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Invited lecture

PATTERNING OF OXIDE THIN FILMS BY UV-LASER ABLATION

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Excimer laser ablation at deep-UV wavelengths (248 nm, 193 nm) is used for the patterning of thin oxide films or layer stacks. The layer removal on extended areas as well as sub-µm-structuring is possible. The ablation of SiO_2, Al_2O_3, HfO_2, and Ta_2O_5-layers and combinations of them has been investigated. Due to their optical, chemical, and thermal stability, these inorganic film materials are well suited for optical applications, even if UV-transparency is required. In contrast to laser ablation of bulk material, in the case of thin films the layer-layer or layer-substrate boundaries act as predetermined breaking points, so that precise depth control and a very smooth surface can be achieved. For the fabrication of optical elements with this method, the film can be ablated on extended areas (1), or on a pixel base with pixel sizes of a few wavelengths (2), or at the resolution limit given roughly by the ablation laser wavelength (3). Typical optical elements belonging to these three ranges are (1) dielectric masks, (2) pixelated diffractive elements, and (3) gratings with high line density.

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1. Introduction

Excimer laser ablation is a versatile and widespread method for micro processing of the materials. Nearly any kind of technical materials like polymers, metals, glass, ceramics, and composite materials have been investigated with respect to their response on intense pulsed UV irradiation [1-2]. Various applications like for instance drilling of micro holes or nozzles, marking of eye glasses or stripping of wires have been developed and transferred into industrial processes. In contrast to the treatment of bulk material, where many laser pulses are required to e.g. drill a material to a certain depth, in the case of thin layers very few or even a single pulse is sufficient to generate the desired ablation pattern.

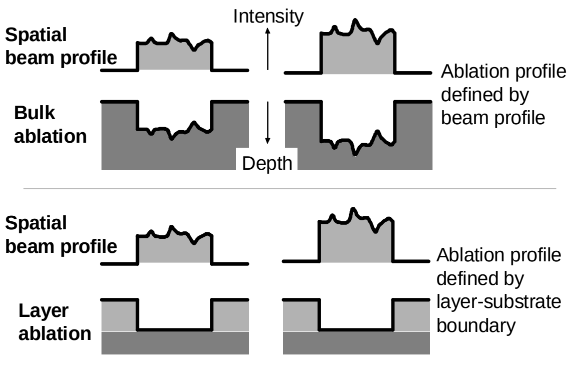

Fig. 1. Effect of the laser beam properties on the ablation profile in the case of bulk material and thin layers.

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Regarding the capability of simultaneous processing of large areas by mask projection, which is enabled by the flat top beam profile of excimer lasers, there seems to be a huge potential of patterning thin films by this method. Because the layer-layer or layer-substrate boundaries act as predetermined breaking points, the ablated depth profile is not directly correlated with the (sometimes inhomogeneous) beam profile. Whereas in the case of bulk material ablation spatial variations of the beam intensity will lead to a correspondingly shaped surface profile (fig. 1), this is not necessarily the case for layer ablation, because there is a certain process window concerning the fluence for complete layer ablation [3]. Thus even with some spatial variations of the irradiation fluence, a very flat surface can be achieved.

Patterning of optical layers is useful for the fabrication of optical components like waveguides, coupling gratings, refractive, reflective or diffractive structures. In most cases transparent films with high transmission in the operation wavelength range have to be used. For applications in the visible or infrared spectral range, often polymeric materials can be applied, though their mechanical and thermal stability is limited. For example, the laser-patterning of layers for fabricating (diffractive) optical elements has been performed already with polyimide films [4]. For UV-applications the control of processing UV-transparent materials, especially inorganic oxide materials, is necessary. Within the broad range of methods for the micro fabrication of optical elements, this paper treats the structuring of (UV-) transparent inorganic oxide layers and layer stacks by laser ablation (Fig. 2).

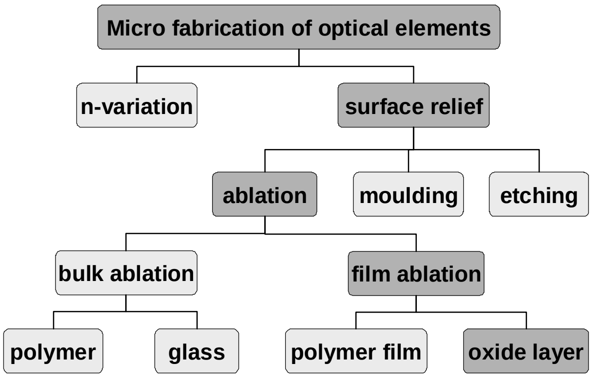

Fig. 2. Classification of methods for micro fabrication of optical elements. In this paper only laser ablation of oxide films is addressed (dark fields).

2. Front side and rear side ablation

Basically there are two different methods to induce layer ablation of a film from a substrate: Either the beam is directed head-on towards the film leading to “front side ablation”, or the beam hits the film from the other side after passing through the substrate (“rear side ablation”) (fig. 3). Rear side ablation is possible, if the substrate is sufficiently transparent at the laser wavelength. For standard excimer laser wavelengths this is the case e.g. for UV grade fused silica.

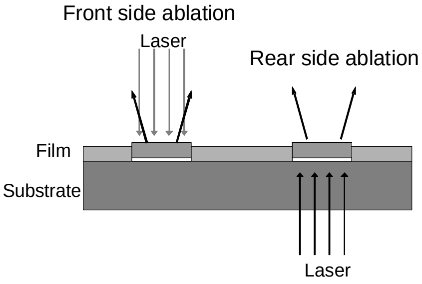

Fig. 3. Definition of the terms “front side ablation” and “rear side ablation”.

Excimer laser processing is usually carried out in a mask projection configuration. A mask consisting of transparent and opaque (or reflective) areas is illuminated by the flat top laser beam. Using a lens or a complex imaging system, the mask is projected on the surface of the work piece, so that the pattern of the mask is reproduced (usually demagnified) in this plane leading to material ablation in the irradiated regions in the case of sufficiently high fluence.

In the case of front side ablation, depending on laser fluence, film thickness, and absorption properties of film and substrate, the whole film or part of it can be ablated. If the film consists of a layer stack, it is even possible to ablate layer after layer by successive laser pulses [5]. In the case of rear side irradiation with sufficient fluence, the whole film or layer stack is ablated with a single laser pulse. The advantage of this method is, that due to the forward transfer of the material in the direction of the laser beam, there is no possibility for the interaction of the laser radiation with already ablated fragments. In the case of front side ablation, this interaction can lead to considerable debris formation around the ablated area, if no countermeasures are applied. Furthermore the required laser fluence for complete ablation is much higher and the edge quality is lower for front side ablation (fig. 4).

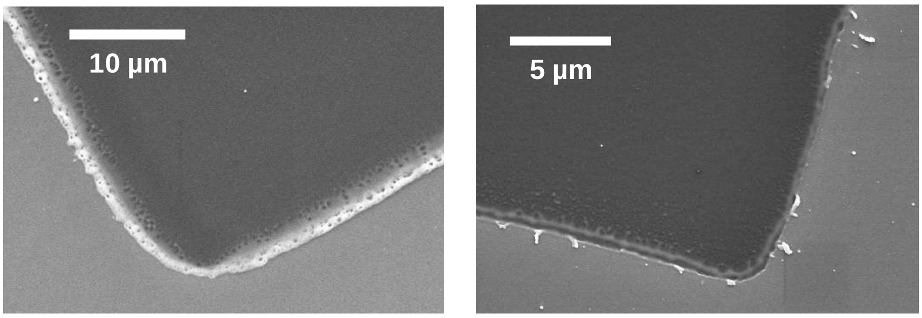

Fig. 4. Ablation spots in a 86 nm thick HfO_2-film on fused silica made by a single laser pulse at 193 nm. Left: front side ablation, 5.3 J/cm², Right: rear side ablation, 0.5 J/cm². (Note the different scales.)

3. Patterning of single layers

The patterning of a transparent film on a transparent substrate is demonstrated here for the example of the fabrication of a binary diffractive phase element (DPE). DPE are very attractive for beam shaping because of there in principle lossless operation. They can be implemented by a (pixelated) surface profile on a transparent optical material and can be applied for beam homogenization, beam splitting or efficient mask illumination. A binary phase element for operation at a UV-wavelength λ can be made by ablation patterning a UV-transparent oxide film with refractive index n and a thickness of $D = \lambda/[2(n-1)]$. Pixel sizes of about 10x10 µm² are convenient for fabrication and application. The ablation process can be performed pixel by pixel according to the calculated DPE design, or by creating the whole structure at the same time by ablation using a mask. For applications of the DPE in the near UV, Ta_2O_5 is an adequate material. Ta_2O_5 absorbs at 248 nm sufficiently, to be patterned by ablation, but is transparent at 308 nm. This means that a DPE for use at 308 nm can be fabricated using 248 nm [6].

For fabricating a phase element to operate in the deep UV, e.g. at 193 nm, a film material that is transparent at this wavelength is necessary, e.g. SiO_2. Because of its transparency it is not possible to ablate this material with the required precision using the same wavelength. A way out of this problem is given by a two step processing in the following way: The material is laser processed in a state with sufficient absorption, and afterwards, e.g. by thermal treatment, transferred into a non absorbing (functional) state. In the case of SiO_2 there is the absorbing metastable state SiO_x with $x < 2$. The UV-absorption strongly depends on x [7]. A value x is chosen, so that the absorption is sufficient for clean ablation at 193 nm or 248 nm. After annealing to SiO_2 the material is highly UV-transparent. Fig. 5 shows a DPE made by this method.

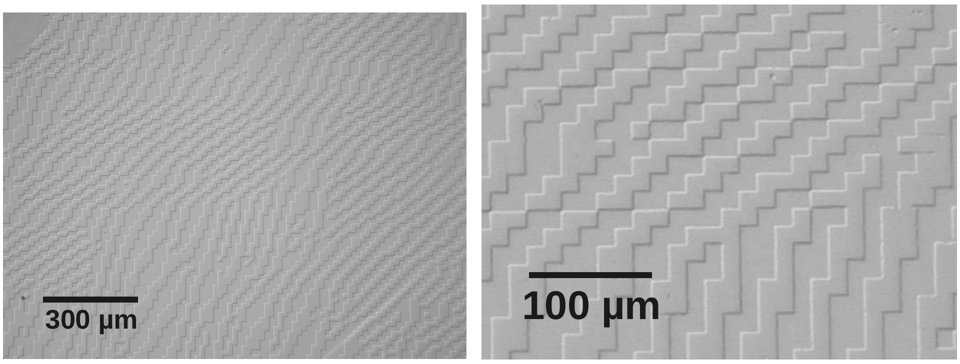

Fig. 5. Binary diffractive phase elements made by laser ablation using mask projection; material: 140 nm SiO_x on fused silica (SiO_2 after thermal annealing), laser parameters: 248 nm, 350 mJ/cm², 1 pulse rear side ablation (mask projection).

4. Patterning of multilayer stacks

A typical application for the patterning of multilayers for optical applications is the fabrication of dielectric optical masks. Such multilayer stacks, e.g. of alternating HfO_2- (high refractive index) and SiO_2-layers (low refractive index) can be ablated by an ArF-excimer laser, because HfO_2 is absorbing at 193 nm. Though the thickness of the film is more than 1 µm, under certain conditions sub-µm edge definition is achieved in the case of rear side ablation (Fig. 6).

For precise and controllable ablation, sufficient absorption of the material is required. If both materials of the dielectric layer stack are transparent at 193 nm, the ablation of these systems has to be performed either at even shorter wavelengths (Vacuum-UV) [8], or with an absorbing subsidiary layer. Thus dielectric mirrors with high reflectivity at 193 nm consisting of a stack of alternating SiO_2- and Al_2O_3-layers were patterned by depositing a 193 nm-absorbing HfO_2 layer between substrate and HR-stack and ablating in a rear side configuration [9].

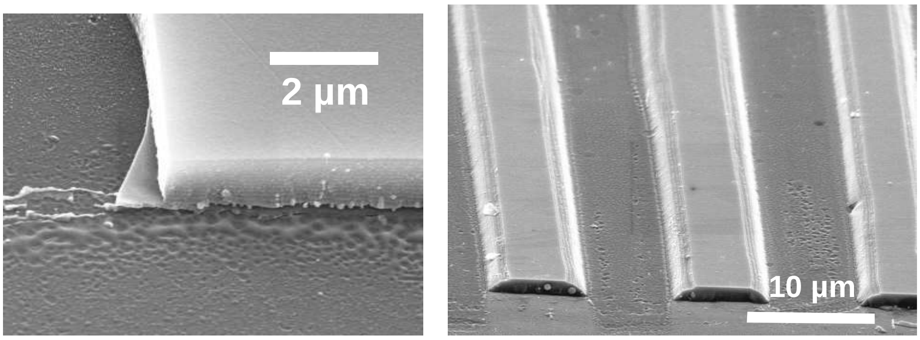

Fig. 6. 193nm single pulse rear side ablation of oxide multilayer stacks Left: HfO_2/SiO_2 (interference layer system highly reflective (HR) at 308 nm) Right: HfO_2/SiO_2 (HR 248nm), ablation fluence: 300mJ/cm².

Dielectric masks fabricated by this method can be applied for high intensity laser applications, where metal masks (Cr on quartz) would be easily damaged. It is even possible to fabricate grey level masks by ablating only a defined number of single layers instead of the whole stack [5]. As this process works only by front side ablation, the edge definition of the ablated structures is limited.

5. Generation of sub micron patterns

Patterning a thin film with high (sub-µm) resolution is desirable for instance for the fabrication of optical gratings. To achieve the required optical resolution at high fluence levels, a mask projection set up using a reflective objective is suitable. The laser pulse duration has to be limited to a value, that thermal diffusion of the energy coupled into the film does not lead to blurring of the sub micron pattern. For metal films, pulse durations as short as 50 ps already lead to diminished structure resolution [10]. For polymer films with their low thermal diffusivity, comparatively long nanosecond-pulses can be applied, but metal oxide films exhibit rather high thermal diffusivities, so that short pulses are required. Then it is possible to adjust the depth of the pattern in the film by the number of pulses, so that the film can be ablated partly or completely down to the substrate (front side ablation). Fig 7 shows a grating with 360 nm period made in Ta_2O_5 with a short pulse excimer laser. Such gratings may by applied for coupling light into planar waveguide, or for so called *grating waveguide structures*, which are used e.g. for biosensors based on fluorescence detection [11-13].

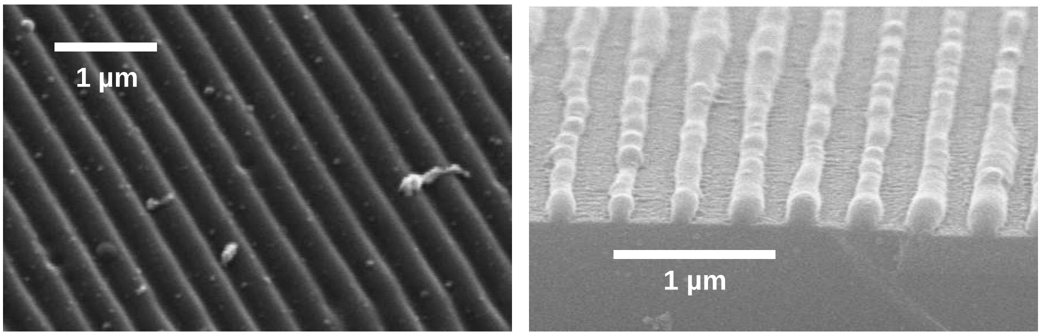

Fig. 7: Sub-µm grating patterns made with a short pulse excimer laser in 150 nm thick Ta_2O_5 waveguide layers. Left: film partly ablated, laser parameters: 248 nm, 0.5 ps, 200 mJ/cm², 1 pulse. Right: film ablated down to the substrate, so that Ta_2O_5-lines with 150 nm width and 150 nm height are formed; laser parameters: 248 nm, 0.5 ps, 90 mJ/cm², 25 pulses.

6. Conclusion

UV-transparent inorganic oxide layers are patterned with excimer laser radiation with high precision. Complete layer stacks or only parts of them are ablated depending on fluence and irradiation conditions. Thus, dielectric masks, pixelated diffractive phase elements, and sub micron gratings are micro fabricated.

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