Improvement of Side-wall Roughness in Deep Glass Etched MEMS Vibratory Sensors

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***Abstract*— In this paper we report an optimized post-fabrication annealing process for improvement of sidewall roughness in deep glass etched resonant MEMS devices. The method utilizes thermal-reflow behavior of glass and does not require chemical or mechanical treatment. Experiments were conducted to explore the trade-off space between roughness improvement and structural deformation by varying temperature from 300 ^{0}C to 900 ^{0}C and duration from 2 to 240 minutes. The optimal results were obtained at 700 ^{0}C for 30 minutes, resulting in an 10x improvement in roughness from 900 nm Ra to 85 nm Ra and low feature deformation of <10%. The method was successfully utilized in deep glass etching of micro-glassblown wineglass resonators, which resulted in very low side wall roughness and sub-hz frequency symmetry.**

Keywords—Deep glass dry etching, post-fabrication annealing, roughness reduction, micro hemispherical resonator, gyroscope.

I. INTRODUCTION

Recently, there has been a growing interest in deep glass etching of fused silica and glass for fabrication of vibratory inertial sensors and timing devices. These materials provide potential advantages over silicon due to lower thermo-elastic dissipation, homogeneity, and high isotropy. Different glass etching processes have been developed for higher aspect ratio (4:1) and deep etching (>100 μm) [1]-[2]. These techniques have been successfully used in fabrication of planar fused silica MEMS devices [3] and electrode structures on glass for 3D wineglass resonators [4]-[5]. Despite these early demonstrations of deep glass etching, high sidewall roughness caused by ion-bombardment and fluoro-polymer deposition remains to be a problem for these devices, because high side-wall roughness can affect the symmetry of the structural element [6] or create unwanted dissipation [7].

To a lesser extent the same problem is present in the silicon DRIE process and researchers have shown that post-etch annealing can help reduce the sidewall roughness. For example, smoothing of silicon structures was demonstrated at temperature exceeding 900 ^{0}C [8]. Hydrogen annealing of silicon features on SOI for temperatures 1100 ^{0}C demonstrated roughness improvement from 20 nm to 0.26 nm [9]. Annealing of 3-hexylthiphene polymer, showed roughness increase for temperature 110 ^{0}C and then decreases from 0.91 nm to 0.75 nm at 150 ^{0}C [10]. Sputtered chromium oxide annealed at 400 ^{0}C demonstrated roughness improvement from 5.5 nm to 3.6 nm [11]. Similar treatment on glass dry etched micro-features has never been investigated.

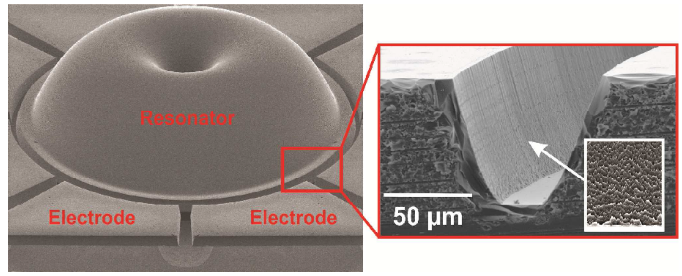

Fig 1. 3D inverted micro-wineglass resonator with co-fabricated integrated electrodes, zoom in view show dry etched gap with roughness of un-treated vertical-wall surface after 100µm glass deep etching.

In contrast to earlier research that focused on surface roughness reduction in silicon, in this paper we focus on post-etch annealing of glass and fused silica for surface roughness reduction. Moreover, we evaluate the trade-off space between surface roughness reduction and shape distortion and identify optimal annealing conditions. Our results showed that thermal treatment can dramatically improve roughness and utilized to fabricate high structural symmetry MEMS resonators with co-fabricated in-situ electrodes [4].

II. EXPERIMENTS AND RESULTS

Fabrication process for 3D micro-resonator begins by defining cavities on a silicon wafer and capping the silicon wafer with a 100µm glass wafer, defining the device layer. Electrodes are defined on the device layer by deep glass etching with a low stress 5 µm electroplated Ni etch mask. The detail of the dry etching and fabrication sequence is described by the authors in [4] and [12]. The design of experiment for roughness reduction is described in this paper. Experiments were performed on glass dry etched (100 µm deep) micro-features of 5 µm to 500 µm, that consisted of trenches, cavities, posts, and channels. Treatment temperatures varied between 300 ^{0}C and 900 ^{0}C and duration between 2 and 240 minutes. Roughness, surface morphologies, and feature deformations were investigated by AFM and SEM. After about 100µm deep etching and ion bombardment the roughness of the side-wall surfaces was about 900nm R_a. Thermal treatment dramatically improved the roughness producing highly smooth surface and roughness of perturbations was reduced to 40nm (Figure 2 and Figure 4d). At lower temperature (300^{0}C), the improvement was small (Figure 4a), but after temperature increased to 500^{0}C the roughness started improving (Figure 4b) due to decrease in viscosity of glass and consequent higher reflow.

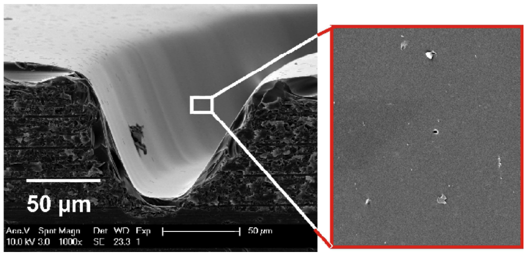

Fig 2. SEM view of thermally treated wall surface (700 ^{0}C, 4 hrs) dramatically improving roughness creating smooth wall surface (inset).

At higher temperature, longer duration time was not required because glass is at transition temperature resulting in low viscosity and high reflows. For example, at 875^{0}C for 1 minute the rough heights (R_p) reduced from 1-2 µm to 300-400 nm (Figure 4c). Results with the variation of temperature and duration of treatment are presented in Table 1. The trades off is deformation of features. When the duration is long the feature deformation is high, creating round edges (Figure 3b). Similarly, when the temperature is high (900^{0}C), the deformation is also high. We derived an optimum treatment regime where the deformation is at minimum, while roughness improvement is high. Results showed that when treated at 700^{0}C for 30 minutes the roughness (R_a) improvement was 10-times and deformation remained lowm <10% (Figure 3d).

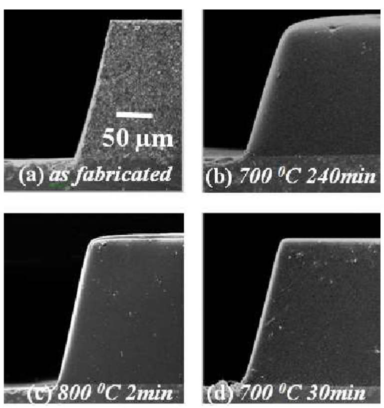

Fig 3. The treatment temperature and duration time were optimized to improve roughness while minimizing feature deformation.

TABLE 1: SUMMARY OF EXPERIMENT AND PROCESS PARAMETERS

Treatment Temperature (^{0}C)	Treatment Duration (Min)	Roughness Improvement	Feature Distortion	Key Process Parameters
400	60,240	Low	No	▪ Feature from 10-500 µm
500	60,240	Low	Very low	▪ Max etch depth 100 µm
600	30,240	Moderate	Low	▪ Etching gas : C_3F_8 30
700	30	High	Low	sccm and Ar 90 sccm
700	240	Very high	Moderate	▪ Max Aspect ratio 1:8
800	2	Moderate	Low	▪ Etch mask- 5 µm Ni
800	15	High	High	▪ Mask Selectivity 1:70
900	2	Moderate	Moderate	▪ Roughness: AFM and
900	15	Very high	Very high	SEM investigation

I. CONCLUSION

This paper reports on dramatic improvement of side-wall roughness (R_a reduced from 900 nm to 85 nm) of glass dry etching. The method is simple to use, do not require physical or mechanical processing. An optimum thermal treatment profile was found at 700 ^{0}C for 30 minutes after dry etching.

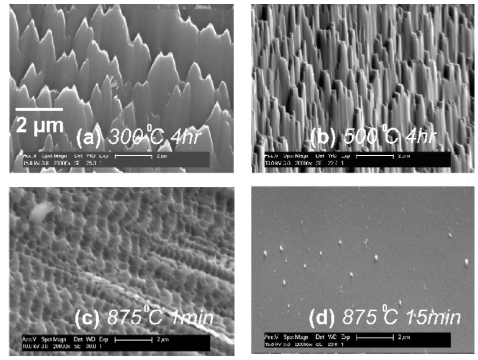

Fig 4. SEM surface morphologies showing roughness decreases with increasing temperature and duration producing smooth surface in (d).

The thermal treatment method presented in this paper can be used to improve mechanical and optical properties of glass resonant sensors that will be valuable for the development of high quality inertial MEMS using glass.

ACKNOWLEDGMENT

This research was supported by DARPA grant W31P4Q-11-1-0006 (Program Manager Dr. Robert Lutwak).

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