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Thickness of over-coated SiO_2 and the Femtosecond laser induced damage

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Abstract

In ultrafast laser application, the top layer of thin film not only serve the spectrum purpose, but also protects the stacks from the application environment, such as plasma, UV light and so on. It is found the thickness of the over-coated silica can affect the laser induced damage even though it is wide bandgap material and sitting in very low electric field intensity.

Keywords: Thin film; Overcoat; Ultrafast laser damage, Blister; Mechanical robustness.

1. Instruction

Silica is commonly employed as top layer of thin film stacks to minimize reflection, optimize the transmission and protect the underlying thin film from environment, plasma and UV to extend its lifetime. In laser application, especially with pulsed laser, a half wave silica overcoat is often used to enhance the laser induced damage threshold (LIDT). However, in Femtosecond laser application, especially for mirror, situation becomes complex. LIDT of individual layer is primarily governed by intrinsic $LIDT_{int}$ and the electric field intensity, or, EFI, Saaxewer Diop et al., 2023. Both high and low index material are extensively investigated as top layer with various thickness. With optimized design (minimized the EFI in high index material), high (Femtosecond) laser LIDT has been achieved using either high index or low index material as top layer. When silica is used as top layer, its thickness is generally less concerned for laser damage due to its wide bandgap. However, this study reveals that a thin top silica layer could significantly degrade the LIDT despite its wide bandgap and sitting in nearly 0 EFI.

2. Sample prepare and laser damage test

The mirror design consists of 17 pairs Ta_2O_5/SiO_2 layers topped with 6 pairs Al_2O_3/SiO_2 as protective layers. These protective layers withstand the high intensity laser pulse and mitigate the electric field intensity (EFI) before reaching the first Ta_2O_5 layer. Design A features 15nm SiO_2 top layer experiencing nearly 0 EFI (Fig. 1a). Design B is topped with 327nm (2 quarter wave) SiO_2, which experiencing the highest EFI (Fig. 1b). Both designs reflect 1030nm at 8^o angle of incidence (AOI). From intrinsic $LIDT_{int}$ and EFI perspective, design A should exhibit comparable, or, even better LIDT as design B because the same EFI distributes over stacks after 1^{st} layer and negligible EFI in 1^{st} layer.

Both designs are deposited on fused silica substrate with standard ion beam sputtering process. Subsequently, 350^oC anneal was performed to optimize the thin film performance.

The LIDT test was conducted with 200fs pulsed laser, 50 kHz repetition rate at 1030nm and 0° AOI. The beam size is 200µm with TEM00 profile. The LIDT test followed S-on-1 (ISO 21254-2) test protocol.

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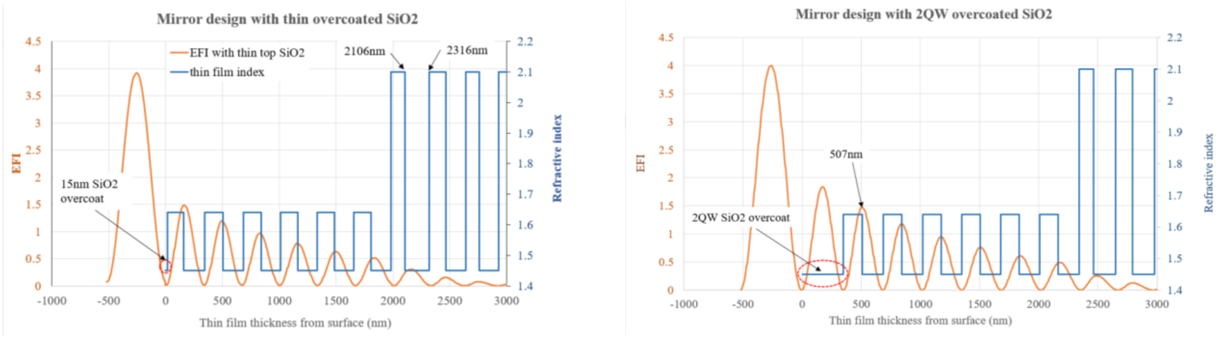


(a) (b)

Fig. 1. Electric field intensity (brown) across stacks (blue). The refractive index is SiO2 (1.46), Al2O3 (1.65) and Ta2O5 (2.1). (a) Over-coated with 15nm SiO_2; (b) Over-coated with 327nm (2QW) SiO_2.

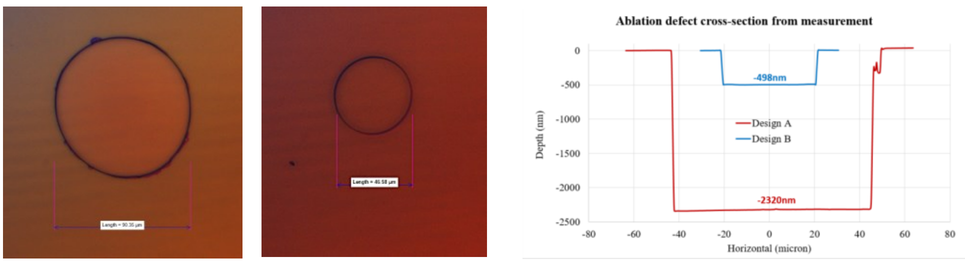
3. Result and analysis

The LIDT report reveals a surprising outcome, as table 1. Design A exhibits significantly lower laser damage resistance compared with design B. Furthermore, the fatigue ratio ($LIDT_{N\text{-on-}1}$ / $LIDT_{1\text{-on-}1}$) also demonstrated a notable difference between the two.

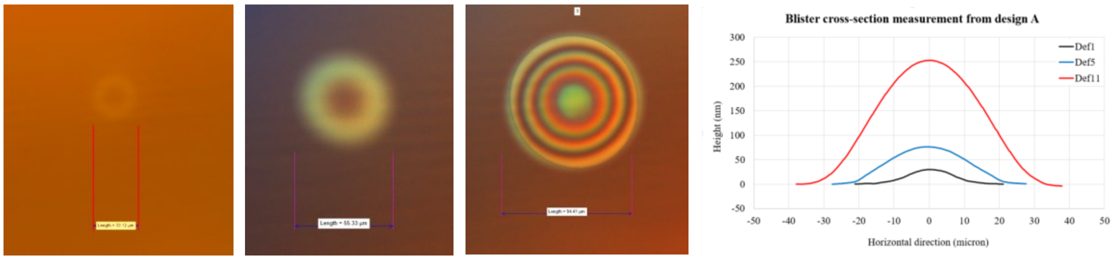
Table 1 LIDT test summary

	LIDT category	catastrophic(J/cm^2)		color mode(J/cm^2)	
		Design A	Design B	Design A	Design B
1	1 on 1	0.529	0.976	0.409	0.886
2	10 on 1	0.438	0.871	0.404	0.811
3	100 on 1	0.435	0.871	0.389	0.811
4	1000 on 1	0.428	0.824	0.389	0.772
5	10K on 1	0.412	0.798	0.312	0.674
6	100K on 1	0.404	0.789	0.258	0.626
7	100K fatigue	76%	81%	63%	71%

Microscopic observation of the damage morphology revealed ablation-type damage in both designs. The damage size in design A is approximately twice of the one in design B (Fig. 2a and 2b). Also, Design A exhibited an ablation depth approximately 5 times of the one of design B (Fig. 2c). Notably, sample of design A also exhibits color shadow and blister formation (Newton rings), a feature is absent in Design B (Fig. 2d, 2e, and 2f).



(a) (b) (c)



(d) (e) (f) (g)

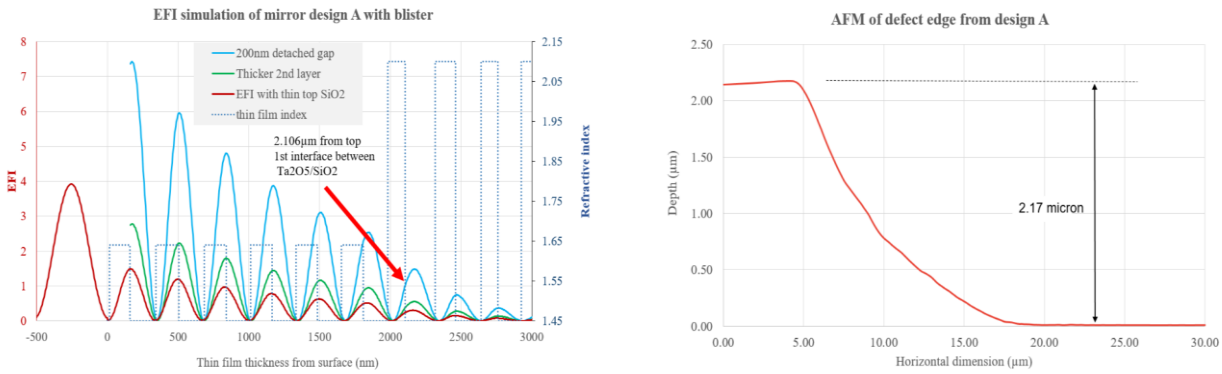
Fig.2 Laser damage morphology (a) Ablation damage (design A); (b) Ablation damage (design B); (c) Ablation defect cross-section from NEXTVIEW measurement (design A vs. B); (d) Initial color shadow (design A); (e) Color shadow growth (design A); (f) A blister with Newton ring (design A). (g) Morphology cross-section of d, e and f from NEXTVIEW (design A).

As depicted in Fig. 2d-2f, the color shadow progressively expands and evolves into a blister (Fig. 2f) with the rising fluence. Detail investigation with NEXTVIEW revealed that the color shadow (Fig. 2d & 2e) represents as an early stage of blister formation (Fig. 2g). According to Table 1 and Fig. 2, the presence of blisters in Design A is a distinct characteristic, indicating early damage initiation (Fig. 2d) and growth (Fig. 2e, 2f), ultimately leading to much significant damage compared to Design B. Given that the only differentiating factor between the designs is the top SiO_2 layer thickness, it is reasonable to conclude that this layer's thickness may be a critical factor influencing ultrafast laser damage, and it is independent of the intrinsic $LIDT_{int}$.

It is widely accepted the LIDT of femtosecond laser is primarily driven by material bandgap (rather than defect) via multi-photon absorption, tunneling effect or avalanche process. However, even in wide bandgap materials, particularly Al_2O_3, pulsed laser irradiation has been shown to generate mid-gap defects and self-trapped excitons (Zehan Li et al., 2015; Maxim V. Shugaev et al., 2016; Juan Du et al., 2015; Mohamed Yaseen Noor et al., 2025). These mid-gap defects can produce free carriers as seeds, initiating the nonlinear absorption, triggering the phase change and plasma formation. This not only generates high internal pressure, it also dramatically alter the material mechanical property, such as Young's modulus, thermal expansion coefficient, leading to the plastically deforming and stress relief within the layers, including the blister formation.

Ultrafast pulsed laser-induced blistering has been reported (S. Rappa et al., 2013; Kyle R. P. Kafka et al., 2016; Joel P. McDonald et al., 2006; Mohamed Yaseen Noor et al., 2025), with proposed trigger mechanisms including nonlinear absorption, plasma formation and non-thermal melting. In both design A and design B, excluding the top SiO_2 layer of design B (Fig. 1b), the 2nd interface between Al_2O_3 and SiO_2 experiences the highest EFI (Fig.1a, 1b). The Al_2O_3 adjacent to this interface appears to be the most susceptible to reaching the critical point (Mohamed Yaseen Noor et al., 2025). Upon reaching this point, this region begins to soften, expand and exert pressure on the overlying SiO_2 layer, which, due to its wide bandgap, remains below the critical point and thus retains its rigidity before thermal equilibrium. A thicker top SiO_2 layer, according to Stoney equation, can better resist this underlying expansion, thereby mitigating the changes to the stack structure profile. This may explain the observed blister formation in Design A (Fig. 2f) and its absence in Design B.

Blister formation directly alters the relative optical thickness in three dimensions. Besides the lens effect, the EFI distortion is deeply concerned. Studies (Kyle R. P. Kafka et al., 2016; Mohamed Yaseen Noor et al., 2025) suggest that the blisters can result from stack buckling or delamination. To simulate the EFI distortion, the blister is simplified as following cases: 200nm thickness increase on layer 2 (representing non-thermal melt and stress relaxing) and 200nm gap between layer 2 and 3 (representing delamination), as Fig.3a. Simulation indicates the EFI more than doubles in both cases, particularly at the interface between the first Ta_2O_5 layer and adjacent SiO_2 (red arrowed). Fig. 3b presents the cross-section of AFM image around the edge region of one ablation damage from Design A, revealing the ablation depth of 2.17 micron, which located at the interface between the 1st Ta_2O_5 layer and the adjacent SiO_2 layer (Fig. 1a). This confirms that a blister can compromise the protection of the top Al_2O_3/SiO_2 stacks, exposing the Ta_2O_5 to high EFI, which leading to the catastrophic damage. Conversely, suppressing blister formation, as in Design B, minimizes this EFI distortion. The Ta_2O_5 layers in design B remain protected until the Al_2O_3/SiO_2 pairs are damaged, as observed in Fig 1b & Fig. 2c, which is ablated at about the 2^{nd} Al_2O_3/SiO_2 interface with much higher LIDT, while Design A exhibits ablation (Fig.1a & Fig. 2c) within Ta_2O_5/ SiO_2 layers with lower LIDT. This explains the prevalence of shadow-to-blister type damage and lower LIDT in Design A, in contrast to Design B, as summarized in Table 1.



(a) (b)

Fig. 3 (a) EFI simulation compare among the designs, when 200nm thicker on 2nd layer and when 200nm gap from delamination between 2nd/3rd layer; (b) AFM cross-section over edge region of damage (design A) reveals the ablation depth locating at interface between the 1st pair of Ta_2O_5 and SiO_2.

4. Summary

Achieving optimal thin-film LIDT performance for femtosecond laser applications requires precise control of the EFI within the multilayer stack. Any factor that alters the EFI has the potential to initiate a cascade of EFI distortion that leads to catastrophic laser-induced damage. The mechanical robustness of the top layer directly influences blister initiation and growth which modulating the EFI, accelerating absorption and phase transitions, promoting blister expansion, and, in return, further distorting the EFI. Ultimately, this compromises the protection of outer layers, resulting in damage at the weakest point deep inside the stacks. In this study, such a cascade events results the Ta_2O_5 layer being exposed to elevated EFI, leading to a degraded LIDT. Conversely, a thicker top SiO_2 layer can significantly enhance mechanical robustness, effectively preventing blister initiation and maintaining the optimized EFI profile across the stacks. Other factors, such as the lens effect, may also contribute to laser-induced damage. Further investigations are currently underway.

Acknowledgements

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Reference:

Saaxewer Diop, Marine Chorel, Éric Lavastre, Nadja Roquin, Laurent Gallais, Nicolas Bonod, AND Laurent Lamaignere, Influence of the multilayer dielectric mirror design on the laser damage growth in the sub-picosecond regime, Vol. 62, No. 7 / 1 March 2023 / Applied Optics.

S. Rappa, M. Domkea, M. Schmidtb, H.P. Hubera, Physical mechanisms during fs laser ablation of thin SiO2 films, Physics Procedia 41 (2013) 727 – 733.

Kyle R. P. Kafka, Noah Talisa, Gabriel Tempea, Drake R. Austin, Catalin Neacsu, and Enam A. Chowdhury, Few-cycle pulse laser-induced damage of thin films in air and vacuum ambience, Proc. of SPIE Vol. 10014 100140D-1 (2016)

Joel P. McDonald, Vanita R. Mistry, Katherine E. Ray, and Steven M. Yalisove, Femtosecond-laser-induced delamination and blister formation, in thermal oxide films on silicon (100), APPLIED PHYSICS LETTERS 88, 153121 (2006)

Zehan Li, Juan Du, Yuanan Zhao, Yueliang Wang, Yuxin Leng, and Jianda Shao, Modeling the effect of nanosecond laser conditioning on the femtosecond laser-induced damage of optical films, 1 Jun 2015 | Vol. 23, No. 11 | DOI:10.1364/OE.23.014774 | OPTICS EXPRESS 14774

Maxim V. Shugaev, Chengping Wu, Oskar Armbruster, Aida Naghilou , Nils Brouwer, Dmitry S. Ivanov, Thibault J.-Y. Derrien, Nadezhda M. Bulgakova, Wolfgang Kautek , Baerbel Rethfeld , and Leonid V. Zhigilei, Fundamentals of ultrafast laser–material interaction, MRS BULLETIN • VOLUME 41 • DECEMBER 2016.

Juan Du, Zehan Li, Bing Xue, Takayoshi Kobayashi, Dongjia Han, Yuanan Zhao, and Yuxin Leng, Ultrafast pre-breakdown dynamics in Al2O3-SiO2 reflector by femtosecond UV laser spectroscopy, 29 Jun 2015 | Vol. 23, No. 13 | DOI:10.1364/OE.23.017653 | OPTICS EXPRESS 17653

Mohamed Yaseen Noor, Emma Deangelis, Simin Zhang, Conrad Kuz, Justin Twardowski, Aaron Davenport, Carmen s. Menoni, and Enam Chowdhury, Pulse duration dependent effects of ultrafast laser induced damage on a 1030 nm multi-layer dielectric mirror for high repetition rate, high average power laser systems, Vol. 15, No. 2 / 1 Feb 2025 / Optical Materials Express.