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Influence of defect shape on laser-induced damage in multilayer coatings

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ABSTRACT

Atomic force microscopy (AFM) was used as a diagnostic for laser damage testing of μm -scale nodule defects in e-beam deposited $\text{HfO}_2/\text{SiO}_2$ multilayer mirror coatings. Earlier experiments in our laboratory showed that there was a significant increase in damage susceptibility for defects with heights greater than $0.6 \mu\text{m}$.

In the present study, e-beam $\text{HfO}_2/\text{SiO}_2$ HR coatings from two additional vendors were also studied. Atomic force microscopy characterization of the defects showed that the defect shape became less "classic" as the defect dimensions, especially height, increased. The characteristic shapes (spatter, multi-lobe, etc.) of the larger defects also varied between vendors. Using the AFM and optical microscopy, laser damage experiments (1064-nm, 3-ns pulses) were performed on various defects found in the coatings of the two new vendors. The data showed once again that the damage susceptibility increased as the height of the defect increased. There was also some difference between vendors in the damage susceptibility of the defects of a given size. Spatter defects, found predominantly in the coatings of one vendor showed the highest susceptibility to damage.

1. INTRODUCTION

It has been known for many years that damage in optical coatings is often initiated at defects in the material.¹ These defects are typically in the form of μm -scale nodules. These nodules grow as a result of self-shadowing effects initiated at seed particles either present on the substrate or deposited on the coating during multilayer deposition. The defect height and width, and their relationship to seed location and size are defined schematically in Fig. 1 for classic nodules assuming omnidirectional deposition.² Recently, focused ion-beam cross-sectioning techniques have been used to better characterize the defect geometries and the seed particles.^{3,4} The cross-sections show that for high damage threshold e-beam deposited $\text{HfO}_2/\text{SiO}_2$ coatings, the seeds are typically particles of HfO_2 ejected from the source during the deposition process. Also, for real defects the constant in the term defining the defect diameter, $D = \sqrt{\text{constant} \cdot h \cdot T}$ is typically found to be in the range

from 3 to 5, rather than 8 as predicted by the simple model.⁴ This suggests that there is a unidirectional component to the deposition flux.

It is generally observed that all defects observed in a coating do not damage at the same laser fluence. In order to identify any correlations between damage susceptibility and defect geometry, the Atomic force microscopy (AFM) has been used to characterize and laser damage test individual defects on coatings. Earlier results for coatings from Vendor A showed that the damage susceptibility of the defects increased with the height of the defect, with a significant increase in susceptibility for defects with heights greater than 0.6 μm .⁵ The correlation of damage threshold to defect diameter was less clear and was attributed to the dependence of defect diameter on defect height predicted by simple models for nodule shape.

The purpose of the present paper is to determine the universality of these observations, at least for other e-beam $\text{HfO}_2/\text{SiO}_2$ coatings. Reported here are the results of characterization and laser damage studies of defects on coatings supplied by two additional vendors.

2. EXPERIMENTAL PROCEDURE

Laser illumination was performed using standard laser-damage testing techniques using a 1064-nm Nd:YAG laser with a 10-ns pulselength. At the damage test plane a $1/e^2$ beam diameter of 1.6 mm was obtained by focusing the beam with a 3-m lens. Laser fluences were determined through beam profiling and total energy measurements.

Defect characterization and damage detection were done using a Large Area AFM (Digital Instruments, Inc.) including a computer controlled sample positioning stage. The system allowed rapid and accurate movement of the sample between a high resolution ($\sim 850\times$) optical microscope, the AFM head, and the laser illumination area. Defects found using the optical microscope were repositioned under the AFM for characterization, moved under the laser for illumination, and then moved back to the AFM to determine if damage had occurred.

The coatings studied were deposited on 2" diameter BK7 substrates. The coatings were high reflectors of quarter-wave stacks designed for use at normal incidence. The top layer of the coatings were half-wave SiO_2 overlayers. The surfaces were cleaned by drag wiping with alcohol prior to testing.

3. RESULTS

3.1 Defect characterization results

The coatings studied, including those in Ref. 4, were deposited by three vendors with extensive experience in high-damage-threshold coating deposition. Some characteristics of the deposition chambers and the coatings are given in Table 1. In general, the deposition tank sizes, deposition angles, e-guns, and source material preparation were different for each vendor. For example, coatings from vendors A⁴ and B were deposited in deposition tanks capable of coating large substrates (1-m diam.) whereas vendor C used a standard size (2' x 2' x 3') box coater. Standard damage tests on the coatings showed that they all displayed laser conditioning effects and had similar damage thresholds.

Defect height vs. diameter plots for vendors B and C are shown in Fig. 2 (See refs. [3] and [5] for vendor A). Over half the defects seen in each sample had heights $<0.5\text{ }\mu\text{m}$, corresponding to seeds of the same diameter. If all seeds were found on the substrate or were deposited at the same time, the height-width data would fall on a single curve. The spread in the data in Figs. 2a and 2b, however, indicates that the seeds were deposited over a range of depths.

Table 1: Some characteristics of the deposition chamber and respective coatings

Vendor	Source-to-substrate	Damage threshold, J/cm ² (3ns, 1064 nm)		Predominant defect types
	distance, cm	S:1	R:1	
A *	>48"	15	20	classic, semi-classic
B	>48"	8	27	classic, multi-lobe
C	~18"	13	26	classic, spatter, pits

* Data reported in refs. [3] and [5]

For both vendors B and C the small defects, heights $<0.4\text{ }\mu\text{m}$, showed classic dome-like structures such as those shown in Figs. 3a and 3c. For larger defects the more complicated multi-lobe or "spatter"⁶ defects shown in Figs. 3b and 3d, respectively, were often observed. These larger defects are generally associated with complex seed shapes.

Vendor C appears to have fewer large defects. We found, however, many defect craters on this sample. In general the craters are due to the natural ejection of large, mechanically unstable nodules. More work needs to be done to characterize these crater defects.

3.2 Laser damage results

Each defect characterized was also illuminated with a single laser pulse of a predetermined fluence. Figure 4 plots the height of each defect vs. the fluences with which it was illuminated. The darkened squares show cases when damage occurred. The lines indicate apparent transitions between regions of no damage, occasional damage, and consistent damage. For both samples the damage probability increased with defect height. While the exact nature of the transition zone between low and high damage probability is different for samples B and C, as well as sample A, the general increase in damage susceptibility seems to consistently occur over a defect height range near 0.5 μm . The transition to high damage probability at relatively low defect heights for sample C might be attributed to the easily ejected spatter defects found on this sample.

Figure 5 plots illumination fluence vs. defect width for the same set of defects shown in Fig. 4. As with defect height, there seems to be a general increase in damage probability as the defect width increases. The correlation is not as clear as for defect height, and, based on the results for studies on sample A, the dependence is believed to be associated with the dependence of the defect width on the seed diameter (i.e., defect height).

For each sample a few crater defects, formed by the intrinsic ejection of nodules from the coating (due to stress or other mechanical instabilities), were illuminated. As in the case for sample A, these crater defects did not appear to show an increased damage susceptibility over the surrounding film.

4. DISCUSSION AND CONCLUSIONS

The results of local damage experiments on defect in $\text{HfO}_2/\text{SiO}_2$ coatings have consistently shown that laser damage susceptibility can be correlated with defect geometry. While the exact nature of the increase in damage susceptibility with defect height varies between vendors, there is typically a strong increase in susceptibility as the defect height increases past 0.5 μm . The defects with these large heights are initiated by large and often complex seeds. The resulting defects often have complex boundaries resulting in poor mechanical stability. It has also been shown that large seeds, particularly those near the coating surface, result in the largest E-field enhancements in the coatings.⁷ It is therefore not surprising that these defects often damage first.

We must also consider, however, that the laser-induced ejection of these weakly held large defects may not be detrimental to the coating. Since the resulting craters are the same size as the original nodule this process may not be easily detected by optical microscopy. The laser-induced ejection of the

more strongly held, typically, more classic defects is more likely to cause damage to the surrounding coating. This collateral damage may then propagate upon further illumination. Therefore, while the larger defects may show the highest damage susceptibility, we should not assume that the smaller defects are acceptable for high fluence applications.

Laser conditioning is often believed to be related to the mechanical stabilization of defects. The low fluence illumination may mechanically alter or stabilize the defects so that subsequent high fluence illumination will not cause catastrophic damage. Some of the more mechanically unstable defects may even be ejected from the coating during conditioning.

5. AUSPICES

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Figure 1: Schematic of an ideal nodule defect showing the dependence of defect height and width on the seed depth and diameter.

Figure 2: Plots of heights and widths of defects measured on samples from (a) vendors B and (b) vendor C.

Figure 3: AFM images of characteristic defects from samples B and C for defect heights (a, c) $< 0.4 \mu\text{m}$ and (b, d) $> 0.8 \mu\text{m}$.

Figure 4: Plots of illumination fluence vs. defect height for defects illuminated on (a) sample B and (b) sample C. The lines indicate the transitions between regions of no damage, occasional damage, and consistent damage.

Figure 5: Plots of illumination fluence vs. defect width for defects illuminated on (a) sample B and (b) sample C. The dashed lines indicate the transitions between regions of no damage, occasional damage, and consistent damage.

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