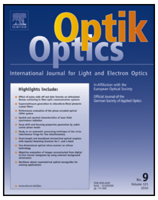
Optik 164 (2018) 654–660

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Original research article

The effect of water vapor on nanosecond laser damage resistance of optical coatings in vacuum

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ARTICLE INFO

Article history:
Received 8 December 2017
Received in revised form 22 March 2018
Accepted 22 March 2018

PACS:
PACS
42.79.Wc
81.70.Fy
68.37.Hk

Keywords:
Vacuum
Laser–induced damage
Water vapor
Oxygen vacancy defect

ABSTRACT

In this paper, the effects of water vapor on the laser-induced damage of e-beam evaporated dielectric anti-reflection coatings in vacuum were investigated. The laser-induced damage resistance of the samples was measured in 1-on-1 and R-on-1 mode in vacuum and water vapor atmosphere. The LIDT of the anti-reflection coatings in vacuum was improved after introducing water vapor. The effects of the oxygen vacancy defect and thermal conductivity and stress change were considered to explain the improved LIDT.

1. Introduction

The study of pulsed-laser-induced breakdown of optical thin films in vacuum has been a subject of interest because of the developing need for the high-intensity laser systems and space-based laser systems. Optical coatings with high damage thresholds, as a key component in the laser systems, have to be developed to allow for reliable operation in vacuum conditions for long terms [1–3]. However, the degradation of laser-induced damage resistance of optical coatings was observed under subsequent vacuum exposure [4,5]. It was found that the degradation of the laser-induced damage resistance of optical films in vacuum was attributed to water desorption for the porous optical films [6,7]. Several effective methods [8–10] were proposed to suppress the degradation of the laser-induced damage threshold (LIDT) and improve laser-induced damage resistance of e-beam evaporated dielectric coatings in vacuum.

Water vapor easily passed in and out for the porous optical films, which would lead to the change of optical, thermal and stress properties of optical films. So, the change in the amount of water vapor was one of the most important factors resulting in the degradation of the laser-induced damage resistance of the porous optical films.

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https://doi.org/10.1016/j.ijleo.2018.03.084

In this paper, the effects of water vapor on the laser-induced damage of e-beam evaporated dielectric anti-reflection coatings in vacuum were investigated. The LIDT of the anti-reflection coatings in vacuum was improved after introducing water vapor. The effects of the oxygen vacancy defect and thermal conductivity and stress were considered to explain the improved LIDT. By these investigations, we aimed to explore the effective improvement techniques of the laser-induced damage resistance of optical films in vacuum environment.

2. Experimental details

2.1. Samples preparation

We considered the anti-reflection coatings of ZrO_2/SiO_2 prepared by E-beam evaporation (EBE) with the base pressure of approximately 1.0×10^{-3} Pa in the same coating run. The films were deposited using the oxide zirconium as starting material by a Leybold 1110 coating machine. High quality BK7 substrates by conventionally polishing process with geometry of Φ 30 mm × 3 mm was cleaned ultrasonically in alcohol solution before deposition. SiO_2 was deposited at a rate of about 0.5 nm/s, while ZrO_2 was evaporated at a lower rate of about 0.3 nm/s, and the substrate temperature was at 150 °C. The film design [A:2.5LH:G] with a reference wavelength of 1064 nm consisted of coating layers of ZrO_2 and SiO_2 on a BK7 substrate, where H denoted the quarter wavelength optical thickness (QWOT) of ZrO_2, L the QWOT of SiO_2, G the BK7 substrate and A the incident medium (air).

2.2. Film characterization methods

The transmittance spectra of films were measured with the Lambda 900 spectrometer. The measurement accuracy of the spectrometer was 0.08%.

The residual stress of samples was analyzed by a Stress Analyzer in different vacuum pressure. Firstly, curvature measurement of sample in different vacuum pressure was made on–line by a KSA MOS Stress Analyzer. The stress of the films was then calculated by Stoney's formula [11].

Laser damage tests were carried out in vacuum and water vapor atmosphere, respectively. The laser damage test apparatus used in this study was described schematically in the previous paper [10]. The LIDTs were measured in the "1-on-1" and "R-on-1" regime using 1064 nm pulsed laser with single longitudinal mode, Gaussian-shaped laser beam and 12 ns pulse duration according to ISO11254 [12]. The spot size of the beam incident on the sample was 400 μm diameters at $1/e^2$ of the maximum intensity. The damage of "1-on-1" test was still estimated by the visual inspection of plasma flash and subsequently detected with a Normarski interferential contrast microscope off-site. The LIDT (J/cm^2) in 1-on-1 mode was defined as the incident pulse's energy density of 0% damage probability which can be obtained by linear extrapolation of the damage probability data to 0% damage probability. The total error of the LIDT measurements was within 10%. Two hundred test sites (20 × 10 array) are exposed for 1-on-1 and R-on-1 test. For the R-on-1 test, the damage was detected with a Normarski interferential contrast microscope off-site. And the laser fluence was ramped from 10% of the LIDT to some designated maximum with the ramp increment rate of 0.01 J/cm^2 and the pulse repetition rate was fixed at 5 Hz. The LIDT (J/cm^2) in R-on-1 mode was defined by the highest fluence for which no damage has been observed.

The measurement pressure of laser damage tests in vacuum was set to 4×10^{-3} Pa. In addition, evacuation time of 6 h was chosen, and the typical vacuum residence time was 5 h. The surface damage morphologies of damage sites were determined by Normarski interferential contrast microscope and Scanning Electron Microscopy.

3. Results and discussions

Fig. 1 shows the measured residual reflection spectrum of the investigated ZrO_2/SiO_2 anti-reflection coatings. It can be seen that the residual reflectance of these thin films is lower than 0.05% at the wavelength of 1064 nm.

The vacuum has an important effect on optical, thermal, and stress properties of optical films. It is well known that e-beam evaporated dielectric coatings show porous structures which lead to water vapor easily entering into or depart from the optical film layers [13]. Vacuum effect is attributed to water vapor adsorbing in the coating from ambient being desorbed, and is hence changing the optical and thermal properties of optical films [6]. When water vapor adsorbing in the coating from ambient is desorbed in vacuum, porous gaps formerly filled with water no longer contain water, and thus constitute voids within the coating. So, vacuum effect can lead to the decrease of the refractive index in film layers according to the relationship [14]:

$$\phi = 1 - \left(\frac{n_{film}^2 - 1}{n_{bulk}^2 - 1} \right) \tag{1}$$