Substrate and coating defect planarization strategies for high-laser-fluence multilayer mirrors

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ABSTRACT

Planarizing or smoothing over nodular defects in multilayer mirrors can be accomplished by a discrete deposit-and-etch process that exploits the angle-dependent etching rate of optical materials. Typically, nodular defects limit the fluence on mirrors irradiated at 1064 nm with 10 ns pulse lengths due to geometrically- and interference-induced light intensification. Planarized hafnia/silica multilayer mirrors have demonstrated $>125 \text{ J/cm}^2$ laser resistance for single-shot testing and 50 J/cm^2 for multi-shot testing for nodular defects originating on the substrate surface. Two planarization methods were explored: thick planarization layers on the substrate surface and

planarized silica layers throughout the multilayer in which only the silica layers that are below one half of the incoming electric field value are etched. This paper also describes the impact of planarized defects that are buried within the multilayer structure compared to planarized substrate particulate defects.

Keywords: nodular defect, laser damage testing, 1064-nm laser, nanosecond pulse length, thin film, multilayer mirror, ion beam sputtering, planarization.

1. INTRODUCTION

High-quality multilayer laser mirrors for 1064 nm wavelength laser systems operated in the nanosecond pulse length regime tend to be fluence-limited by micron-scale nodular defects [1-6]. These defects originate as inclusions that are then over coated with multilayer thin films. Electric-field modeling has clearly shown light intensification due to the geometric and interference nature of these defects [7-16]. The inclusions are caused by contaminants on the surface or from particulates generated during the coating process that become imbedded inclusions within the multilayer stack. Previous work has explored planarization of substrate surface inclusions and an associated improvement in laser resistance [17-18]. Planarization technologies were originally developed for extreme ultraviolet lithography mirrors [19-20] and then extended to optical materials and scaled from nanometer to micron-size defects.

Nodular defects can occur throughout the multilayer structure and not just on the substrate surface as shown in Fig. 1. Previous attempts to planarize silica layers throughout the multilayer structure resulted in flat-bottom-pit laser damage at the interfaces with the highest electric-field peaks [17]. A proposed solution has been to not planarize the outer silica layers, in order to reduce the electric-field value within the etched layers to one half of the electric-field value of the incoming laser beam [18]. Specifically, the multilayer mirrors were manufactured with no etching of the half-wave overcoat and the outer three quarter-wave silica layers. Figure 2 shows the effectiveness of both types of planarization methods on 1 μm tall cylindrical pillar defects. This work describes a study of planarization in multilayers of hafnia and silica in which micron-size defects are simulated to occur within a depth where the electric field value of the incoming beam is reduced to one half. Different designs and planarization protocols were considered. Planarization was found to be particularly effective in doubling the laser resistance of typical non-engineered coating defects.

2. EXPERIMENTS AND RESULTS

The planarization process is described in detail elsewhere [17-18]. The coating design used in this study was Air: L(LH)¹⁵: Substrate where L = silica and H = hafnia, the same coating design used in previous studies. The layers are quarter-wave optical thicknesses that are angle-matched at 45 degrees incidence angle for a high reflector centered at 1064 nm. The physical thicknesses are approximately 210 nm for silica and 152 nm for hafnia and there are a total of 30 layers with the final layer being a half-wave silica overcoat.

The deposition process used for planarization is dual ion beam sputtering (IBS) [21]. The secondary ion source is pointed normal to the substrate and used for etching the deposited silica layers. The etch rate increases with increased incidence angle to a maximum near 50 degrees. Nodular defects have a range of incident angles that increase radially due to their domed geometry. Normally nodular defects tend to increase in diameter as the multilayer structure is deposited over the defect [3]. The etching process, however, is most efficient at the nodule edges resulting in shrinking (or smoothing) of the nodule diameter as more material is added.

Substrate defects were manufactured via contact lithography and dry etching of the substrate. 1 μm tall cylindrical pillars were fabricated with diameters of 1, 2, and 5 μm . Additionally, 1 μm deep pits with a diameter of 5 μm were also etched into the substrate. The spacing between defects was ten times the defect diameter. A 1 mm diameter laser beam was used for laser damage testing allowing sampling of a significant number of defects at each testing site.

2.1 THICK PLANARIZATION LAYER ON THE SUBSTRATE VS. PLANARIZATION THROUGHOUT THE MULTILAYER – ENGINEERED SUBSTRATE DEFECTS

To validate the effectiveness of planarization via either a thick planarization layer on the substrate or planarization of silica layers throughout the multilayer, four sets of samples were created and then laser damage tested.

- Sample 1: No planarization
- Sample 2: 3 μm thick silica planarization layer deposited on the substrate
- Sample 3: 2.29 μm thick silica planarization throughout the multilayer (etching first 11 silica layers)
- Sample 4: A combination of both the thick silica planarization layer deposited on the substrate and planarization of the silica layers throughout the multilayer structure

The samples were created in a combination of three coating runs, with sample 4 coated in two coating runs, one with sample 2 and the other with sample 3. Before coating, the substrates were cleaned with lens tissue and a solvent wipe. The laser resistances of the four coating types are shown in Fig. 3. Previous single-shot damage testing of coatings with thick planarization layers on the substrate demonstrated a laser resistance exceeding 100 J/cm^2 [17-18]. The results from this study, with a single shot laser resistance exceeding 125 J/cm^2 , confirm these previous results. The single-shot laser resistance of multilayer planarization was not as high as the thick planarization layer for the largest size defect. Sample 3, with both planarization technologies, has comparable single-shot laser resistance of Sample 1. Finally the control sample without planarization also had similar laser resistance to previously published results. Both planarization processes lead to a significant (about 20-fold) improvement in laser resistance over the standard deposition process.

Multi-shot damage testing was also performed on the samples to gain an understanding of how relevant these planarization technologies are to real-world laser applications. The damage testing proceeded using 10 J/cm^2 incremental steps in laser fluence, however, each site was exposed to 600 shots instead of single shot testing. If laser damage was observed at 10 J/cm^2 , then the sample was

irradiated at 5 J/cm^2 . The laser resistance over multiple shots was reduced in half compared to the single-shot laser resistance for the planarized defects. It is not uncommon for the laser resistance of multi-shots to be reduced compared to single shots, particularly for such high laser resistance mirrors [22]. Interestingly, the single- and multiple-shot laser resistance of the non-planarized defects were fairly similar. One possible explanation is the lower fluence decreases the probability of accumulation effects. Both planarization strategies worked effectively at increasing the laser resistance compared to non-planarized defects. Unexpectedly, sample 4 with a combination of a thick planarization layer on the substrate and planarization throughout the multilayer did not perform as well as the other planarized samples for the multi-shot damage testing. It is unknown if the interruption of vacuum (venting process) between coating runs had any detrimental impact on the laser resistance of sample 4. This issue is also further discussed in the next Section.

2.2 MULTILAYER PLANARIZATION – ENGINEERED DEFECTS WITHIN THE MULTILAYER STRUCTURE

Nodular defects can occur within the multilayer structure and not just at the substrate surface. To test the effectiveness of planarizing defects within the multilayer structure, platinum defects were deposited in an array between layers fourteen and fifteen of a thirty-layer mirror coating as illustrated in Figs. 4 and 5. The platinum defects were locally deposited with a FIB instrument at Lawrence Livermore National Laboratory (LLNL). Platinum defect dimensions of $1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$, $2 \text{ } \mu\text{m} \times 2 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$, and $2 \text{ } \mu\text{m} \times 2 \text{ } \mu\text{m} \times 2 \text{ } \mu\text{m}$ (length $\times$ width $\times$ height) were designed. Sample charging during the FIB process made it difficult to achieve the aforementioned desired

defect dimensions. The final defect dimensions were to within less than 40% of the as-designed ones. Although highly absorbing inclusions in nodular defects generally have very low laser resistance [16,23], the desire for a well-defined defect shape and location to facilitate cross sectioning necessitated selection of a metal such as platinum.

The first fourteen layers of the multilayer mirror were deposited at Colorado State University (CSU). The coating chamber was then vented to ambient pressure so the samples could be sent to LLNL for deposition of the platinum defects. The samples were then returned to CSU to complete the deposition of layers fifteen through thirty. No etching was done in the final four silica layers, identical to sample 3 described above.

Laser damage testing was performed on the samples. Because of the highly-absorbing nature of the platinum defects, extremely low laser resistances were measured as illustrated in Fig. 5. Because laser damage occurred at low fluence, nodule ejection could occur without collateral damage of the surrounding pit, making it difficult to tell with optical microscopy at what fluence the nodule ejection occurred. Imaging with an Atomic Force Microscope between fluence steps would have significantly improved the detection of the nodule ejection fluence. Because of this uncertainty, an upper limit of 3 J/cm^2 was determined for the non-planarized defects. Laser damage detection was a bit easier to determine on the planarized samples due to a greater amount of collateral damage due to higher fluence ejection. However, only a very slight improvement in the laser resistance was observed for the planarized platinum defects.

To understand the impact of planarization on real-world coating defects that are likely not nearly as absorbing as platinum, witness coating samples were placed in these same coating runs. These witness samples obviously also went through the same chamber vent process although no platinum defects were deposited on them. To facilitate an understanding of the potential detrimental impact of the venting cycle, a second set of coating witnesses were manufactured with a multilayer mirror coating with no vent during the middle of the coating deposition. Both a planarized and non-planarized witness sample were coated.

The samples were damage tested at Spica Technologies, Inc. (New Hampshire) over a 1 cm² area using the raster scanning technique described by Borden [24]. The advantage of this technique is that it samples a large area, improving the probability of irradiating a large range of defect types. Damage testing was performed with a 1064 nm laser at a 3 ns pulse length. The results are listed in Table 1. A very significant (10×) improvement was observed in the laser resistance of the samples that were manufactured without venting the coating chamber halfway through the coating run. A detailed study of the physics and effects of the venting process on the laser resistance was not performed as part of this work. It is possible that the venting process and exposure of the samples to ambient environment introduce particulates and other contaminants that dramatically reduce the laser resistance of multilayer samples. Planarization also appears to have a positive (2×) impact on the laser resistance of multilayer mirror coatings.

Table 1 Laser damage threshold comparison over 1 cm² of multilayer mirror coatings to determine the impact of planarization and chamber venting in the middle of the coating run.

Sample type	Deposition type	Laser damage threshold (J/cm ²)
No etching	With vent	1
Planarization etching	With vent	1
No etching	No vent	10
Planarization etching	No vent	22

3. CONCLUSIONS

Planarization of IBS coatings through discrete deposition and etching of silica can increase the laser resistance of hafnia/silica multilayer mirrors by a 20-fold factor, above 125 J/cm² and 50 J/cm² for single- and multi-shot damage testing respectively, for a wavelength of 1064 nm and pulse length of 10 ns. Equally good laser resistance was observed for both a thick planarization layer deposited on the substrate and for planarization of the silica layers throughout the multilayer as long as the outer silica layers remained unetched. Planarization of the silica layers throughout the multilayer has the added benefit of being able to planarize coating defects generated during the coating process. Coatings that were manufactured with this technique had a laser resistance that was twice that of coatings deposited without any planarization. Venting and prolonged exposure to ambient environment halfway during the multilayer coating deposition and planarization processes was

shown to dramatically lower the laser damage threshold of multilayer mirrors, however, only a single set of samples were evaluated so this is by no means an exhaustive study of this phenomenon

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Fig. 1 SEM image of a Focused Ion Beam (FIB) cross section of nodular defects imbedded within an e-beam deposited hafnia/silica multilayer interference coating for laser mirrors. Hafnia layers are shown as bright while silica layers are dark.

Fig. 2 Visual comparison (SEM imaging) of no planarization (left images), thick planarization layer on substrate only (central images), and planarization throughout the hafnia/silica multilayer coating (right images) for a range of different cylindrical pillar widths. Hafnia layers are shown as bright while silica layers are shown as dark in these images.

Fig. 3 Single shot (left) and 600 shot (right) laser damage thresholds of multilayer mirror coatings as a function of planarization process.

Fig. 4 Theoretical electric field profile of the deposited coating with an indication of the location of the buried defect and the planarization layers (left). FIB images of engineered platinum defects that were written by FIB (top right image are 1 μm cubes and bottom right image are 2 μm cubes).

Fig. 5 FIB cross sections of platinum defects buried within a multilayer mirror structure and the associated laser damage thresholds for a low number of shots (top images are not planarized, and the bottom images are a coating with planarization of the silica layers throughout most of the multilayer structure).

Figures (if any)
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