of about 20% near the edge, and this increase had to be compensated with an additional mask close to the mirrors that shadowed less of the center. Figure 4 is a photo of the two Schwarzschild mirrors in their coating fixture together with the final masks and of the mock-up of the condensor mirror. During the first iterations of the mask shape we used the reflectometer at $\lambda = 0.154$ nm or the laser plasma source, while the reflectometer at the LBNL storage ring [5] was used later in the process and for the final tests. All testing methods can measure multilayer periods to about 0.01 nm; to transfer data from measurements at $\lambda = 0.154$ nm to 13.4 nm one has to know the optical constants of all components in the multilayer at both wavelengths and use model calculations. The LBNL reflectometer allows one to measure the reflectivity curves at any position of the mirror at any incidence angle and was always used for the final tests.

4. RESULTS

Reflectivity

The performance of the coated mirror was tested by measuring the reflectivity curves at different radii. Fig. 5 is an example. The incidence angle was kept constant for all measurements at one mirror with values $\varphi = 10°$, $4°$, and $5°$ for the small and large camera mirror and for the condensor respectively. In the optical system the mirrors are illuminated at these angles at radii of 5.5, 35 and 50 mm. We determined λ_{max}, $\lambda_{centroid}$, R_{max}, and the halfwidth from each of the reflectivity curves. The thickness profiles derived from $\lambda_{centroid}$ are shown in Fig. 6 (points) together with the desired profile (full curves) and the tolerance range (dashed curves). It is remarkable that the deviation of the data points from smooth curves are less than 0.1% or 0.01 nm in $\lambda_{centroid}$ and that the profiles can be reproduced with this precision from run to run. This capability might make it possible to match coatings with that precision, provided that the deposition system has sufficient stability to also reproduce the absolute values in the thickness. The absolute thickness values or the position of the reflectivity maximum were adjusted by changing the speed of the spinning substrates in their travel over the magnetron sources. Table 1 lists the centroid position of the $R(\lambda)$- curves for the three last depositions. The rotation speed was adjusted after each deposition in order to obtain the desired value. However, especially for the small mirror we have deviations of more than 0.05 nm from the goal of $\lambda_{centr} = 13.4$ nm. Further improvements of the deposition system are needed in order to match its stability to the capabilities in metrology and the reproducibility of the profile. The measured centroid wavelengths for the two condensor mirrors were $\lambda_{centroid} = 13.6$ and 13.8 nm. After coating the first condensor mirror (circles in Fig. 6) we made a small correction to the innermost part of the mask to increase the multilayer periods at the inner edge of the condensor; the effect of this correction can be seen in Fig. 6 (difference between circles and squares for $r < 20$ mm).
We obtain a peak reflectivity of 67% in our coating system on superpolished substrates. The reduction of the reflectivity to values around 60% with a 1.2° detector size for our optics is due to the substrate roughness and the missing intensity occurs as a halo of scattered light around the specular beam.

ID	λ_{centr}, big mirror (nm)	λ_{centr}, small. mirror (nm)
M1-970702	GOx 13.477	GOx 13.38
M1-970708	SN 1 13.36	SN 1 13.31
M1-970711	SN 3 13.4	SN 2 13.46

Table 1. Position of the centroid of the reflectivity curve for the big camera mirror at r=35 mm and 4° incidence angle and for the small camera mirror at r=5.5 mm and 10°. The first coating was on mirror surrogates, the others on the actual mirrors.

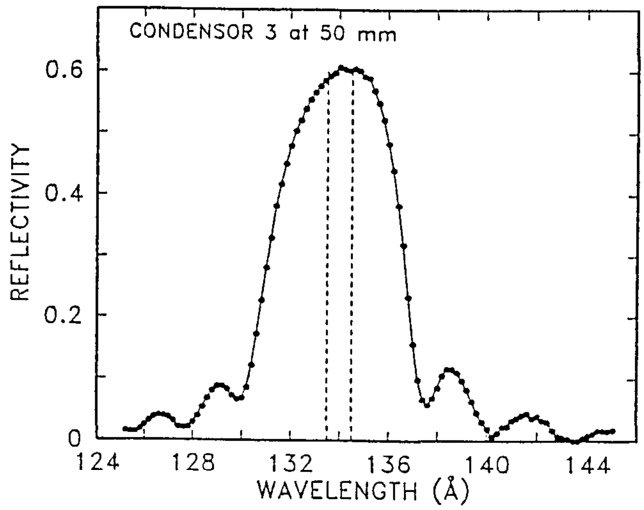

Fig. 5. Example of one measured reflectivity curve for the condensor at 5° angle of incidence. The dashed vertical lines mark our tolerance for the position of the curve.

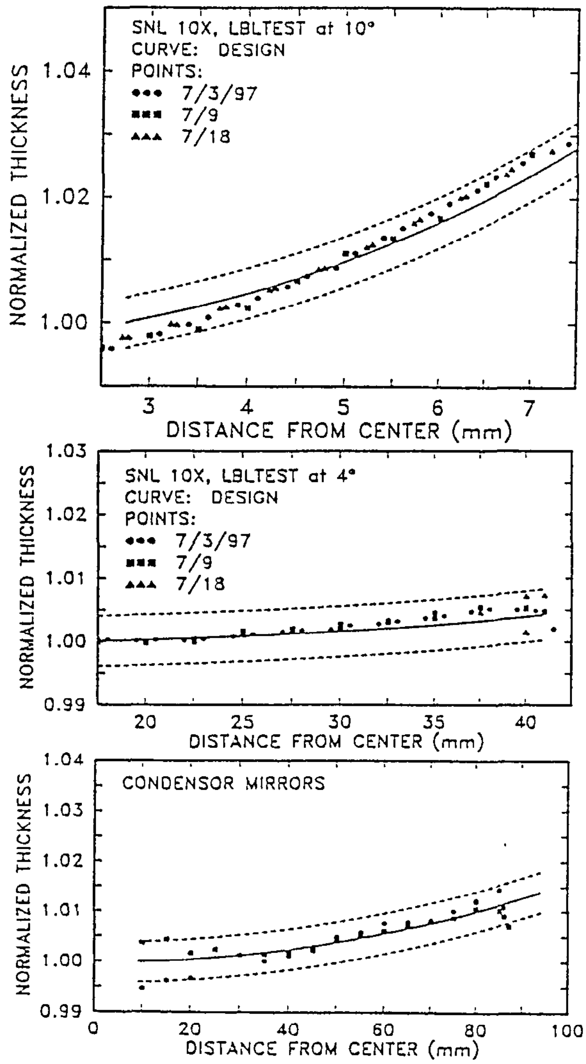

Fig. 6. Normalized measured thickness profiles (points) for the small (top), big (middle) Schwarzschild mirrors, and the condensor mirrors (bottom). The full lines are the design values, the dashed lines give our tolerances.

Scattering

Figure 7 shows how the measured reflectivity decreases when the aperture of the detector is decreased and more of the scattered light is excluded from the detector. The intensity of scattered radiation can be calculated from the power spectral density (PSD) of the surface. With the assumption that the substrate roughness is replicated throughout themultilayer stack and for small scattering angles from normal, we obtain

$$\frac{1}{I_0}\frac{dI}{d\Omega} = 16\frac{\pi^2}{\lambda^4}R\ PSD_2(f), \tag{2}$$

where dI is the intensity scattered into solid angle $d\,\Omega$, f is the spatial frequency that corresponds to each scattering angle and R is the specular reflectivity. The PSD of the small mirror obtained from an optical profilometer and an atomic force microscope is plotted in Fig. 8. For comparison we show also the PSD of the top surface of a coated superpolished optical flat (GO flat). For high spatial frequencies (f>0.03nm) the multilayer growth determines the topography of the boundary and roughness does not depend on the quality of the substrate, while the substrate is replicated for low frequencies. We notice that the PSD of our mirrors is nearly 3 orders of magnitude higher than that of the superpolished flat around f=0.001 nm^{-1}, therefore we can expect that the scattering around scattering angles of 0.1 ° will be increased by factor of 1000. The following paper by Gullikson will give measured scattering intensities and compare the results to our predictions. A summary of all the tests performed on our optics is given in Table 2.We can use the data to predict the imaging performance of the optical system: the mirror substrate roughness reduces the reflectivity of each mirror by about a factor two, but most of the scattering occurs outside the field of the camera and reduces throughput but not image quality. The figure errors of 0.6 nm obtained from the interferometer will affect the image quality. We can use the Strehl factor $\exp(-4\pi\sigma/\lambda)^2 = 0.73$ as a measure for the loss in contrast compared to a camera with perfect mirrors. A more detailed analysis using the interferometric data and comparing the analysis to the actual performance of the system will be given at a later time.

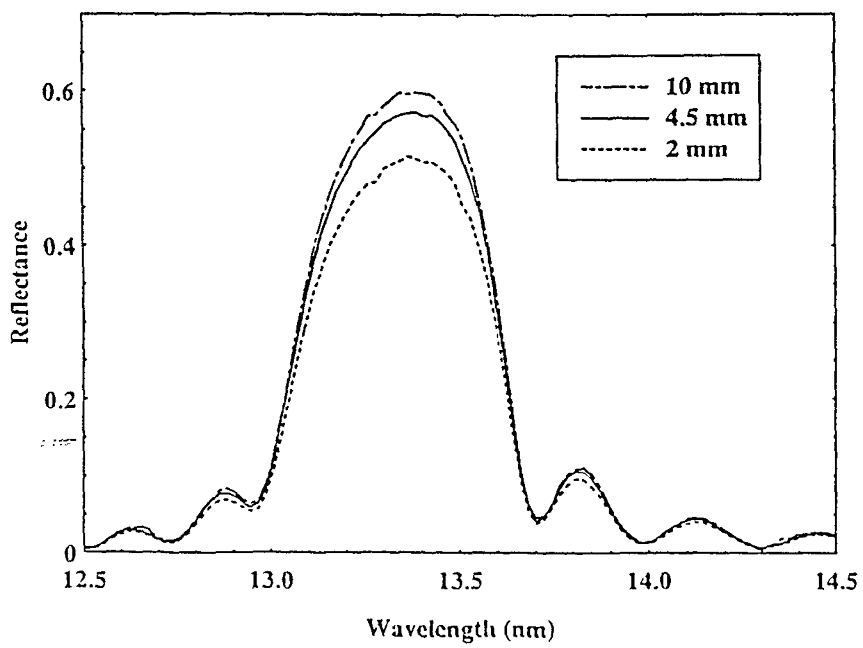

Fig. 7. Reflectivity curves for the big Schwarzschild mirror measured for different detector apertures. Mirror-aperture distance = 225 mm. See the following paper by Gullikson for extens ion to smaller apertures.

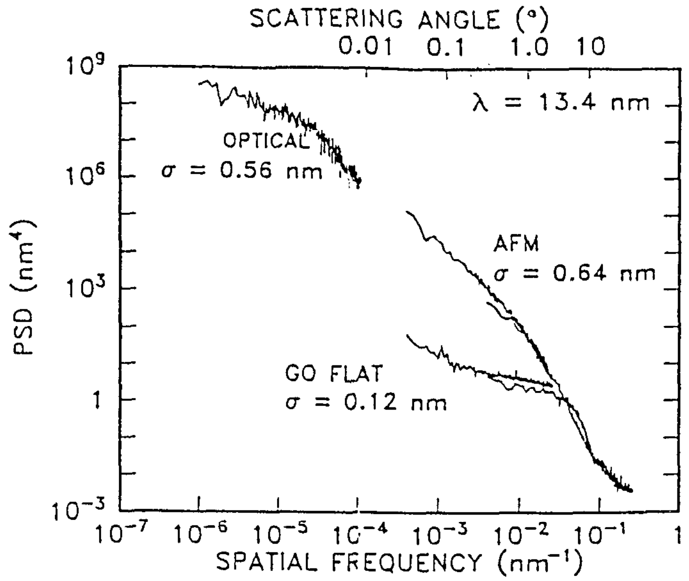

Fig. 8. Power Spectral density of the surface of the large Schwarzschild mirrors obtained by optical profilometry and atomic force microscopy with PSD of a high quality superpolished optical flat. The roughness values given are obtained by integrating over each of the PSD curves.

Spatial Period	**Method**	**Data obtained**
diameter - 1mm	Interferometry (Zernike)	Deterministic map of complete mirrors for both mirrors
1 mm - 1 µm	ZYGO NEW VIEW surface maps of sections	PSD (statistical average), both mirrors
10 µm - 5 nm	AFM surface maps of sections	PSD small mirror
1 µm - 20 nm	EUV scatter	PSD big mirror

Table 2. Methods used to test the Schwarzschild optics

Change of mirror figure by the coatings

The top surface of the coated mirror differs from that of the uncoated mirror due to the grading of the coating thickness. The coating thickness can be obtained from the measured profiles in Fig. 6 and the data in Table 1. Using a polynomial fit to the profiles and the fact that for the small mirror M1-970708 at r =5.5 mm, $\varphi=10°$ we have λ_{centr} =13.31 nm, Λ=6.85 nm, we obtain for the coating thickness

$$t = 268.37 + 0.19193\, r^2,$$

where the thickness is obtained in nanometer when the radius is entered in mm. The coating increases the radius of curvature of the mirror by 0.268 µm and adds a quadratic term with a maximum thickness of 9.4 nm near the edge.

The same arguments for the big mirror with the fact that at r = 35mm, $\varphi = 4°$, λ_{centr} = 13.358 nm, Λ=6.895 nm yields

$$t = 274.2 + 0.0012\ r^2$$

for the thickness of the coating. The dominant effect of the coating is a small change in the radius of curvature. For the coatings M1-970711 the values given above should be multiplied by the ratios of λ_{centr} given in Table 1 (1.003 for the big and 1.011 for the small mirror).

The change in the mirror parameters can easily be compensated for by a slight change in the spacing of the mirrors and does not deteriorate the optical performance of the Schwarzschild system.

5. SUMMARY

We have coated and tested the mirrors for two sets of Schwarzschild projection optics for the Sandia 10X-II microstepper system. The coatings need radially graded thickness to assure maximum reflectivity and equal phase retardation for all rays. Tolerances are about 0.1 nm or 0.75% for λ_{max}. The mirrors were coated by DC magnetron sputtering. Substrates are mounted on spinners and are spun about their optical axis. The spinners are on a platter that rotates them over the sputtering targets. Shadow masks in front of the spinning optics produce the desired thickness profile, while the absolute value of the thickness is adjusted with the rotation speed of the mirror supporting platter. The shape of the shadow mask is obtained in several iterations using data from a previous mask to derive the required change in mask shape. For the first iterations we used flat Si wafers mounted on a mock up of the mirrors and tests at $\lambda = 0.154$ nm and grazing incidence plus EUV wavelengths from a laser plasma source near normal incidence. Actual Schwarzschild mirrors of lower quality and tests with synchrotron radiation at LBL were used for the last iterations. The LBNL reflectometer was also used for the final tests (reflectivity and diffuse scattering) of the optics. Mask making iterations were stopped when the deviations from the desired profile were less than ±0.4% peak. We found that we can reproduce the thickness profile from deposition run to run within 0.1% error, about a factor of eight better than the present specifications. The absolute value of the multilayer thickness showed larger variations from run to run with a standard deviation of 0.08 nm, just within the allowed tolerances. It will be necessary to reduce these variations if we want to make use of the excellent reproducibility of the profile data.

The peak reflectivity of the coatings is above 66% when deposited on the Si substrates and about 58% on the actual optics when measured with a detector that intercepts an angular range of a 1.2° square. The reduction in specular reflectivity is due to the mid-frequency roughness of the mirror substrates, and the missing intensity appears as a diffuse halo of scattered light around the specular beam. The power spectral density (PSD) of the surface roughness obtained by atomic force microscopy and optical profilometry is used to predict the amount of scattering from the optics. The scattered intensity of the mirrors for a scattering angle of around 0.5° is more than a factor of 100 higher than that from a superpolished flat. The total integrated scattered intensity is of the same order as specular beam intensity. Most of the scattered light appears outside the field of the camera and reduces throughput, and has only a small effect on image contrast. We expect that mirrors with reduced mid-frequency roughness will be obtained in the near future.

6. REFERENCES

[1] D. A. Tichenor, G. D. Kubiak, S. J. Haney, R. P. Nissen, K. W. Berger, R. W. Arling, A. K. Ray-Chaudhuri, K. B. Nguyen, R. H. Stulen, J. B. Wronosky, J. D. Jordan, T. G. Smith, J. R. Darnold, P. M. Kahle, A. A. Jojola, S. M. Kohler, R. S. Urenda, D. R. Wheeler, J. E. Bjorkholm, I. O. R. Wood, G. N. Taylor, and R. S. Hutton, "Recent results in the development of an integrated EUV Laboratory tool," *Proc. SPIE*, vol. 2437, pp. 292-307, 1995.

[2] G. E. Sommargren, "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," in *OSA Trends in Optics and Photonics Vol.4, Extreme Ultraviolet Lithography*, vol. 4, G. Kubiak and D. Kania, Eds. Washington, DC: Optical Soc. of America, 1996.

[3] D. Bajuk and R. Kestner, "Fabrication and testing of EUVL optics," presented at Soft x-ray optics: technical challenges, Yamanaka-ko, Japan, 1996.
[4] D. L. Windt and W. K. Waskiewicz, "Multilayer Facilities Required for Extreme-Ultraviolet Lithography," *J Vac Sci Technol B*, vol. 12, pp. 3826-3832, 1994.
[5] J. H. Underwood, E. M. Gullikson, M. Koike, and P. J. Batson, "Beamline for metrology of x-ray/EUV optics at the Advanced Light Source," *Proc. SPIE*, vol. 3113, pp. 214-221, 1997.

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