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Effect of γ-ray irradiation on the optical property and laser damage performance of silica

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ABSTRACT

High purity fused silica samples have been irradiated by ^{60}Co γ-ray at the doses of 50, 500 and 5000 kGy, and the effect of γ-ray irradiation on the optical property and laser damage performance of silica have been investigated. After γ-ray irradiation, there is no obvious change on the surface of silica observed. However, the surface roughness increases slightly with increasing γ-ray irradiation dose. When the irradiation dose reached 500 kGy and above, a broad absorption band at 215 nm, ascribed to E′ color center, is significantly observed and its intensity increases greatly with increasing dose. After laser irradiation, the distribution of laser induced damage threshold (LIDT) is related to γ-ray dose, and the LIDT decreases monotonously with increasing dose. A mechanism for the degradation of laser damage resistance is presented.

1. Introduction

Fused silica has been widely used as optical components in the space optics and nuclear fusion system due to its excellent characteristics, such as low thermal coefficient, high Ultraviolet (UV) transmission and radiation resistance [1]. In addition, another important application is that it has been employed as the final optics in a high-power laser system, such as nation ignition facility (NIF) [2] in America, Shenguang (SG) series [3] in China. Thus, these projects based on irradiation are not only high irradiation dose but also long duration, where it will inevitably affect the properties of the optical components, such as survivability, recycle, optical transmission and irradiation hardness.

Fused silica has attracted numerous interests of researchers due to the rapid development and emergent demands of engineering. Previous studies have obtained important progress in many aspects of silica irradiated by γ-ray, especially in the understanding defects induced by irradiation. Griscom [4] reviewed in detail the various defects in silica glass. It is suggested that most of the intrinsic paramagnetic color center defects, such as E′ center [5–7] and non-bridging oxygen hole center (NBOHC) [8–10], are probably arisen from the conversion of the diamagnetic defect, oxygen deficient center (ODC) [11–13], as precursor under irradiation conditions, i.e. neutron, γ-ray and ultraviolet, which has been confirmed by some other findings. Marshall et al. [14] reported that the ODC defect can be produced in the condition of neutron irradiation in silica, and then the ODC can be converted to E′ color centers by γ-ray or ultraviolet irradiation. Imai et al. [15] found that the E′ concentration is closely related to the pre-existing Si—Si bonds in silica, i.e. the E′ precursors. Furthermore, there are a large number of investigations focused on the effect of γ-ray irradiation dose on the optical absorption and the generation of E′ center in silica. Agnello et al. [16] found that the signal of E′ center can not be detected until the γ irradiation reached at a certain dose, and the growth of E′ concentration depends on the irradiation dose. Islamov et al. [17] reported that an absorption band appears after ^{60}Co γ-ray irradiation and its optical density grows up and then saturates. In fact, these color centers induced by irradiation are usually unstable, their optical densities will decrease sequentially with time [18]. The induced defect absorption will nearly recover to the original condition after a UV pulse or thermal annealing [14]. Therefore, understanding the behavior of evolution and effect of the irradiation-induced color centers are essential and helpful for the optical components to determine whether they are sustainable under such serious conditions. However, to our knowledge, there has been no report about the effect of γ-ray on the laser damage resistance of silica. It is very important and meaningful to understand the laser damage resistance of optical components after

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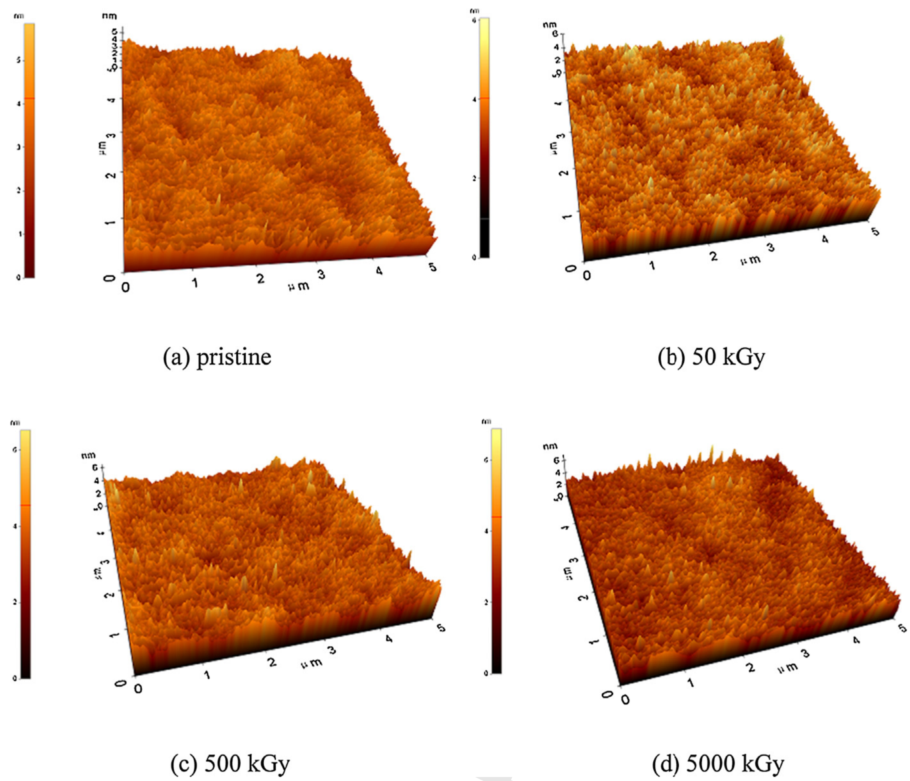

Fig. 1. Atomic force microscopic images of silica irradiated by γ-ray with different doses. (a) pristine, (b) 50 kGy, (c) 500 kGy, (d) 5000 kGy.

γ-ray irradiation, especially at different doses, because of its application in laser system. Based on these motivations, in this work, the microstructure evolution and optical property as well as the laser-induced damage threshold (LIDT) of silica irradiated by different doses of γ-ray are investigated.

2. Experimental process

In this work, high purity fused silica samples with two-side polished surfaces were irradiated at room temperature by ^{60}Co γ-ray at the doses of 50, 500 and 5000 kGy, respectively. The dose rate of ^{60}Co source γ-ray is 2.9 Gy/s. The irradiated silica samples, with size 30 mm × 30 mm × 4 mm, were labeled as S_1, S_2 and S_3, respectively. The pristine silica sample without any treatment, marked as S_0, was used as a reference. All of samples were characterized under the same conditions after each gamma irradiation experiments. A Nikon PSIA XE-100 atomic force microscope (AFM) was utilized to observe the surface morphology of samples before and after γ-ray irradiation. The optical absorption spectra were collected by a Perkin-Elmer Lambda 950 UV–vis–NIR spectrophotometer in the wavelength range 190–1200 nm. In order to investigate the laser damage resistance capability of fused silica before and after γ-ray irradiation, the LIDT was tested with R-on-1 procedure [19], i.e. multiple shots of increasing laser fluence at a single site of the material. In the present experiment, each sample was tested with 15 damage points. After removing the 5 large deviation points, the remaining 10 points is used to calculate the average LIDT. The LIDT tests were conducted by using a single mode Nd:YAG laser operated at 355 nm with pulse width of 4.6 ns. The laser beam was a spatial near-Gaussian distribution with beam area of 1 mm^2 at $1/e^2$. The beam areas were observed by a scientific CCD camera to monitor the initial damage in several microns on the surface of silica samples. The laser fluence fluctuates less than 5%. An EMP 1000 energy meter was used to collect the energy data of each shot. A Nikon ECLIPSE LV100 optical microscope was used to observe the laser damage morphologies of the samples.

3. Results and discussion

3.1. Surface morphology

In order to investigate the process of microstructure of evolution in silica, the surface morphologies have been measured with AFM. The atomic force microscopic images of silica irradiated by γ-ray with different doses are shown in Fig. 1. Comparing Fig. 1(a)–(d), although the γ-ray irradiation dose is as high as 5 MGy, it can be seen that there is no obvious change on the surface of silica before and after γ-ray irradiation, which is totally different from electron beam irradiated silica [20]. Analyzed from the mechanism of γ-ray interaction with matter, the γ-ray irradiation is mainly manifested as bulk damage due to its extreme penetration, ionizing radiation occurs primarily within the material, and consequently it has less impact on the surface of material. Therefore, it is observed at the micro-scale that a significant change did not occur on the surface. Guo et al. [21] pointed out the formation of new defect species may be due to the interaction between the lattice or impurity and the γ-ray, and some precursors may be formed during exposure to γ-ray. However, the high-energy electronic lines generated by electron beam irradiation interact with matter, which occurs mainly on the surface of the material. Afterwards, the thermal effects due to the energy deposition at the surface lead to the material to produce micro-crack, or even fracture on the surface.

To quantitatively analyze the difference before and after γ-ray irradiation, the root mean square roughness (R_q) is also measured. It is clearly shown that the surface roughness slightly increases with increasing dose, where the R_q is 0.545 nm, 0.571 nm, 0.589 nm and 0.684 nm, respectively. It is indicated that the γ-ray irradiation doses have less effect on the surface morphology of silica, and the