A deep micro-trench on silica glass fabricated by laser-induced backside wet etching (LIBWE)

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Abstract. By using laser-induced backside wet etching (LIBWE), we have fabricated very deep micro-trenches in silica glass of 9-μm width and 300-μm depth (aspect ratio ≈ 33). In this paper, we present the details of fabricating the micro-trenches, and discuss why such a deep micro-trench is available by the LIBWE method.

1. Introduction
Silica glass has excellent properties such as good optical transparency from the deep ultraviolet (DUV) to the near infrared (NIR) region, good thermal stability, mechanical hardness, and endurance against chemicals. Thus, silica glass has been utilized in various fields, and micro-/nano-structuring of silica glass has been strongly requested for its widespread application. However, the good optical transparency makes fabrication of silica glass by lasers difficult, and numerous researches have been studied for micro-/nano-fabrication of silica glass by lasers [1-17]: usage of focused ultrashort lasers [2, 3], vacuum ultraviolet (VUV) lasers [2, 4, 5], CO₂ lasers [6], laser-induced plasma [2, 5], laser-induced X-ray [7], and laser ablation of highly laser-absorbing liquids [2, 8-17].

We have developed a method of surface microstructuring silica glass by using laser ablation of liquids, and named it laser-induced backside wet etching (LIBWE) [2, 8-15]. A schematic of the LIBWE method is shown in figure 1. A nanosecond (ns) pulsed laser beam, such as an excimer laser beam, transmits a silica glass plate, and is strongly absorbed by a highly laser-absorbing liquid which is in contact with the rear surface of the silica plate. Thus, liquid ablation occurs, causing etching of the silica plate. By this LIBWE method, various transparent materials beyond fused silica can also be etched well: quartz crystal, CaF₂, MgF₂, sapphire, fluoride polymer (FEP), Pyrex, etc. Advantages of

| Table 1. Advantages of the LIBWE method. |
|------------------------------------------|
| * Resist-free, single-step process       |
| * Simple pre-/post-treatment             |
| * Surface structuring of any shape by using a mask projection system or a galvanometer scanning system |
| * Control of etch depth in nm scale      |

Figure 1. Schematic of the LIBWE method.
the LIBWE method are listed in Table 1. Due to these advantages, several research groups in the world are studying to apply the LIBWE method for the fabrication of various devices [16-19].

In this report, by applying another characteristic of the LIBWE method, that is, etching a transparent plate from the rear surface, we demonstrate etching of a very deep micro-channel on silica glass by the LIBWE method. Deep etching of a silica glass with high aspect ratio is an important technique for fabricating various micro-devices.

2. Experiment
A KrF excimer laser beam (EMG-201MSC, \(\lambda = 248\) nm, \(\tau_{\text{FWHM}} \approx 30\) ns) was patterned with a metal photomask, and passed through a silica glass plate (thickness: \(t = 2.0\) mm) at \(F = 1.0\) J cm\(^{-2}\) fluence and 10 Hz repetition rate. The beam intensity distribution was made uniform with a homogenizer. The photomask was designed to fabricate a trench with a width of approximately 9 \(\mu\)m and a length of 1 mm. The laser beam was absorbed by a saturated pyrene/acetone solution which was in contact with the rear surface of the silica plate to facilitate liquid ablation driven etching of the glass. During etching, the silica plate was moved away from the projection lens at 10 \(\mu\)m per 1,000 pulses to adjust the laser-etching front with the imaging plane of the lens. For comparison, similar etching was executed while moving the silica plate away from the lens at 10 \(\mu\)m per 2,000 pulses, which yields only one half of the target movement in the above case.

After etching, the silica plate was rinsed with acetone, ultrasonically washed in distilled water, and cut in half perpendicular across the trench to observe the etch cross sections with a scanning electron microscope (SEM, Keyence, VE-7800). Before SEM observation, the silica plates were rinsed and washed again, and were coated with gold.

3. Results and Discussion
Figure 2 shows cross sectional SEM images of the deep trench fabricated by the LIBWE method with the irradiation of 20,000 pulses while translating the silica plate at 10 \(\mu\)m per 1,000 pulses. From figure 2 (a), the depth of the trench was approximately 300 \(\mu\)m. Figure 2 (b) shows magnified images of figure 2 (a), showing that the sidewalls were straight, parallel and smooth. The bottom of the deep trench had a slight U-shape. The shape of the sidewalls and bottoms were almost the same for shallower trenches under irradiation of smaller pulse numbers.

Figure 3 shows a cross-sectional SEM image of another deep trench, irradiated with 10,000 pulses at similar exposure conditions, except that the silica plate was moved away from the lens at 10 \(\mu\)m per 2,000 pulses. The etch depth was only 85 \(\mu\)m, less than 1/3 of that in figure 2 (a), and the sidewalls

![Figure 2](image_url). Cross sectional SEM image (a) of the deep trench on silica glass fabricated by the LIBWE method, and in higher magnification (b). Irradiation of 20,000 pulses was applied at \(F = 1.0\) J cm\(^{-2}\) and 10 Hz. The silica plate was moved away from the lens at 10 \(\mu\)m per 1,000 pulses.
were more rough and not so straight as compared with those in figure 2 (b).

Figure 4 shows etch depth versus pulse number for two different sample speeds. In the case of (■), a nearly uniform etch rate of ~15 nm pulse\(^{-1}\) is noted that increases only slightly with pulse number, especially in the 0-10,000 pulse range. Because of the large imaging area of the telecentric projection lens, the etch depth advances almost linearly even though the silica plate motion (10 \(\mu\)m / 1,000 pulses) is slower than the etch front. By better synchronizing this sample movement with the etch front, we succeeded in fabricating a deeper micro-trench of ~7 \(\mu\)m width and 420 \(\mu\)m depth (aspect ratio = 60) by irradiating 25,000 pulses at 80 Hz, yielding an average etch rate of 17 nm pulse\(^{-1}\) for a total processing time of ~ 5 min [14]. In contrast, slower scanning in the case of (●) in figure 4 yielded a decrease in the etch rate with increasing exposure. Here, the etch front advanced more quickly than the movement of the lens imaging plane, resulting in an overall decreased etch rate.

The reason of successful deep etching on silica glass in the LIBWE method is as follows. As shown in figure 5, the laser beam transmits through the silica glass to be strongly absorbed by the organic solution in a very thin region, the order of microns [9, 11, 13]. Then liquid ablation occurs, yielding an instantaneous local temperature increase and vaporization, causing a very high transient pressure. This drives etching in a very local region of the silica glass with etch rates as small as 10 nm pulse\(^{-1}\). Etching proceeds with each irradiation pulse, resulting in a very deep microetching by cumulative laser irradiation. As etching proceeds, the etch front moves towards the projection lens and therefore requires a synchronous counter movement of the silica plate away from the lens to keep the etch front positioned at the lens imaging plane. Figures 3 and 4 clearly demonstrate that incorrect positioning of the etch front seriously worsens the results for deep etching.

In contrast, direct laser microetching of the front surface of a material leads to a tapered or a V-

**Figure 3.** Cross sectional SEM image of the a deep trench on silica glass fabricated by the LIBWE method. Irradiation of 10,000 pulses was applied at \(F = 1.0 \text{ J cm}^{-2}\) and 10 Hz. The silica plate was moved away from the lens at 10 \(\mu\)m per 2,000 pulses.

**Figure 4.** Etch depth versus the number of laser pulses for cases where the silica plate was moved away from the lens at (■) 10 \(\mu\)m per 1,000 pulses and (●) 10 \(\mu\)m per 2,000 pulses.

**Figure 5.** Schematic of deep microetching by the LIBWE method.
shaped trench when attempting to form deep trenches. This is due to the limited depth of focus of the lens, making difficult the formation of deep trenches with parallel sidewalls [20].

4. Conclusion
The LIBWE method of driving rear surface laser ablation in a strongly absorbing liquid was successfully applied to fabricate high aspect ratio micro-trenches in glass. The method combines high lateral resolution of micron to sub-micron with deep etching (hundreds of microns) to expand the range of possible microstructures that can be fabricated, including various microdevices such as micro-optics, micro-electromechanical systems (MEMS), and micro-fluidics.

Acknowledgements
This study was partly supported by Industrial Technology Research Grant in ’05 from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References
[1] Bäuerle D 2000 Laser Processing and Chemistry 3rd Ed. (Berlin: Springer Verlag) chapter 13.6 pp 276-279, chapter 14.4 pp 301-305
[2] Kawaguchi Y, Niino H and Yabe A 2003 Microfabrication of Transparent Materials by Laser Processing Photo-Excited Processes, Diagnostics and Applications - Fundamentals and Advanced Topics ed Peled A (Boston: Kluwer Academic Publishers) chapter 12 pp 339-357.
[3] For example, Varel H, Ashkenasi D, Rosenfeld A, Wähmer M and Campbell E E B 1997 Appl. Phys. A 65 367-373.
[4] Ihlemann J, Müller S, Puschmann S, Schäfer D, Wei M, Li J and Herman P R 2003 Appl. Phys. A 76 751-753.
[5] Sugiooka K, Obata Hong M H, Wu D J, Wong L L, Lu Y F, Chong T C and Midorikawa K 2003 Appl. Phys. A 77, 251-257, and references therein.
[6] Kitamura N, Fukumi K, Nishii J, Kinoshita T and Ohno N 2003 Jpn. J. Appl. Phys. 42 L712-L714.
[7] Makimura T, Mitani S, Kenmotsu Y, Murakami K, Mori M and Kondo K 2004 Appl. Phys. Lett. 85 1274-1276.
[8] Wang J, Niino H and Yabe A 1999 Appl. Phys. A 68, 111-113.
[9] Wang J, Niino H and Yabe A 2000 Appl. Surf. Sci. 154-155, 571-576.
[10] Ding X, Kawaguchi Y, Niino H and Yabe A 2002 Appl. Phys. A 75 641-645.
[11] Niino H, Yasui Y, Ding X, Narazaki A, Sato T, Kawaguchi Y and Yabe A 2003 J. Photochem. Photobiol. A: Chemistry 158 179–182.
[12] Ding X, Kawaguchi Y, Sato T, Narazaki A, Kurosaki R and Niino H 2004 J. Photochem. Photobiol. A: Chemistry 166 129-133.
[13] Kawaguchi Y, Ding X, Narazaki A, Sato T and Niino H 2005 Appl. Phys. A 80, 275–281.
[14] Kawaguchi Y, Sato T, Narazaki A, Kurosaki R and Niino H 2005 Jpn. J. Appl. Phys. 44 L176–L178.
[15] Niino H, Ding X, Kawaguchi Y, Sato T, Narazaki A and Kurosaki R 2005 SPIE Proc. 5662 18-23 and references therein.
[16] Kopitkovas G, Lippert T, David C, Canulescu S, Wokauna A and Gobrecht J 2004 J. Photochem. Photobiol. A: Chemistry 166 135-140 and references therein.
[17] Zimmer K and Böhme R 2005 Appl. Surf. Sci. 243 415-420 and references therein.
[18] Cheng J Y, Yen M H, Wei C W, Chuang Y C and Young T H 2005 J. Micromech. Microeng. 15 1147-1156.
[19] Fujito K, Hashimoto T, Samonji K, Speck J S and Nakamura S 2004 Thin Solid Films 272 370-376.
[20] Tseng A A, Chen Y T and Ma K J 2004 Opt. Lasers Eng. 41 827-847.