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Laser Based Rapid Fabrication of SiO_2-phase Masks for Efficient UV-laser Micromachining

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The laser based fabrication of surface relief SiO_2 phase masks is demonstrated: First, a UV-absorbing coating of silicon monoxide (SiO, thickness 150-300 nm) is deposited on a fused silica substrate. Second, the SiO-coating is patterned by excimer laser ablation (248 nm or 193 nm) at fluences of 0.2 to 0.5 J/cm² to form the desired phase structure. Third, the SiO-material is oxidized to UV-transparent silicon dioxide (SiO_2). Applications of these phase masks in combination with suitable imaging optics for efficient laser micro machining are demonstrated.

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1. Introduction

Phase masks are very useful for efficient laser micro machining. In combination with suitable imaging optics they can be used for high precision micro fabrication by laser ablation. Especially for the fabrication of periodic micro-and nano-structures they exhibit superior performance compared to amplitude masks [1]. They can be realized in form of a height profile corresponding to the required phase modulation engraved in an optically transparent material. If they are made from SiO_2 (fused silica), they are characterized by low loss and high damage threshold even in the ultraviolet spectral range.

Conventionally, quartz phase masks are made by a lithographic process including reactive ion etching [2]. To avoid this complex procedure for the processing of silica glass, many attempts have been made to pattern fused silica by laser ablation. Direct ablation using UV-lasers [3], VUV-lasers [4] or femtosecond lasers [5-6] has been investigated. To overcome the lack of absorption of fused silica from the deep UV to the near IR, which makes precise ablation difficult, indirect processes utilizing the absorption of a liquid or solid layer which is in contact with the silica surface have been applied [7-10]. In this paper we describe a different approach utilizing the absorption of SiO, a solid precursor material of SiO_2, to generate precise ablation patterns and converting this patterned precursor material into SiO_2 afterwards. I.e., instead of creating the surface relief by removing material directly from a fused silica slab, the profile is generated by laser ablation patterning of an optical layer deposited on a fused silica substrate [11]. Basically there are three steps:

1. A UV-absorbing coating of silicon monoxide (SiO) is deposited on a fused silica substrate.

2. The SiO-coating is patterned by ArF- or KrF-excimer laser ablation to form the desired phase structure.

3. The SiO-material is oxidized to UV-transparent silicon dioxide (SiO_2).

Large area linear phase gratings of medium resolution (5 – 50 µm period) are made by ablating the grooves one after the other with a line focus beam. Complex patterns and high resolution structures are fabricated using a specifically designed lens objective with large image field. Applications of these phase masks for excimer laser micro machining are demonstrated.

2. Fabrication of phase masks

The fabrication process and the two optical set-ups that are used for the patterning of SiO layers depending on the desired pattern, are described in this section.

2.1 Process

The fabrication of phase masks comprises three steps:

1. Deposition: a silicon monoxide layer (SiO) or a substoichiometric SiO_x-layer with $x < 2$ is deposited on a fused silica substrate. This is done by a commercial coating shop (Laseroptik, Garbsen, Germany). The thickness of the layer is adapted to the required phase delay of the element to be fabricated. For a binary phase grating with suppressed zero diffraction order, a duty cycle of 0.5 (equal width of lines and spaces) and a height of the lines (i.e. thickness of the layer) of $d = \lambda / 2(n-1)$ (λ operation wavelength, n refractive index) are required.

2. Rear side ablation: The absorption coefficient of SiO at 193 nm is about 2×10^5 cm^{-1}. This means that there is a strong absorption contrast between this coating and the UV-transparent substrate. The patterning process can therefore be performed in a rear side configuration, where the laser beam hits the coating after passing through the substrate. This leads to better results concerning edge quality and debris contamination compared to a front side configuration [11].

3. Oxidation: The patterned sample is heated in an oven in air environment to 1000 °C for several hours. Thus the remaining SiO-material is oxidized to SiO_2. A thickness in-

crease of about 40% has to be taken into account when designing the coating layer. The element is now completely UV-transparent down to 190 nm.

2.2 Large area phase gratings of medium resolution

For the fabrication of large area phase gratings a rather simple set up is used. The excimer laser illuminates a slit, and the slit is imaged by a fused silica cylindrical lens on the SiO-coated target. Using a cylindrical lens of 100 mm focal length in a configuration for 10:1 demagnification, the required fluence of about 300 mJ/cm² can be easily reached on a line length of 20 mm. Spatial line widths of 5 µm to some 100 µm can be reached by adjusting the slit width. As one laser pulse is sufficient for the ablation of one line, a cm²-sized grating with a line density of the order of 100 lines/mm can be fabricated within a few seconds, if the sample movement from pulse to pulse is controlled with sufficient precision. This set up can be operated with a KrF-excimer laser as well as with an ArF-excimer laser.

2.3 Complex phase patterns

To create not only linear phase gratings but also arbitrary patterns, another mask projection set-up is used in combination with a KrF-laser at λ = 248 nm with a pulse duration of 25 ns. In this case a 4x/10-248 objective (MicroLas, Göttingen, Germany) was used to demagnify a Cr-on-quartz-mask four times, resulting in a process field of 2.5 mm x 2.5 mm, when using a mask field of 1 cm x 1 cm. This means that a field of 1 cm² can be processed with µm-resolution applying only 16 laser pulses.

3. Characterization of the fabricated phase masks

The fabricated phase masks are investigated by optical microscopy, profilometry, scanning electron microscopy (SEM), and atomic force microscopy (AFM). The optical performance is characterized by applying the elements for excimer laser micro machining.

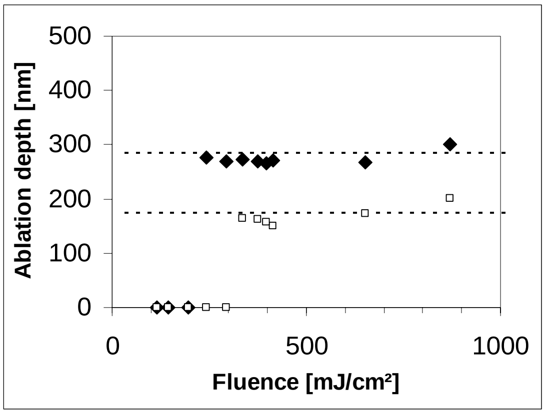

Fig. 1*: Single pulse 193 nm laser ablation depth of SiO on fused silica measured with a Dektak profilometer; ♦ 285 nm SiO; □ 171 nm SiO.*

The ablation depth after single pulse rear side exposure at 193 nm (pulse duration 20 ns) is shown in Fig. 1: Below about 200 mJ/cm² no ablation occurs. Above a threshold at about 250 mJ/cm² the complete layer is ablated, the measured ablation depth corresponds to the layer thickness. At about 1 J/cm², the ablation depth exceeds the layer thickness, which means that some part of the substrate is ablated, too. This indirect ablation behavior has been observed for various layer materials [12-13]. The best edge quality is obtained in the center of the process window at 300 to 500 mJ/cm².

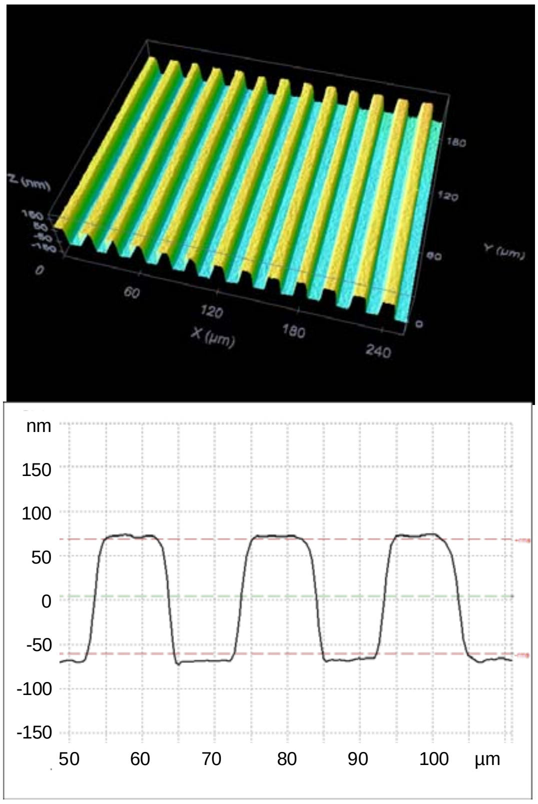

Fig. 2*: Profile of a SiO_2-phase mask fabricated by laser patterning of a SiO layer and subsequent oxidation. Data taken by confocal microscopy.*

Fig. 2 displays the height profile of a phase mask optimized for application at 193 nm.

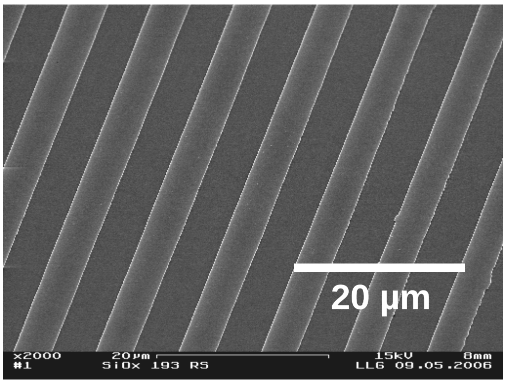

Fig. 3*: Pattern of 5 µm lines and spaces made by rear side ablation of a 250 nm thick SiO layer; laser: 193 nm, 540 mJ/cm², 1 pulse. (Scanning electron microscopy)*

Figs. 3 and 4 display examples of patterned SiO-layers. Whereas the pattern of Fig. 2 was made by using the slit imaging method and generating line after line by successive pulses, these patterns with 5 µm resp. 1 µm wide lines and spaces have been made by imaging a Cr on quartz grating, so that the complete multiline pattern was genrerated with one single laser pulse.

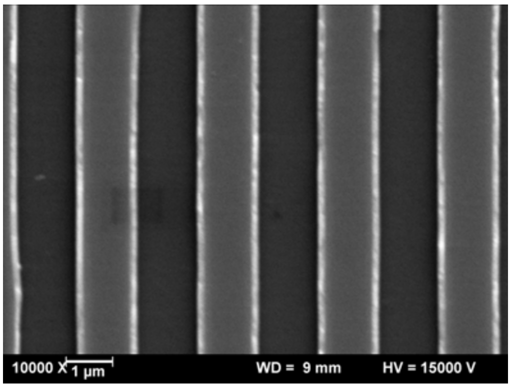

Fig. 4*: Pattern of 1 µm wide lines and spaces made by rear side ablation of a 223 nm thick SiO-layer; laser: 248 nm, 200 mJ/cm², 1 pulse. (Scanning electron microscopy)*

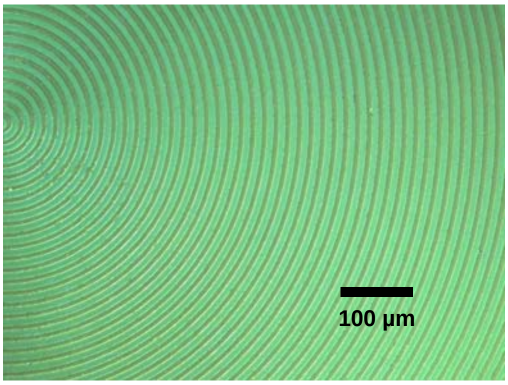

Fig 5*: Ring pattern made by rear side ablation of a 171 nm thick SiO-layer; laser: 248 nm, 320 mJ/cm², 1 pulse. (Optical microscopy)*

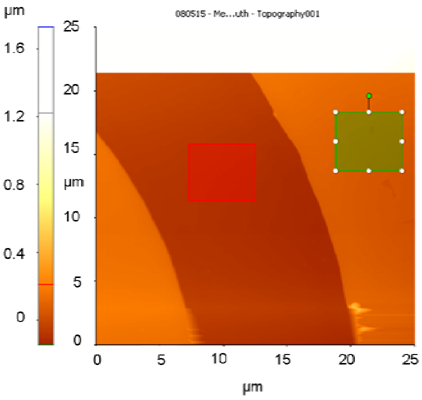

Fig. 6*: Detail of a ring pattern ablated in a 223 thick SiO-layer on fused silica; Roughness in the ablated zone (red area, left): R_a = 7 nm; Roughness in the non-ablated zone (green area, right): R_a = 12 nm. (Atomic force microscopy)*

Fig. 5 displays a ring pattern made by single pulse exposure. The obtained surface roughness was determined by AFM-measurements (Fig. 6). The roughness R_a in the ablated grooves (uncovered substrate) R_a = 7 nm is even lower compared to the value R_a = 12 nm of the not ablated layer. The roughness of the substrate before coating is R_a < 1 nm.

For the fabricated linear phase gratings, diffraction efficiencies of up to 80% in the ± 1st order and suppression of the 0th order below 1% could be obtained.

4. Application of phase masks for micro machining

4.1 Large area patterning

The application of the laser fabricated phase masks for large area patterning of a polymer surface is shown in fig. 7. The phase mask was imaged using the same 4:1 objective which was used for phase mask fabrication.

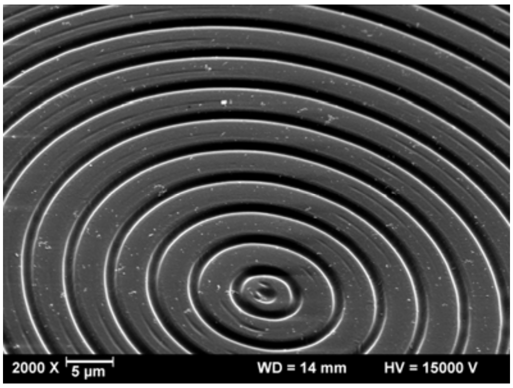

Fig. 7*: Ring pattern ablated in polycarbonate by applying the phase mask shown in fig. 5 and 4:1 projection using a KrF-laser (248 nm). (Scanning electron microscopy)*

4.2 High resolution patterning

The capability of the fabricated phase masks for laser micro machining is demonstrated here for the case of processing fused silica with highest resolution. An indirect ablation process is used, where the laser pulse is absorbed by a solid layer deposited on the fused silica sample.

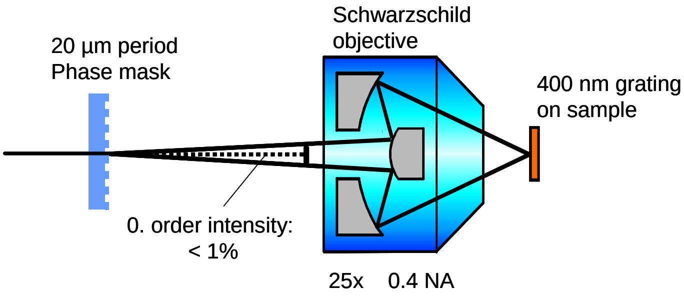

Fig. 8*: Optical set up for the fabrication of high resolution patterns by phase mask projection. High efficiency in the ± first diffraction orders serves for high fluence on the work piece, though the zero order beam is blocked.*

The ablation is performed by imaging the phase mask with a Schwarzschild type reflective objective (Fig. 8). The Schwarzschild design leads to blocking of any part of the beam, which is on or near the optical axis. Thus, if efficient utilization of the available light is desired, either an off-axis illumination has to be used [14], or the intensity of the zero order beam has to be minimized, and the energy has to be distributed mainly into the first order beams. These conditions can be perfectly fulfilled using a phase mask with a duty cycle of 0.5, i.e. equal width of lines and spaces and a height of the lines of $d = \lambda / 2(n-1)$ (λ operation wavelength, n refractive index). In this case the intensity of the first orders is maximized and that of the zero order beam is minimized. If only the first order beams fit into the aperture of the objective, and the zero order is blocked, the intensity pattern generated in the image plane is formed by two beam interference. In the case of a phase mask period of 20 µm and a demagnification of 25x, the resulting intensity period on the sample will be 400 nm due to the missing zero order (Fourier filtering).

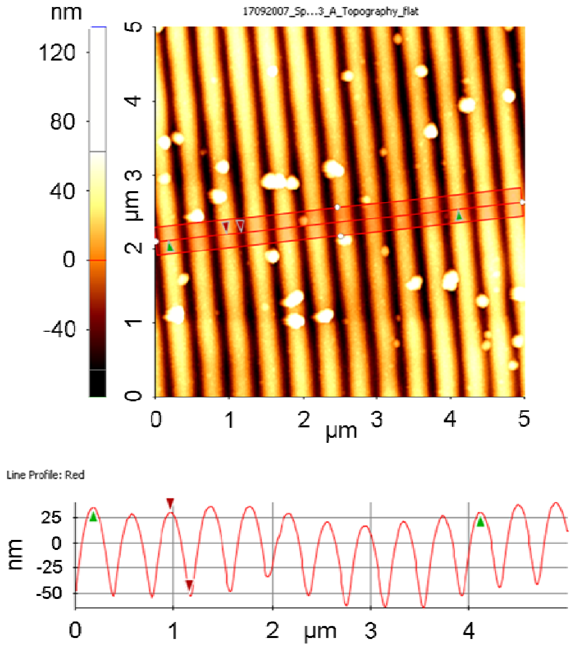

***Fig. 9**: Surface relief grating in fused silica with 400 nm period and 80 nm modulation depth fabricated by single pulse front side ablation; absorber coating: 28 nm SiO, laser: 193 nm, 16 J/cm². (Atomic force microscopy)*

Fig. 9 shows a relief grating with 400 nm period fabricated in fused silica by this method. The fused silica sample coated with a 28 nm thick SiO-absorber layer is irradiated with one laser pulse leading to a relief grating with a modulation depth of 80 nm. It is interesting to note that in this high fluence / high resolution case the absorber is removed over the whole area, while the fused silica substrate exhibits the desired grooves. An additional cleaning pulse to remove the absorber layer in the unexposed lines between the grooves, which is applied otherwise [13], is not necessary here. Only some droplets on the surface may originate from the absorber layer.

5. Conclusion

Laser patterning of a UV-absorbing SiO-coating on a fused silica substrate and subsequent oxidation of the SiO to transparent SiO_2 is a simple but effective method for the fabrication of UV-grade phase elements. These phase elements exhibit perfect depth compliance and surface quality. They can be applied for efficient laser micro machining.

Acknowledgments

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References

[1] J. Turunen, F. Wyrowski eds. Diffractive Optics for Industrial and Commercial Applications Akademie Verlag, Berlin 1997

[2] K. Zimmer, R. Böhme, A. Braun, B. Rauschenbach, F. Bigl, Appl. Phys. A **74**, 453-456 (2002).

[3] J. Ihlemann, B. Wolff, P. Simon, Appl. Phys. A **54**, 363-368 (1992).

[4] P.R. Herman, R.S. Marjoribanks, A. Oettl, K. Chen, I. Konovalov, S. Ness, Appl. Surf. Sci. **154-155**, 577-586 (2000).

[5] J. Krüger, W. Kautek, Appl. Surf. Sci. **96-98**, 430-438 (1996).

[6] H. Varel, D. Ashkenasi, A. Rosenfeld, M. Wähmer, E.E.B. Campbell, Appl. Phys. A **65**, 367-373 (1997).

[7] J. Wang, H. Niino, A. Yabe, Applied Physics A **68**, 111-113 (1999).

[8] K. Zimmer, R. Böhme, B. Rauschenbach, Journal of Laser Micro/Nanoengineering **1**, 292 (2006).

[9] J. Zhang, K. Sugioka, K Midorikawa, Optics Letters **23**, 1486-1488 (1998).

[10] B. Hopp, Cs. Vass, T. Smausz, Appl. Surf. Sci. **253**, 7922 (2007).

[11] M. Schulz-Ruhtenberg, J. Ihlemann, J. Heber, Appl. Surf. Sci. **248**, 190-195 (2005).

[12] B. Hopp, Cs. Vass, T. Smausz, Zs. Bor, J. Phys. D: Appl. Phys.. **39**, 4843-4847 (2006).

[13] J. Ihlemann, Appl. Phys. A **93**, 65 (2008).

[14] J. Ihlemann, M. Schulz-Ruhtenberg, T. Fricke-Begemann, Journal of Physics: Conference Series **59**, 206 (2007).

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