Temperature Fields of Al₂O₃/MgF₂ HR Coatings Prepared at Different Working Pressure

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Abstract. A series of samples were deposited by electron beam evaporation using the same deposition process at different working pressure. Transmittance of the HR coatings was measured by Lambda 900 spectrometer. Laser-induced damage threshold (LIDT) was measured by a 355 nm Nd:YAG laser with a pulse width of 7 ns. The LIDT results range from 2.69 J/cm² to 11.03 J/cm² with the working pressure changing. It was found that working pressure has important effects on the absorption and LIDT of 355nm Al₂O₃/MgF₂ HR coatings. The temperature rise of HR coatings under laser irradiation was calculated by interfaces absorption model based on the theory of temperature fields. The results of temperature fields agree with the results of LIDT.

1. Introduction
High-power laser damage to optical devices seriously restricts the development of high-power laser systems. It is of great significance to have research on the laser damage and hardening of the optical devices [1]. Moreover, LIDT of 355 nm HR coatings is a more severe problem than that of 1064 nm HR coatings [2]. One of the continuing challenges facing the high energy laser field is to develop 355nm HR coatings that can withstand higher laser energy densities. the understanding of the origin and mechanism of LIDT in 355 nm HR coatings is very important for improving the LIDT [3].

For applications in the UV spectral range, the number of useful coating material is very limited due to the high absorption at wavelengths near to the electronic band-gap of the materials. Magnesium fluoride (MgF₂) thin film has transparency in the far ultraviolet (FUV) down to 115 nm[5], so it is widely used for optical applications in the UV and deep UV range [6]. Alumina (Al₂O₃) is one of the most important oxide thin film materials for the manufacture of interference coatings in the UV spectral region, down to 200 nm [7]. As a consequence, they are widely used to realize optical coatings for high performance and laser-damage resistant applications [8-9]. In this paper the temperature rise of Al₂O₃/MgF₂ HR coatings under laser irradiation was calculated by interfaces absorption model based on the theory of temperature fields. It is helpful to elucidate the damage mechanism of Al₂O₃/MgF₂ HR coatings prepared at different working pressure.

2. Experiment details
All the samples were deposited by electron beam evaporation in the same coating chamber with different process condition. The fused silica and U BK7 substrates were high quality super-polished with surface and cleaned by ultrasonic wave in alcoholic solution before deposition. The details of coating stack and working pressure are listed in Table 1, where H stands for high index material,
Al₂O₃, with one QWOT (Quarter Wavelength Optical Thickness) and L stands for low index material, MgF₂, with one QWOT, respectively. All the samples were annealed in the coating chamber for 2 hours after deposition.

Table 1. The details of three-group samples.

| Sample ID | Coating stack | Working pressure |
|-----------|---------------|------------------|
| A         | 13 (hl) h     | 6.0 × 10⁻³ Pa    |
| B         | 10 (hl) h     | 6.0 × 10⁻³ Pa    |
| C         | 10 (hl) h     | 2.0 × 10⁻² Pa    |

3. Results and discussion

Transmittance of the HR coatings was measured by Lambda 900 spectrometer. The LIDT test was performed in the ‘‘1-on-1’’ mode, according to ISO standard 11254-1.2, by a 355nm Nd: YAG pulse laser with a pulse width of 7 ns. The LIDT (J/cm²) was defined as the incident pulse’s energy density when the damage occurred at 0% damage possibility, and it could be obtained by linear extrapolation of the damage probability data to zero damage probability.

The transmittance results of the samples in UV region are given in Figure 1. It can be found that the transmittance results of the sample A and C are the lowest and highest among three samples, respectively. Lower transmittance means higher absorption. The sample C, which have higher working pressure, have higher transmittance and lower absorption in the UV region. The reason is that increasing working pressure can make the samples more fuller oxidation during deposition, which leads to lower absorption in sample C.

Figure 2 illustrates the LIDT results of the samples. It shows that the sample C has the highest LIDT among three samples. Sample A, which is 27 layers, has the lowest LIDT. Compared with sample B and C, it can be found that increasing working pressure can improve LIDT effectively.

As far as the LIDT and transmittance are concerned in Figure 2 and 1, it can be found that sample A with the lowest transmittance and highest absorption in UV region has lowest LIDT among three samples. That is low LIDT emerging simultaneously with high absorption, which is agreed with the results in the reference [10].

According to the experimental results presented above, the most relevant damage mechanism associated with absorption is observed on 355nm Al₂O₃/MgF₂ HR coatings. In order to facilitate analysis of the damage mechanism, the temperature rise of different absorption in the HR coatings under laser irradiation can be calculated by interfaces absorption model based on the theory of temperature fields.
The theory of temperature fields is based on the reference [11]. Figure 3 shows HR coatings with N-layer structure, which is illuminated on the surface by a Gaussian beam of light. The following Maxwell equations apply to the electric and magnetic field components in the kth layer:

\[
\left( \frac{d^2}{dz^2} + \frac{2\pi n^{(k)}}{\lambda_0} \right) E_k(z) = 0
\]

\[
(d/dz)E_k(z) + i(2\pi/\lambda_0)H_k(z) = 0
\]

The general solution to these equations can be written:

\[
E_k(z) = A_1^{(k)} \exp \left[ -\frac{i2\pi n^{(k)}}{\lambda_0} \left( z - \sum_{j=k+1}^{N+1} z_j \right) \right] + A_2^{(k)} \exp \left[ +\frac{i2\pi n^{(k)}}{\lambda_0} \left( z - \sum_{j=k+1}^{N+1} z_j \right) \right]
\]

\[
H_k(z) = n^{(k)} A_1^{(k)} \exp \left[ -\frac{i2\pi n^{(k)}}{\lambda_0} \left( z - \sum_{j=k+1}^{N+1} z_j \right) \right] - A_2^{(k)} \exp \left[ +\frac{i2\pi n^{(k)}}{\lambda_0} \left( z - \sum_{j=k+1}^{N+1} z_j \right) \right]
\]
With E and H determined, the rate of flow of energy through the multilayer can be calculated by invoking the Poynting vector theorem. The average amount of power per unit area that crosses the plane perpendicular to the Z axis at z can now be written

\[ Y(z) = \text{Re}[E(z) \cdot H^*(z)/2] \]  

(5)

Starting at time \( t = 0 \), a narrow, circularly symmetric, Gaussian beam of light propagating in the z direction illuminates the surface. The incident intensity distribution can be written:

\[ I(r,t) = \left[ P_0(t)/(\pi r_0^2)\right] \exp\left[-(r/r_0)^2\right] \]  

(6)

Where, \( r_0 \) is the \( \exp(-1) \) radius of the Gaussian beam and \( P_0(t) \) is the instantaneous output power of the laser. From that equation the following equation can be obtained:

\[ g(r,z,t) = \frac{d[I(r,t)Y(z)]}{dt \cdot dr \cdot dz} \]  

(7)

g(r,z,t) is the power delivered to the unit volume by the laser.

Based on the theory of temperature fields mentioned above, the temperature rise of different absorption in the HR coatings under laser irradiation can be calculated by interfaces absorption model [12]. For HR coatings, we assume that the laser energy is 10J/cm² (355nm, 7ns).

Figure 4 gives the result of temperature rise of Sample A, B and C. The highest temperature is occurred at about 300nm from the surface of samples. Under the same laser irradiation, Sample A, which has the highest absorption, also has the maximal temperature rise about 3500k. The maximal temperature rise of the sample C is about half of the sample A. correspondingly the LIDT and the absorption of the sample C is the highest and lowest, respectively. It is illustrated that the temperature rise of the HR coatings shows good correspondence with the LIDT and absorption results, which means that the damage mechanism for 355nm Al2O3/MgF2 HR coatings is confirmed with temperature fields and interfaces absorption model.

4. Conclusions

As far as the temperature field of Al2O3/MgF2 HR coatings deposited at different working pressure are concerned, it is found that the Al2O3/MgF2 HR coatings with higher working pressure have higher transmittance, lower absorption in the UV region. Sample C has the highest LIDT among the samples. The damage mechanism for 355nm Al2O3/MgF2 HR coatings is confirmed with temperature fields.

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