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Micro patterning of fused silica by laser ablation mediated by solid coating absorption

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Abstract Precise patterning by laser ablation requires sufficient absorption. For weak absorbers like fused silica indirect methods using external absorbers have been developed. A novel approach using a solid SiO absorber coating is described. Irradiation by an ArF excimer laser (wavelength 193 nm) is leading to ablation of the coating and, at sufficiently high fluence, of the fused silica substrate. The remaining coating in the unexposed areas is removed afterwards by large area irradiation. The fluence threshold for substrate ablation using a 28 nm thick absorber layer is about 1.1 J/cm^2. Single pulse ablation rates of up to 800 nm and a surface roughness of $R_a < 5$ nm are obtained. High resolution grating patterns with 400 nm period and a modulation depth of 80 nm are possible. The process can be described as controlled plasma mediated ablation.

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1 Introduction

Fused silica is a weak absorber from the deep UV to the near IR. Precise patterning by laser ablation requires sufficient absorption. Therefore, ablation is generally performed using vacuum UV lasers emitting at 157 nm [1] or femtosecond lasers inducing multi photon absorption [2]. Beside these direct ablation processes, methods utilizing external absorbers are applied. *Laser induced backside wet etching* (LIBWE) [3, 4] and *laser induced plasma assisted ablation* (LIPAA) [5] are established indirect methods. Variations of these methods are *Laser etching at a surface adsorbed layer* (LESAL) [6] or the utilization of a thin carbon layer as absorber [7]. Recently, also metallic absorber films have been applied for *laser induced dry etching* (LIBDE) [8]. All these processes are applicable in a backside configuration, i.e. the laser beam has to pass the workpiece before inducing ablation at the backside. This causes restrictions concerning the shape of the workpiece, i.e. generally a flat front surface is necessary.

We propose an indirect ablation method that can, in principle, be applied for both, back side and front side processing. The fused silica substrate to be machined is coated with a UV-absorbing silicon monoxide (SiO) film. This film is irradiated using an ArF excimer laser leading to ablation of the film and, at sufficiently high fluence, to surface ablation of the fused silica substrate (Fig. 1). The ablation depth in the silica can be controlled by the fluence. The remaining coating in the unexposed areas is removed afterwards by large area irradiation of the whole surface at a fluence above the threshold of film ablation, but below the threshold of substrate ablation [9].

2 Front side and rear side ablation

For the ablation experiments a nanosecond ArF-excimer laser (wavelength 193 nm, pulse duration 20 ns) in combination with a mask projection set up was applied. To create homogeneous ablation spots, a rectangular aperture (2 mm × 2 mm) was inserted in the mask position and imaged onto the sample surface using a UV-achromat of 100 mm focal length with a demagnification ratio of 11:1. This arrangement results in ablation spots with 175 µm × 175 µm size.

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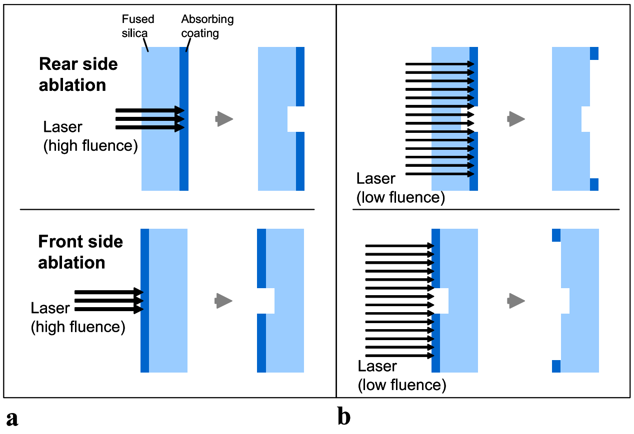

Fig. 1 Scheme of rear side- and front side-configuration. After the coating mediated ablation of the silica substrate at high laser fluence (**a**), the residual coating can be ablated at low laser fluence without damage of the substrate (**b**)

The samples were positioned with the coating in the image plane, either in a "rear side" or in a "front side" configuration (Fig. 1). A field lens (focal length 750 mm) was inserted 180 mm in front of the mask position. It causes an intermediate focus between mask and imaging lens and avoids the existence of a region of high intensity just in front of the image plane. This is necessary in the case of rear side ablation to avoid unwanted front side damage of the substrate. The fluence was varied using a variable attenuator at the laser output. Only single pulse exposures were performed.

For the generation of periodic patterns of moderate line density, a Cr-on-quartz mask with 50 μm wide lines and spaces was inserted in the mask plane. For high quality imaging the use of an achromatic imaging lens is important, because in this case the spherical aberration is minimized at the same time. So, it is possible to utilize a mask area of 5 mm × 5 mm and process a 0.5 mm × 0.5 mm area with sufficient resolution in one exposure. To remove the residual coating after ablation, the mask was removed and the whole area of 0.5 mm × 0.5 mm was exposed to one single pulse at a fluence above the threshold for layer ablation (300 mJ/cm^2), but below the threshold for substrate ablation (1 J/cm^2).

For high resolution patterning a fused silica phase mask with 20 μm period was applied. This phase mask was imaged on the sample surface using a Schwarzschild objective with 25× demagnification and a numerical aperture of 0.4. The phase mask design serves for the suppression of the zero order beam, so that only the ± first diffraction orders are recombined in the image plane. This results in a periodic intensity profile with 400 nm period.

The samples were fused silica substrates coated on one side with a silicon monoxide (SiO) layer (Laseroptik GmbH, Garbsen). Coatings with a thickness of 28 nm (and for comparison 175 nm) were used. SiO is strongly UV-absorbing

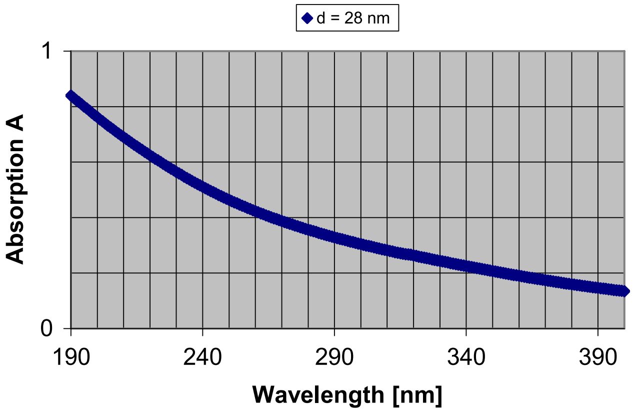

Fig. 2 UV-absorption spectrum of 28 nm SiO on fused silica. $A = \log_{10}(I_0/I)$

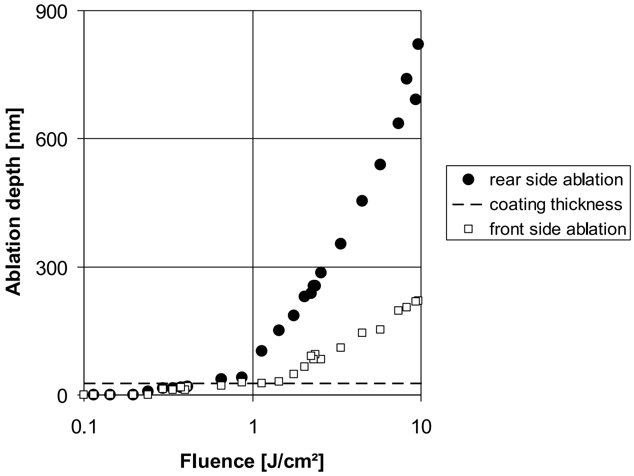

Fig. 3 Measured ablation depth of 28 nm-SiO-coated fused silica as a function of the laser fluence (single pulse ablation with ArF-laser). The displayed depth is the sum of ablated coating depth and ablated substrate depth. The *horizontal line* indicates the coating–substrate interface

(Fig. 2) [9]. The absorption coefficient $\varepsilon = \log_{10}(I_0/I) \times d^{-1}$ (with coating thickness d) is about $\varepsilon = 2 \times 10^5$ cm^{-1} at 193 nm.

Ablation depth and roughness were measured with a stylus profilometer (Dektak 3030).

3 Results and discussion

The measured single pulse ablation depth in rear side and front side configuration is displayed in Fig. 3. In the case of rear side ablation, starting at a fluence threshold around 300 mJ/cm^2 the ablation depth increases rapidly to an amount corresponding to the coating thickness. In the range between 300 mJ/cm^2 and 1 J/cm^2 the depth remains rather constant, the coating is completely ablated, and the fused silica substrate remains undamaged. That the ablation stops at

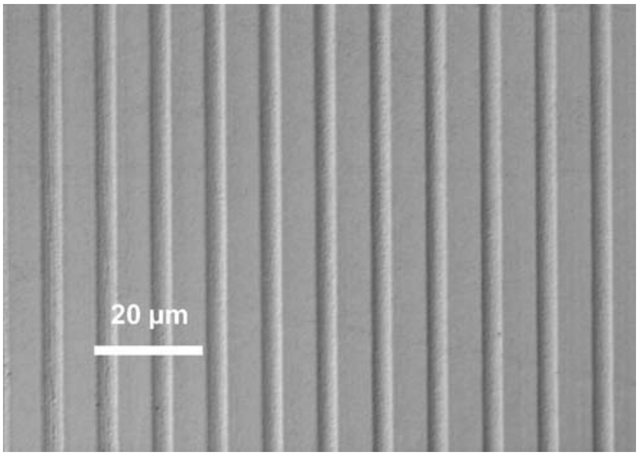

Fig. 4 9 µm period ablated grating in fused silica after coating removal (optical microscope). Parameters: 175 nm SiO on fused silica, rear side ablation at 193 nm, 1 pulse at 1.1 J/cm^2 for grating ablation, 1 pulse at 0.33 J/cm^2 for removal of residual coating

the coating–substrate interface can also be concluded from the low roughness values of $R_a = 2$ nm measured in these ablation spots which are near to the original substrate surface roughness. Increasing the fluence above 1 J/cm^2, the fused silica substrate is ablated, too. This threshold is significantly lower than the value of about 3 J/cm^2 for uncoated fused silica [10]. The ablation at fluences >1 J/cm^2 is accompanied by a bright white luminescence indicating the onset of plasma formation. The depth increases with growing fluence, until at about 10 J/cm^2 it becomes unstable and tends to decrease again. This limit originates from the onset of front side ablation of the bare fused silica, leading to plume attenuation, so that only a fraction of the pulse energy is still reaching the rear side. In the case of front side ablation the behaviour is quite similar at low fluences. The increase of the ablation depth at high fluence is not as strong as compared with rear side ablation. At 8 J/cm^2 only 200 nm/pulse instead of 800 nm/pulse are reached. This is probably due to the attenuation of the incident laser pulse by the expanding plume, which is only effective in the configuration of front side irradiation.

The obtained surface quality in the case of rear side ablation is very good ($R_a < 5$ nm), for front side ablation at high fluence the plume effect leads to diminished surface quality ($R_a \approx 10$ nm).

Figure 4 displays a pattern of lines and spaces made by rear side ablation. In this case a second, low fluence pulse was applied to the sample without mask to remove the remaining coating in the unexposed areas. A fluence between 300 mJ/cm^2 and 900 mJ/cm^2 is required for this kind of a "cleaning pulse". This way it is possible to fabricate a pure fused silica surface pattern. The method of coating mediated ablation can also be used for patterning with sub micron resolution. Figure 5 shows a linear pattern with 400 nm period made by front side ablation using high resolution phase mask imaging. The modulation depth of this grating is about 80 nm (measured by atomic force microscopy). This value is higher compared to those obtained by using a silver absorber layer [11]. These results show, that the applied method is, besides smooth large area ablation, capable of producing high resolution patterns with good surface quality. By applying single pulses of varying fluence to a SiO-coated fused silica sample, it is possible to generate a multilevel height profile (Fig. 6). Such patterns can be used, e.g. as diffractive phase elements.

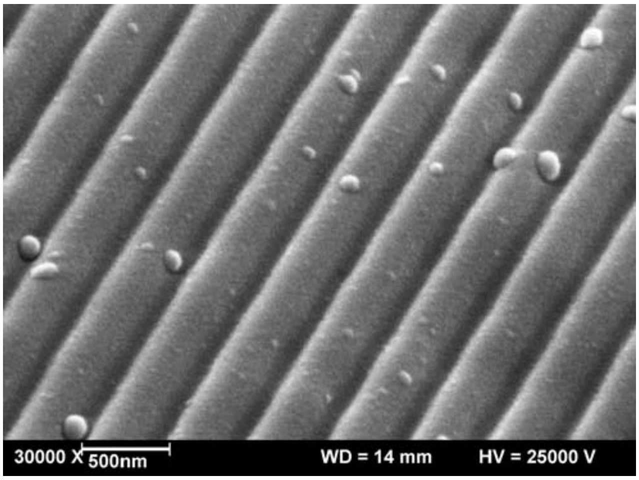

Fig. 5 400 nm period grating in fused silica (Scanning electron microscope). Parameters: 28 nm SiO on fused silica, front side ablation at 193 nm, 1 pulse at 16 J/cm^2(grating formation and complete coating removal within one pulse)

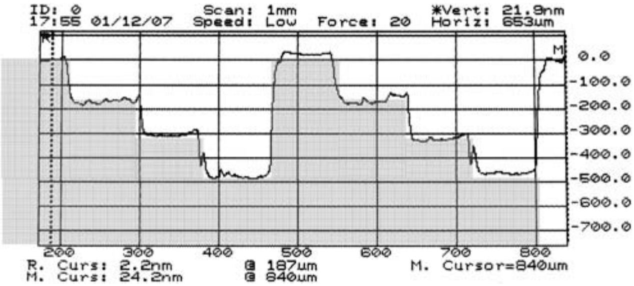

Fig. 6 Comparison of the design of a surface profile of a diffractive phase element (*grey area*) and the fabricated profile in fused silica (recorded by a Dektak stylus profilometer, *black line*). The steps have a height of about 150 nm and a width of 80 µm. Each position was ablated with a single pulse under variation of the fluence

The significantly higher ablation depth for rear side ablation compared to the front side case indicates that plume attenuation limits the fraction of energy effective for the front side ablation process. On the other hand, the threshold fluences of the coating mediated ablation of fused silica are very similar for front- and rear side ablation. This might indicate that the basic mechanism above the threshold of substrate ablation is the same in both cases: plasma medi-

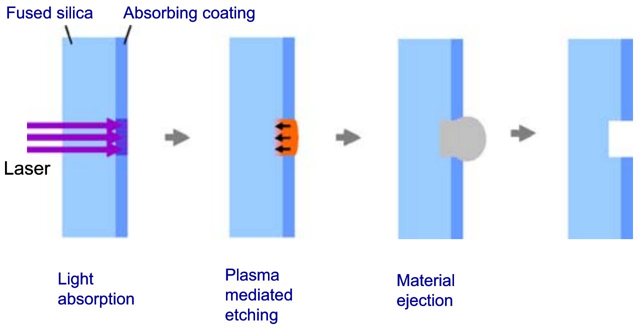

Fig. 7 Scheme of plasma mediated ablation after coating absorption

ated ablation similar to that of other transparent materials (Fig. 7). The term *plasma mediated etching* was first used in [12] to describe the effect of optical breakdown initiated by absorbing states at the surface of transparent magnesium oxide. The difference here is that the initial source of charge carriers is not represented by defect states at the surface, which have to be accumulated by incubation pulses. Instead, the thin strongly absorbing coating material is rapidly heated and ionized thus mediating substrate ablation. The onset of this plasma-process not far above 1 J/cm^2 is consistent with the observation of plasma ignition thresholds on strongly absorbing solids of less than 10^8 W/cm^2 (less than 2 J/cm^2 for 20 ns-pulses) [13].

4 Conclusion

Ablation of fused silica with a standard ArF-excimer laser is possible by utilizing a solid coating for absorption of the laser radiation. Plasma formation leads to material removal from the non-absorbing silica. Depending on the irradiation configuration, ablation from the front side or the rear side is enabled. Single pulse ablation depths from a few nm to 800 nm are obtained depending on the laser fluence. The resulting surface roughness is in the range of $R_a = 2-10$ nm. Residual coating material is removed by irradiation at low laser fluence. High resolution (400 nm periodic line patterns) is achieved. The method may be useful for the rapid fabrication of surface relief patterns, e.g. gratings and diffractive optical elements.

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