MICROMACHINED 3-D GLASS-BLOWN WINEGLASS STRUCTURES FOR VIBRATORY MEMS APPLICATIONS

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ABSTRACT

This paper presents a new fabrication process for microscale 3-D structures with potential utilization as a vibratory element in signal processing, timing, and inertial sensor applications. Wafer level glassblowing and blow molding techniques have a potential to provide low surface roughness, highly symmetric and balanced dynamic structures. Two approaches were investigated in order to increase the energy decay time constant of 3-D glass-blown structures, a key parameter in prolonging standing wave propagation. The first method relies on reduction of anchor losses by reducing the sphere attachment radius, through the use of a stencil layer. The second method addresses the reduction of resonant frequency by creating open-top wineglass structures by laser micro-machining of fabricated glass-blown spherical shells. Laser Doppler Vibrometer (LDV) was used to characterize the frequency response of the structures. The results were compared to the vibration of a complete sphere, which had no reduction in attachment radius. The first vibrational mode of the wineglass structure was observed at 45.6 kHz, with approximately 40 times improvement in time constant τ over the complete glass-blown sphere.

KEYWORDS: 3-D micro-machining, micro glass-blowing, wineglass resonator, hemispherical shell.

INTRODUCTION

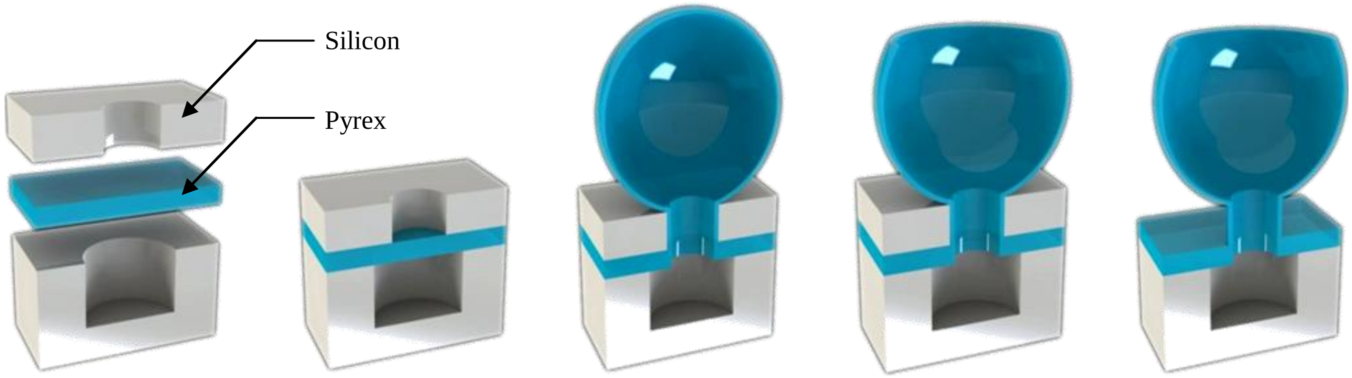
Three dimensional axisymmetric microstructures are desired for emerging architectures of MEMS resonators for timing, signal processing devices and inertial sensors due to potential advantages in symmetry, surface quality, energy loss, and aspect ratios. The high performance potential of 3-D shells has been previously demonstrated on macro scale, e.g. inertial grade fused quartz Hemispherical Resonator Gyroscope [1]. With the emergence of novel 3-D micro-machining techniques [2-5], batch fabrication of spherical and hemispherical microstructures are becoming feasible. For instance, etching of highly isotropic molds in <111> single crystal silicon for future manufacturing of hemispherical resonators have recently been reported in [2]. By etching <111> silicon instead of <100> silicon more than 50% reduction in preferential etching was obtained. A batch process combining ultrasonic machining, lapping and electro-discharge machining ("3-D-SOULE") has been recently introduced in [3] for fabrication of concave and mushroom-shaped microscale resonators and vibratory gyroscopes.

This paper reports our recent progress in developing an alternative manufacturing approach based on a wafer-level glassblowing technique [4-8] which pursues the production of low-loss hemispherical micro-resonators with reduced anchor attachment radius. Previously, glass-blown spherical shells with low surface roughness and integrated electrodes have been introduced for 3-D MEMS resonators using this technique [6, 7]. This paper discusses two approaches for increasing the structural energy decay time constant of these 3-D glass-blown microstructures, a key parameter in prolonging standing wave propagation. The first method relies on reduction of anchor losses by reducing the sphere attachment radius, through the use of a stencil layer. The second method addresses the reduction of resonant frequency by creating open-top wineglass structures by laser micro-machining of the glass-blown spherical shells.

FABRICATION APPROACH

Micro glassblowing process utilizes an etched cavity on a substrate wafer and a glass layer that is bonded on top of this cavity, creating a volume of trapped gas for subsequent glassblowing of self-inflating spherical shells. When the bonded wafer stack is heated above the softening point of the structural glass layer, two effects are activated at the same time: (1) the glass layer becomes viscous, and (2) the air pressure inside the pre-etched cavity raises above the atmospheric level. This results in plastic deformation of the glass layer, driven by gas pressure and surface tension forces (glass-blowing). The expansion of air (and hence the formation of the shell) stops when the pressure inside and outside of the glass sphere reaches an equilibrium. During this deformation, the surface tension acting on the (now viscous) glass layer works towards minimizing the surface area of the structure, as a result a highly symmetric spherical shell with low surface roughness forms [7].

In this work an additional stencil layer is introduced to the process. Through holes are first etched in a thin silicon wafer, which is then aligned and bonded on top of the glass layer prior to glassblowing, Figure 1. During the glassblowing step, the glass is forced to flow through the small stencil openings to form the spherical shell structures. As a result the attachment radius of the shell structures is constrained, which is important for minimization of energy dissipation through the substrate. After glassblowing, the silicon stencil wafer can be etched away, creating a stem standoff for the spherical structures. Once the spherical shell structures on stems are manufactured using the stencil glassblowing process, laser micro-machining is employed for creation of open-top wineglass structures on stems. A laser micro-machining tool is used to make a cut along (or parallel to) the equator of the glass-blown sphere. The resultant opening drastically lowers the stiffness of the 4 and 6-node wineglass modes of the shell structure, yielding more than an order of magnitude drop in the resonant frequency.



a) Etching of Silicon *b) AC anodic bonding* *c) Glassblowing* *d) Laser cutting* *e) Stem release*

Figure 1: Fabrication process flow for manufacturing of microscale glass-blown wineglass structures with stems.

FABRICATION PROCESS FLOW

The fabrication process is shown in Figure 1. The process starts by DRIE etching of the substrate and the stencil layers, followed by AC anodic bonding of the Silicon-Pyrex-Silicon stack. The devices are singulated and glass-blown in an annealing furnace. Once the spherical shells are obtained the cap of the glass-blown structure is cut using laser micro-machining to create the wineglass structures. If a wineglass structure with stem is desired, a final step which involves etching of the stencil layer can be applied.

A 1 mm substrate silicon wafer, 200 µm Pyrex wafer and 400 µm stencil silicon wafer were used in the process. Both the substrate and the stencil wafers were patterned using AZ 4620 positive photoresist. The substrate layer was etched to ~660µm using STS DRIE to create the cavities, whereas the stencil layer was etched to define through holes. The Pyrex wafer was polished to have low surface roughness (Ra 25 Angstrom). After DRIE etching, each wafer was cleaned with solvents and oxygen plasma, aligned with the help of an optical microscope and finally placed into the anodic bonding setup.

In order to obtain a high quality bond an AC anodic bonding approach [9] was used to bond the silicon-glass-silicon stack. In traditional (DC) anodic bonding a Na^+ depletion layer forms close to the bond interface due to the diffusion of the Na^+ ions towards the silicon layer. Depletion of Na^+ ions next to the bond interface increases the resistance of the glass silicon stack. This increased resistance at the bond interface makes bonding a second silicon wafer to the glass-silicon stack difficult. To alleviate this issue AC anodic bonding was used to bond the substrate layer, glass layer and the stencil layer simultaneously. This was achieved by driving the high voltage current source using a function generator. The bond was performed at 400 °C using a square wave at 0.1 Hz and 400 V amplitude. By using this method a high quality bond was obtained between the glass layer and the two silicon layers. In our experiments over 98% of the dies survived the singulation process. The ones that did not survive, separated at the glass silicon interface, which is attributed to bond defects caused by particulates. Shorter bonding times were also observed, as well as an order of magnitude increase in current flow. Furthermore no saturation point or decay of the current was observed within the 30 mA limits of the high voltage power supply, Figure 2.

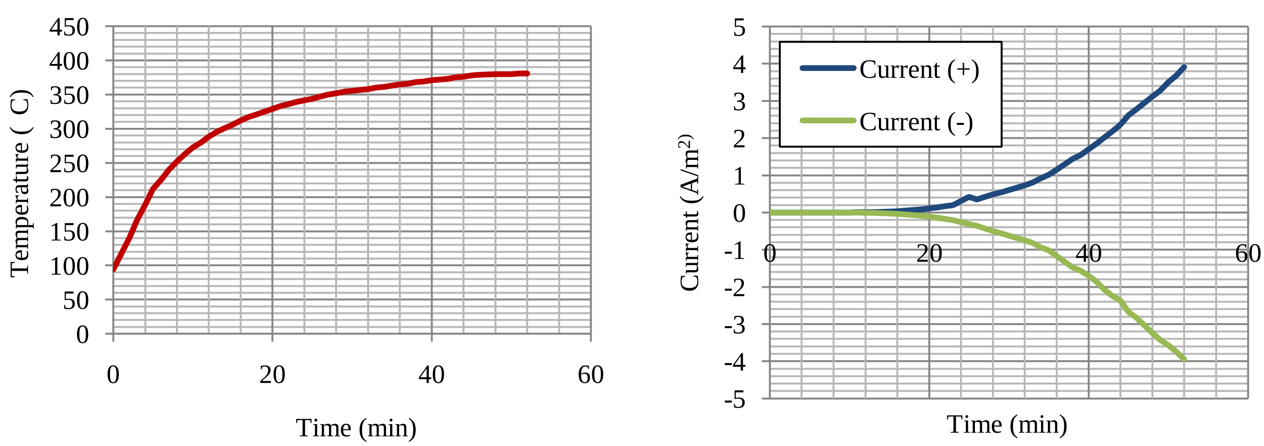
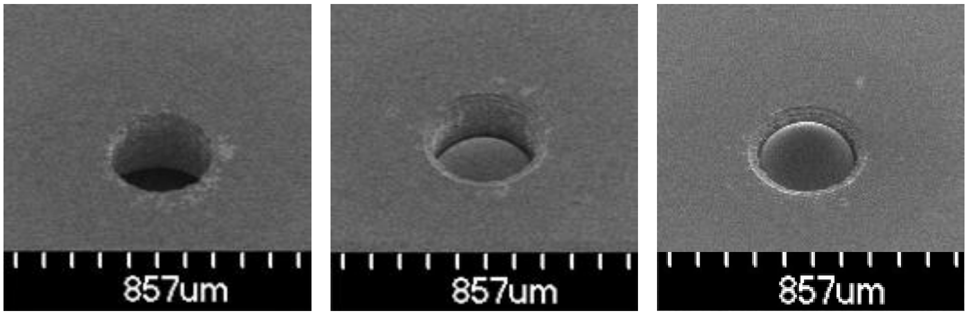


Figure 2: Current flow per unit area during the AC anodic bonding process. Current (+) and Current (-) indicate current flow when +400 V and – 400 V are applied respectively.

Once the bonding is complete, the wafer was singulated and glass-blown in an annealing furnace set to 850 °C, above the Pyrex softening point. The dies were kept at this temperature for 135 secs and promptly removed to room temperature air for cooling. SEM images illustrating the glassblowing process through the stencil layer are shown at different stages in Figure 3.

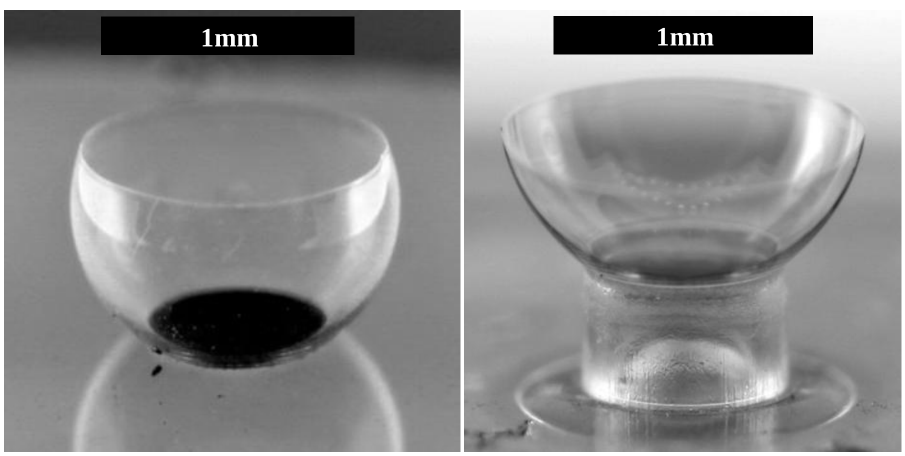


a) Etched hole in a stencil wafer b) Glass emerging through the stencil wafer hole at 850 ºC

Figure 3: SEM images illustrating stages of the glassblowing process with a stencil wafer.

The cap of the glass-blown spherical shells were removed using laser micro-machining to create the wineglass structures. An Excimer laser ablation tool was used for this purpose (Resonetics RapidX 250). The laser was aligned parallel to the substrate wafer and the dies were moved in a linear fashion to cut away the cap. A pulse frequency of 50 Hz was used at 20 mJ power with a feed rate of 5 µm/s. The fabricated hemispherical shell microstructure is shown in Figure 4 (a).

To create a free-standing wineglass structure, the stem was released by etching away the stencil layer. An in-house XeF_2 etcher was used for this purpose. Pulse etching with a chamber process pressure of 3000 mTorr and 80 seconds pulse duration was used. The 400 µm stencil layer on a single die was etched after 30 pulses, resulting in a glass-blown wineglass shell with a released stem, Figure 4 (b).



(a) (b)

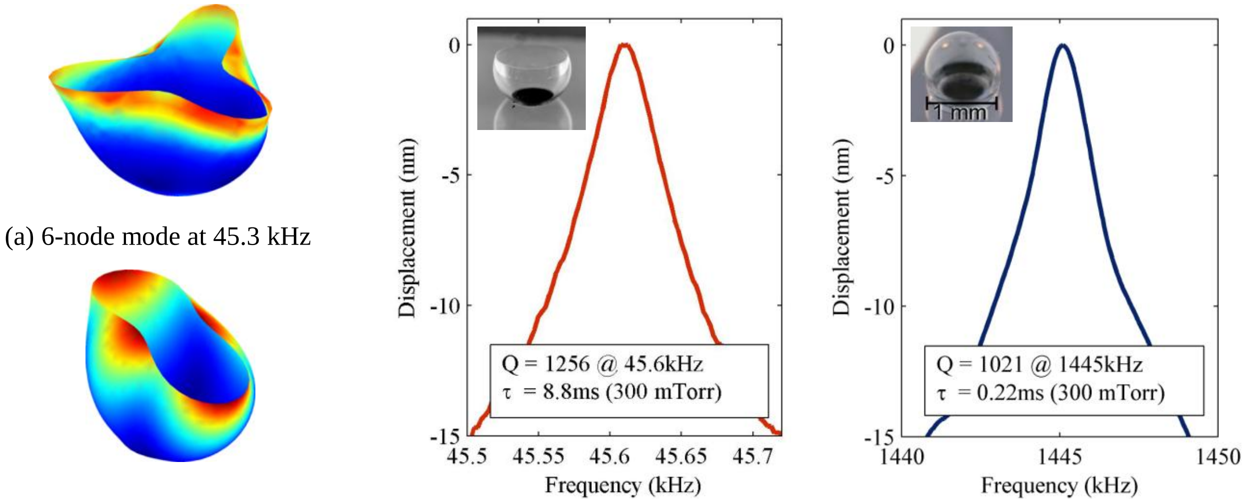
Figure 4: Optical micrographs of wineglass structures (a) w/o stem and (b) with stem.

RESULTS

A finite element modal analysis of the wineglass structure was performed to identify spectrum of vibrations. A 3-D shell mesh with the dimensions of the wineglass structure from Figure 4 (a) was used for the simulation. Running the simulations with a shell diameter of 1142 µm, rim diameter of 1052 µm, attachment diameter of 600 µm and average thickness of ~4 µm suggests 45.3 kHz resonant frequency for 6-node wine-glass mode, Figure 5 (a). The wine-glass mode shown in Figure 5 a is inherently balanced (6 nodes alternate with 6 antinodes), thus enabling high Q-factor and long energy decay time constants.

For experimental characterization hemispherical wineglass structures were bonded to a piezo-actuated vibration plate (by Physik Instrumente) and mounted in a vacuum chamber with an optical port. The frequency response was measured using a Polytec OFV5000 single-point Laser Doppler Vibrometer. The Agilent 4395A network analyzer was used to sweep the frequency of the PZT in a kHz range and measure the shell response.

First vibratory mode was observed at 45.6 kHz with a Q-factor of 1256 at 300 mTorr vacuum ($\tau_{wineglass}$ = 8.8 ms), Figure 5c. Previously 6-node wineglass mode of a complete glass-blown sphere was observed at 1445 kHz with a quality factor of 1021 (τ_{sphere} = 0.22ms), Figure 5d. Over 40 times increase in energy decay time constant can be observed for the wineglass structures as opposed to a complete sphere. We believe further increase in τ can be obtained at lower pressure and even smaller attachment radii.



(a) 6-node mode at 45.3 kHz

(b) 4-node mode at 62.8 kHz

(c)

(d)

Figure 5: Finite element analysis of the wine glass structure: (a) 6-node mode and (b) 4-node mode. Frequency responses of (c) the wineglass structure and (d) spherical shell, revealing energy decay time constants.

CONCLUSION

A new fabrication method for fabrication of 3D wineglass structures was developed and experimentally demonstrated. Preliminary results indicate ~40 times improvement in energy decay time constant ($\tau_{wineglass}$=8.8 ms vs τ_{sphere}=0.22 ms), which can be attributed to smaller attachment radius and reduced resonance frequency through laser micro-machining. Even though the presented results are the initial steps toward anchor loss minimization and frequency tuning of glass-blown vibratory structures, we believe the approach is a step toward the realization of dynamically balanced, high precision 3-D vibratory MEMS devices.

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