Graded index broadband antireflection coating prepared by glancing angle deposition for a high-power laser system*

Kong Wei-Jin(孔伟金)[a)†], Shen Zi-Cai(沈自才)[b)], Wang Shu-Hua(王淑华)[a)], Shao Jian-Da(邵建达)[c)], Fan Zheng-Xiu(范正修)[c)], and Lu Chao-Jing(卢朝靖)[a)]

[a)] *College of Physics Science, Qingdao University, Qingdao* 266071, *China*
[b)] *Beijing Institute of Spacecraft Environment Engineering, Beijing* 100094, *China*
[c)] *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*

(Received 24 November 2008; revised manuscript received 6 July 2009)

This paper reports that SiO_2 is selected to fabricate broadband antireflection (AR) coatings on fused silica substrate by using glancing angle deposition and physical vapour deposition. Through accurate control of the graded index of the SiO_2 layer, transmittance of the graded broadband AR coating can achieve an average value of 98% across a spectral range of 300–1850 nm. Moreover, a laser-induced damage threshold measurement of the fabricated AR coating is performed by using a one-on-one protocol according to ISO11254-1, resulting in an average damage threshold of 17.2 J/cm^2.

Keywords: broadband antireflection coating, graded index, glancing angle deposition

PACC: 4280X, 4225B

1. Introduction

It is well known that reflections will inevitably appear when light propagates across a boundary between two materials with different refractive indices.[1] The reflection, which depends on the polarization of incident light, the angle of incidence, the dielectric constants of the media and the wavelength, should be suppressed at the interfaces of the optical instrumentation to increase the light throughout.[2] There are two approaches to reduce the reflection across the interface of two different media: one is based on the interference of a multi-layer stack, the other is based on the graded index layer between the incident layer and the output layer.[3] In a high-power laser system, the anti-reflective coating should have broadband and high laser resistance performance.[4] Though the former method with multi-layer dielectric can reduce reflection, most of this kind of coating suffers from limited bandwidths as well as very restricted laser-induced damage resistance performance.

Glancing angle deposition (GLAD) is a method capable of producing thin films with engineered nanoscale porosity variations.[5−7] Graded index coating prepared by GLAD serves to reduce the difference of refractive index of the layers and subsequently reduce the reflection that results from the index mismatch at the surface. When the continuous graded index layer is carefully controlled, a high transmitted antireflection (AR) film can be obtained across the given wavelength band. This graded index broadband AR coating can be widely used in fields such as solar cells, optics communication, ultraviolet spectral range and especially for high-power laser windows.

Silicon dioxide (SiO_2) is useful for optical devices because of its desirable properties such as low refractive index, high transparency in the visible, near-infrared region and high damage threshold value for high-power lasers. In this paper, a SiO_2 graded index broadband AR coating was prepared by electron beam evaporation with the GLAD technique. The optical performances, such as reflectance, transmittance and laser-induced damage threshold, were investigated.

2. Theory

The reflection of thin film coatings is mainly caused by differences in permittivity and permeability

*Project supported by the National Natural Science Foundation of China (Grant No. 10804060), Higher Educational Science and Technology Program of Shandong Province of China (Grant No. J08LI05).
†Corresponding author. E-mail: kwjsd@163.com
© 2010 Chinese Physical Society and IOP Publishing Ltd

from interface to interface. When the light is normally incident upon the interface of two different media with refractive indices of n_1 and n_2 respectively, the reflection from the interface can be obtained according to the Fresnel function as follows:[8]

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2. \quad (1)$$

As can be seen from the above equation, there will be no reflection at the interface if the refractive index of the two media is equal. In such a way, effective media with continuous variation of graded index can serve to reduce index mismatch at the interface and achieve high transmittance. As a result of the enhanced shadowing effect and limited atom diffusion, GLAD thin films have high porosity and anisotropic growth behaviour.[9,10] By controlling the orientation of the substrate relative to the impinging vapour flux, micro-structurally controlled materials can be three-dimensionally fabricated on a 10-nm scale for use in optical, chemical, biological, mechanical, magnetic and electrical applications.[11,12]

When the interface between two media is eliminated, the reflection will not exist. If the refractive index of thin film coatings is gradually changed from substrate to exterior medium, as shown in Fig. 1, the refractive index interface will be eliminated and the interface reflection will not take place. In this study, we take the graded index material as SiO_2 ($n = 1.46$) and the substrate as fused silicon ($n = 1.46$). The refractive index of graded SiO_2 can be changed from 1 to 1.46 by employing GLAD. There will be a graded index variation from air to substrate and no reflection across the interface, except for the mini step at the glass interfaces which is due to the discrepancy between the substrate and the deposited SiO_2.

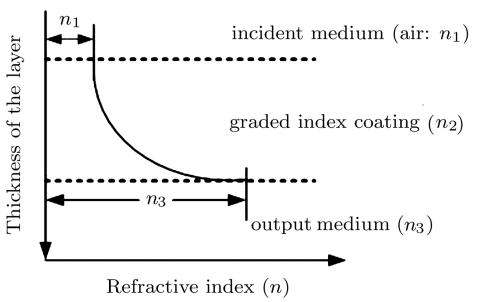


Fig. 1. Representation of a graded index layer at the interface between incident layer and output layer.

3. Experiment

3.1. Sample preparation

The GLAD process has been reported in detail in previous work.[13,14] The SiO_2 films were deposited on fused silicon by electron beam evaporation. Flux incident angles α, defined as the angle between the incident flux and the substrate surface normal, were designed to be 0°, 30°, 40°, 50°, 60°, 70° and 80°. The target-to-substrate distance was 37 cm. During the deposition process, the background pressure was about 1.8×10^{-3} Pa, and deposition pressure was about 3.0×10^{-3} Pa. The deposition was performed at room temperature. The average deposition rate was about 0.9 nm/s. After deposition, SiO_2 films were annealed at 200–400 °C in air for 3 hours.

The optical thickness of each sample of B, C, D, E, G, and H is controlled to be $8H$, where H represents the optical thickness of a quarter wavelength of 800 nm. The physical thickness is closely connected with the GLAD.[13]

3.2. Spectra test

Transmittance and reflectance spectra were measured by a Lambda 900 spectrophotometer (Perkin Elmer Company). The measurement accuracy of the spectrophotometer was ±0.08%.

3.3. Laser-induced damage test

A laser-induced damage threshold (LIDT) test was performed in the one-on-one mode, according to ISO standard 11254-1,[15] by an Nd:YAG single-pulse mode, Q-switched laser, with a working wavelength of 1064 nm, a pulse width of 12 ns, and TEM_{00} mode.[16,17]

4. Results and discussion

4.1. Refractive index analysis

The refractive index has a important influence on the optical properties of graded index AR coatings.[18] In this paper, the substrate is fused silica, and its refractive index is 1.46. The exterior medium is air and its refractive index is 1.0. Figures 2 and 3 show the influence of refractive index on the optical properties of graded index coatings, which lies in the interface of thin film coating and exterior medium and in the interface of thin film and substrate.

From Figs. 2 and 3, we know that the refractive index of the film near the exterior medium has a larger influence on the residual reflection of graded index AR coatings. So it is a suitable choice for controlling the former refractive index to a relative low transmittance to get ideal antireflective performance.

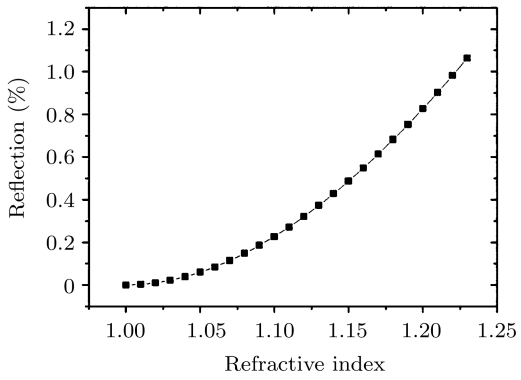


Fig. 2. Influence of former refractive index on the reflection of AR coatings.

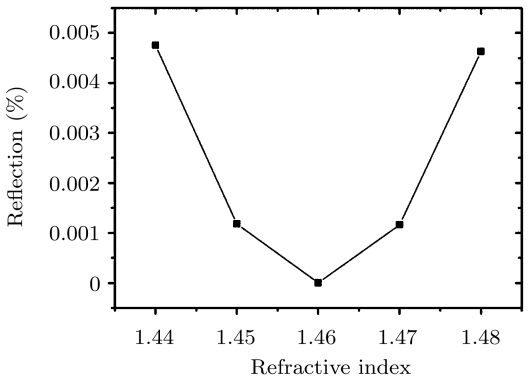


Fig. 3. Influence of refractive index near substrate on the reflection of AR coating.

The reflection spectra of the fabricated graded index SiO_2 films deposited with different glancing angles are shown in Fig. 4. It can be seen that reflection decreases with the increase of incident angle. The effective refractive index of fabricated SiO_2 films decreases with the increase of flux incident angle (shown in Fig. 5). At wavelength $\lambda = 600$ nm, the effective refractive index changes from 1.48 to 1.1, and the fitted polynomial expression is as follows:

$$\begin{aligned} & n(\theta) \\ &= 1.478 - 1.60836 \times 10^{-4} \times \theta + 1.66219 \times 10^{-5} \times \theta^2 \\ &\quad - 6.87101 \times 10^{-7} \times \theta^3. \end{aligned} \tag{2}$$

Based on the Bruggeman effective medium approximation,[19−20] we can obtain the relationship between packing density and effective refractive index of the fabricated SiO_2 film, as shown in Table 1.

The packing density of SiO_2 films decreases with the increase of incident angle. The decrease of the refractive index and packing density in SiO_2 film can be ascribed to the porous structure. By adjusting the flux incident angle, the effective refractive index and packing density of the graded index films can be fabricated in a continuous range. One might also combine the microstructure evolution with the refractive index to produce refractive index gradient materials or other new optical coatings.

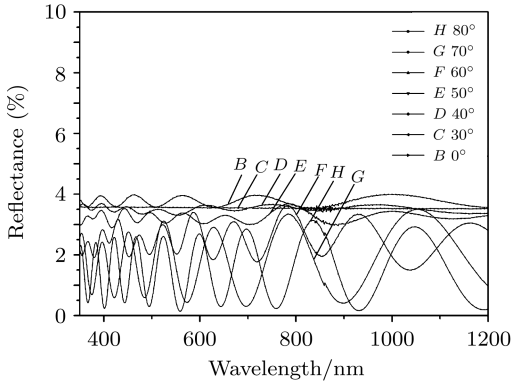


Fig. 4. Transmittance spectra of GLAD SiO_2 films.

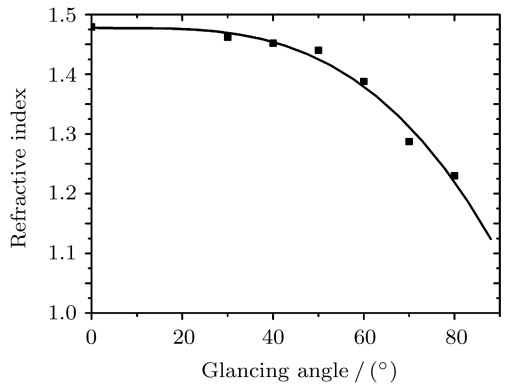


Fig. 5. Fitted refractive index of the fabricated SiO_2 films.

Table 1. Relationship between packing density and effective refractive index of GLAD SiO_2 film.

flux angle	0°	30°	40°	50°	60°	70°
refractive index	1.478	1.462	1.452	1.440	1.388	1.287
packing density	1	0.966	0.946	0.921	0.816	0.612

From the above polynomial expressions, we know that the refractive index of SiO_2 is 1.46 with an oblique angle of 37°. So, the graded SiO_2 broadband AR film should be fabricated as the glancing angle changes from 37° to 90°.

4.2. Optical performance

We fabricated the SiO_2 broadband AR film on fused silicon substrate, and its refractive index changes gradually from substrate refractive index to almost the index of air. As for the deposition process, the glancing angle changes from 37° to 90° with a deposition rate of 0.9 nm/s. Sample 1 is deposited AR film on a double surface and sample 2 is deposited on a single surface.

The residual reflectance for single surface SiO_2 films is lower than 0.5% in the range of 300–1850 nm as shown in Fig. 6(a). The transmittance for single and double surface SiO_2 films is larger than 99% in the range of 600–1850 nm as shown in Fig. 6(b), which show that the fabricated graded index SiO_2 can be used as a broadband AR film.

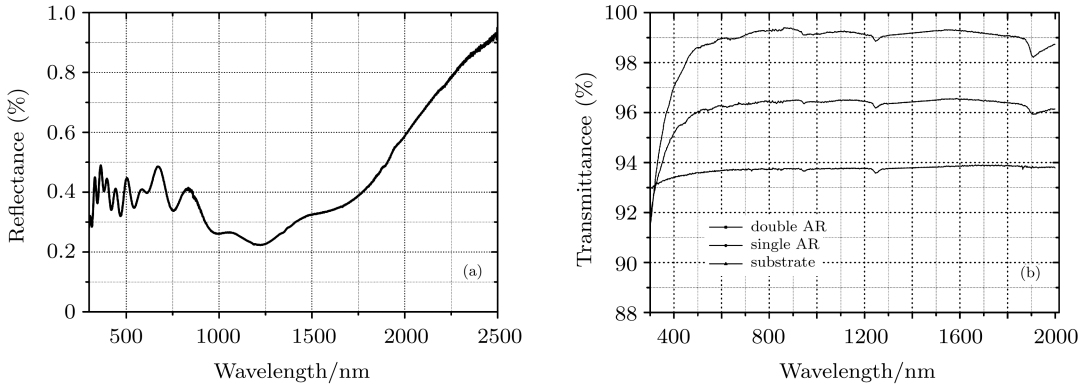


Fig. 6. Reflectance spectrum (a) and transmittance spectrum (b) for SiO_2 films on fused silicon substrate.

4.3. Laser-induced damage threshold

The sample with AR film on a double surface is selected for the laser-induced damage threshold test. According to the 0% probability fitting method, the results of the LIDT are shown in Fig. 7. The LIDT of broadband AR SiO_2 film is 17.2 J/cm^2. The damage morphology of the graded index AR coating is mapped by a Nomarski microscope and the typical damage morphology is illustrated in Fig. 8. From Fig. 8, we can clearly see that the damage is thermal in nature and is characterized by melting and boiling. A possible damage mechanism is that free carriers are heated by interaction with the laser beam and subsequently transfer energy to the crystal lattice. So damage occurs via conventional heat deposition resulting in the melting and boiling of the graded index dielectric material.

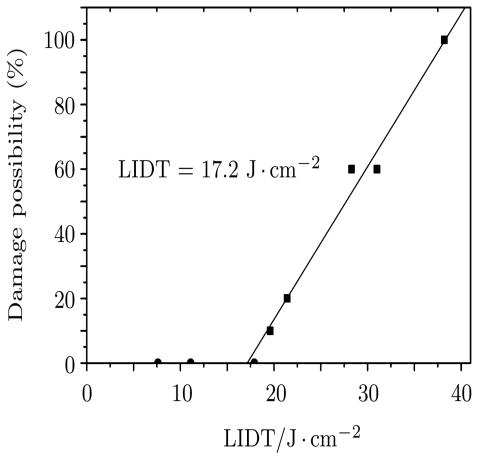


Fig. 7. The LIDT for double graded index AR coating.

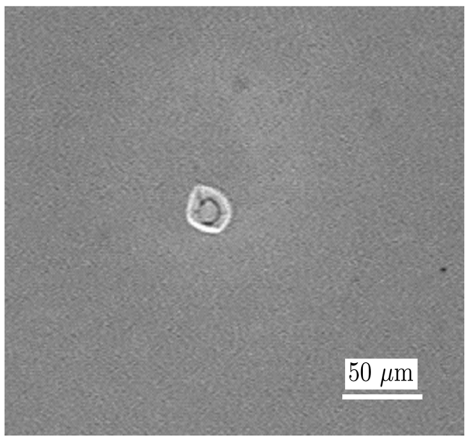


Fig. 8. Typical damage morphology of graded index AR coating.

5. Conclusion

In conclusion, we have prepared ultra broadband graded index SiO_2 AR coatings on fused silica by GLAD, and their residual reflection per surface is less than 0.5% in the spectral range 300–1850 nm. When the double surfaces of fused silica are all coated with this graded index AR coating, the transmittance is larger than 99% in 600–1850 nm. Finally, the damage threshold measurement of SiO_2 AR coating on a double surface is performed by using the one-on-one protocol according to ISO11254-1, resulting in an average damage threshold of 17.2 J/cm^2, and the damage is mainly caused by the heat from laser radiation. Because of its broad bandwidth and high laser resistance ability, the graded index AR coating should have practical applications in high-power laser systems.

References

[1] Zhang B and Wang Z 2007 *Acta Phys. Sin.* **56** 1404 (in Chinese)

[2] Shen Z C, Shen J, Liu S J, Kong W J, Shao J D and Fan Z X 2007 *Acta Phys. Sin.* **56** 1325 (in Chinese)

[3] Chen D 2001 *Solar Engery Materials and Solar Cells* **68** 313

[4] Liu M C, Lee C C, Liao B H, Kaneko M, Nakahira K and Takano Y 2008 *Appl. Opt.* **47** 214

[5] Popta A C, Hawkeye M M, Sit J C and Brett M J 2004 *Opt. Lett.* **29** 2545

[6] Liu L and Su X R 2008 *Chin. Phys.* B **17** 2170

[7] Wang S M, Xia G D, Fu X Y, He H B, Shao J D and Fan Z X 2007 *Thin Solid Film* **515** 3352

[8] Macleod H A 1999 *Thin Film Optical Filters* **3** 87

[9] Robbie K and Brett M J 1997 *J. Vac. Sci. Technol.* A **15** 1460

[10] Lakhtakia A, Messier R, Brett M J and Robbie K 1996 *Innovations Mater. Res.* **1** 165

[11] Kennedy S R and Brett M J 2003 *Appl. Opt.* **42** 4573

[12] Hodgkinson I J and Wu Q H 1999 *Appl. Phys. Lett.* **74** 1794

[13] Wang S M, Fu X Y, Wang J G, Shao J D and Fan Z X 2006 *Appl. Sur. Sci.* **252** 8734

[14] Popta A C, Hawkeye M M, Sit J C and Brett M J 2004 *Opt. Lett.* **29** 2545

[15] ISO 11254-1:2000 2000 *International Organization for Standardization* Switzerland

[16] Zhao Y A, Wang T, Zhang D W, Shao J D and Fan Z X 2005 *Appl. Surf. Sci.* **245** 335

[17] Wang Y J, Zhao Y A, Gao W D and Fan Z X 2004 *Opt. Eng.* **43** 87

[18] Feng Y D, Wang Z M, Ma Y L and Zhang F J 2007 *Chin. Phys.* **16** 1704

[19] Aspnes D E, Theeten J B and Hottier F 1979 *Phys. Rev.* B **20** 3292

[20] Wang J G, Shao J D and Fan Z X 2005 *Chin. Opt. Lett.* **22** 223