Optik 125 (2014) 756–760

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

# Optical characterization and laser damage of fused silica optics after ion beam sputtering

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ARTICLE INFO

*Article history:*
Received 11 March 2013
Accepted 6 July 2013

*Keywords:*
Ion beam sputtering
Fused silica
Sputtering yield
SRIM
LIDT

ABSTRACT

The sputtering process of fused silica bombarded by Ar ion beam is simulated with the SRIM software. The effects of ion beam energy and incident angle on sputtering yield and surface damage are computed. Since ion beam sputtering will result in defects in fused silica, such as *E′* color centers and other lattice defects and probably Argon bubbles, the optimized sputtering energy is selected below 1 keV so that the projected range of Ar ions is less than 10 Å. The experimental results show that the scratches in subsurface of fused silica can be smoothed obviously and better surface can be obtained as the optimized parameters are used for ion beam sputtering. The laser induced damage threshold of fused silica increases by about 18% after ion beam sputtering.

## 1. Introduction

As a preferred optical material for high-fluence optics, fused silica is widely used as the window glasses and lens in many laser facilities, such as the National ignition facility (NIF) in USA and the laser mega joule (LMJ) in France. And the laser-induced damage of fused silica optics has been one of the major focuses in the laser systems [1–3]. Generally speaking, the laser induced damage threshold (LIDT) of the conventionally polished surface of fused silica is much lower than the dielectric breakdown threshold of the bulk due to the surface and subsurface defects [4] (including mechanical defects, light-absorbing contaminations, defect centers, cracks and scratches, etc.), which limit the development of high power laser systems.

During the past decades, a number of sputtering techniques, e.g., acid etching [5], plasma or reaction ion beam etching [6,7], ion beam sputtering [8–10], and laser conditioning [11], have been reported to remove the surface and subsurface defects to enhance the surface damage resistance of fused silica. However, the acid etching will broaden and deepen the scratches to increase the surface roughness. Plasma and reaction ion beam etching will decrease the LIDT of target materials because of the carbon contamination from the reaction gas $CF_4$. After the laser conditioning, stress induced by the local heating will be left in the sample, which makes optics easy crack and even fracture under subsequent laser shots. Inert ion beam sputtering/etching is an efficient means to remove defects without any degradability of the surface roughness. It is a clean and physical technique with highly controllable sputtering depth and other advantages such as good anisotropy, low-damage and little stress produced in the target materials. As a non-contactable super-smooth (root mean square (RMS) roughness <0.5 nm) machining technique, ion beam sputtering has been used to sputter the surfaces of various materials, e.g., semiconductor materials Si, InP [12], $CuInSe_2$ [13], and the insulator materials SiC [14], $CaF_2$ [15], $CsLiB_6O_{10}$ [8], etc. For fused silica material, there have been some reports on the LIDT improvement by ion beam sputtering. For example, Kamimura et al. [9] utilized low-energy ion-beam sputtering to improve the LIDT. It was found that the LIDT of fused silica was enhanced to approximately a factor of 2.0 at the wavelength of 355 nm and 1.3 at 1064 nm. Xu et al. [10] used ion beam sputtering to remove the surface damage induced by laser irradiation and the LIDT of optics was recovered to that of the un-irradiated fused silica. However, there is no systematic investigation on the relationship between the sputtering rate and ion beam parameters or how to choose the optimized sputtering parameters.

In this work, the process of Ar ion beam bombarding the fused silica surface are simulated by the stopping and range of ions in matter (SRIM) software to understand the correlations between

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http://dx.doi.org/10.1016/j.ijleo.2013.07.039

**Table 1**
Target material parameters for computer simulation.

| Atoms | Density ($\mathrm{g\,cm^{-3}}$) | Displacement energy (eV) | Lattice binding energy (eV) | Surface binding energy (eV) |
|---|---|---|---|---|
| Si | 2.2 | 15 | 2 | 4.7 |
| O | | 28 | 3 | 2 |

ion beam sputtering rate of fused silica and ion energy and incident angle. The projected range of the incident ions and the damage level dpa (displacements per atom) are analyzed to indicate the damage depth and degree to target materials induced by incident ions so that we can obtain the optimized ion energy and incident angle for ion beam sputtering. After that the experiments are carried out with the optimized parameters. An optical microscope, an atom force microscope (AFM) and a profilometer are used to characterize the surface evolution after ion beam sputtering. Finally, the LIDT measurements of the fused silica are conducted to study the effect of ion beam sputtering on the damage resistance of fused silica optics.

## 2. Computer simulation

Ion beam bombardment of solid targets is a complicated process with the production of atomic recoils and defects within the target materials and the ejection or sputtering of atoms from the surface. During ion sputtering process, the energy transferred to atoms of the solid is large enough to cause their displacement from their equilibrium positions and the surface atoms are ejected out of the material by the energetic ions. The sputtering depth is highly controllable by the sputtering time with the nano-scale accuracy. It is an atomic level physical process [16].

SRIM is a software package concerning the stopping and range of ions in matter [17]. Using a quantum mechanical treatment and statistical algorithms, it can calculate the stopping and range of ions (up to 2 GeV/amu) into matter efficiently. The information about the interaction between ions and target atoms can be obtained though the computer simulation, including the distribution of incident ions within the target materials, the energy loss of ions and recoil atoms, the numbers of back scattered ions and transmitted ions and the sputtering yield of ions. In this work, the interaction between Ar ions and target atoms of fused silica is simulated with SRIM-2008 code. And the target material parameters for computer simulation are listed in Table 1.

## 3. Results and discussion

### 3.1. Sputtering rate VS. sputtering parameters

Eq. (1) shows the relationship between the sputtering rate $R(\theta,E_i)$ and the sputtering yield $Y(\theta,E_i)$ (atoms, clusters of atoms or molecules ejected per incident ion) [16]. It is clear that $R(\theta,E_i)$ is the function of ion beam incident angle $\theta$ (the angle between the ion beam direction and the normal direction to the sample surface) and ion beam energy $E_i$. And the sputtering yield can be obtained directly from the simulated results.

$$R(\theta, E_i) \propto Y(\theta, E_i)\cos\,\theta \tag{1}$$

The energy range of the SRIM simulation is from 100 eV to 200 keV, and ion incident angle is from 0° to 89°. Fig. 1 shows the correlation between simulated sputtering yield and ion energy at the fixed incident angle $\theta = 75°$. The sputtering yield (SY) of target atoms (both silicon and oxygen atoms) increases first and then decrease with the increasing incidence energy. There is a maximum value at about $E_i = 50$ keV for both atoms. From Eq. (1), the maximum sputtering rate is also achieved at $E_i = 50$ keV when the incident angle is fixed at 75°.

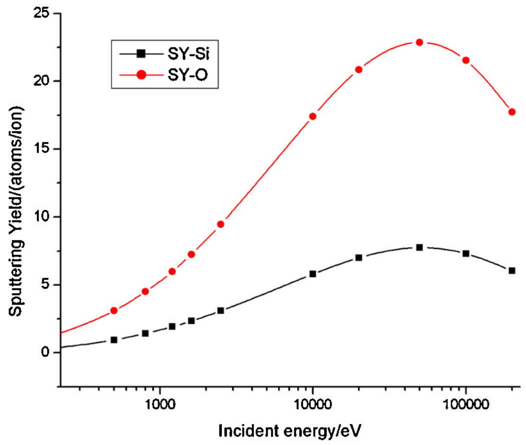

**Fig. 1.** Correlation between simulated sputtering yield and ion energy at the fixed incident angle $\theta = 75°$.

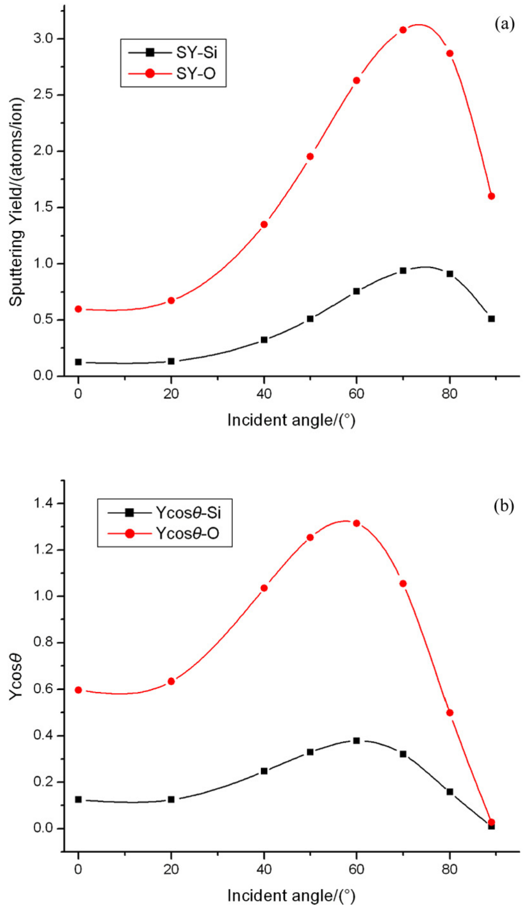

**Fig. 2.** Correlations between sputtering yield (a) and sputtering rate (b) and incident angle when $E_i = 500$ eV.