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Polishing micro-optical components fabricated by femtosecond laser micromachining

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ABSTRACT

Femtosecond laser irradiation followed by chemical etching (FLICE) is a powerful and enabling technology for microstructuring glass substrates in 3D. The irradiated focal volume expresses increased etching selectivity with respect to the pristine material, enabling the fabrication of optical components with micrometric resolution, but with critical residual roughness (about 400 nm rms). Here we compare the surface quality of microlenses processed with different methods as CO_2 laser annealing, thermal annealing in oven and polishing by direct dielectric barrier discharge inert gas plasma at atmospheric pressure. The optimized optical elements will be integrated on more complex devices for optical investigations of biological specimens.

KEYWORDS: surface polishing, micro-optical components, CO_2 laser annealing, thermal annealing, plasma polishing, femtosecond laser micromachining (FLM).

1. INTRODUCTION

Integrated micro-optical components fabricated through femtosecond laser irradiation followed by chemical etching (FLICE) play a crucial role in integrated optical circuits on glass substrates [1]. These components ensure optical stability and precise alignment, enabling the creation of compact and portable devices, such as lab-on-chip (LOCs) systems and microscopes-on-chip (MOCs).

However, when micro structures are fabricated using FLICE, a typical roughness of around 400 nm root mean square (rms) characterizes the surface. To address this, several methods have been developed to enhance surface quality and reduce roughness. The most common techniques include oven annealing and laser polishing. Of these, laser polishing is suitable for external surfaces, whereas furnace annealing is effective for both external surfaces and internal walls of hollow structures, such as buried microfluidic channels. All these methods involve heating the glass above its transition temperature, allowing the surfaces to relax and smooth [2-3]. Alternatively, plasma polishing employs a 'cold' dielectric barrier discharge at atmospheric pressure to clean and polish irradiated surfaces [4].

In this manuscript, we present preliminary results on polishing a circular tilted collimating micromirror with a 500 nm diameter, fabricated superficially in a fused silica substrate. Three different polishing methods will be compared and evaluated: CO2 laser polishing, oven annealing and plasma polishing.

2. MATERIALS AND METHODS

2.1 Device fabrication

The method employed for fabricating the microstructures is femtosecond laser micromachining (FLM), a technique that allows precise and direct irradiation of the lens profile within the glass [5]. By focusing a femtosecond laser on the fused silica substrate, the material can be locally modified based on specific fabrication parameters.

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This technique is highly versatile. It enables the creation of a smooth refractive index change to produce waveguides, which convey the light inside the glass. Alternatively, it can induce a birefringent refractive index change, forming nanogratings that enhance chemical etching. This selective material removal facilitates substrate microstructuring. This approach, known as Femtosecond Laser Irradiation followed by Chemical Etching (FLICE), permits to fabricate the microlenses used in this study. The external profile was irradiated with a femtosecond laser at 515 nm (Light Conversion, Carbide), with a repetition rate of 1 MHz, focused through a 50x objective with the correction collar set to 0.6 Si correction. The power employed was 290 mW and the speed was 1 mm/s, the pulse picker was set to 1. The polarization of the beam was perpendicular to the writing velocity, to enhance chemical etching. The pitch chosen was of 1 μm. An image of the irradiated structure is reported below in figure 1. Post irradiation, the structures are immersed in Hydrofluoric Acid (HF) for 50 minutes at 35°C with an ultrasonic bath. After this chemical process, the final tilted lens is visible in figure 2, along with the residual roughness exhibited by the surface.

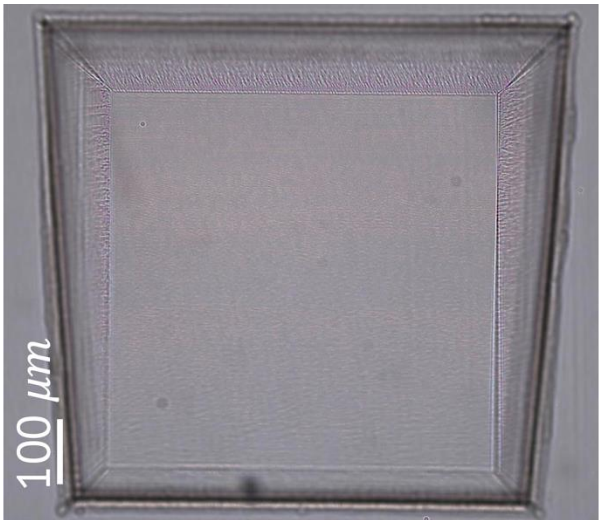

Figure 1- Irradiated structure before chemical etching

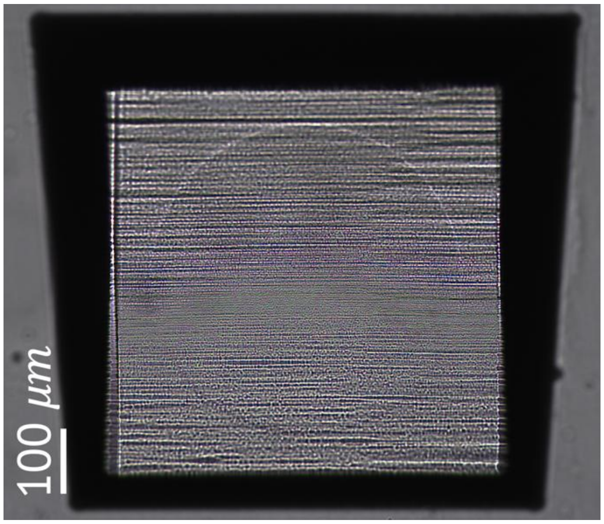

Figure 2 - Tilted microlens after chemical etching

2.2 CO_2 laser annealing

CO_2 laser annealing of the samples was executed at the Department of Applied Physics of KTH Royal Institute of Technology in Stockholm. A CO_2 laser source (Synrad, Firestar ti100HS) operating at 10.6 μm and a translation stage (Aerotech, ALS130H-50) were used to scan the beam across the sample, and polish microstructures' surface. The beam diameter of 2 mm was focused on the sample through a ZnSe cylindrical lens with a focal length of 127 mm and aligned perpendicular to the glass slide. Optimum polishing was achieved by performing a double scan across the microstructures, in forward and then backward direction. Different powers (from 15 to 24 W) and scanning speeds (from 0,1 to 0,5 mm/s) were tested.

2.3 Thermal annealing

The surface thermal annealing was carried out using a NaberTherm furnace (Nabertherm, 50/250/13) operating in a controlled atmosphere. The sample was positioned inside the furnace tube using a crucible. After placement, the vacuum pump was activated, followed by flushing nitrogen (N_2) into the furnace. Various heating profiles were tested to determine the optimal annealing temperature, after which the cooling procedure was refined. Each process was conducted on two samples to ensure reproducibility and facilitate comparison of the results.

2.4 Plasma polishing

Plasma polishing treatment was performed at the University of applied sciences and arts (HAWK) in Göttingen. The conic plasma source employed works thanks to dielectric barrier discharge (DBD). In this manner, a low-temperature filament plasma in non-thermal equilibrium can be realized. In the setup employed, an internal high-voltage (HV) hollowcore electrode is placed and a gap between both the electrode and the outer cone acts as gas channel for the Argon. The gas flow is regulated by a valve. A ground electrode was mounted perpendicular to the nozzle and in between, the glass microstructure was placed acting as dielectric. The electrode distance (from 2 to 10 mm) and the signal driven by a signal generator were changed during process optmization. The sample roughness was measured with a laser scanning microscope after each treatment to observe the progression and the effect of the polishing.

2.5 Measurements

The roughness measurements were carried out at PoliFab employing an optical profilometer (Filmetrics, Profilm3D). This instrument uses light interferometry to measure the roughness profile of the surface, by sampling the interference pattern generated by the superposition of two reflected white beams coming from the sample and the reference mirror. The interference signal of each pixel exploits maximum modulation when the optical path length of the reference and the sample beams coincides, so the z-position of the stage represents the height value for that pixel and a mapping of the surface profile is possible. All the data collected were processed with the provided software ProfilmOnline. The residual roughness was measured with the ASME B46.1 standard.

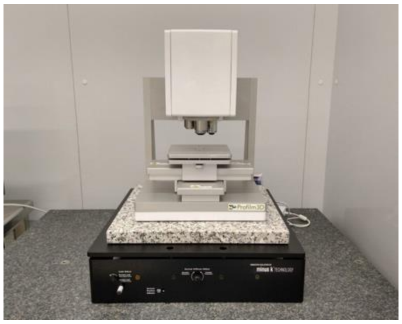

Figure 3 - Optical profilometer employed for the roughness analysis

3. RESULT AND DISCUSSION

The roughness of the micro-optical component was measured with the optical profilometer before the different polishing treatments in order to have a reference value. The average line roughness of the surface, measured with a 50x objective with 0.55 NA, was 469 nm. After performing the annealing treatment on different samples of the same kind, the roughness was measured to assess the most efficient one which guarantee the major reduction of Ra. With CO_2 laser annealing, an effective and visible reduction of the roughness was achieved (Ra = 49 nm), however, due to the instability of the laser power, it could happen to locally vaporize the silica and burn the surface, as shown in figure 5, on the edge of the structure one the far right. Due to the nature of the process the profile of the structure was deformed, and this could be detrimental for the optical alignment. Moreover, the beam of the laser leaves a mark on the silica that cannot be avoided, scanning the surfaces multiple times. On the other hand, the thermal treatment in an oven with controlled N_2 atmosphere preserve the shape of the microlens lens, but cracks can occur damaging the surface as shown in figure 4. The measured residual roughness was improved (Ra = 175 nm), but the heating curve should be optimized to get rid of chinks.The plasma polishing results for the roughness were comparable with the Oven annealing (Ra = 150 nm) and no cracks occurred on the surface. However, after a certain time, the treatment can’t polish the structure anymore and we reach a threshold, so the process saturates and can’t further lower the roughness.

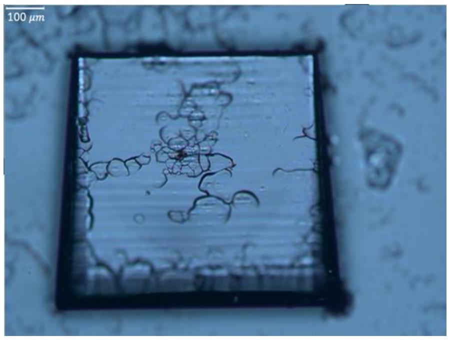

Figure 4 - Microlens cracked after the oven treatment

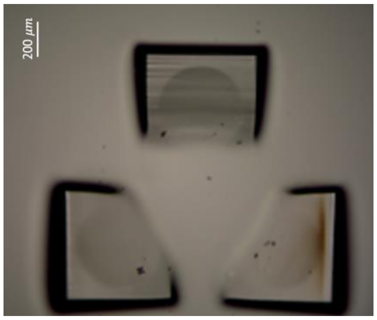

Figure 5- Microlenses polished with CO2 laser

4. CONCLUSIONS

In this work we have presented three effective ways to polish optical microstructures fabricated by Femtosecond Laser Micromachining. The three processes reduced the roughness of the optical surfaces, which should be integrated on more complex devices such lab on chips or integrated microscopes. However, each of these techniques has advantages over the other, as well as limitations. Regarding the average roughness value, this optimization process allowed us to identify CO_2 as the most effective method to reduce the Ra value. All the processes presented should be further tuned to obtain smooth surfaces without defects and profile deformation.

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