FUSED SILICA MICRO BIRDBATH SHELL RESONATORS WITH 1.2 MILLION Q AND 43 SECOND DECAY TIME CONSTANT

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ABSTRACT

We report a micro-scale fused silica (FS) birdbath (BB) shell resonator with a high mechanical quality factor ($Q = 1.2$ million), long decay time constant ($\tau = 43.6$ s), a resonant frequency of 8.8 kHz for wineglass modes, and excellent symmetry resulting in a frequency split of only 6.7 Hz between two wineglass modes. The resonator has a volume of 41 mm^3 (radius = 2.5 mm, anchor radius = 0.5 mm, height ~ 2.1 mm). The resonator is useful in a wide range of applications, including inertial sensors, timing devices, and chemical and biological sensors.

INTRODUCTION

A high Q and long decay time constant (τ) are desired in many sensing applications, because they reduce mechanical noise and bias drift. A silicon gyroscope with $f \sim 2$ kHz and Q of 1.16 million has been reported [1]. Macro-scale FS wineglass resonators with Q of tens of millions at 3 kHz [2] or 1 million at >70 kHz have been reported [3]. For micro vibratory gyroscopes, an f of ~10 kHz is preferred, because the sensor 1) can operate above the f of environmental noises, 2) has good flexibility, which results in a large scale factor, and 3) and has a long decay time constant (τ) leading to good bias stability. On the micro scale, there has been a lack of materials and fabrication techniques to achieve an ultra-high Q and a long τ in this frequency range. It is difficult to achieve >1 million Q with Si in the ~10 kHz frequency range due to high thermoelastic damping (TED). FS suffers less TED than Si; however, it is difficult to etch or form complicated FS structures using conventional fabrication processes. We overcame these challenges and achieved both very high Q , long τ , and very small frequency split (Δf) in our birdbath shell resonators.

FABRICATION

We fabricated our shells using a 3D micro blowtorching process (Figure 1) [4]. A thin FS substrate (thickness ~ 100 μm) is placed on top of a graphite mold and is controllably heated by a propane-oxygen blowtorch at >1600 $^\circ\text{C}$ while applying vacuum from the bottom of the mold. The shells were released using conventional lapping and CMP processes. The devices have a 2.5 mm radius, 0.5 mm anchor radius, ~2.1 mm height (Fig. 2), and ~60 μm rim thickness (Figure 2).

Figure 1: Three dimensional micro blowtorch molding process

DEVICE CHARACTERIZATION

The f and τ of an uncoated BB resonator were measured by

AS&T using conformal Laser Doppler Vibrometry [5] while driving it with a PZT actuator. We tested a metal-coated BB resonator (sputtered Cr/Au = 15/50 $\text{\AA}$) using a capacitive measurement method. Both tests were done at <1 mTorr pressure at room temperature. Both samples were cleaned using BHF for 3–30 s before testing. The uncoated BB resonator has $n = 2$ wineglass modes at 8.718 kHz with $\tau = 42.18$ s ($Q = 1.16$ million) and 8.725 kHz with $\tau = 43.58$ s ($Q = 1.19$ million) (Figure 3). These time constants are the longest reported for small wineglass structures. The coated BB resonator has wineglass modes at 10.163 kHz with $\tau = 15.24$ s ($Q = 486\text{k}$) and 10.188 kHz with $\tau = 9.70$ s ($Q = 310\text{k}$) (Figure 4). We believe that a combination of large device height, BHF etching, and a thinner metal layer led to the improvement of τ . Figure 5 shows the dependency of τ on the BHF etching duration as well as the thicknesses of the metal coating on six different devices. We found ~2 $\times$ improvement in τ due to the reduced metal thickness and 30 s BHF etching. However, after longer BHF etching (95 s), we found a reduction in τ even with the same metal thickness, likely due to increase in surface roughness.

Figure 2: (a) Illustration, (b) photograph, and (c) SEM image of fused silica micro birdbath shell resonator. The shell is coated with Cr/Au = 15/50 $\text{\AA}$. Device dimensions: radius ~ 2.5 mm, anchor radius = 0.5 mm, height ~ 2.1 mm, rim thickness ~ 60 μm .

Figure 3: Ring-down time plot of $n = 2$ wineglass modes of uncoated BB resonator using conformal Laser Doppler Vibrometry: (a) $f = 8.718$ kHz and $\tau = 42.18$ s ($Q = 1.16$ million). (b) $f = 8.725$ kHz and $\tau = 43.58$ s ($Q = 1.19$ million) [5].

Figure 4: Ring-down time plot of $n = 2$ wineglass modes of coated BB resonator using capacitive measurement method: $f = 10.163$ kHz and $\tau = 15.24$ s ($Q = 486k$). Another mode has $f = 10.188$ kHz and $\tau = 9.70$ s ($Q = 310k$).

Figure 5: Dependency of τ on metal coating and BHF etching for six different samples. These devices have resonant frequencies at 9.5 ~ 11 kHz.

CONCLUSION

We report a micro BB resonator with a small volume (~ 41 mm³) with one of the best Q s ($= 1.2$ million), τ s ($= 43.58$ s), and structural symmetries ($\Delta f = 7$ Hz). The good resonance characteristics are due to the low TED and ultra-low surface roughness (< 1 nm) achieved using the 3-D micro blowtorch molding process. The process can be adopted to fabricate a wider variety of high-performance micro sensors and actuators. We found strong dependency of τ on the conductive metal coating and surface cleaning.

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