

COMPLEX 3D GLASS STRUCTURES BY LASER-ASSISTED FLICE METHOD

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Abstract— Hybrid laser-based methods of glass micromachining enable the development of innovative all-in-glass devices with extraordinary features for multiple applications. In this work, we demonstrate the capability of the FLICE method (femto-second laser irradiation followed by chemical etching) to generate complex high-aspect ratio geometries with high spatial resolution and smooth surfaces, that are of great importance for microsystem technology.

Keywords— 3D micromachining, FLICE, glass, femto-second laser, wet etching

I. INTRODUCTION

The glass materials are widely used in the microsystems technology due to attractive combination of excellent physical and chemical properties, long-term stability, close CTE match to Si (Pyrex-type glass), and relatively low cost of high quality substrates. Various applications take advantage of their remarkable optical transmission (MOEMS, gas microcells for time-frequency devices), natural hydrophilicity and biocompatibility (Lab-on-chip, Bio-MEMS), good electrical insulation (micro-sensors) or high thermal/chemical resistance (chemical microreactors). However, the glass micromachining is challenging for traditional technologies because of its high hardness and brittleness as well as easy crack formation. Great effort has been made to develop new machining methods to overcome these technological difficulties and to fulfil **new challenging requirements** of emerging applications where small structures with 3D complex geometries need to be fabricated:

R1: 3D machining capability of complex geometry with high spatial resolution (μm range)

R2: No global modification of physical glass properties

R3: High aspect ratio (AR) features in large range of glass thickness (a few mm range)

R4: No sub-surface damages (mechanical stress)

R5: No heat-affected zones (thermal stress)

R6: Smooth surfaces

In particular, the hybrid laser-based methods have made a true breakthrough in this field. They explore non-linear light-matter interaction phenomena (e.g. multiphoton absorption) observed during irradiation of glass material with ultrashort laser pulses with extremely high peak intensities (in TW/cm^2 range). In this paper, the FLICE method (femto-second laser irradiation followed by chemical etching) is presented as a versatile technological solution for advanced 3D manufacturing of glass microstructures.

II. FLICE METHOD

Since the first demonstration in the 2000s [1,2], the FLICE has sparked significant interest as a powerful subtractive and non-direct glass machining method, allowing mask-free fabrication of various 3D microstructures in fused silica and other transparent dielectric materials with high spatial precision. The basic principle is that the irradiation of glass by focused femto-second laser beam triggers the generation of nano-structures that allow much faster penetration of irradiated glass by an etchant than the bulk glass (i.e. typically 50-300 times faster, depending on etchant type). This process must be precisely tuned to achieve optimal conditions (maximal etch rate) that are different for each type of glass material and writing objective used.

The general process flow is composed of three steps (Fig.1). First, a laser 3D scanning trajectory is programmed in dedicated software and a machining code (job file) is generated. Next, the substrate is scanned in its volume by the focused f-s laser pulses, defining the cutting surfaces for subsequent wet etching. Only very thin contours are typically exposed by laser around the glass parts to be removed in order to minimize the machining time and to lower the process-related mechanical stress. In the final releasing step, the exposed glass is selectively wet etched in aqueous solution of HF (at room temperature) or KOH (typ. 80°C). In the latter case, the ultrasonic vibrations US are also activated periodically to enhance penetration of KOH through the high-aspect structure and to stabilize the etching rate.

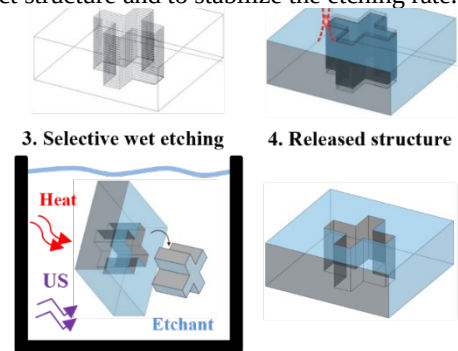


Fig. 1: Main steps of glass micromachining process by FLICE method.

In the following sections, the characteristic features of the FLICE will be described according to R1-R6 requirements. Exemplary microstructures were fabricated in Fused Silica (Corning 7980) by use of a commercial system f100 aHEAD Enhanced (FEMTOprint, Switzerland), equipped with a 5W Yb:YAG f-s laser operating at $\lambda=1030\text{ nm}$.

III. FLICE FEATURES

Since glass is transparent at $\lambda = 1030$ nm, the laser beam can be positioned freely in its volume allowing direct writing of arbitrary 3D patterns (**R1**). After exceeding the threshold pulse energy, the glass is transformed only locally in the small volume, so-called laser affected zone (LAZ). Hence, no global modification of glass properties occurs (**R2**). The LAZ has asymmetric form of very stretched ellipsoid with central X-Y axis diameter of 1-2 μ m and Z-axis height from $\sim 8\mu$ m to $\sim 40\mu$ m, for writing objective of 50x and 10x, respectively. The direct consequence of the LAZ shape is that the FLICE naturally generates flat and smooth vertical surfaces ($R_a < 100$ nm), as shown in Fig. 2a, also in thick mm-range glass layers (**R3**). This feature is advantageous in the fabrication of various high-aspect ratio structures, such as vias (Fig. 2d), MEMS, micro-engineered materials or flexible $\sim 2\mu$ m-thick vertical membranes, as shown in Fig. 3.

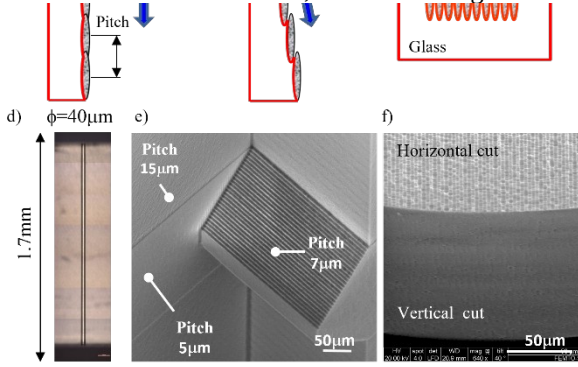


Fig. 2: FLICE features: a-c) impact of LAZ shape and writing direction on the surface quality, d) example of via hole (AR=42), e-f) comparison between vertical and inclined surfaces fabricated with 20x objective (SEM)

Characteristic feature of FLICE is that the laser exposure process generates an important mechanical stress that may cause a significant damage in the glass volume (i.e. local cracks, fracture) before releasing step. Therefore, some design rules must be respected to minimize this effect. Fortunately, wet etching process removes exposed glass as a source of mechanical stress. Moreover, an additional thin layer of non-exposed glass, that may contain some local damages, is also removed. As demonstrated in [2], this allows fabrication of structures with defect-free surface (**R4**, **R5**) that exhibit an exceptional elastic behavior, very important for micromechanics or for MEMS applications.

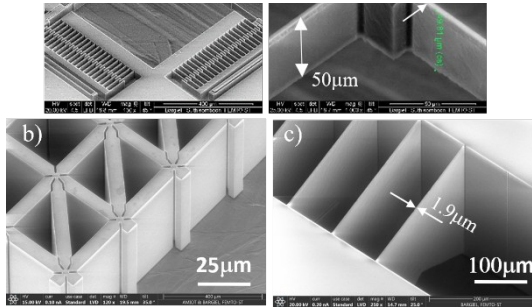


Fig. 3: Examples of high-aspect ratio structures by FLICE (SEM): a) combs and flexible suspensions (AR=20), b) vertical membranes (AR=210).

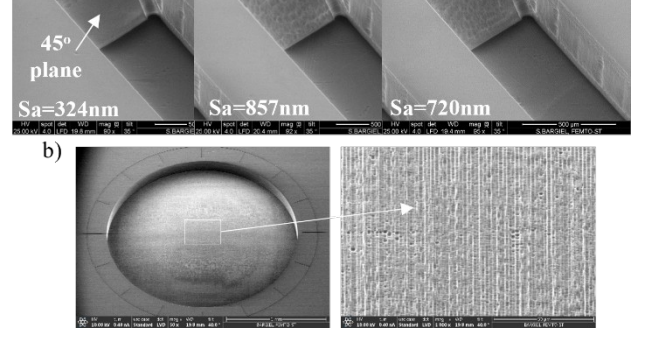


Fig. 4: Improvement of surface quality: a) impact of writing strategy on 45° surface, b) optimized plano-convex lens (~ 1.6 mm) before polishing step.

IV. CHALLENGING MICRO-OPTICS FABRICATION

Another consequence of the LAZ shape is that the quality of machined surface, for given writing objective, depends strongly on its 3D orientation. Vertical cutting generates flat and smooth surface whereas inclined/horizontal cuts reveal the surface with visible laser lines traces, having relatively high roughness in the range of $R_a = 300-800$ nm. An improvement of surface quality is crucial for optical applications and can be achieved initially by process optimisation, i.e. laser writing strategy, cutting resolution and wet etching conditions (Fig. 4). Nevertheless, additional post-treatment step is necessary to achieve optical grade surface. As shown recently in [3], a local polishing by CO_2 laser beam allowed rapid decreasing of surface roughness of an axicon microlens to some nm without modification of its profile. Further results of laser-based polishing will be presented in the final paper. The FLICE can be also combined with other methods, e.g., to define precisely the glass volume to be transformed by thermal micro-reflow into microlens with perfect surface and very repeatable diameter (Fig. 5).

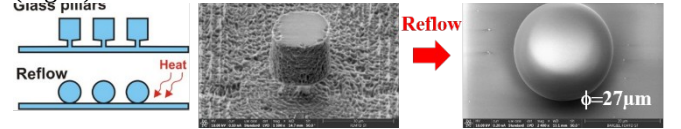


Fig. 5: Hybrid FLICE + μ Thermal Reflow for fabrication of ball microlens,

V. CONCLUSION

The FLICE is a powerful, subtractive 3D glass machining method that opens up new perspectives for manufacturing of innovative devices for multiple applications.

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