Effect of Vacuum on the Laser-Induced Damage of Anti-Reflection Coatings *

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In the comparison of damage modifications, absorption measurement and energy dispersive x-ray analysis, the effect of vacuum on the laser-induced damage of anti-reflection coatings is analyzed. It is found that vacuum decreases the laser-induced damage threshold of the films. The low laser-induced damage threshold in vacuum environments as opposed to air environments is attributed to water absorption and the formation of the O/Si, O/Zr sub-stoichiometry in the course of laser irradiation.

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Laser-induced damage in optical materials is a key issue for high power laser applications, and a significant number of studies have been done. At present, the laser system is widely allied in the domain of space. Laser optics used in space laser systems is usually exposed to high vacuum conditions in the absence of air or oxygen. Compared with the atmosphere, the vacuum circumstance is more complicated. It is well known that optical dielectric coatings show a change in damage performance when altering the environmental condition from air to vacuum, which necessitates a fundamental understanding of the damage behavior of dielectric coatings in vacuum environments.[1,2] The deleterious effects of vacuum have been scarcely mentioned in the literature. A negative effect of vacuum on optics is reported due to the reduction of the UV laser damage initiation probability.[3] The performance of coatings is affected by the build-up of contamination under high fluence irradiation in vacuum.[4,5] Still, there is a lack of understanding of the damage characteristics of dielectric optics exposed to vacuum.

In this letter, the damage characteristics of ZrO_2/SiO_2 anti-reflection films irradiated by 1064 nm YAG laser in vacuum and air environments are investigated. The damage thresholds in vacuum and air environments are compared. Through the observation of damage modifications, absorption measurement and energy dispersive x-ray analysis, the effect of vacuum on the laser-induced damage of anti-reflection coatings is analyzed and discussed.

Anti-reflection design [Air:2.5LH:K_9] with a reference wavelength of 1064 nm consists of coating layers of ZrO_2 and SiO_2 on a K_9 substrate, where H stands for quarter wavelength optical thickness (QWOT) of ZrO_2 and L stands for QWOT of SiO_2. All films under investigation are deposited by electron beam evaporation in the same coating run. High quality K_9 substrates are polished and cleaned ultrasonically in alcohol solution before deposition. The residual reflectance spectrum of the film shown in Fig. 1 is measured with the Lambda 900 spectrometer. The measurement error of the spectrometer is within 0.08%.

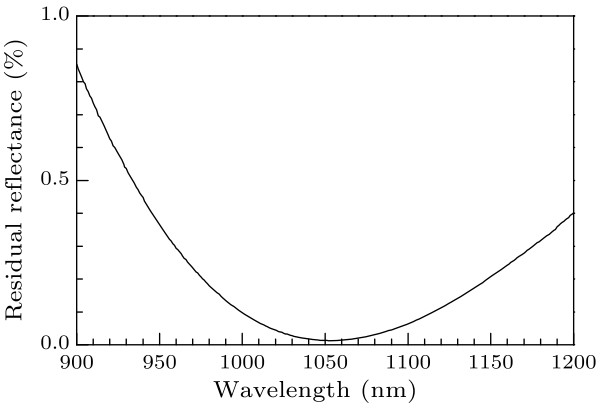


Fig. 1. Residual reflectance spectra of the sample.

The experimental setup is shown schematically in Fig. 2. An Nd:YAG laser delivers a single longitudinal mode, Gaussian-shaped laser beam of high spatial quality at a wavelength of 1064 nm with a pulse length of 12 ns (i.e. full width at half maximum (FWHM)), laser repetition rate of 5 Hz and a $1/e^2$ diameter of 450 μm at the sample plane. Beam diameter is measured by Beam ViewTW beam diagnostics. A stabilized He–Ne laser is made collinear with the main Nd:YAG beam and both the beams are directed onto the sample surface with a convex lens. The samples are fixed in a sample holder within the vacuum chamber, which can be moved and positioned laterally rel-

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ative to the beam with an x/y translation stage controlled by a PC computer. Behind the chamber, the main Nd:YAG beam is blocked.

According to the standard ISO11254-1,[6] the test method of LIDT is 1-on-1 mode. Laser damage tests were carried out in vacuum and laboratory atmosphere. The measurement pressure was set between 2×10^{-2} Pa and 4×10^{-3} Pa. In addition, an evaluation time of 6 h was chosen, and the typical vacuum residence time was 5 h. To eliminate the influence of differing samples, each sample surface was measured half in vacuum and half in air. The LIDT value (J/cm^2) was defined as the incident pulse's energy density when the damage occurred at 0% probability, and it could be obtained by linear extrapolation of the damage probability data to 0% damage probability. The error margin of the LIDT measurements is about 10%.

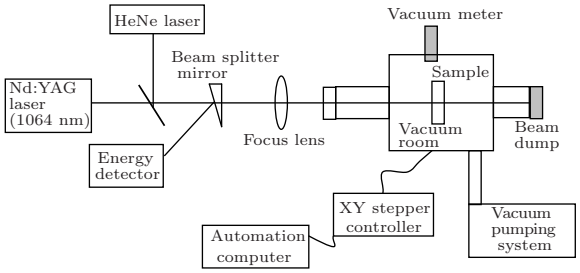


Fig. 2. Measurement setup of laser-induced damage threshold.

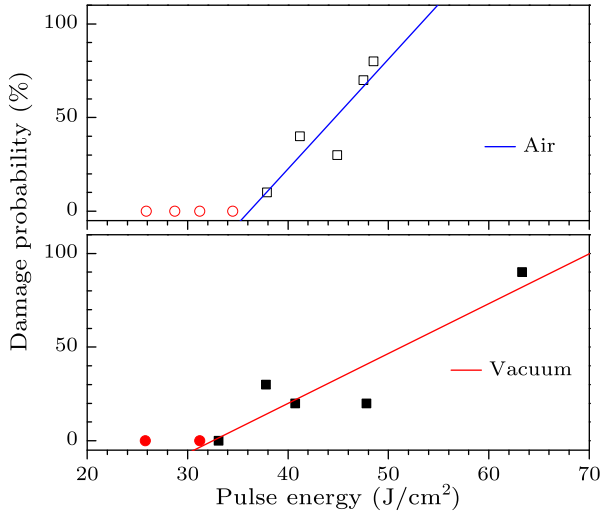


Fig. 3. Tests of 0% damage probability under air and vacuum.

A Leica-DMRXE optical microscope of 100_magnification was deployed to confirm whether the radiation sites were damaged or not. The damage morphologic changes of samples were observed by the Leica-DMRXE optical microscope and a scanning electron microscope. An Alpha2Step 500 meter was used to record the depth profiles of the damaged sites.

Figure 3 shows that there is about a 4.1 J/cm^2 decrease in the damage probability curve for tests in vacuum. The morphology of the damaged site mapped by optical microscopy and scanning electron microscopy (SEM) shows a particular difference. As displayed in Figs. 4 and 5, a systematic characteristic of the respective test conditions is found. In contrast to the vacuum morphology, where always a sharp, almost annular and circular edge between the damaged area and the intact coating is observed by SEM, the irradiation in air induces a flaked area at the edge of the damaged spot. Figure 6 shows that the damage in the atmosphere environments is mainly to the top layer, while the damage irradiated by the same laser fluence in the vacuum environments deepens below the top layer.

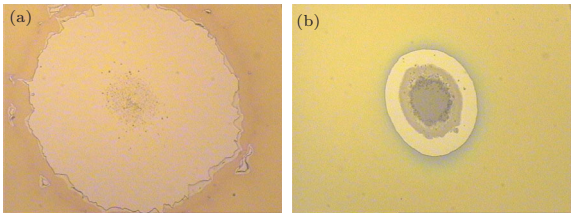


Fig. 4. Damage morphology under air (a) and vacuum (b) by Leica-DMRXE optical microscope.

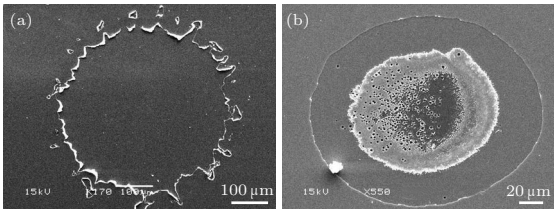


Fig. 5. Damage morphology under air (a) and vacuum (b) by SEM.

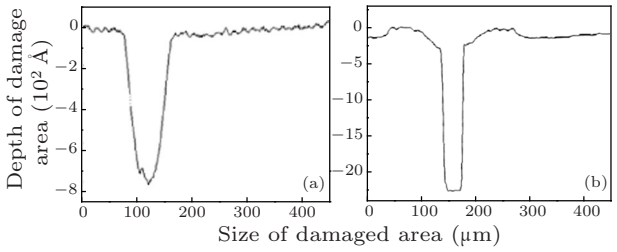


Fig. 6. Depth measurements of damage sites under air (a) and vacuum (b).

The surface thermal lensing technique (STL) was used to measure the absorption of films. First, absorption of the sample was measured and then the sample was placed in vacuum environments of 5×10^{-3} Pa. After several hours, absorption of the sample was measured again. From Fig. 7, we can see that absorption of the sample placed in vacuum environments increases compared to that of air environments.

KTKY Series Quadrupled Mass Spectrometer was used to ascertain the gaseous composition in vacuum environments. Figure 8 shows that the main composition in vacuum environments is H_2O. This offers a hint

that the increasing absorption of the sample placed in vacuum environments and the drop in damage threshold are related to the content of water in the coatings. Especially in the IR, water shows strong absorption bands when water is adsorbed in the dielectric layer.

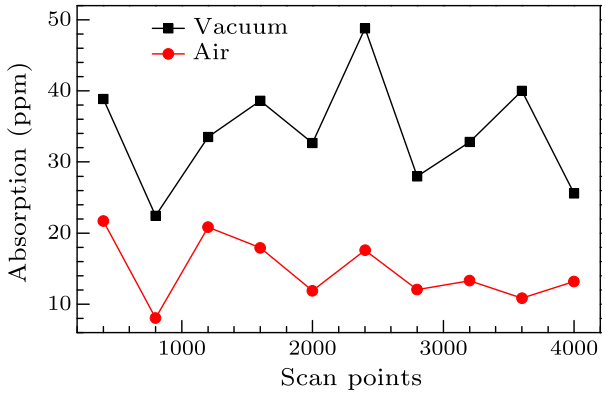


Fig. 7. Absorption of sample in air and vacuum environment.

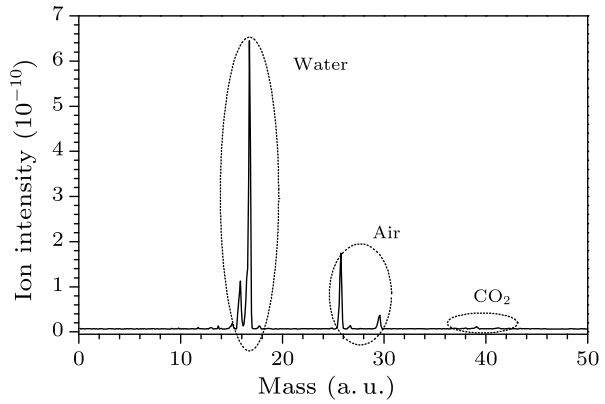


Fig. 8. Ion intensity of vacuum gaseous composition.

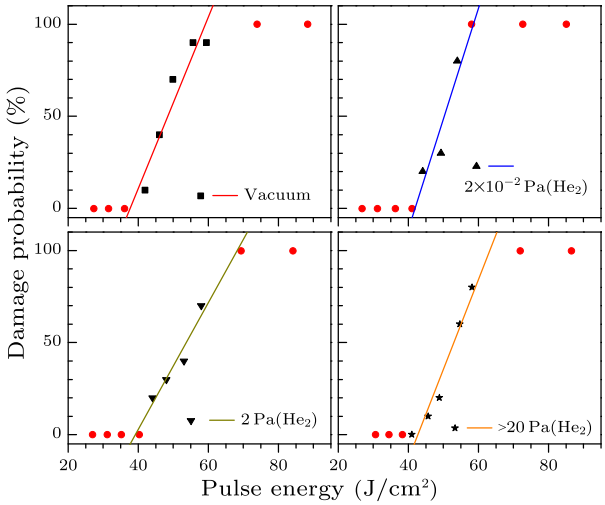


Fig. 9. Tests of 0% damage probability under vacuum and various pressures of helium.

In order to analyze the influence of gas heat conduction on the difference of damage thresholds in air and vacuum conditions, the laser-induced damage threshold and the morphology of the damaged sites were analyzed at various pressures of helium. The results are given in Figs. 9 and 10. No influence is found on the gas conductivity, and the measurements at high pressure with a highly conductive gas compared to vacuum show no difference. Thus gas heat conduction has little influence on the difference of damage under the two conditions.

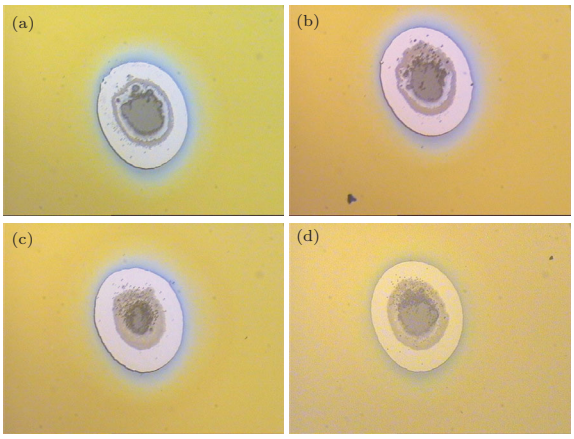


Fig. 10. Damage morphologies of AR coating irradiated by the same laser energy under vacuum and helium: (a) vacuum, (b) 2×10^{-2} Pa He_2, (c) 2 Pa He_2, (d) above 20 Pa He_2.

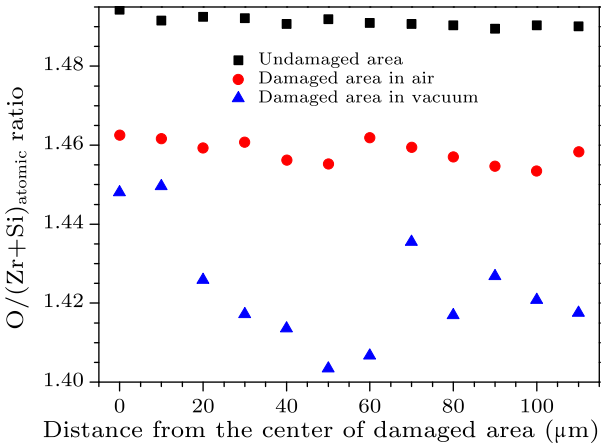


Fig. 11. O/(Zr+Si) stoichiometry of the damaged area in vacuum environments compared to air environments and the undamaged area.

In order to obtain information on the Si/O, Zr/O stoichiometry in the damaged area, energy dispersive x-ray analysis was performed on damaged and undamaged sites using 15 keV electrons. The Zr, Si and O contents at each point are reported as the element atomic ratio. In Fig. 11, we contrast O, Zr and Si contents of damaged area irradiated by laser in air and vacuum environments and of an area away from damaged area. The major difference of the laser-induced damaged region as opposed to the surrounding undamaged area is reduced signal for oxygen in air environments and more reduced signal for oxygen in vacuum environments. This confirms that the laser

irradiation results in much more loss of oxygen and thus lower O/Si, O/Zr stoichiometry of the damaged area in vacuum environments compared to the air environments and undamaged area. Thus, formation of more Si/O, Zr/O sub-stoichiometry on the surface in the vacuum environments enhances the probability of catastrophic damage. As shown in Fig. 12, experiments have not found more impurity in the damaged area of vacuum environments compared to air environments. Thus, impurity is not attributed to the low laser-induced threshold in vacuum environments.

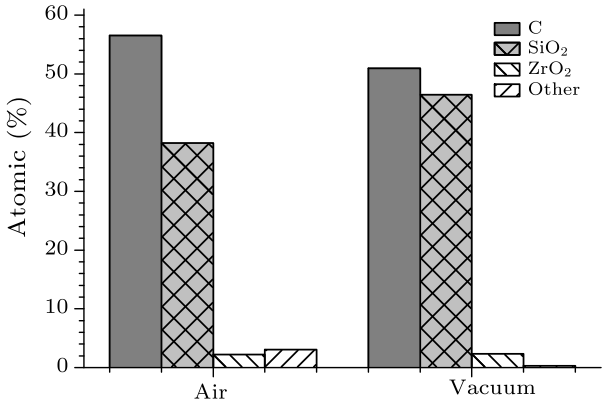


Fig. 12. EDS results of laser-induced damage sites under air and vacuum.

In summary, effect of vacuum on the laser-induced damage of anti-reflection coatings centered at the wavelength of 1064 nm is analyzed. The damage characteristics of anti-reflection films in vacuum and air environments are investigated at 1064 nm with a 12 ns laser pulses in the 1-on-1 mode. The damage thresholds in vacuum and air environment are compared. Through the observation of damage morphologies, depth measurement of damage sites, absorption measurement and energy dispersive x-ray analysis, the difference of damages in two environments is discussed. The low laser-induced damage thresholds in vacuum environments as opposed to air environments are attributed to water absorption and formation of the O/Si, O/Zr sub-stoichiometry in the course of laser irradiation.

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