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Micro patterning of fused silica by ArF- and F_2-laser ablation

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Abstract. Surface-relief gratings on optical materials are required for various telecommunication applications, as light couplers for planar optical waveguides, Bragg reflectors, or alignment grooves for liquid crystals. Vacuum-UV-laser ablation enables precise machining of fused silica. A comparison of ablation results obtained at 157 nm and 193 nm wavelength leads to the following conclusion: at 193 nm the surface properties (e.g. mainly roughness) have strong influence on the ablation behaviour. At 157 nm, the volume properties (e.g. mainly bulk absorption) are dominating instead. Though there are severe constraints concerning deep hole drilling at 193 nm, because irregular cracking can hardly be excluded, the generation of high resolution surface patterns is possible at this laser wavelength. As an example, sub-half-micron surface-relief gratings were fabricated on fused silica by laser ablation with nanosecond (ns) pulses at 193 nm from an ArF excimer laser. The grating relief was generated by imaging a transmission amplitude grating with a Schwarzschild objective of 25x demagnification. To provide high resolution in combination with high fluence, which is required for ablating fused silica, an off-axis mask projection scheme utilizing superposition of the zero order beam with the +1st diffraction order was applied.

1. Introduction

Laser ablation of UV-transparent materials like fused silica has been a subject of numerous investigations. There are at least three different approaches to overcome the problem of substantial coupling of laser energy into a non-absorbing material. One possibility is to use ultrashort pulses with high peak power density, so that the energy is coupled to the material via two- or multiphoton absorption [1-3]. The second way is to use an indirect process, where the laser energy is coupled into an auxiliary material which is in close contact with the material to be ablated. This auxiliary material can be either an absorbing liquid as in the case of LIBWE [4] or a thin layer deposited by the ablating laser pulse when it hits an auxiliary target in close distance from the material to be ablated (LIPAA) [5]. The third method is to choose the laser wavelength as short as necessary to achieve substantial direct linear absorption. In the case of fused silica, 157 nm seems to be appropriate to induce well defined ablation [6, 7]. Sub-micron gratings [8], pixelated diffractive elements [9], and micro lenses [10] have been fabricated using F_2-laser ablation at 157 nm. However, for all these methods rather severe constraints concerning the practical applicability are given. Either complex femtosecond laser systems are required for multiphoton absorption, or strictly defined geometrical conditions have to be obeyed (LIBWE and LIPAA), or complex optical systems with oxygen free beam delivery paths have to be provided for 157 nm radiation. Therefore it is of interest to which extent rather simple set-ups with standard excimer lasers are appropriate to produce special ablation features in fused silica. The possibility to drill holes in quartz glass with moderate quality at wavelengths 308 nm, 248 nm, and

193 nm with nanosecond pulses, has already been demonstrated [3]. In this paper we evaluate the differences between 157 nm- and 193 nm-ablation and show that it is possible to fabricate submicron surface patterns on fused silica surfaces by means of 193 nm radiation.

2. Ablation of fused silica at 157 nm and 193 nm

The ablation threshold at 157 nm is significantly lower compared to 193 nm. At 157 nm, ablation starts at about 1 J/cm², and the ablation rates grow continuously with increasing fluence [6]. At 193 nm the threshold is about 3 J/cm², and above this value the ablation rate jumps abruptly to rather high values of about 100 to 200 nm/pulse. To study the differences in more detail, in this paper the ablation behavior at these two wavelengths is investigated for various material- and surface properties of fused silica. Ablation experiments were performed using an ArF excimer laser (Lambda Physik LPX 300) and an F_2-laser (Lambda Physik LPF 220), each in combination with mask projection optics. F_2-laser ablation was carried out in a nitrogen flushed chamber to avoid oxygen absorption of the vacuum-UV-radiation. The surface roughness of the used samples and the ablation depths were measured with a surface profilometer (Dektak). Material- and surface properties of the silica samples studied here are displayed in table 1.

Table 1. Properties of the investigated fused silica samples

Volume properties		Surface properties	
Material	OH-content [ppm]	Material	Surface roughness Ra [nm]
Suprasil 1	800	Suprasil 1, polished	< 10
SQ 1	1200	Suprasil 1, 3µ polished	100
Herasil 1	150	Suprasil 1, 5µ polished	140
Spektrosil A	1000	Suprasil 1, 9µ polished	170
		Suprasil 1, unpolished	260

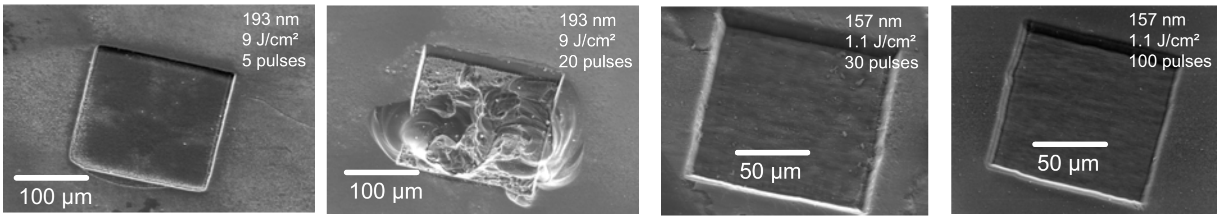

Figure 1. Comparison of ablation patterns on Suprasil at 157 nm and 193 nm.

Figure 1 shows some typical ablation spots generated at these two laser wavelengths. Using 193 nm, for low pulse numbers there is a rather well defined ablation area with sharp edges. After a number of pulses large cracks appear and the ablation pattern is completely destroyed. In contrast, at 157 nm the hole grows deeper without distortion of its rectangular shape, when the number of pulses is increased.

In figure 2 ablation rates vs. fluence are displayed for various values of the surface roughness. At 157 nm the same ablation rates are measured independently of the surface roughness. Only the perfectly polished sample shows higher ablation rates. At 193 nm there is a clear dependence of the ablation rate on the roughness. A higher surface roughness leads to a higher ablation rate.

In figure 3 a comparison of ablation rates at 157 nm and 193 nm for various bulk properties of fused silica is displayed. Bulk absorption data of these materials at 157 nm are not available. In table 1, the OH-content is specified instead, though the UV-absorption depends less strongly on the OH-content compared to the IR-absorption. At 193 nm the ablation curves for all materials are very similar. At 157 nm there are significant differences of the ablation rates for the different materials.

This behaviour can qualitatively be explained as follows: At 193 nm the bulk absorption of fused silica (of each type) is negligibly small. Absorption centres are only represented by surface defects. The density of surface defects in turn strongly depends on the roughness, leading to the observed behaviour: a rough surface serves for strong coupling of laser energy leading to a deep removal via plasma mediated ablation [11]. In the case of a smooth surface, the absorbing defects have to be created by the laser pulse before substantial material removal will occur, causing the averaged ablation rate to be lower. At 157 nm, bulk absorption is significantly higher, so that the contribution of the surface defects vanishes. In this case the volume absorption, which depends on the silica quality, determines the ablation rate.

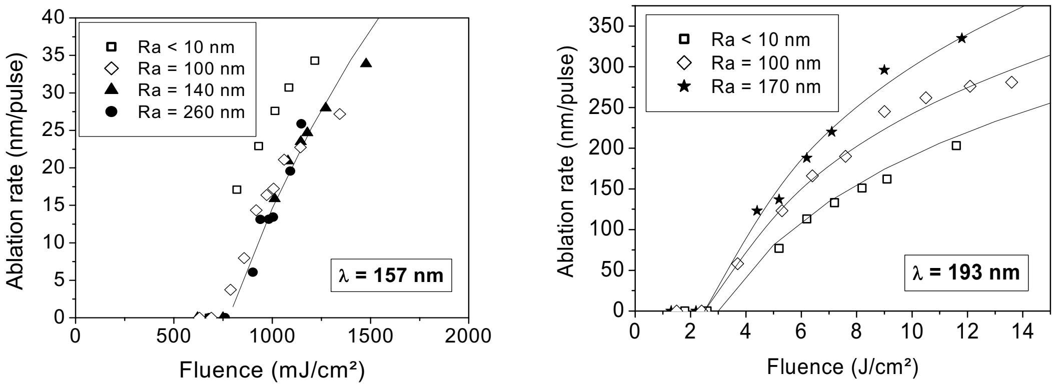

Figure 2. Fluence-dependence of the ablation rate for various values of surface roughness at 157 nm (left) and 193 nm (right). Lines represent fitted curves according to ablation rate d = α_{eff}^{-1} log (F/F_t), where α_{eff} is the effective absorption coefficient, F is fluence, and F_t is the ablation threshold fluence.

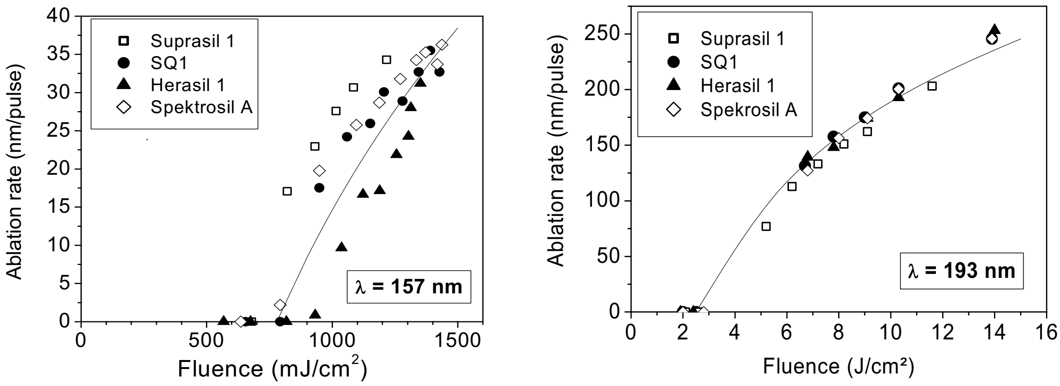

Figure 3. Fluence-dependence of the ablation rate for various silica glass types at 157 nm (left) and 193 nm (right). Lines represent fit curves according to ablation rate d = α_{eff}^{-1} log (F/F_t), α_{eff} effective absorption coefficient, F fluence, F_t ablation threshold fluence.

3. High resolution surface patterning of fused silica at 193 nm

In the following we show, that if only the surface has to be patterned at high resolution, a wavelength of 193 nm, which is much easier to handle compared to 157 nm, can be applied. However, the optical resolution A is limited by the wavelength λ and the numerical aperture NA of the imaging optics according to $A \approx \lambda / 2NA$. Reflective objectives of the Schwarzschild type combine relatively high NA with long working distance which is useful in ablation applications to avoid damage of the objective by deposition of ablated particles. Using such a Schwarzschild objective with NA = 0.4, a 800nm grating was fabricated by 157 nm-radiation using a 20 µm period amplitude transmission grating and 25x demagnification [8]. A grating with half this period, i.e. 400 nm, was obtained on metals by using 248 nm femtosecond laser pulses in an arrangement where the zero order beam was blocked, so that interference of ± first order beams generated by a 20 µm grating resulted in a 400 nm grating [12]. Taking into account that diffraction by amplitude gratings yields only 10-20% of the intensity in the first order beams and more than 80% in the zero order beam, this method is very inefficient. However, the ablation threshold of metals in the case of femtosecond radiation is rather low, and these losses are tolerable. In contrast, the ablation threshold of fused silica at 193 nm is about 3 J/cm² [3], a value difficult to reach using only the weak first order beams. More efficient approaches are either to use a phase mask causing higher intensity in the first order beams [13, 14], or to use an off axis scheme utilizing the interference of the zero order beam and one of the first order beams, which is shown in figure 4. Of course, the contrast of the irradiation pattern is diminished compared to the ± first order superposition, but due to the threshold behavior of ablation, a very clear surface grating with 400 nm period can be fabricated this way (figure 5).

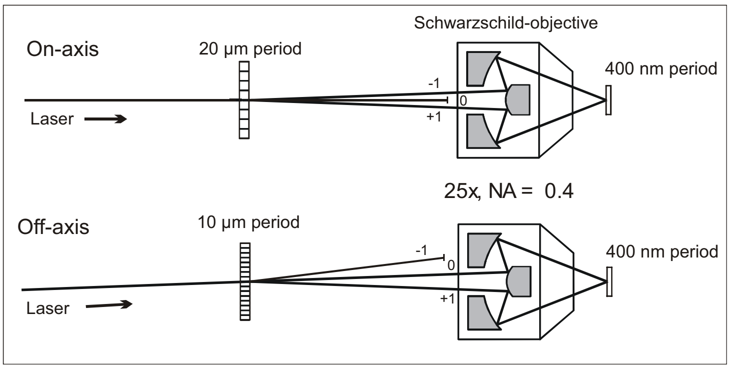

Figure 4. On axis projection with high contrast, but low overall fluence, and off-axis projection with moderate contrast, but high overall fluence.

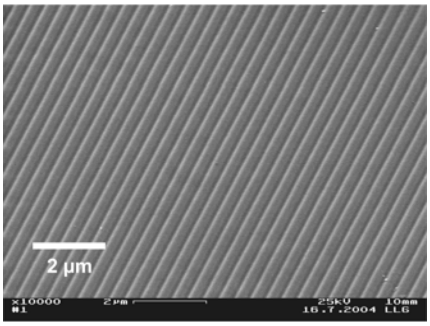

Figure 5. 400nm-period grating made by 193 nm-ablation using the off-axis scheme (3.9 J/cm², 2 pulses).

4. Summary

The ablation behavior of fused silica at 193 nm depends on the surface characteristics (roughness), whereas at 157 nm the volume optical properties are of major importance. Though material cracking appears at 193 nm after multiple pulse application, gentle submicron patterning is possible, if the irradiation dose per position is reduced to very few pulses. For controllable and finely adjustable deep ablation structures, the use of 157 nm-radiation is otherwise required.

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