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Investigation of surface characteristics evolution and laser damage performance of fused silica during ion-beam sputtering

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ABSTRACT

Surface characteristics have great influence on the optical properties especially the laser radiation resistivity of optics. In this paper, the surface characteristics evolutions of fused silica during ion-beam sputtering and their effects on the laser damage performance were investigated. The results show that roughness change is strongly removal depth dependent and a super-smooth surface (0.25 nm RMS) can be obtained by the ion-induced smoothing effect. The concentration of metal impurities (especially Ce element) in subsurface can be effectively decreased after the removal of polishing re-deposition layer. During ion-beam sputtering process, the plastic scratches can be removed while the brittle cracks can be broadened and passivated without increase in the depth direction. Laser damage threshold of fused silica improved by 36% after ion-beam sputtering treatment. Research results have a guiding significance for ion-beam sputtering process technology of fused silica optics.

1. Introduction

Because of its excellent optical properties, fused silica is widely used as transparency optics for large high power output systems such as the National Ignition Facility (NIF) in USA [1], the Laser Mega Joule (LMJ) in France [2] and the SG III laser facility in China [3]. However, laser-induced damage on the exit surface of fused silica remains today a key limitation for the stable operation and load capacity improvement of high power laser systems. And what's more, the laser-induced damage threshold (LIDT) of a conventionally polished optical surface is much lower than the dielectric breakdown threshold of its bulk. Therefore, it has become a hot and difficult issue in recent decades to reveal the mechanism of damage and find ways to improve the LIDT of fused silica. As for the nature of damage initiators, it is now well admitted that they can be of two main kinds. A first possible source is highly absorptive contaminants (e.g., Al, Ce, Fe, etc) in the Beilby layer coming from polishing [4,5]. A second possible source is subsurface cracks produced during grinding and polishing processes. This subsurface damage (SSD) is embedded under the polishing re-deposition layer [6,7]. These precursors decrease the LIDT by either high absorption of UV (355 nm) laser or reduction of the mechanical strength or enhancement of local optical field [8]. Thus, it is of great importance to minimize or eliminate these detrimental effects.

The fabrication process of optical surface has been improved considerably during the past decades with the aim of improving resistance and lifetime of fused silica optics. The magneto-rheological finishing (MRF) can realize the elastic super-smooth polishing of optical materials, but it will introduce contaminants such as Fe element on the surface, which has a bad impact on the improvement of LIDT [9]. Hydrofluoric (HF) acid etching is one of the most effective and conventional post processing treatments for increasing the optic damage threshold [10,11]. It provides an effective approach to reveal and blunt subsurface damage, reduce the contaminant concentration by removing the Beilby layer. However, further etching often results in a decrease rather than an increase of damage threshold due to impurities re-deposition and surface roughness deterioration [12,13]. Ion-beam sputtering (IBS) based on physical sputtering effect is a kind of highly deterministic processing method, with highly controllable sputtering depth and other advantages such as good anisotropy, low-damage and little stress produced in the target materials [14]. As a clean and non-contact machining technique, IBS can achieve super-smooth

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surface without introduction of other metal impurities such as Fe element and re-deposition layer on the surface compared with MRF and HF etching [15,16]. At present, there have been some researches with good results on the LIDT improvement of fused silica by IBS. Kamimura et al. utilized low-energy IBS to remove the polishing re-deposition layer without degrading surface quality. And the LIDT of fused silica was enhanced to about 2.0 times and 1.3 times at wavelengths of 266 nm and 1064 nm, respectively [17]. Xu et al. used IBS to remove the surface damage induced by laser irradiation and found the LIDT recovered to that of the unirradiated fused silica [18]. However, there is still lack of systematic investigations on surface characteristics evolutions during IBS and the relationship between surface characteristics evolutions and the laser damage performance of fused silica. Consequently, more researches are necessary to clarify the mechanism of IBS on the changes of surface characteristics and surface-damage resistance.

The purpose of this work is to give a comprehensive insight into the effects of IBS on surface characteristics evolutions and laser damage performance of polished fused silica in UV laser. In this study, removal of different depths by IBS and laser damage tests were carried out on fused silica samples. The changes of surface roughness, impurity element concentration as well as the morphology evolution of typical scratches during IBS were studied. The influence of surface characteristics evolutions on damage threshold were theoretically analyzed and simulated. The results further clarify the influence law of surface characteristics evolutions on damage performance of fused silica during IBS, which provides technical guidance for the application of IBS to improve the LIDT of fused silica optics.

2. Experiments of IBS and laser damage test

Three commercial fused silica samples (Heraeus 312) derived from the same material were treated by conventionally chemical–mechanical polishing (CMP) process, with similar surface roughness (0.3–0.4 nm RMS(root mean square)). And CeO_2 was used as the abrasive particle in CMP process. Sample A with size of $50 \times 50 \times 5$ mm^3 was used for the measurement of surface roughness and laser damage test. Sample B with size of $10 \times 10 \times 2$ mm^3 was used for detection of impurity elements concentration. Sample C with size of $50 \times 50 \times 5$ mm^3 was used for the study of morphology evolution of typical scratches.

All IBS experiments were performed in our self-developed IBS system (2.5×10^{-3} Pa work pressure) under the bombardment of Ar + ions at normal incidence. Within the experiments, the sputtering conditions were fixed at an ion source energy $E_{ion} = 900$ eV, beam current $J_{ion} = 13$ mA, and work temperature T $\approx$ 60 °C. As shown in Fig. 1, sample A was divided into 7 regions, with removal depths of 50 nm, 100 nm, 200 nm, 300 nm, 500 nm, 1000 nm, respectively. The ScanAsyst mode of Bruke Dimension Icon atomic force microscope (AFM) was used to measure the surface roughness in different depths and 5 positions were selected randomly to calculate the average roughness for each region. The laser damage test experiment was carried out on our own-built laser damage test platform. After each sputtering, sample A was firstly cleaned with deionized water and dried with high-pressure nitrogen, then followed by the laser damage test. Surface metal impurities of sample B were detected before and after IBS by Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) with a high sensitivity (on the order of magnitude of ppm to ppb for most species). Sample C was sputtered with different depths of 30 nm, 130 nm, 230 nm, 530 nm, 1130 nm, 1830 nm, respectively. Tapping Mode of AFM was used to observe the morphology evolution of typical scratches. AFM measurements were performed at a fixed scan size of 10 μm × 10 μm for surface roughness and 50 μm × 50 μm for morphology evolution, with a resolution of 512 × 512 pixels and a scan rate of 1.0 Hz. High aspect ratio Si scanning probe with a vertex radius less than 10 nm was used to ensure the accuracy of the AFM results and to minimize any tip convolution of the shape measured.

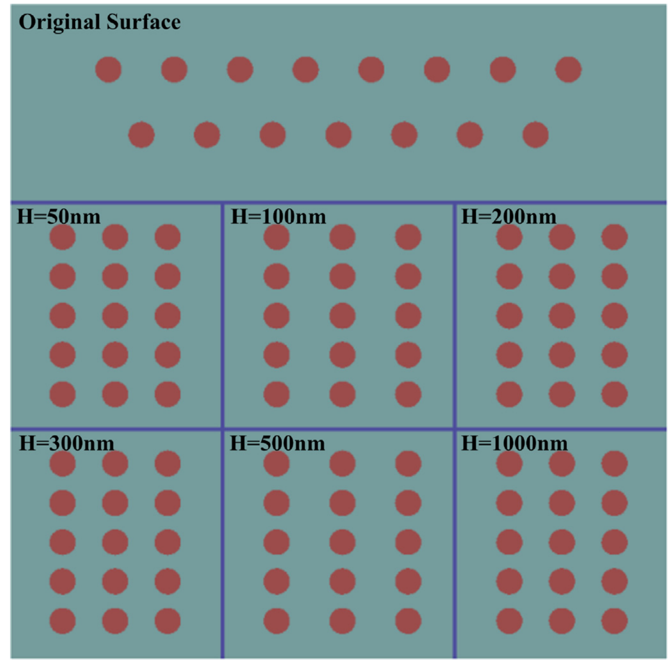

Fig. 1. The laser damage test positions distribution of sample A. 15 points were tested in each region.

3. Results

3.1. Surface roughness change

Fig. 2 shows the experimental results of the removal depth-dependent morphology evolution of fused silica surface during IBS process. Fig. 3 displays the corresponding change of surface roughness. As can be seen from Fig. 2, the original surface of sample A is relatively smooth with a roughness of 0.339 nm RMS. There is no other obvious manufacturing defect in the field of vision (10 μm × 10 μm) except for subtle polishing traces. However, with the increase of removal depth, the surface quality deteriorates seriously because of the gradual exposure of residual polishing particles and subsurface damage hidden by the polishing re-deposition layer. Accordingly, the surface roughness value increases dramatically from 0.339 nm RMS to 0.662 nm RMS. The surface quality becomes the worst (0.662 nm RMS, Fig. 2(d)) when the material removal is up to 200 nm. It can be think that the polishing re-deposition layer has been completely removed, and the subsurface damage is fully exposed at this time [19]. When the removal depth exceeds 200 nm, the surface quality improves significantly with the continuous increase of removal depth, and the roughness value decreases sharply to a level (0.283 nm RMS, Fig. 2(f)) better than the original surface without IBS processed. This may be because the subsurface damage layer is gradually removed by IBS, and the smoothing effect induced by ion sputtering at near-normal incidence. The roughness value remains stable (0.25 nm RMS) when the removal depth is greater than 500 nm. For further investigation of surface quality change during IBS, we take the power spectral density (PSD) function of the data from AFM images for comparison. Fig. 4 displays the PSD analysis curves of morphology evolution at different removal depths. It is evident that