Fabrication of Multilevel Fused Silica Diffractive Phase Elements by Laser Processing of Silicon Suboxide

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Laser processing of fused silica is challenging due to its high optical transmission. In contrast, UV-absorbing silicon suboxide (SiO_x, x ≈ 1) offers excellent conditions for laser ablation. By pattering the silicon suboxide with excimer lasers and subsequent oxidation, microstructured components made entirely of fused silica are fabricated. By repeating the ablation step after recoating the structured surface with additional layers of silicon suboxide, multilevel structures are produced.

1 Introduction

Compared to conventional refractive optics microstructured optical elements allow for new functionalities. With a more compact and flexible design and the possibility to combine several tasks in one component they offer high potential applications in imaging, microscopy and laser processing [1, 2]. Diffractive phase elements (DPE) provide, as a part of these microstructured elements, a significantly higher efficiency compared to amplitude elements. The required phase modulation is implemented by a height profile on an optically transparent material. For many applications there are fast and cheap optical fabrication methods, as the excimer laser ablation of polymers or the femtosecond laser ablation of indium tin oxide films [3, 4]. But the laser ablation of highly transparent materials, like fused silica, is challenging, though highly desirable. Besides the high transmission fused silica offers a good chemical resistance, a high electrical resistance and a low thermal expansion and therefore enables a broad range of applications. Conventionally fused silica DPEs are made by expensive and time consuming lithographic processes. We present an alternative cheap and precise method to fabricate these elements.

2 Fabrication method

To bypass the problems of laser ablation of fused silica arising from the high transmission, an alternative material is structured. Silicon suboxide (SiO_x, x ≈ 1) has a high absorption in the UV as seen in figure 1. Subsequent oxidation in air converts the structured element to SiO_2. In the transmission spectra the 700 nm thick SiO_x layer is annealed at 1000 °C in air. The transmission is measured every 8 hours and it can be seen that the material is fully oxidized after 40-48 hours. To create high precision structures, the SiO_x is patterned by rear side ablation. This means the laser pulse traverses the substrate and hits the coating at the interface of substrate to the coating. In this case, the ablation is a binary process - the film is either completely removed or not at all. To produce a multilevel phase element the processes of ablation and coating are repeated as seen in figure 2. In this process a four-level blazed structure is fabricated by repeating the cycle 3 times. The laser ablation takes place in the shaded areas. In a final step the structure is oxidized.

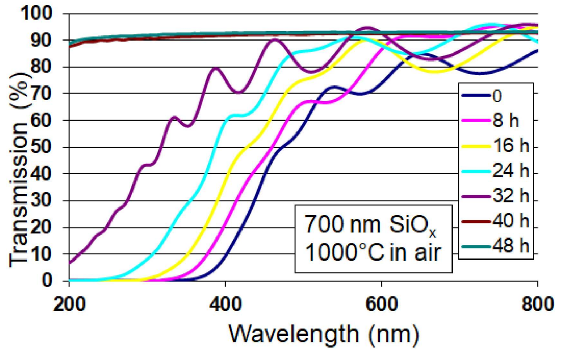

Fig. 1 *Transmission spectra of a 700 nm thick SiO_x layer oxidized at 1000°C in air. [5]*

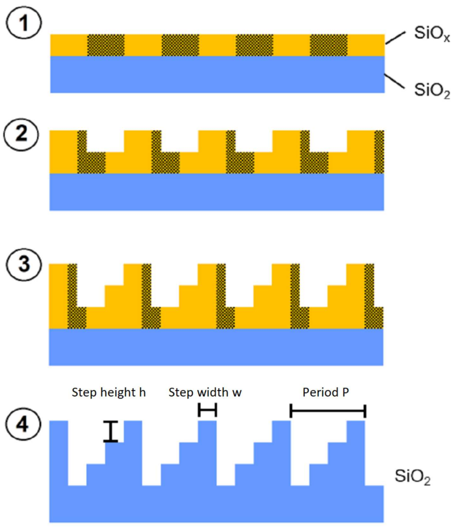

Fig. 2 *Process steps of the fabrication of a four-level blazed phase element. [6]*

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The laser ablation is performed by mask projection with a cylindrical quartz lens (f = 100 mm) in rear side configuration. With a demagnification of about 10:1 a fluence of 500 $\frac{\mathrm{mJ}}{\mathrm{cm}^2}$ is used to pattern the SiO_x with an ArF-excimer laser (λ = 193 nm) by one pulse (pulse length $\approx$ 20 ns). The coatings are produced with a Leybold Univex 350 system and thermal evaporation of SiO. The resulting structures are analyzed with an atomic force microscope (Park Systems XE-150) and a scanning electron microscope (Zeiss EVO MA10).

3 Results

The resulting four-level blazed structure is shown in figures 3 and 4. Four steps with equal width and height are produced. The roughness has been measured in the AFM data on every step resulting in a quadratic roughness between R_q = 2 nm and 4 nm. In contrast, using bulk ablation of fused silica at 157 nm, a surface roughness of R_q = 13 nm is obtained [7].

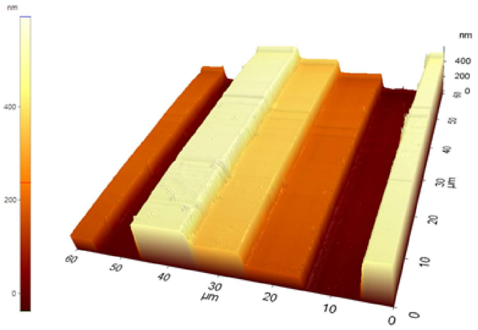

***Fig. 3** 3D depiction of the AFM measurement of the four-level blazed structure.*

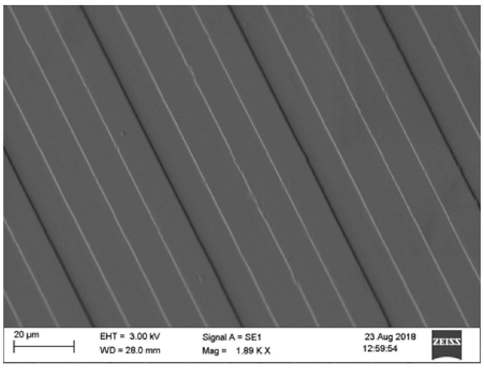

***Fig. 4** SEM picture of the four-level blazed structure.*

The diffraction efficiency was theoretically calculated using scalar diffraction theory. At a wavelength of λ an element with step height h_i, step width w_i and a period of P exhibits a diffraction efficiency in the m-th order of:

$$D.E. = \left| \frac{1}{P} \int_{-P/2}^{P/2} t(x) e^{-2\pi i m \frac{x}{P}} dx \right|^2$$

with a transmission function depending on the refractive index n of:

$$t(x) = \sum_{i=1}^{4} e^{i \frac{2\pi}{\lambda}(n-1)h_i} rect\left(\frac{x - x_i}{w_i}\right)$$

The calculated data are compared to measurements at three wavelengths (308 nm, 405 nm, 633 nm) for the 0th, +/-1st and +/-2nd order in figure 5. For 405 nm the +1th diffraction order is maximized to 73 % and therefore close to the theoretical limit of 81 %. Other orders are well suppressed (less than 3 % each) in the vicinity of the design wavelength.

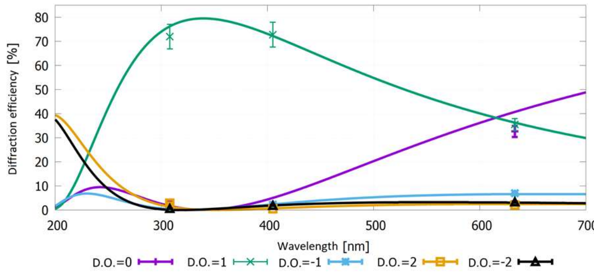

***Fig. 5** Comparison of the diffraction efficiencies of the calculated and measured datas.*

4 Conclusion

The recoating of the structured surface allows for the fabrication of precise multilevel diffractive phase elements with high diffraction efficiencies.

References

[1] F. W. J. Turunen, "Diffractive Optics for Industrial and Commercial Applications," Akademie Verlag, Berlin (1997).

[2] D. C. OShea, T. J. Suleski, A. D. Kathman, and D. W. Prather, "Diffractive Optics: Design, Fabrication, and Test," SPIE (2003).

[3] G. P. Behrmann and M. T. Duignan, "Excimer laser micromachining for rapid fabrication of diffractive optical elements," Applied Optics **36**(20), 4666 (1997).

[4] M. Baum, J. Strauß, F. Grueßel, I. Alexeev, and M. Schmidt, "Generation of phase-only holograms by laser ablation of nanoparticulate ITO layers," Journal of Optics **16**(12), 125,706 (2014).

[5] T. Fricke-Begemann, J. Meinertz, R. Weichenhain-Schriever, and J. Ihlemann, "Silicon suboxide (SiOx): laser processing and applications," Applied Physics A **117**(1), 13–18 (2014).

[6] L. J. Richter, C. Beckmann, J. Meinertz, and J. Ihlemann, "Laser Processing of Silicon Suboxide for the Fabrication of Multilevel Fused Silica Diffractive Phase Elements," Journal of Laser Micro/Nanoengineering **13**, 249–253 (2018).

[7] M. L. Ng, P. R. Herman, A. H. Nejadmalayeri, and J. Li, "F2-laser microfabrication of multilevel diffractive optical elements," Journal of Physics: Conference Series **59**, 696–699 (2007).