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Sub-micron grating formation in Ta_2O_5-waveguides by femtosecond UV-laser ablation

F. Beinhorn [a], J. Ihlemann [a,*], P. Simon [a], G. Marowsky [a], B. Maisenhölder [b], J. Edlinger [b], D. Neuschäfer [c], D. Anselmetti [c]

[a] *Laser-Laboratorium Göttingen, Hans-Adolf-Krebs-Weg 1, D-37077 Göttingen, Germany*
[b] *Balzers Thin Films, Balzers, FL Liechtenstein, Switzerland*
[c] *Novartis, 4002 Basel, Switzerland*

Abstract

Sub-micron-period surface gratings on Ta_2O_5 waveguide layers were produced by ablation with a sub-ps-UV-laser. The structure is generated by projection imaging of a primary transmission grating mask. A grating of 500 nm period with a surface modulation depth of 10 nm on a sample area of about 300 μm × 300 μm can be produced with a single laser pulse of about 100 mJ/cm^2 at 248 nm. Adjustment of the modulation depth to specific requirements can be accomplished by varying laser fluence or pulse number. The structures can be used as grating couplers. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Ta_2O_5 is a very important material in various areas of optical technology. Due to its good transparency and the high refractive index ($n > 2.2$ in the visible range) it is used for multilayer dielectric mirrors or masks [1,2] and for planar waveguides [3].

Planar waveguides find applications in optical communications technology and integrated optical sensors [4]. The efficient coupling of laser light into the waveguide is of great importance. In most cases this is accomplished by focusing the laser on a surface grating on the waveguide (or on a cover layer). These gratings can be produced by a lithographic process, e.g., holographic exposure of a photoresist and subsequent dry etching.

In this paper we describe sub-μm-period grating fabrication on Ta_2O_5 by laser ablation using a short pulse laser system in combination with a high resolution optical imaging arrangement, an approach which has already been successfully applied to the structuring of metals [5] and lithium-niobate ($LiNbO_3$) [6].

Until now UV-laser ablation of Ta_2O_5 has been investigated with respect to layer deposition [7] and

* Corresponding author. Tel.: +49-551-503544; Fax: +49-551-503599; E-mail: jihle@llg.gwdg.de

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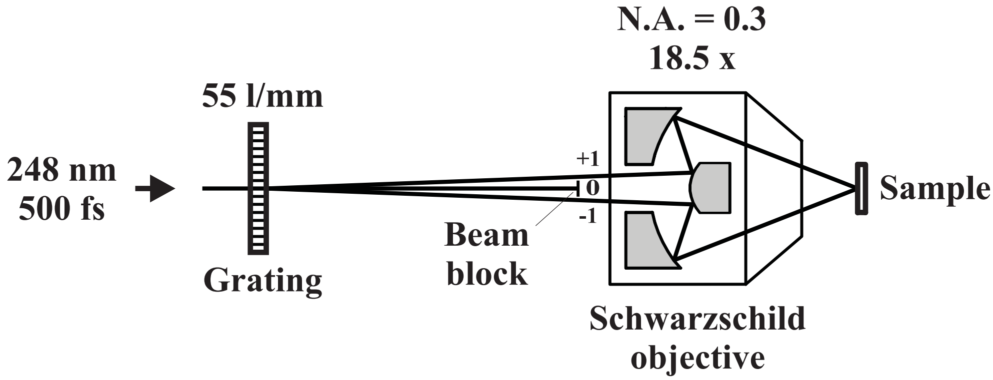

Fig. 1. Mask projection set-up with Schwarzschild objective.

plume analysis [8], but not with the aim of microstructuring.

2. Experiment

Ta_2O_5 was deposited on glass substrates (Corning 7059) by reactive low voltage ion plating (RLVIP) leading to extremely hard and dense layers. The layer thickness was 150 nm.

Ablation experiments were performed with a short pulse KrF-laser system described elsewhere [9]. The output is about 10 mJ at 248 nm with a pulse duration of 500 fs. Irradiation was carried out in a mask projection set-up shown in Fig. 1. For mask imaging a Schwarzschild type reflective objective was used. This insures high power transmission in the UV and prohibits pulse front distortion for femtosecond pulses. This objective had a numerical aperture of 0.3 and was used with a demagnification of $18.5\times$.

For the ablation of the periodic structures a transmission grating (55 lines/mm Cr on quartz) was imaged onto the samples. The zeroth order of the diffraction pattern was blocked in order to increase the created line density by a factor of two. With this arrangement an intensity pattern with a period of about 500 nm was projected onto the samples. The fluence was varied with a dielectric attenuator between 10 and 800 mJ/cm^2. To avoid air breakdown in the focus between objective and image plane, some of the experiments were performed in a vacuum cell ($< 10^{-1}$ mbar).

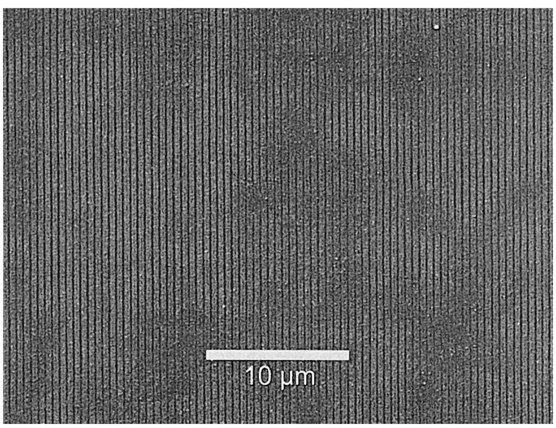

Fig. 2. SEM-micrograph of a Ta_2O_5-grating made with a single laser pulse (248 nm, 0.5 ps, 100 mJ/cm^2, vacuum).

3. Results

Fig. 2 shows a surface grating produced with a single pulse at a fluence of 100 mJ/cm^2 recorded by

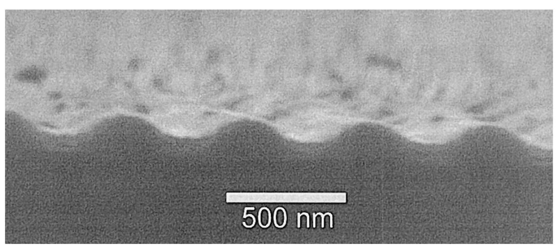

Fig. 3. SEM-micrograph of a Ta_2O_5-grating made with 2 laser pulses (248 nm, 0.5 ps, 300 mJ/cm^2, vacuum).

scanning electron microscopy (SEM). A smooth and homogeneous structure is achieved over the whole irradiated area of about 300 μm × 300 μm. Fig. 3 shows a cross section of a Ta_2O_5-surface structure made by 2 pulses of 300 mJ/cm^2 resulting in a sinusoidal profile. The dependence of the surface

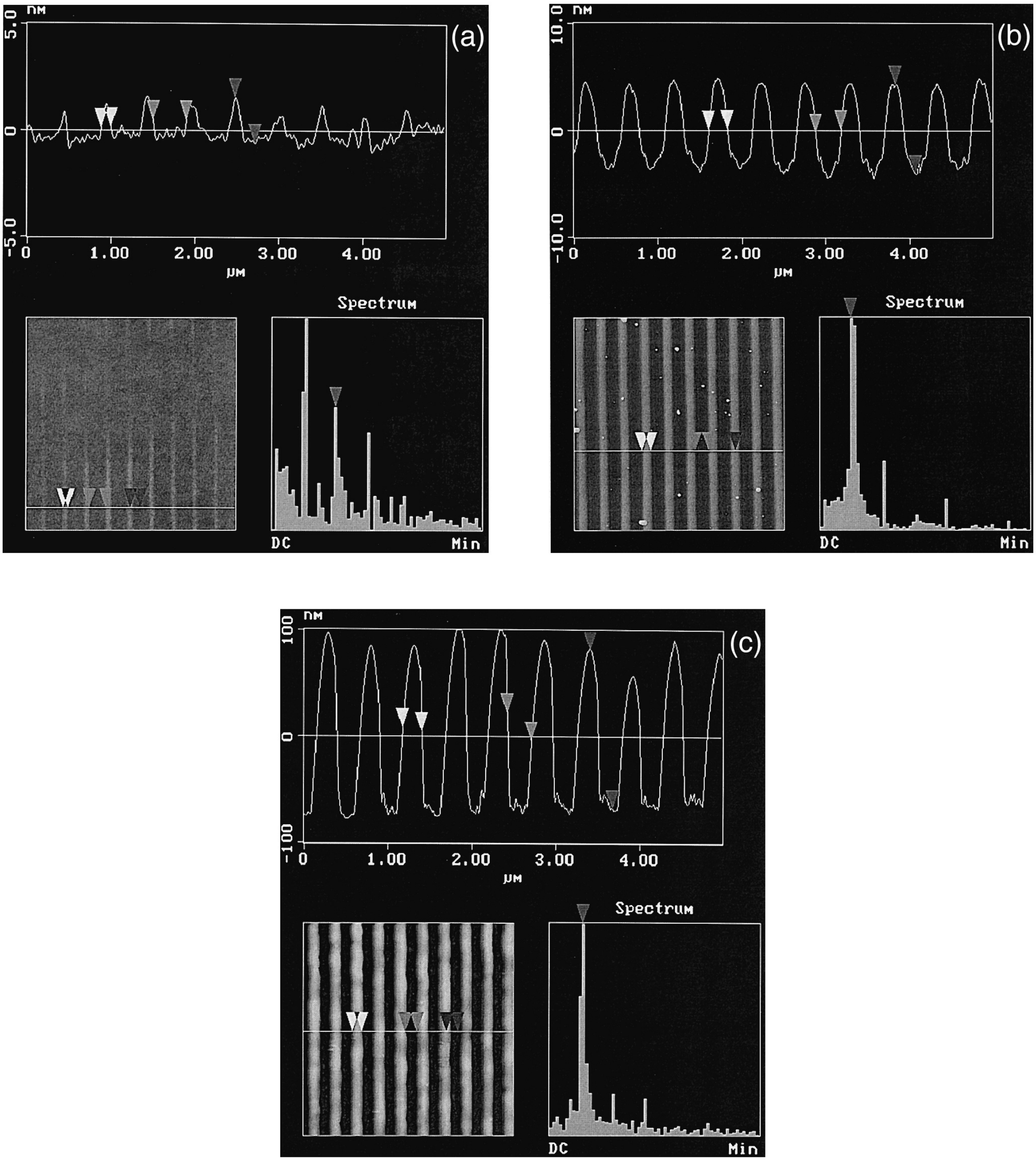

Fig. 4. AFM-records of Ta_2O_5-gratings made by laser ablation at 248 nm, 0.5 ps (in air): (a) 30 mJ/cm^2, 2 pulses, (b) 100 mJ/cm^2, 1 pulse, (c)100 mJ/cm^2, 100 pulses.

modulation depth on fluence and pulse number can be seen from the atomic force microscope (AFM) data shown in Fig. 4a–c. The fluence threshold for the development of a periodic surface profile is about 30 mJ/cm^2. With an average fluence of 30 mJ/cm^2 the grating structure appears only in limited areas of the irradiation spot (Fig. 4a). At 100 mJ/cm^2 a surface modulation of about 10 nm is reached with a single laser pulse (Fig. 4b). By applying several pulses of this fluence, the layer can be structured down to the glass substrate. Fig. 4c shows a grating with completely removed Ta_2O_5-layer in the grooves. Even the glass substrate is ablated to some extent.

Using for comparison nanosecond laser pulses (20 ns) instead of the sub-ps pulses, a maximum modulation depth of 1 nm with a single pulse and no more than 3 nm with 5 pulses was observed.

4. Discussion

For the ability to generate structures with sub-μm feature size not only the optical resolution but also the resolution limit of the material response due to thermal diffusion of the absorbed laser energy has to be considered. A characteristic measure is the thermal diffusion length $L = (2D\tau)^{0.5}$, where $D = \Lambda\rho^{-1}c_p^{-1}$ is the thermal diffusivity of the material (Λ thermal conductivity, ρ density, c_p specific heat capacity) and τ the laser pulse duration, or, for ultrashort pulses, the electron phonon coupling time determining the speed of lattice heating. If L exceeds the optical resolution limit, which is of the order of the used laser wavelength, lateral heat exchange will prevent high contrast structure formation.

Exact thermal conductivity data of layered materials are scarcely available. The data depend on deposition method, layer thickness, and temperature, and differ also for the various methods of measurement [10,11]. For Ta_2O_5 data range from 0.03 to 15 W m^{-1} K^{-1}, leading to thermal diffusion lengths of 20 nm to 500 nm for a laser pulse duration of 20 ns. Assuming an average value of about one hundred nanometer, it is understandable, that with nanosecond pulses a period of some hundred nanometers is the ultimate limit for ns-structuring leading only to the observed shallow structures with no more than 3 nm modulation depth. Using picosecond- or femtosecond pulses, heat diffusion can be neglected and deep modulation is possible.

5. Conclusion

Laser ablation patterning can be used as a one step process for the generation of surface gratings. Ultrashort UV-pulses lead to sub-μm structures of high contrast on Ta_2O_5. A single laser pulse is sufficient for the fabrication of a grating that can be used for the coupling of light into a Ta_2O_5-waveguide. Experiments for the detailed optical characterization of the gratings are in progress.

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