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Authors

Salmassi, Farhad
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Spin-on-glass coatings for the generation of super-polished substrates for extreme ultraviolet optics

Farhad Salmassi, Patrick P. Naulleau, and Eric M. Gullikson

Center for X-Ray Optics, Lawrence Berkeley National Laboratory
1 Cyclotron Rd., Berkeley, CA 94720

Substrates intended for use as extreme ultraviolet (EUV) optics have extremely stringent requirements in terms of finish. These requirements can dramatically increase the cost and fabrication time, especially when non-conventional shapes, such as toroids, are required. Here we present a spin-on-glass resist process capable of generating super-polished parts from inexpensive substrates. The method has been used to render diamond-turned substrates compatible for use as EUV optics. Toroidal diamond-turned optics with starting rms roughness in the 3.3 to 3.7 nm range have been smoothed to the 0.4 to 0.6 nm range. EUV reflectometry characterization of these optics has demonstrated reflectivities of approximately 63%.

OCIS codes: *220.5450**,** 220.1920**,** 230.4040**,** 230.4170**,** 310.1620, 340.7470, 260.7200*

Introduction

As extreme ultraviolet (EUV) lithography **[1-3]** approaches commercialization the need for development and metrology systems grows. The extremely tight finish requirements of EUV optics (typically less than 0.5-nm rms), renders optics with even loose figure specs, extremely expensive. Examples of such components are illuminator optics. High optic costs can often lead

to prohibitive system costs or undesired design trade offs, especially when dealing with research and development tools.

To address the issue of substrate cost, Soufli et al. **[4]** have developed a resist-based planarization process capable of rendering moderately priced optics with relatively poor finish specifications compatible for use as EUV substrates. The method relies on spinning a layer of polyimide with an approximate thickness of 3 μm directly onto the substrate and then depositing the EUV reflective multilayer over the coating. Using this method, an EUV reflectivity of approximately 64% was demonstrated with an added slope error of only 100 μrad in the 1 to 10 mm period range.

Here we present a similar process but based on hydrogen silsesquioxane (HSQ) **[5]**, a spin-on-glass resist made by Dow Corning. This material has been successfully used for the fabrication of relief substrates for EUV blazed gratings **[6,7]**. The benefits of this material over the previously used material [4] is that the finished coating is even more stable and robust and tests have shown that thinner layers can be used. After cross-linking and developing, the HSQ material becomes a layer of SiO_2. The coating is stable under vacuum, extremely high temperatures, and radiation. Annealing tests have demonstrated that this material can handle temperatures approaching 900° C [6], much higher than the temperature capabilities of an EUV multilayer. Moreover, the SiO_2 coating is free of outgassing problems.

While the polyimed approach requires a coating thickness on the order of 3 μm, similar levels of smoothing with HSQ can typically be achieved with layers as thin as 500 nm. Moreover, significant smoothing is observed with coatings as thin as 100-nm. The process is also amenable to repetitive spin steps allowing individual thin layers to be deposited, enabling the smoothing procedure to be stopped as soon as the target has been met. This in turn facilitates

minimization of the coating thickness. In practice, coating thickness minimization is important since maximum potential added figure error is proportional to the thickness of the added layer.

Panarization of diamond-turned toroidal optics

The HSQ smoothing process has been applied to diamond-turned toroidal optics used in a synchrotron illuminator **[8]** for a high (0.3) numerical aperture EUV microlithography test station implemented at Lawrence Berkeley National Laboratory. The toroid is a concave optic with *x* and *y* radii of curvature of 174 mm and 220 mm, respectively. The part is rectangular with x and y dimensions of 20 mm and 13.5 mm, respectively. Two different substrates were procured from two different vendors, one copper [9] and one aluminum [10]. Atomic force microscope (AFM) characterization results of the as-delivered aluminum and copper parts are shown in Figs. 1(a) and (b), respectively. Note that the scan dimensions are different for the copper and aluminum parts. Considering periods up to 10 μm, the aluminum and copper optics had rms roughnesses of 3.7 nm and 3.3 nm, respectively.

The planarization process involves spinning on and curing 100-nm layers of HSQ. A total of five layers were used in this application. The spin step is performed using a conventional resist spinner using a custom-fabricated chuck to hold the optic. The spin was done at **XXX** RPM and an HSQ concentration of **XXX** was used. The curing step is performed using a UV-ozone cleaner chamber. The optic was exposed to UV ozone for **XXX** to cure each individual layer.

Figures 1(c) and (d) show AFM scans of the smoothed aluminum and copper optics, respectively. Figure 1(e) is the same AFM image as Fig. 1(c), but rescaled to accentuate the surface features. The surface roughness has been reduced to 0.39 nm and 0.62 nm (periods up to 10 μm) for the aluminum and copper optics, respectively. It is also instructive to consider the

power spectral density of the roughness before and after smoothing (Fig. 2). Figure 3 shows the achieved frequency-dependent smoothing factor (or transfer function) for the two cases. In both cases, we see the smoothing efficiency start to role off at approximately 25-μm period, however the smoothing is observed to be more effective on the aluminum in the period range of 25 to 1 μm. The reason for this is not known, investigation of the process stability is underway.

Finally, the optics were coated with molybdenum/silicon multilayers designed to reflect at 13.5-nm wavelength and an angle of incidence of 28 degrees. The coated optics were characterized at the calibration and standards bend-magnet beamline 6.3.2 at the Advanced Light Source located at Lawrence Berkeley National Laboratory [11] and found to have reflectivities on the order of 63%. Noting that on super-polished substrates, multilayers can be expected to support reflectivies on the order of 65 to 70%, these results demonstrate the high efficiency and utility of the presented smoothing process.

Characterization of added figure error

Another important metric for the process is added figure error. When dealing with illuminator optics, figure-quality specifications are typically rather loose; nonetheless it is important to quantify the effect of the coating in terms of figure error. For the toroid of concern here, the figure error specification is less than 1 mrad slope error. It is instructive to consider the worst possible figure error from the process presented here. Assuming figure error to encompass periods down to 1 mm and taking the worst-case scenario of full 500-nm thickness variation over this period, we find the maximum slope error to be 0.5 mrad, still a factor of two better than our specification. This is the benefit of using such a thin smoothing layer. In practice, of course, we would expect significantly better performance from the coating.

Direct characterization of the figure on the toroidal part can be quite difficult. To facilitate the characterization process, a separate added-figure-error test was performed on a conventionally super-polished 50-mm diameter sphere with a radius of curvature of 230±1 mm. The surface was intentionally roughened through a chrome deposition process such that the spin step would be interacting with a surface of roughness comparable to the roughness of the diamond-turned optics.

The sphere was coated as described above again using a 500-nm thick layer of HSQ applied in five steps. A Zygo [12] interferometer was used to characterize the optic before and after smoothing. The optic was marked with fiducials for alignment purposes. Figures 4(a) and (b) show the optic before and after smoothing, respectively. The alignment fiducials are clearly visible. In addition, the smoothed optic shows a series of imperfections arising from large particulate contamination of the part during the five-step coating and curing process. This is not of fundamental concern and could readily be addressed by improving the environment of the spin and UV ozone facilities. Figure 4(c) shows the direct point-by-point difference between Figs. 4(a) and (b) and Fig. 4(d) shows a lowpass filtered version of the difference, thereby eliminating the effect of the contamination while preserving up to approximately 6 cycles across the optic, well representative of the figure-error regime. The added figure error is found to be 2.7 nm and the maximum slope error is only 4.3 μrad. Note that the above measurements are with the base sphere removed. Comparing the radius of curvature numbers reported by the interferometer, we find values of -229.34 ± 0.01 mm and -229.33 ± 0.01 mm for the part before and after smoothing, respectively. The radius of curvature is unchanged to within the error bars of the measurement.

Summary

The use of spin-on-glass coatings for the smoothing of EUV substrates has been demonstrated. The method has been applied to diamond turned toroidal optics used in a synchrotron-based EUV lithography system. Using a total layer thickness of only 500-nm, the method has demonstrated roughness reduction from 3.7-nm rms to 0.39-nm rms on an aluminum diamond turned optic yielding an EUV reflectivity of 63% after multilayer coating. Figure-control studies have further demonstrated the process to support added slope errors of less than 5 μrad.

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12. Zygo Corporation, 21 Laurel Brook Road, Middlefield, CT 06455.

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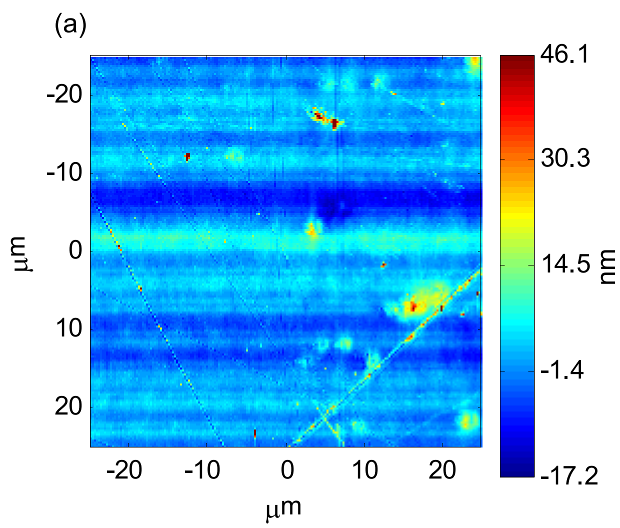
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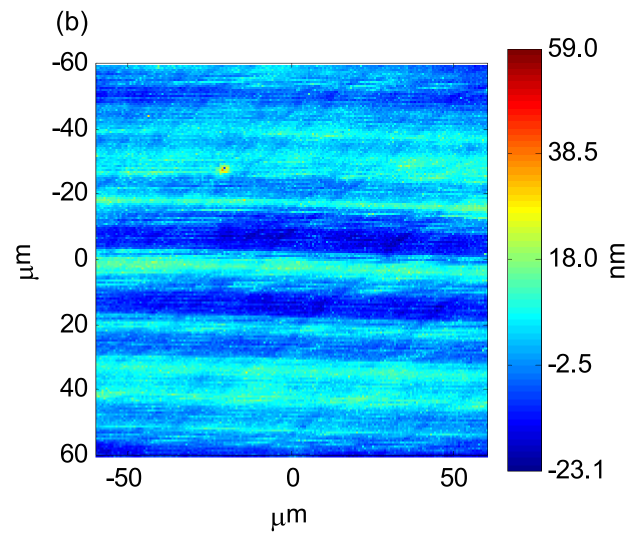
nm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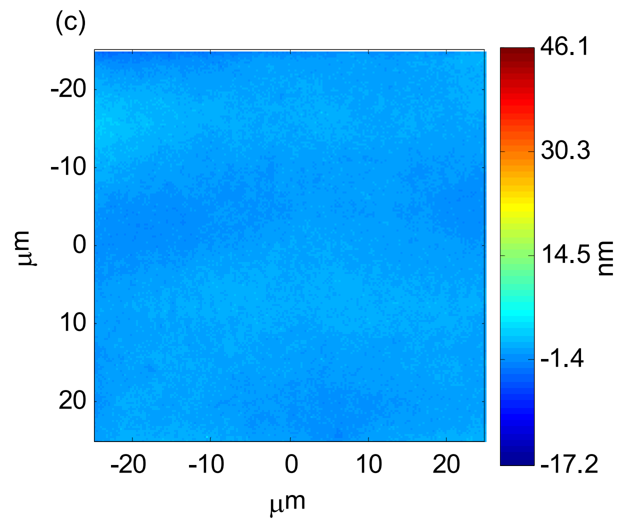
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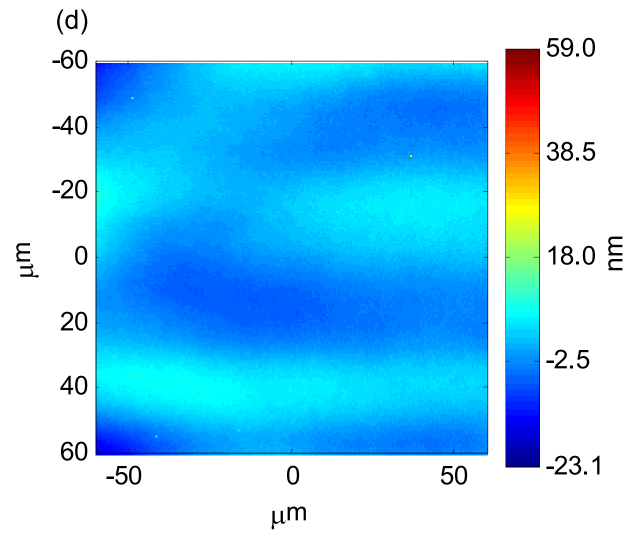
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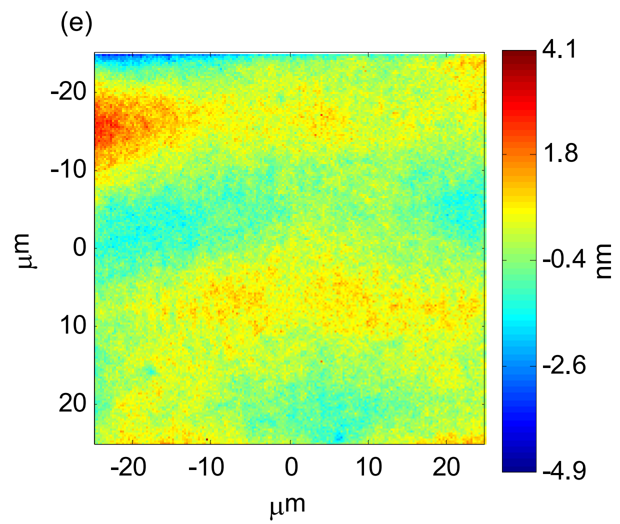
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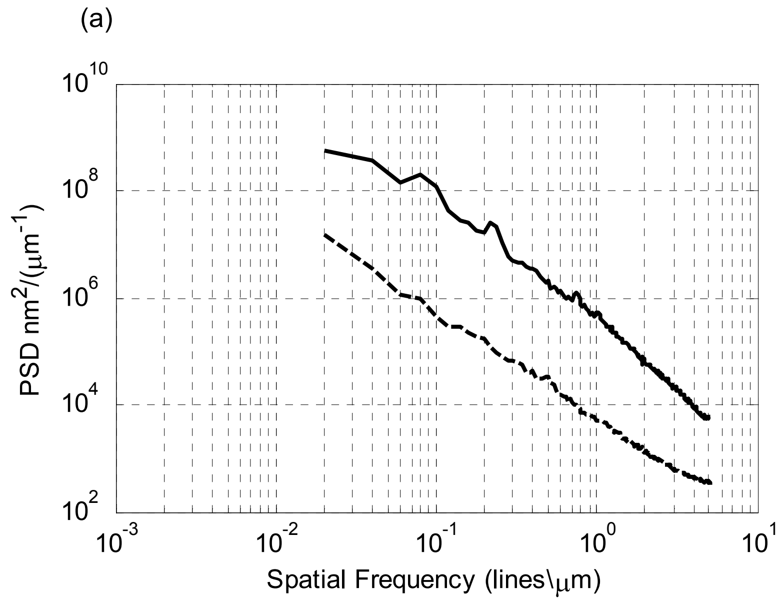
nm

(a)



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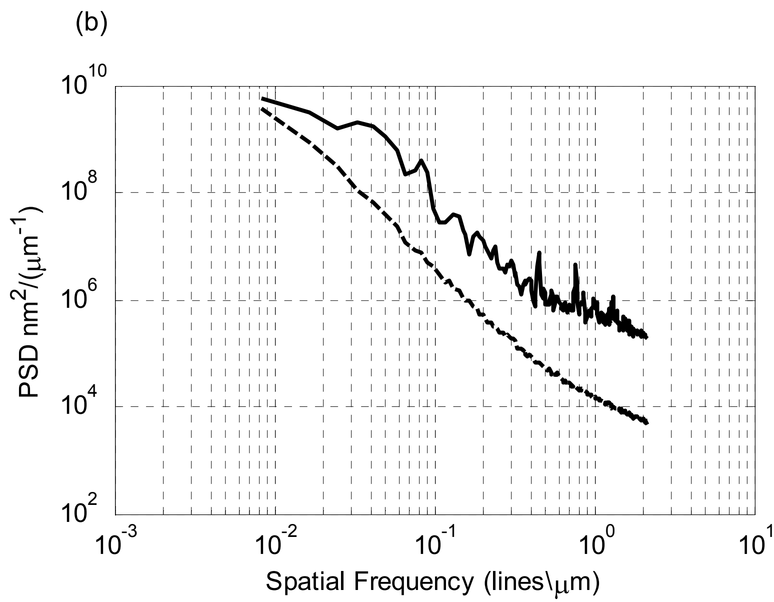

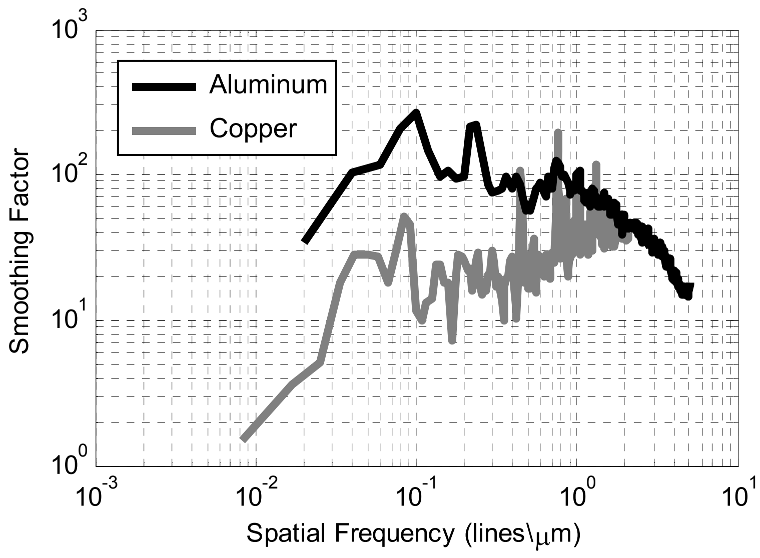

Aluminum
Copper
Smoothing Factor
Spatial Frequency (lines\μm)
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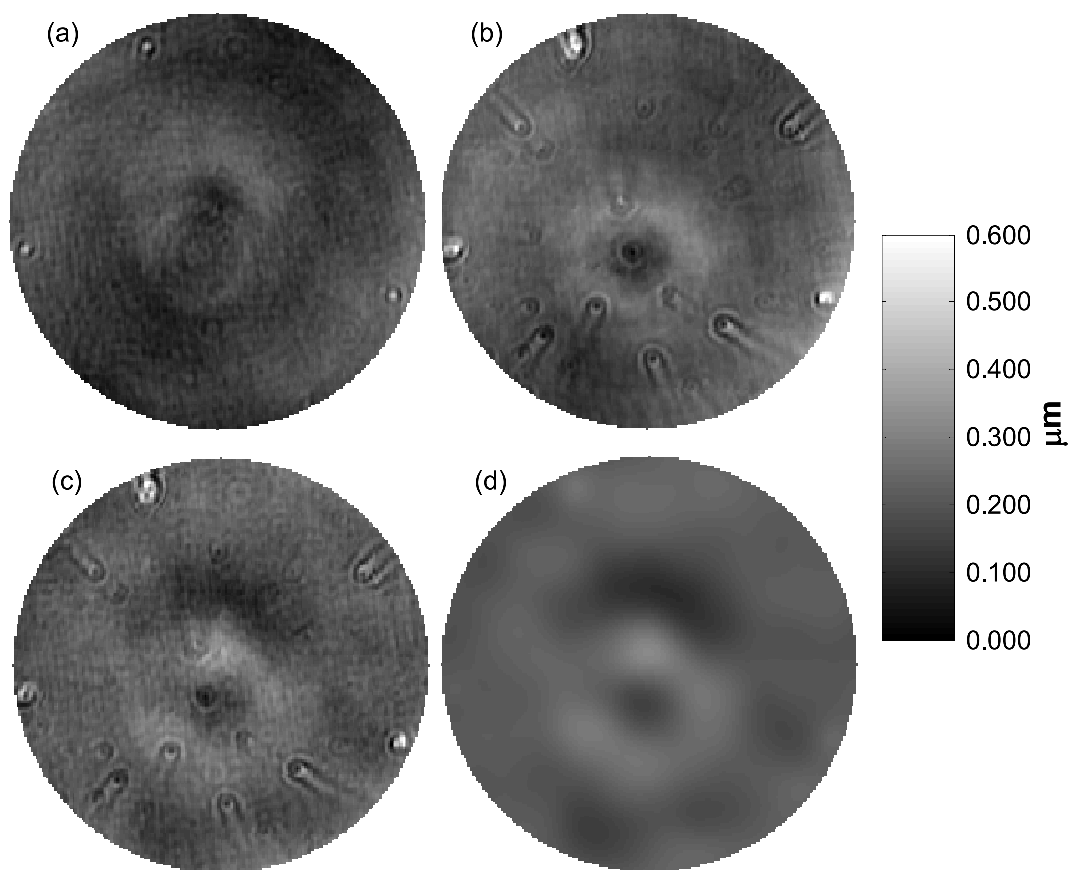
10^1
10^2
10^3
10^{-3}
10^{-2}
10^{-1}
10^0
10^1


(a)
(b)
(c)
(d)
0.600
0.500
0.400
0.300
0.200
0.100
0.000
μm