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TITLE: *ANGULAR DEPENDENCE OF THIN-FILM DIELECTRIC COATING DAMAGE THRESHOLDS*

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Angular Dependence of Thin-Film Dielectric Coating Damage Thresholds Revisited

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Newnam et al. [1] reported experiments showing that the angular dependence of 351-nm laser damage thresholds in HfO_2/SiO_2 multilayer dielectric reflectors was much weaker than even the $1/\cos\theta$ expected from simple geometric fluence dilution. Several plausible explanations were suggested, but none were convincing. We propose a simple geometric model based on a cylindrical form for the coating defect responsible for damage initiation. We have measured 248-nm damage thresholds for bare fused silica, evaporated aluminium films, and HfO_2/SiO_2 and Al_2O_3/SiO_2 dielectric reflectors at angles out to 85°. The measured data agree well with our simple model.

Key words: angular dependence; aluminium oxide; coating defects; evaporated aluminium; fused silica; hafnium oxide; laser damage thresholds; multilayer dielectric reflectors; silicon dioxide.

1. Introduction

Before the experiments of Newnam et al. [1], it was believed that the laser damage thresholds for an S-plane polarized beam would increase with incident angle (θ) due to simple geometric fluence dilution and also due to the decrease in S-polarization electric field within the film. Geometric fluence dilution alone predicts a $1/\cos\theta$ increase in damage threshold and peak electric field calculations predicted an even more dramatic increase. Figure 1 compares the laser damage thresholds of HfO_2/SiO_2 reflectors reported in ref. 1 with a $1/\cos\theta$ angular dependence. If these results are general for multilayer dielectric reflectors, we have an opportunity to extend our understanding of laser induced damage.

We wished to verify the weak angular dependence and also utilize this behavior to gain further understanding of damage phenomena. In addition to verification, several other questions beg answers. Is this phenomena unique to HfO_2/SiO_2 multilayers or will it also occur in others such as Al_2O_3/SiO_2? Does it occur in bulk material such as fused silica? Is it sensitive to polarization? Of course the big question is, why do we not observe at least the simple $1/\cos\theta$ increase in laser damage thresholds with increasing incident angle. In this paper we propose an extension of geometric fluence dilution by considering the interaction of the diluted fluence with an absorbing defect. In addition we report experiment results which answer some of the questions raised above. The role of absorbing defects in laser damage has an observational basis [2] and additional support from theoretical work [3,4].

2. Proposed Model

A model which accounts only for geometric fluence dilution at the surface or within the bulk cannot account for the experimentally observed angular dependence of laser damage thresholds in some multilayer dielectric reflectors. It is apparent that the interaction cross-section does not decrease as rapidly as it would for a uniformly absorbing spherical defect. A simple extension of the uniformly absorbing spherical defect model is that which considers a uniformly absorbing cylindrical defect embedded in the film with the cylinder axis orientated normal to the film surface. Additional assumptions in this model are that the total energy which the defect must absorb for damage to occur is a constant independent of incident angle and that the cylinder height is the thickness of the film.

We now consider not only fluence at the film surface, but in the medium as well. Refraction modifies the beam geometric cross-section slightly. The following expression gives the ratio of the incident fluence to fluence in the medium of refractive index n as a function of angle.

$$B = \frac{\left(1 - \sin^2\theta / n^2\right)^{1/2}}{\cos\theta} \qquad (1)$$

This modification of the $1/\cos\theta$ behavior is modest (about twenty percent for HfO_2 at 85°) and is included primarily for completeness. A cylindrical defect of radius r embedded in a film of index n and thickness t presents a cross-sectional area

$$A = (2rt/n)\sin\theta + \pi r^2 \cos\theta \qquad (2)$$

to the incoming beam. As the film is tilted the fluence in the medium is diluted and the defect area is modified. The area may increase or decrease depending on the aspect ratio of the cylinder. The aspect ratio therefore becomes the chief free parameter of this model. When we impose the condition that the absorbed energy required to initiate damage at the defect is independent of angle, we arrive at an expression relating the damage threshold fluence at any angle $F(\theta)$ to the normal incidence damage threshold fluence F_0.

$$F(\theta) = \frac{F_0}{(2t/\pi nrB)\sin\theta + \cos\theta} \qquad (3)$$

This model is compared with the laser damage thresholds of HfO_2/SiO_2 reflectors from reference [1] in figure 2. We note that for small aspect ratios this model overestimates the increase in thresholds at large angles, but not so much as the $1/\cos\theta$ model. For large aspect ratios the present model predicts a decrease in damage thresholds over a broad range of angles before thresholds rise. Given the simplistic nature of many of our assumptions and also experimental uncertainties in the experimental results, this model is quite successful in explaining the weak angular dependence observed. We performed additional experimental tests of this model which comprise the remainder of this paper.

3. Test Procedures and parameters

The test setup and procedure was the standard multiple-shot used at Los Alamos and described in some detail previously.[1,5,7] Significant modifications include thin-film polarizers, a low intensity uv diagnostic illumination beam picked off before the beam attenuator, two-dimensional beam profile characterization generated by scanning a reticon array across the focal plane, computerized fluence measurement and control, and computerized data reduction. Table 1 below details specific test parameters.

Table 1. Damage Test Parameters

Wavelength:	248 nm
Pulselength:	23 ns
Repetition Rate:	50 Hz
Spot Size:	0.2 x 0.8 mm at normal inc.
Shots/Site:	100
Polarization Ratio:	1000:1 for S-polarization experiments

With the exception of the evaporated aluminium film test samples, the damage diagnostic was the telescope and video camera with the uv diagnostic beam for illumination. The fluence in the diagnostic beam was 5-10 mJ and too small to contribute to damage. The telescope was maintained at an angle of fifteen degrees with respect to the sample normal in an effort to maintain constant diagnostic sensitivity. For the aluminium films we found that visual examination with a low-power stereo microscope and white light provided the best reliability.

4. Test Samples

We tested four groups of samples. All samples were two inches in diameter. Bare evaporated aluminium films on BK7 were chosen to represent the case where damage is expected to occur at the surface due to bulk absorption. Fused silica(Corning 7940) was chosen to represent a non-absorbing bulk material. The HfO_2/SiO_2 multilayer reflectors were shipped by a coating vendor instead of the Al_2O_3/SiO_2 reflectors ordered. HfO_2 films are absorbing at 248 nm and do not represent defect dominated laser damage initiation. The HfO_2/SiO_2 reflectors were designed for seventy-five degree angle of incidence and coated in a single run. The S-plane polarized reflectance band for this design angle is broad enough that these coatings are good reflectors at all test angles. The Al_2O_3/SiO_2 multilayers were also designed for seventy-five degrees, but were coated in several coating runs. The Al_2O_3/SiO_2 multilayer reflectors are expected to behave at 248 nm as the HfO_2/SiO_2 reflectors did at 351 nm in ref. [1].

5. Experimental Results

The normalized laser damage threshold test results for the Corning 7940 fused silica are shown in figure 3. All samples are from the same lot and normal incidence damage thresholds were obtained by measurements on the 45 and 60 degree test samples. Most of these data are for unpolarized light and only the simple 1/cosÈ geometric fluence dilution enhancement of the damage threshold is expected. The damage thresholds obtained with unpolarized light follow a $1/\cos\theta$ scaling quite well. We also measured a few samples with S-polarized light to see if the stronger enhancement due to decreased peak electric field was present.[1] The results do indicate some additional enhancement, but the present data are insufficient to characterize this additional enhancement.

Figure 4 gives the normalized damage thresholds for evaporated aluminium on BK7. The normalization is the normal incidence damage threshold for this lot (0.12 J/cm^2). These results for the test with unpolarized light show at least the $1/\cos\theta$ geometric fluence dilution scaling. Tests with S-polarized light again show an additional enhancement. We do not understand why the scatter for the test with polarization is so much greater.

Figure 5 displays normalized damage thresholds for both the HfO_2/SiO_2 and Al_2O_3/SiO_2 multilayer reflectors. All of these results are for s-polarized light and the normalization is chosen to make the sixty degree points fall on the $1/\cos\theta$ curve for comparison. We immediately see that the HfO_2 damage thresholds follow the 1/cosÈ curve quite well at 248 nm. The Al_2O_3/SiO_2 damage threshold values, however, increase more slowly. We note that this implies that our normalization constant is probably too large and that the eighty five degree thresholds are more likely about four or five times greater than the normal incidence thresholds. Figure 6 compares the multilayer dielectric damage thresholds with spherical and cylindrical defect models. Here the Al_2O_3/SiO_2 damage thresholds are normalized so that the value at sixty degrees agrees with our model and chosen aspect ratio and the average values at each angle are plotted for clarity.

6. Summary

We have verified that multilayer dielectric reflector laser damage thresholds may not scale with simple geometric fluence dilution at the film surface. Figure 6 shows that the Al_2O_3/SiO_2 laser damage thresholds scale less rapidly than $1/\cos\theta$ and are in good agreement with our cylindrical model with $r/t = 0.4$. Our model and assumptions would imply a defect radius of about 10 nm and that melting of the defect would require absorption of about one percent of the incident energy. The results for aluminum films, bare fused silica, and the HfO_2/SiO_2 multilayers which are absorbing at 248 nm do scale with geometric fluence dilution at the sample surface. For the aluminium and HfO_2/SiO_2 multilayers, it is probable that bulk absorption is more important than local defects. The $1/\cos\theta$ scaling of the fused silica damage thresholds implies that either the defects are more spherical or that the energy-absorption mechanism is different than in multilayer dielectric films.

7. References

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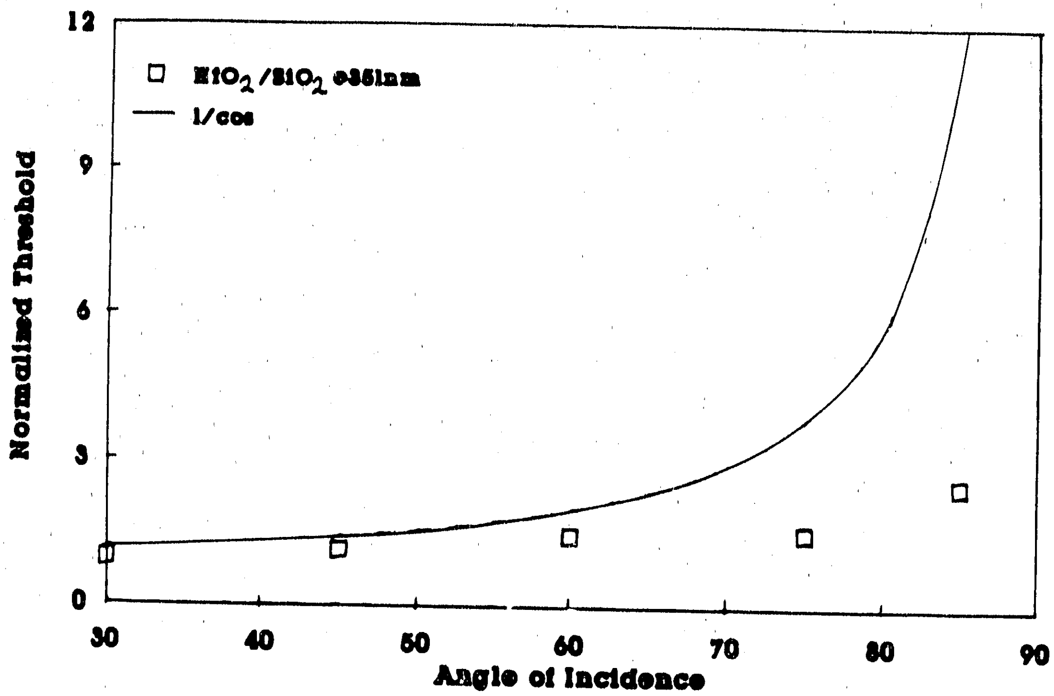

Figure 1. Comparison of the experimental damage threshold values from reference [1] with the 1/cosθ expected from simple geometric scaling

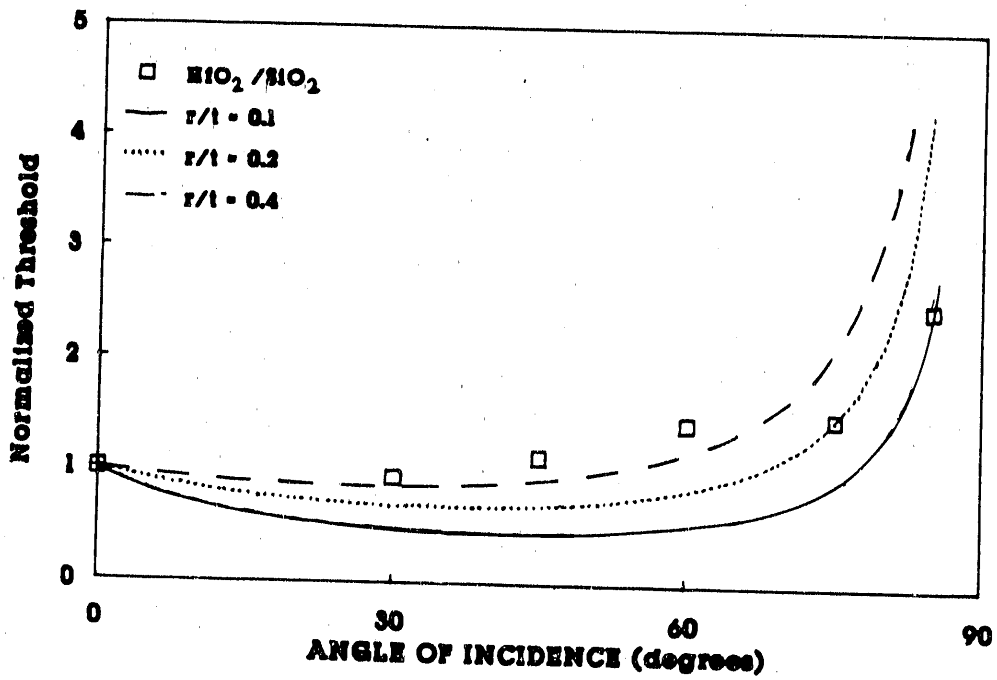

Figure 2. Comparison of the experimental damage threshold values from reference [1] with the cylindrical defect extension to simple geometric scaling

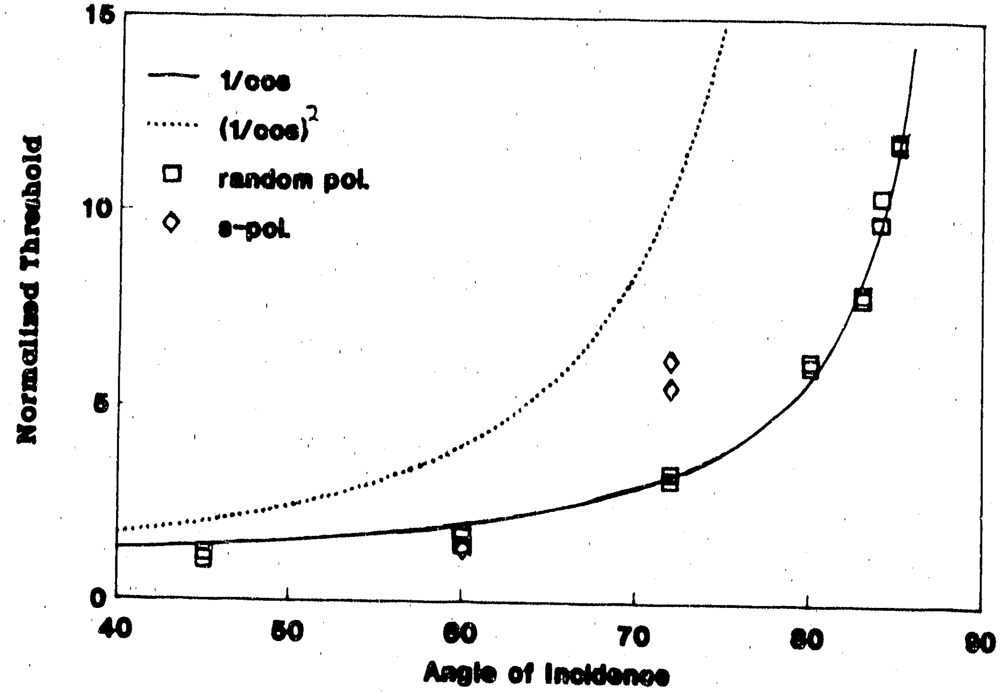

Figure 3. Laser damage threshold values for uncoated Corning 7940 fused silica with random polarization scale as 1/cosθ. The S-polarization results are further enhanced.

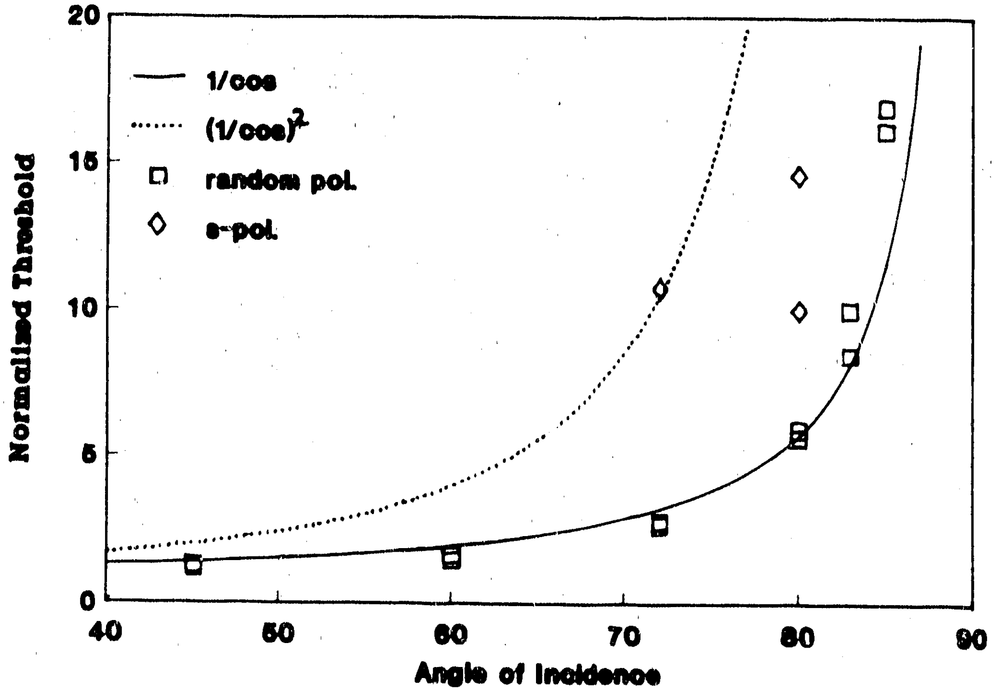

Figure 4. Laser damage threshold values of evaporated aluminium with random polarization scale as 1/cosθ. The thresholds for the S-polarization results are enhanced more than the uncoated fused silica.

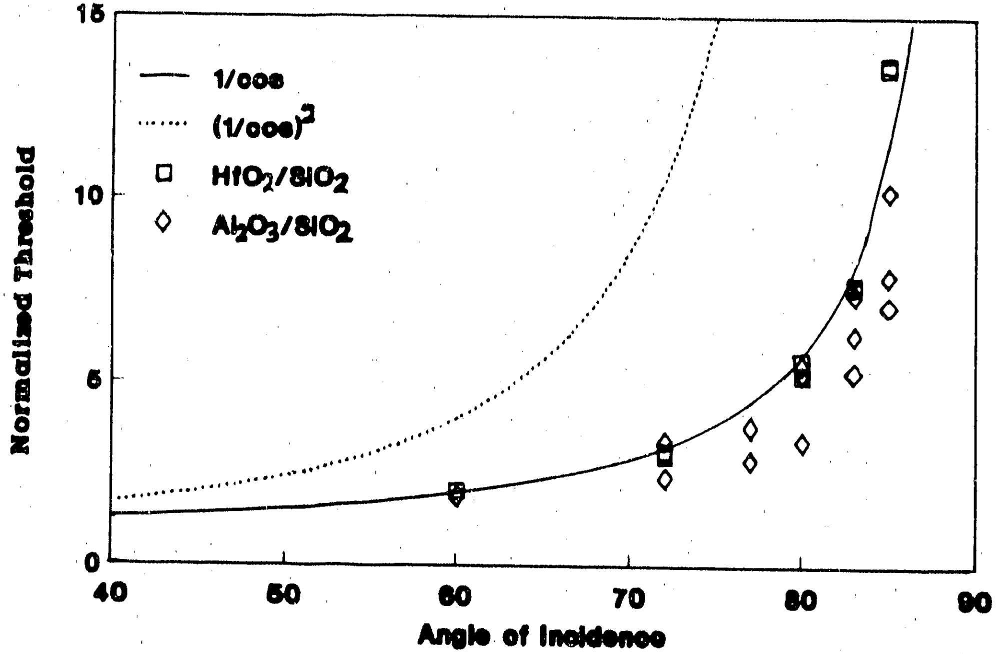

Figure 5. The laser damage threshold values for HfO_2/SiO_2 and Al_2O_3/SiO_2 multilayer dielectric reflectors are compared with $1/\cos\theta$ and $1/\cos^2\theta$.

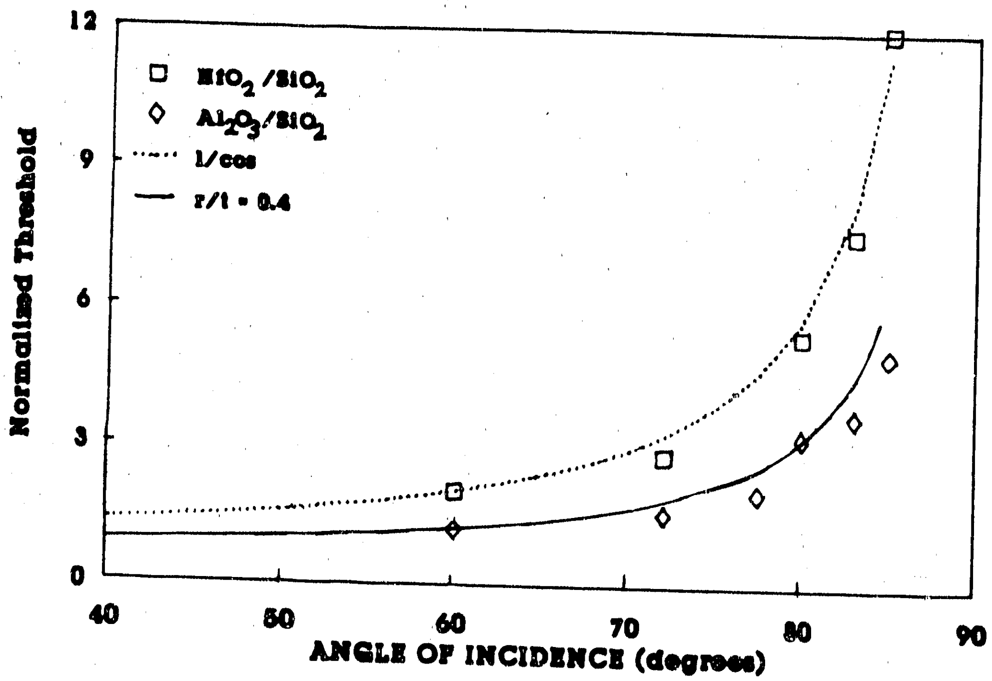

Figure 6. The laser damage threshold values for HfO_2/SiO_2 and Al_2O_3/SiO_2 multilayer dielectric reflectors are compared with $1/\cos\theta$ and the cylindrical defect model with $r/t = 0.4$.

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