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Laser-induced front side etching: An easy and fast method for sub-µm structuring of dielectrics

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Abstract

Laser-induced front side etching (LIFE) is a method for the nanometer-precision structuring of dielectrics, e.g. fused silica, using thin metallic as well as organic absorber layer attached to the laser-irradiated front side of the sample. As laser source an excimer laser with a wavelength of 248 nm and an pulse duration of 25 ns was used. For sub-µm patterning a phase mask illuminated by the top hat laser beam was projected by a Schwarzschild objective. The LIFE process allows the fabrication of well-defined and smooth surface structures with sub-µm lateral etching regions ($\Delta x \leq 350$ nm) and vertical etching depths from 1 nm to sub-mm.

Keywords: Laser etching; LIFE ; SAL-LIFE; excimer laser; fused silica; metallic absorber layer

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1. Introduction

The sub-µm structuring of dielectrics by laser-solid interaction is a great challenge for laser processing. However, laser-induced sub-µm patterning has an outstanding potential for the ultra-precision fabrication, e.g. for micro-optical elements. Different laser approaches are known for etching of dielectrics, e.g. by direct ablation using VUV, ps, and fs lasers [1, 2] and by excimer laser radiation at high laser fluences [3, 4]. However, the direct ablation of dielectrics can tend to an increased surface roughness. An improved method for structuring is the application of thin adsorbing layers to the laser-irradiated surface to absorb the laser radiation. Based on this concept, different methods were developed, e.g. laser etching using a surface-adsorbed layer (LESAL), laser-induced back side dry etching (LIBDE), laser-induced back side wet etching (LIBWE) [5-7], and laser-induced front side etching (LIFE) as well as laser-induced front side etching using self-regenerating adsorber layer (SAL-LIFE). These methods allow the fabrication of nm-precision high-quality etching trenches with a low surface roughness. For the

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lateral sub-µm structuring, the intensity modulation of the laser beam is required, e.g. by interference methods like the beam-splitting phase mask projection [8] and the multi-beam interference [9]. In the following study, LIFE using chromium layer and SAL-LIFE using toluene were used for submicron patterning of dielectrics applying the phase mask projection.

2. Experimental

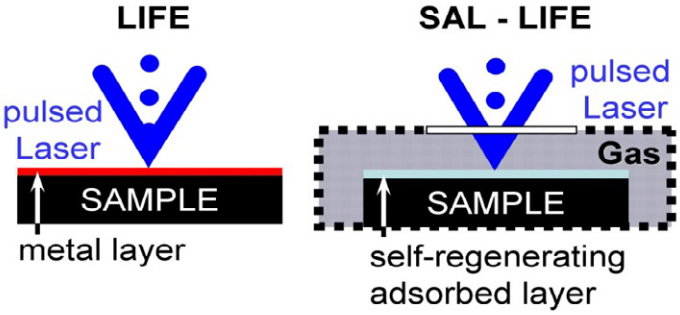

Fig. 1. Schematic illustration of the laser-induced front side etching (LIFE) method using a metal layer and the LIFE method using a self-regenerating adsorbed layer (SAL-LIFE)

In the following study, laser-induced front side etching using chromium metal layer and self-regenerating toluene adsorber layer was used. For the chromium layer, the polished fused silica surface was coated by magnetron sputtering with different metal layers. The thin toluene layer was induced by adsorption from a pressure-controlled toluene gas mixture in a vacuum chamber. The schematic illustration of the LIFE and the SAL-LIFE systems is shown in figure 1. The covered surfaces were irradiated by an excimer laser with a wavelength and a pulse duration of 248 nm and 25 ns, respectively. The laser has a top hat beam profile with an energy deviation in the mask plane of below 5% rms. Furthermore, the laser beam irradiates the beam splitting phase mask that was imaged onto the sample surface by projection optics (see figure 2). The etched surfaces were analysed by white light interferometry (WLI) and scanning electron microscopy (SEM).

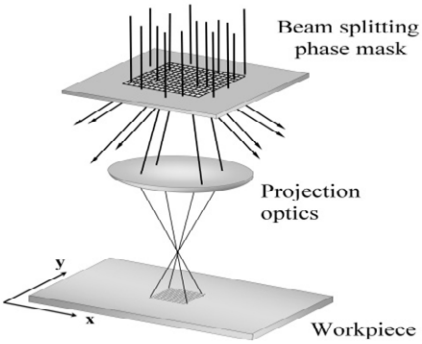

Fig. 2. Schematic illustration of applying phase masks for the production of sub-µm structures

3. Results and Discussion

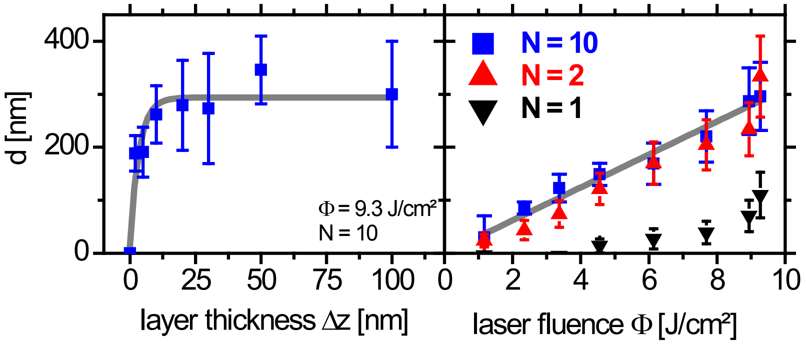

Fig. 3. Etching depth d = d(Φ,N,Δz) dependency on laser fluence Φ, metal layer thickness Δz, and pulse number N for the LIFE method measured by white light interferometry. The etching depth - layer thickness dependency was fitted by d ∝ (1-exp(-$\alpha^{\#}\cdot\Delta z$)) and the etching depth - laser fluence dependency was approximated by a linear function (see grey line)

The LIFE- and SAL-LIFE-induced etching trenches were measured by white light interferometry and the measured etching depth d in the fused silica dependency on the fabrication parameters is summarized in Fig. 3 and Fig. 4, respectively.

Summarizing the LIFE process, the etching depth d dependents on the laser fluence Φ and on the metal layer thickness Δz but is independent on the pulse number N, for N more the initial pulses, and on the repetition rate f [10].

The etching depth increased with rising metal layer thickness Δz and achieved an almost constant value for Δz higher than 20 nm. This behaviour can be analytically described by an exponential function (see fig. 3 (left) black line) very well. Furthermore, the etching depth increases almost linear with the laser fluence Φ. The etching depth dependencies are summarized in tab. 1. The etching depth can be approximated analytically by [10]:

$$d(\Phi,\Delta z) \approx \delta_0 \cdot \left(\Phi - \Phi_{th}^{LIFE}\right) \cdot \left(1 - \exp\left(-\alpha^{\#} \cdot \Delta z\right)\right) \qquad (1)$$

with: the ablation threshold Φ_{th}^{LIFE}, the slope coefficient δ_0 and the modified absorption coefficient $\alpha^{\#}$. The exponential dependency of etching depth on the chromium layer thickness can most likely be explained by the absorption of the laser radiation in the film. Under assumption of the Beer–Lambert law and an absorption coefficient α of 96.3 μm^{-1}[11], the major part (~ 90%) of the laser radiation is absorbed after 20 nm. The linear etching depth dependency was also found for the LIBWE process [12-14].

The LIFE process allows the production of well-defined etching trenches with a low surface roughness (with roughnesses lower than 10 nm rms) and an etching depth up to 300 nm.

In contrast to the LIFE process, the SAL-LIFE process presented a significant more complex etching depth dependency. At the SAL-LIFE process, the etching depth d is dependent on the laser fluence Φ, on the laser repetition rate f, on the pulse number N as well as on the toluene partial pressure p. The dependencies are summarized in fig. 4. The etching depth increases with rising of the laser fluence, the laser repetition rate, the pulse number as well as the toluene partial pressure. In agreement with the LIFE process, the etching depth for the SAL-LIFE process can be analytically described, too.

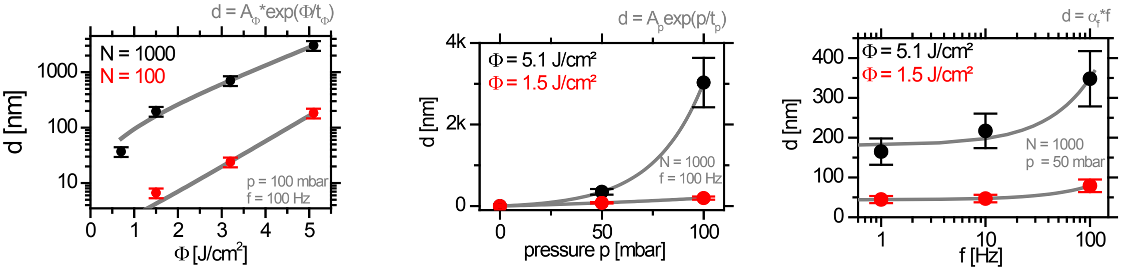

Fig. 4. Etching depth d = d(Φ,N,p,f) dependency on laser fluence F, pressure p, repetition rate f, and pulse number N for the SAL-LIFE method measured by white light interferometry. The etching depth dependencies were approximated by equation 2 (plot see grey line)

The etching depth presented an exponential dependency on the laser fluence as well as on the toluene partial pressure and a linear dependency on the pulse number as well as the repetition rate (see fig. 4). In summary, the etching depth can be analytically described by:

$$d(\Phi, N, p, f) \approx \eta \cdot (N - N_0) \cdot f \cdot \exp\left(\frac{\Phi}{\tau_\Phi} + \frac{p}{\tau_p} \right) \qquad (2)$$

with: the slope coefficient η, the initial pulses N_0, and the exponential coefficients τ_Φ and τ_p.

The experimentally found etching depth dependency for the SAL-LIFE method features significant differences to the back side etching methods: LESAL and LIBWE [5-7]. In agreement with the LIFE process, the SAL-LIFE process allows the fabrication of well-defined etching trenches with a low surface roughness. An example for SAL-LIFE µm-structured fused silica surface is presented in fig. 5. A surface roughness of the treated surface down to 1 nm rms is possible.

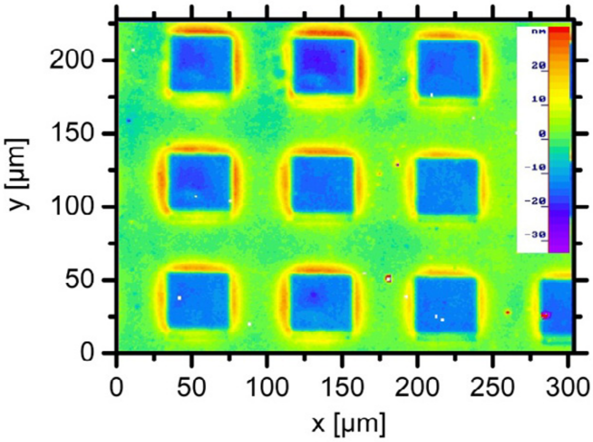

Fig. 5. WLI image of a SAL-LIFE µm-structured fused silica (periodicity 60 µm) (p = 50 mbar, f = 100 Hz, Φ = 4.2 J/cm², N = 100)

Beside the µm-structuring also the sub-µm structuring of fused silica is possible by using a beam splitting phase mask projection (see fig. 6). Different sub-µm surfaces structured by LIFE and SAL-LIFE are presented in fig. 6. The LIFE and the SAL-LIFE methods allow the fabrication of well-defined sub-µm etching trenches in fused silica with a low surface roughness and a high aspect ratio. With the actually used optical system of the laser workstation the production of structures with a lateral size down to 300 nm is possible.

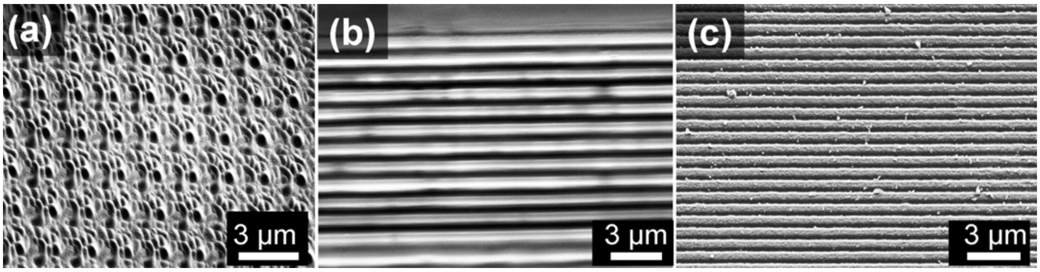

Fig. 6. SEM images of different sub-µm structures in fused silica produced by LIFE (figures (a) and (b)) and by SAL-LIFE (figure (c))

4. Conclusion

The LIFE and SAL-LIFE processes allow the fabrication of well-defined, smooth and nm-precise sub-µm structures in fused silica. The lateral size of the etchings range from sub-µm ($\Delta x \leq 350$ nm) to a few cm and etching depth from a few nm to 300 nm (LIFE) and to sub-mm (SAL-LIFE) can be achieved.

Acknowledgement

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References

[1] Herman, P. R., Marjoribanks, R. S., Oettl, A., Chen, K. P., Konovalov, I., and Ness S.,, “Laser shaping of photonic materials: deep-ultraviolet and ultrafast lasers” Appl. Surf. Sci. 154–155, 577-586 (2000).

[2] Lenzner M., Krüger J., Kautek W., and Krausz F., “Precision laser ablation of dielectrics in the 10-fs regime“ Appl. Phys. A 68 (3), 369-371 (1999).

[3] Ihlemann, J., Wolff, B., and Simon, P., “Nanosecond and femtosecond excimer laser ablation of fused silica”, Appl. Phys. A 54 (4), 363-368 (1992).

[4] Ihlemann, J. and Wolff-Rottke, B., “Excimer laser micro machining of inorganic dielectrics” Appl. Surf. Sci. 106, 282-286 (1996).

[5] Boehme, R., Zimmer, K., Ruthe, D., and Rauschenbach, B., “Backside Etching at the Interface to Diluted Medium with Nanometer Etch Rates”, J. Laser Micro/Nanoeng. 1(3), 190-194 (2006).

[6] Zimmer, K., Boehme, R., Vass, C., and Hopp B., “Time-resolved measurements during backside dry etching of fused silica”, Appl. Surf. Sci. 255(4), 9617-9621 (2009).

[7] Ehrhardt, M., Raciukaitis, G., Gecys, P., and, Zimmer, K., “Laser-induced backside wet etching of fluoride and sapphire using picosecond laser pulses”, Appl. Phys. A 101 (2), 399-404, 2010.

[8] Yang, G., “Laser Ablation in Liquids” Pan Standford Publishing, Singapore, 2012 ISBN 978-981-4310-95-6.

[9] Moon, J. H., Ford, J., Yang, S., “Fabricating three-dimensional polymeric photonic structures by multi-beam interference lithography”, Polym. Adv. Technol. 17 (2006) 83-93, DOI:10.1002/pat.663.

[10] Lorenz, P., Ehrhardt, M., Zimmer, K., “Laser-induced front side etching of fused silica with KrF excimer laser using thin chromium layers” Phys. Status Solidi A, in press, DOI 10.1002/pssa.201127672.

[11] Landolt-Börnstein Database, Springer Materials, www. springermaterials.com (Springer, Heidelberg, Berlin, 2010).

[12] Tseng A. A., Phys. Status Solidi A 204, 709 (2007).

[13] Hopp, B., Smausz, T., Vass, C., Szabo, G., Böhme, R., Hirsch, D., Zimmer, K., Appl. Phys. A 94, 899 (2009).

[14] Zimmer, K., Böhme, R., Rauschenbach, B., Appl. Phys. A 86, 409 (2007) .