DIGITAL MANUFACTURING OF RESONANCE MEMS FROM A SINGLE-LAYER FUSED SILICA MATERIAL

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ABSTRACT

This paper presents a laser-based manufacturing process for fabrication of Micro-Electro-Mechanical (MEM) resonators from Fused Silica (FS) as the structural material. Femtosecond Laser-Induced Chemical Etching (FLICE) has been an enabling technology to micromachine complex 3-dimensional micro-fluidics and micro-optics from FS material. We utilized FLICE in a 3-steps process for fabricating capacitive MEM resonators, for the first time. For demonstration, a Disk Resonator Gyroscope (DRG) design was "digitally written" and released using the introduced process, and structural characterization results are presented. We experimentally demonstrated electrostatic actuation and detection of the 100 kHz FS-DRG and measured a quality factor on the order of 0.6M. By optimizing laser-writing parameters, we demonstrated that channels with an aspect ratio as high as 55:1 could be achieved. Our results demonstrate the potential of FLICE-like processes to become an alternative to conventional plasma etching technology for realizing high quality factor FS MEM resonators with ultra-high capacitive transduction.

KEYWORDS

Femtosecond laser, fused silica, resonator, gyroscope, fabrication, digital manufacturing.

INTRODUCTION

Fused Silica (FS) material has been exploited in micro-fluidic and micro-optic applications due to its high optical transparency, low Thermal Expansion Coefficient (TEC), chemical inertness, thermal stability, and high electrical resistance. In the context of fabricating vibratory Micro-Electro-Mechanical-Systems (MEMS) with a high quality factor and isotropic mechanical properties, FS is an excellent candidate to substitute the conventional single-crystal silicon as the structural material [1]. Despite its many desirable properties, micromachining of FS micro-structures has remained a challenge.

Micromachining of FS material has been primarily performed through wet etching techniques. The wet etching of FS does not provide anisotropic etch profiles; the process lacks the precision, controllability, and repeatability needed for fabrication of vibratory MEMS. In the last decade, utilization of plasma technology for anisotropic etching of fused silica has been the focus of the community [2]. Fabrication of FS resonators through plasma etching is a complex process, which includes wafer bonding, multiple lithography steps, metal coating, electroplating, metal etching, etc. [3]. More importantly, due to the chemical inertness of FS, plasma etching yields a limited Aspect Ratio (AR), typically below 10:1, and it produces a large amount of stress due to TEC mismatch between different layers.

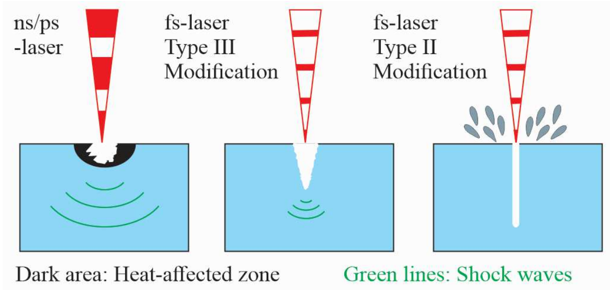

Figure 1: A comparison between etch profiles, etch quality, and the minimum feature size which can be realized using different laser technologies.

To overcome these limitations, we explored the Femtosecond Laser-Induced Chemical Etching (FLICE) process for fabrication of FS MEMS resonators for the first time.

Sub-bandgap laser light emitted with short pulses results in non-linear photoionization when focused tightly within a dielectric material [4]. Using a femtosecond laser with ultrashort pulses, the absorption of optical energy induces a variety of highly localized modifications to the material's structure while leaving the surrounding material largely unaffected. Femtosecond laser irradiation of FS, with a fluence below the ablation threshold, results in nano-grating with a sub-wavelength period, locally increasing the material's chemical etching rate by several orders of magnitude [5]. The etching side of this two-step process is a matter of submerging the irradiated material in a bath of aqueous HF or KOH solutions, depending on how accurate or rapid we wish to etch the material. In [5], the traditional laser ablation process is referred to as type-III modification and the FLICE process is referred to as type-II modification.

For ultrafast femtosecond lasers, energy deposition occurs on a timescale that is short compared to atomic relaxation processes. As a result, the Heat-Affected Zone (HAZ) in the material is minimized, illustrated in Fig. 1. Also, at lower pulse energies required for the type II modification, we avoid generating shock waves which potentially result in micro-crack in the material. Since the material modification is confined to the laser focal volume, laser inscribing can be performed deep within a transparent substrate. Translating the material through the laser focus in three dimensions, therefore, allows for arbitrarily shaped channels, planes, or volumes to be inscribed. A femtosecond laser provides an ultra-high-resolution of etching primarily determined by the pulse energy and beam spot size. The FLICE has been an enabling technology for fabrication of micro-optics and micro-fluidics, reviewed in [6].

In the following, we report our initial results on optimization and implementation of FLICE for fabricating Fused Silica (FS) vibratory MEMS along with initial experimental data on structural characterization.

2022 IEEE 35th International Conference on Micro Electro Mechanical Systems Conference (MEMS) | 978-1-6654-0911-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/MEMS51670.2022.9699685

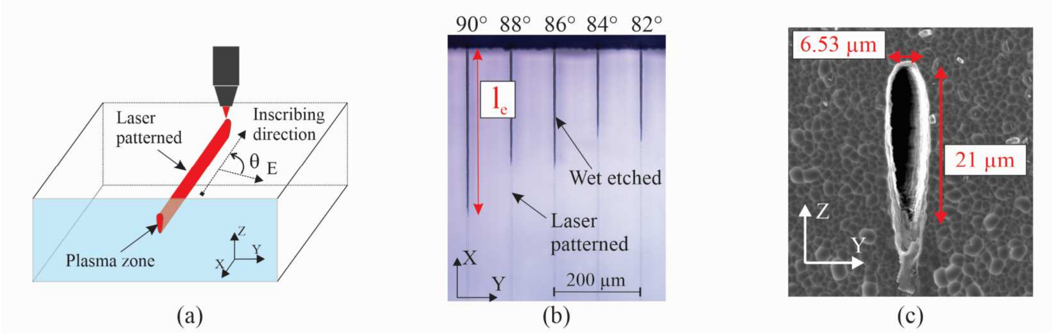

Figure 2: a) Schematics of a 1D laser inscription. Laser parameter optimization was performed based on the measured etch rate of 1D channels. (b) An optical image of wet etched 1D channels patterned using FLICE at different polarizations (top view). (c) Cross-section SEM image of an etched 1D channel inscribed inside of the material.

FLICE PROCESS

For digital manufacturing of MEMS resonators through FLICE, we used a custom-designed femtosecond laser station, comprised of a 1030 nm wavelength CARBIDE femtosecond laser source (Light Conversion Inc.), sub-micron accuracy air bearing cartesian XYZ stages, a servo-controlled half-wave plate linear polarizer, and a Mitutoyo 50X magnification lens (NA=0.42).

Since laser-based manufacturing is performed in series, to achieve high throughput manufacturing, optimization of the process parameters is required. Optimization was performed with three main goals: (a) to increase the selectivity of wet etching, (b) to increase the laser marking speed, and (c) to achieve optimal surface quality. For fabrication of MEMS resonators, a higher selectivity is correlated with the etch profile and the maximum achievable AR of etching; increasing the laser marking speed would allow us to perform wafer-level fabrication in a short process time. Last but not least, we need to choose optimal process parameters to reduce surface roughness and other defects in micro-structures patterned using FLICE. Among the process parameters which must be optimized are pulse energy, pulse width, repetition rate, and marking speed.

Inscribing and wet etching of 1-Dimensional (1D) channels in the bulk of fused silica material, illustrated in Fig. 2(a), is commonly used to optimize the parameters of the FLICE process [7]. In our experiment, we inscribed 30 mm long straight lines, with different laser parameters, 100-microns deep below the surface of FS samples. The samples were mechanically diced so that the entrance of the channels was exposed to a 8M KOH solution at 85°C during the wet etching step. After 1 hour of wet etching, due to the birefringence effect, the etched channels appeared darker as compared to the laser-modified but non-etched areas, shown in Fig. 2(b). A cross-section Scanning Electron Microscope (SEM) image of 1D channels after wet etching is shown in Fig. 2(c). By measuring the length of the wet-etched channels (l_e), we investigated the optimum parameters for the FLICE process.

Polarization

It has been reported that a linearly polarized laser beam with an orientation perpendicular to the direction of inscription provides the highest selectivity in FLICE [5,7]. We investigated this by laser inscribing and wet etching multiple 1D channels along the X-axis and setting the orientation of polarization (θ) at different values using the servo-controlled half-wave plate.

As illustrated in Fig. 3, we observed a high correlation between polarization and etch rate. These results confirmed that the polarization of laser must be kept perpendicular to the marking direction to achieve the highest selectivity in the FLICE process. This observation is partly explained by the fact that in type-II modification, nano-gratings are formed perpendicular to the polarization direction. By having self-aligned nano-gratings along the marking direction, the wet etching process is facilitated and the etch rate increases.

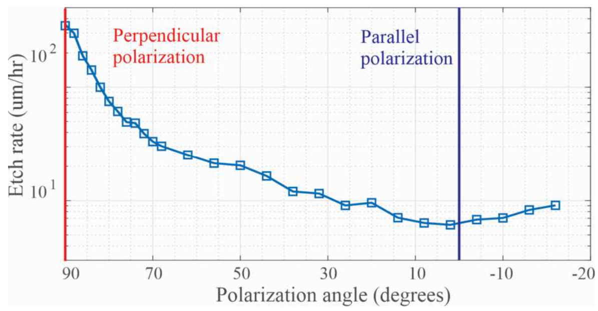

Figure 3: Measured etch rate of 1-dimensional channels patterned using FLICE at different polarization angles annotated as θ in Fig. 2(a).

For laser patterning of MEMS resonators, especially gyroscopes, it is vital to have a high and consistent etch rate at different areas. Therefore, we implemented a function through which the servo-controlled polarizer dynamically adjusts polarization based on the direction of travel. Through the dynamic polarizer, we were able to pattern circular and other complex shapes

Pulse Energy and Marking Speed

For a repetition rate of 250 kHz, the etch rate was characterized for pulse energies ranging from 0.5 µJ to 4 µJ and marking speeds from 0.1 mm/s to 20 mm/s. Generally, we measured the highest etch rate (selectivity) at moderate pulse energies at low marking speeds, shown in Fig. 4.

At higher marking speeds, we observed a significant drop in etch rate due to an insufficient effective number of pluses per area [8]. At high pulse energies and high repetition rate, we observed lower etch rates, possibly due to accumulation of heat in the material causing molten and resolidified features (i.e., Type-III modification).

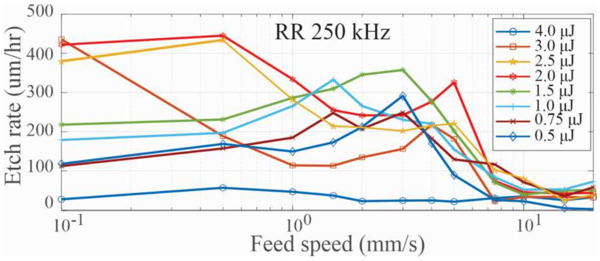

Figure 4: Measured etch rate for 1D channels patterned using the FLICE process at different pulse energies and marking speeds for a repetition rate of 250 kHz.

Using 8M KOH as the etching agent, we determined that for a pulse duration of 360 fs, a pulse energy of 2 µJ yielded the highest etch rate, on the order of 325 µm/hr, at a relatively high marking speed of 5 mm/s.

Based on the etch rate of pristine FS in 8M KOH solution at 85 °C, which is around 0.38 µm/hr, we were able to achieve a selectivity on the order of 855:1 using the FLICE process. We believe that by researching a broader range of parameters, we can further optimize the process and achieve similar selectivity at an order of magnitude higher marking speeds.

2D Channel Patterning

To pattern 2-Dimensional (2D) and 3-Dimensional (3D) features, 1D channels need to be stacked along Z and Y axes, as illustrated in Fig. 5(a). In resonators, high AR 2D channels can be implemented for definition of capacitive electrodes, suspension elements, etc.

Based on the results shown in Fig. 5(b), we observed that to achieve a higher etch rate in patterning 2D planes, the overlap between two consecutive patterns needs to be maximized through setting the Z-step size to 1 micron. As reported in [7], reducing the Z-step size would also help reduce the roughness on the sidewalls. We inscribed 300-microns deep 2D planes in FS and features with an AR as high as 55:1 were demonstrated. We believe that higher AR can be achieved through optimization of the same process.

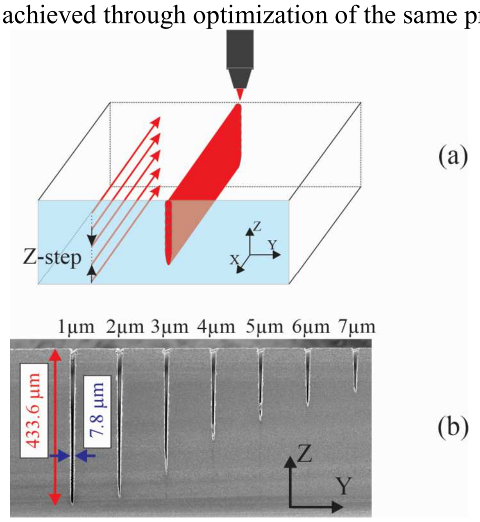

Figure 5: a) fabrication of 2-D planes using the FLICE process by inscribing lines at different Z-positions. (b) Effect of the Z-step size on etch rate is illustrated.

MICRO-RESONATOR FABRICATION

We integrated FLICE as part of a 3-steps process for fabrication of stand-alone micro-resonators [10], illustrated in Fig. 6. In the first step, the femtosecond laser is tightly focused in bulk of FS to inscribe a cavity and the resonator from bottom to top. In the second step, the structure is submerged in an aqueous KOH solution to selectively etch the modified material, precisely defining and releasing the resonator. In step three, through sputter coating, a thin layer of metal is uniformly deposited on the structure to achieve the conductivity required for electrostatic actuation and detection.

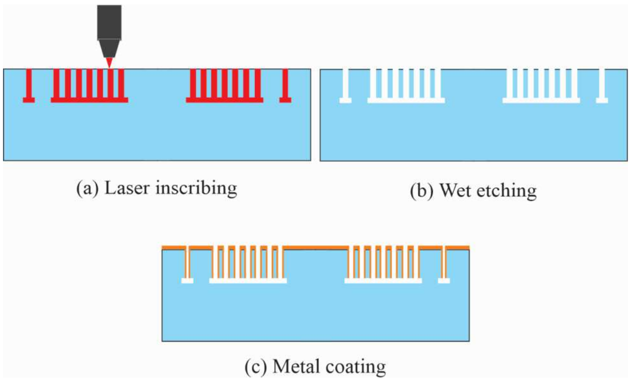

Figure 6: The proposed 3-steps process for fabrication of fused silica resonators from a single-layer fused silica material. This process benefits from a homogenous integration of the device and handle layers and eliminates the need for wafer bonding.

To demonstrate feasibility of the process, a 25mm^2 Disk Resonator Gyroscope (DRG) structure [9] was fabricated using the proposed process with a design shown in Fig. 7. The Thermo-Elastic Damping (TED) quality factor and natural frequency of the DRG was simulated to be on the order of 20M and 103 kHz, respectively.

The DRG structure and the corresponding release cavity were inscribed in FS with the optimized laser parameters, followed by 2 hours of wet etching in KOH solution. Optical and SEM images were utilized to make sure the resonator was fully released, shown in Fig. 8(a) and 8(b), respectively. As illustrated, we were able to successfully fabricate and release a FS-DRG, with a device-layer thickness of 113 µm and gap size of 9.6 µm (11.8:1 AR).

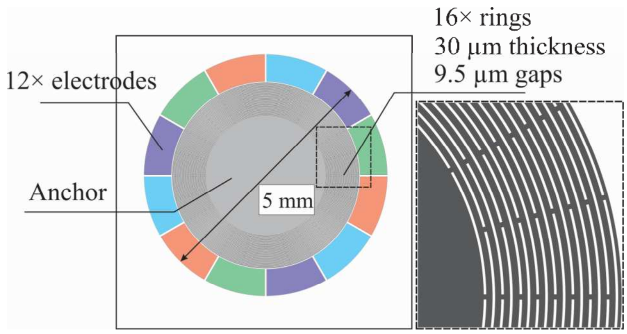

Figure 7: The DRG, which was designed to operate in the n=3 wineglass modes. The concentric rings were connected to each other in-series through spokes with 30-degrees angle separation.

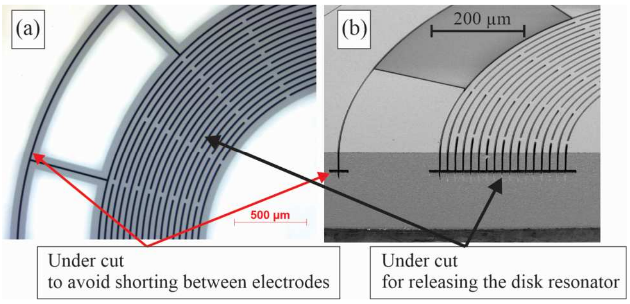

Figure 8: In step two of the fabrication process, an optical image was utilized to check for full release of the structures, shown in (a). SEM cross-section image of a fully released FS-DRG patterned using the FLICE process is shown in (b).

For electrostatic characterization, the DRG was sputter coated with a 15 nm chromium/gold layer (1:2) using an AC sputter coater. The frequency response (Fig. 9) and ringdown response of two FS-DRGs were measured in 30 µtorr vacuum to characterize the frequency split and quality factor summarized in Table 1.

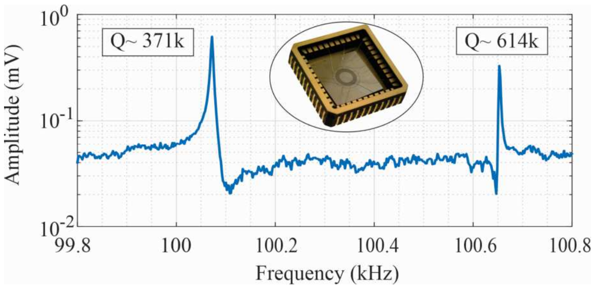

Figure 9: Frequency response of the FS-DRG measured through electrostatic actuation and detection. The measured frequency split and quality factor are summarized in Table 1.

The results revealed a frequency split on the order 580Hz and a quality factor as high as 614k. Notably, the measured quality factor for the metal coated DRG was 5-times higher than the quality factor reported for plasma etched FS-DRGs [9]. These are only the very initial results and further optimization is possible.

Table 1: Characterization results on two FS-DRG fabricated through the FLICE.

Parameters	DRG1	DRG2
Resonant frequency1 (kHz)	100.075	100.135
Resonant frequency2 (kHz)	100.655	100.365
Frequency split (Hz)	580	230
Quality factor 1	371k	437k
Quality factor 2	614k	534k

CONCLUSION

For the first time, we introduced a FLICE-like fabrication process for manufacturing stand-alone fused silica MEMS vibratory structures. Through a process optimization, we demonstrated that with a femtosecond laser-induced etching selectivity on the order of 855:1, rectangular channels with an aspect ratio on the order of 55:1 could be realized, ideal for fabrication of capacitive MEMS resonators. FS-DRGs were fabricated through the introduced process and initial results on structural characterization were reported.

Integration of FLICE for fabrication of MEMS resonators is a new topic and more research needs to be performed to better understand limitations and advantages as compared to conventional plasma etching technology.

ACKNOWLEDGEMENTS

This material is based on work supported by the Office of Naval Research (ONR) under Contract No. N00014-19-1-2338 and the Defense Advanced Research Projects Agency (DARPA) and U.S. Navy under Contract No. N66001-16-1-4021.

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