Surface Microstructuring of Inclined Trench Structures of Silica Glass by Laser-induced Backside Wet Etching

Hiroyuki Niino, Yoshizo Kawaguchi, Tadatake Sato, Aiko Narazaki, and Ryozo Kurosaki

Photonics Research Institute,
National Institute of Advanced Industrial Science and Technology (AIST),
Tsukuba Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan
niino.hiro@aist.go.jp

We have investigated a one-step method to fabricate a microstructure on a silica glass plate by using laser-induced backside wet etching (LIBWE) that consists of diode-pumped solid state (DPSS) laser beam scanning system. The focused laser beam of a DPSS UV laser at λ = 266 nm on the repetition rate of 10 kHz was directed to the sample cell of the glass. Deep vertical microtrenches having an aspect ratio of ca. 6 were fabricated on the surfaces of silica glass. Inclined trench structures at the angle of 60 degree were successfully fabricated by changing the incident angle of the laser beam onto the glass surface through an equilateral prism at the normal incidence of the laser baem.

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1. Introduction

The high precision surface microfabrication of the UV-transparent materials such as a silica glass is one of the key technologies of photonics research and development. However, silica glass is a hard and brittle material, and precision surface microfabrication is very difficult. Laser-induced micro-fabrication of various materials has served as an important technique in surface structuring for optics and optoelectronic devices. [1] In particular, significant attention has been given towards the micro-fabrication of silica glass, since, in spite of the difficulty involved, silica is a commonly used material. The use of pulsed lasers can involve several approaches, such as conventional UV laser ablation, [2] vacuum UV laser processing, [3,4] femtosecond laser micromachining, [2,5] laser-induced plasma-assisted UV ablation, [6,7] and laser-induced backside wet etching (LIBWE). [8-74] The micro fabrication of such transparent materials as silica glass [8,11-15,17-53,55-58,63-68], quartz [9,34,37,58-62,74], glasses (Pyrex etc.) [36], calcium fluoride [11,34,59], magnesium fluoride [34], barium fluoride [59,61], fluorocarbon resin [10], borosilicate glass [71], soda lime glass [72,73], and sapphire [16,34,54,59,69,70] was reported.

In this paper, we report an extended study on the fabrication of deep trench structures on silica glass using the laser-induced backside wet etching (LIBWE) upon UV laser irradiation at a kHz repetition rate. The laser beam was incident on the sample with a galvanometer-based point scanning system of a single-mode laser beam from a diode-pumped solid state (DPSS) laser at the wavelength of 266 nm. Vertical and inclined trench structures were fabricated on the glass by changing the incident angle of the laser beam.

The LIBWE method is based on the deposition of laser energy onto a thin layer at the glass-liquid interface during the ablation of a liquid substance. Assuming negligible UV absorption by the silica glass, the incident laser beam passes through the glass plate resulting in the excitation of a dye or organic solution. If the dye solution, which has a strong absorption at the laser wavelength, becomes ablated by laser irradiation with sufficient fluence, etching on a surface layer of the silica glass is achieved.

2. Experimental

An Nd:YVO_4 laser at the fourth harmonic wavelength (λ = 266 nm, FWHM 30 ns, $M^2 < 1.3$) was used as a light source in ambient condition. The laser was operated at the repetition rate of 10 kHz. The laser beam with a horizontal Gaussian beam profile in intensity, was scanned with galvanometer-based point scanning module (GSI Lumonics, HPM10M2). Optics of a zoom-beam-expander (Sill Optics), pinhole and telecentric scan lens (Sill Optics, focus length: 100 mm) were used to obtain a scanning laser beam with a small focused spot size (diameter: 4 μm) [28]. Laser fluence was estimated with a division of laser energy by the beam diameter. A fused-silica glass plate (Tosoh SGMCo., ES grade) with a thickness of about 0.5 mm was used as a sample. After the glass sample was mounted at an optimized position on the stage, the sample position was fixed during the laser irradiation at a repeating scan for a deep trench fabrication in the case of normal incidence (Fig. 1).

An equilateral prism of silica glass was used for changing the incident angle of the laser beam onto the glass surface. The prism was attached to the silica glass plate with the immersion liquid of distilled water as index matching (Fig. 2(b)).

Toluene (Wako Pure Chemical Industries Ltd., S grade) was used without further purification. The penetration depth (d) of pure toluene solution at the wavelength of 266 nm was estimated to be 6.1 μm on the basis of single photon absorption (d = Mw/ερ; molecular weight, Mw = 92 g mol^{-1}; density, ρ = 0.86 kg dm^{-3}; absorption coefficient, ε = 175 mol^{-1} dm^{3} cm^{-1} (hexane solution) [75]).

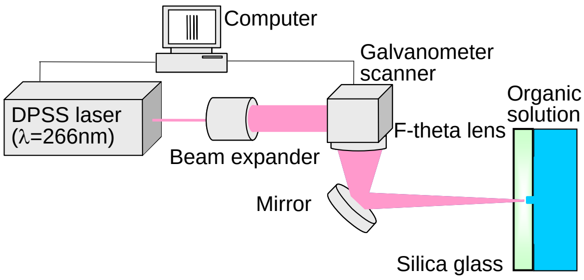

Fig. 1 Experimental setup for the LIBWE by using Galvanometer-based point scanning system (laser beam at normal incidence).

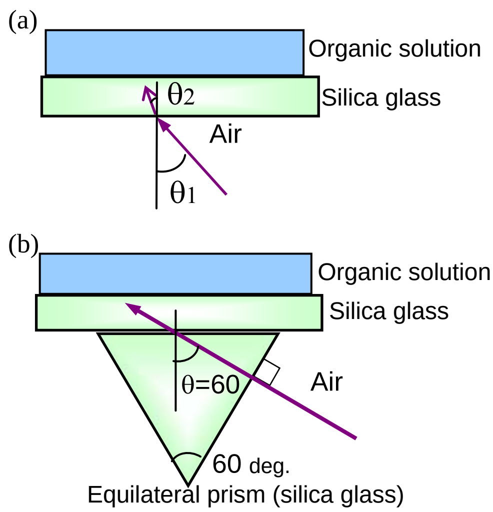

Fig. 2 Schematic drawing of laser beam irradiation at oblique incidence onto the silica glass plate for LIBWE; (a) without a prism, (b) through a prism.

3. Results and Discussion

3.1 Microstructuring of silica glass with galvanometer scanning system

Well-defined microtrenches, which were free of debris and microcracks around the area, were fabricated by UV laser irradiation using a single-mode laser beam, as shown in Fig. 3. The laser irradiation at the incident angle of 0 degree onto the glass surface was carried out at a laser energy of 1 μJ $pulse^{-1}$ with a repetition rate of 40 kHz and a scanning rate of 100 mm s^{-1} (fluence: 8.0 J cm^{-2} $pulse^{-1}$). The groove with 4 μm in width and 25 μm in depth was produced by repeated scanning irradiation up to 50 times. As the laser beam scanning was controlled with galvanomirrors by a computer system in Fig. 1, microstructures that consist of multi-groove on the glass were flexibly fabricated by the modification of layout designs stored in the computer [28,31,33]. The depth of focus (DOF) of the irradiation system was estimated to be 70 μm [28].

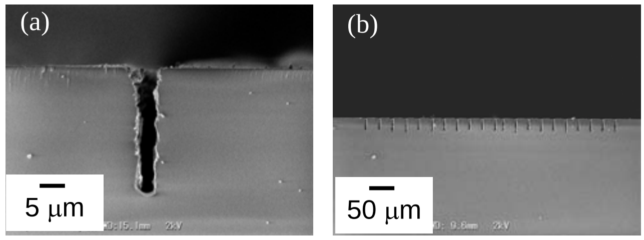

Fig. 3 Cross-sectional SEM pictures of groove structures on silica glass at normal incidence (width: 4 μm, depth: 25 μm).

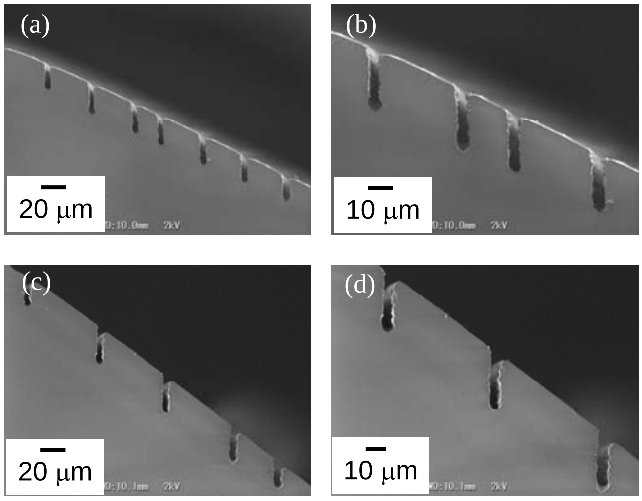

Fig. 4 Cross-sectional SEM pictures of groove structures on silica glass at oblique incidence; (a, b) θ_1= 45 degree (width: 4 μm, depth: 20 μm), (c, d) θ_1= 60 degree (width: 4 μm, depth: 20 μm).

When the laser beam was incident on the sample at an oblique angle, the etching front at the trench bottom proceeded to the incident direction of the beam, resulting in inclined trench formation on the glass. Fig. 4 shows inclined trenches, where the laser beam was incident from the air to the glass at 45 degree and 60 degree. The laser irradiation was carried out at 1.5 μJ $pulse^{-1}$ with 40 kHz at a scanning rate of 40 mm s^{-1} (fluence: 10.5 J cm^{-2} $pulse^{-1}$ at θ_1= 45 degree, 9.7 J cm^{-2} $pulse^{-1}$ at θ_1= 60 degree). The grooves were produced by repeated scanning irradiation up to 100 times. These results show that LIBWE is able to provide vertical and inclined trench structures with a high aspect ratio on the glass by changing the incident angle of the laser beam.

In LIBWE, the etching took place on the backside surface of the laser incidence, as shown in Fig. 1. At the oblique incidence, the beam was refracted at the interface between the air and the glass by Snell's law, as shown in Fig. 2(a):

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \qquad (1)$$

where n_1 is the refractive index of the air (n_1 = 1.00), θ_1 the incident angle of laser beam from the air to the glass, n_2 the refractive index of silica glass (n_2 = 1.50 at λ= 266 nm) and θ_2 is the refracted angle into the glass. In the trench formation in Fig. 4(c), (d), the inclined angle of the trench at 36 degree was experimentally observed. As θ_1 in Eq. (1) was 60 degree, θ_2 was calculated to be 36 degree. Because there was good agreement between the inclined trench angle and θ_2, the etching front at the bottom of the trench was guided towards the direction of laser incidence in a deep trench fabrication by LIBWE. Our results show that the depth direction of the trenches was coincident with the direction of the incident laser beam.

3.2 Equilateral prism insertion for LIBWE

On the basis of the Snell's law, the oblique angle of ca. 40 degree is the maximum when the laser beam is incident onto a co-planar silica glass plate for LIBWE [29]. An equilateral prism was employed to fabricate an inclined trench. The laser beam was perpendicularly incident on the prism, as shown in Fig. 2(b). Figure 5 shows cross-sectional SEM pictures of the sample that was irradiated at 7 μJ $pulse^{-1}$ with 10 kHz at a scanning rate of 20 mm s^{-1}. A well-fabricated groove was formed by repeated scanning irradiation up to 20 times. In this fabrication, the laser energy was required up to 7 μJ $pulse^{-1}$ because of energy loss at the immersion liquid with a poor index matching.

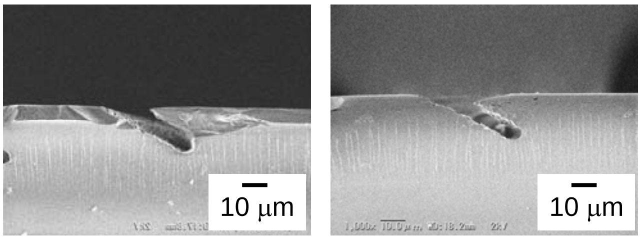

Fig. 5 Cross-sectional SEM pictures of groove structures on silica glass at oblique incidence through an equilateral prism (width: 4 μm, depth: 20 μm).

These results also show that LIBWE with a prism is able to provide inclined trench structures with a high aspect ratio on the glass by changing the incident angle of the laser beam.

4. Conclusions

We have demonstrated that a well-defined micropattern on a silica glass plate was fabricated by LIBWE method using galvanometer-based point scanning of employing a DPSS UV laser. As the laser system provides a large DOF degree, a deep trench structure is readily fabricated by LIBWE method. Vertical and inclined trench structures were also fabricated on the glass by changing the incident angle of the laser beam. As the laser beam is scanned on the sample surface with the galvanometer controlled by a computer for flexible operations, galvanometer-based point scanning system is suitable for a rapid prototyping process according to electronic design data in the computer.

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