259 SECOND RING-DOWN TIME AND 4.45 MILLION QUALITY FACTOR IN 5.5 KHZ FUSED SILICA BIRDBATH SHELL RESONATOR

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ABSTRACT
The fused silica birdbath (BB) resonator is an axisymmetric 3D shell resonator that could be used in high-performance MEMS gyroscopes. We report a record quality factor (Q) for a 5-mm-radius resonator, which is expected to reduce gyroscope bias drift. We present measurement results for two sizes of resonators with long vibratory decay time constants (τ), high Qs, and low damping asymmetry (Δτ⁻¹) between their n = 2 wine-glass (WG) modes. We find a reduction in damping for larger resonators and a correlation between higher Q and lower Δτ⁻¹, as well as evidence of a lower bound on Q for resonators with low damping asymmetry.

INTRODUCTION
Considerable reduction in the bias drift of MEMS gyroscopes has been achieved over the past two decades, yet they still lack the long-term accuracy required for dead-reckoning. Dead-reckoning is a method of navigating by estimating the direction and distance traveled that can be accomplished with inertial sensors. It is employed to enable reliable navigation in GPS-denied environments. With the advent of drones and autonomous vehicles and the perpetual need for improved defense and consumer technology, many systems stand to benefit from affordable MEMS gyroscopes with low noise and bias instability (B) of 0.01 °/hr.

The vibratory decay time constant and damping asymmetry (Δτ⁻¹ = |1/τ₁ − 1/τ₂|) of a gyroscope resonator are important parameters that are related to bias instability (B ≈ Δτ⁻¹ [1], B ≈ Δτ⁻¹ [2]). Unfortunately, τ of silicon gyroscopes is typically limited to < 5 s at frequencies greater than 10 kHz. A 1.7 kHz quad mass silicon gyroscope with τ = 344 s and Q = 1.83 million was reported in [3].

Over the past few years, our group has demonstrated the fused silica BB resonator gyroscope (BRG) [4], [5]. The three-dimensional BB shell resonator (Figure 1) has a high-aspect ratio axisymmetric design that offers several advantages to conventional two-dimensional MEMS resonators. Designing in the third dimension provides greater control over the frequencies of the desired WG and undesired parasitic resonant modes, helping prevent unwanted mode coupling and thereby reducing environmental noise interference. Controlling height also allows for stiffness tuning so the WG mode frequency remains lower than is possible for a disk resonator with similar dimensions. The axisymmetric design lends itself to both rate and whole-angle mode operation. The BB resonator gyroscope is a significant step toward a low-cost micro-scale high-performance MEMS gyroscope.

Figure 1: Two sizes of BB resonators, attached to silicon substrates with glass frit.

Figure 2: Nominal dimensions of the 5-mm-radius BB resonator shown on the right side of Figure 1.

Many techniques have been tried to form micro shell resonators. Compared to others, the BB resonator has several key advantages for achieving long τ and low bias instability.

First, the anchor and the rest of the resonator are self-aligned. Misalignment between the anchor and rim is known to be a key source of anchor loss in hemispherical resonators [6]; the BB resonator can achieve low anchor loss by automatically aligning the anchor and shell during a single reflow-molding step using a radially symmetric mold. Other techniques, such as those used in [7]-[9] require alignment of multiple layers and are prone to misalignment.

Second, the BB resonator has a long, smooth transition region that connects the rim to the anchor. This isolates the portion with the most mechanical energy (rim) from the energy sink (anchor). The smooth curvature reduces the concentration of mechanical stress near the anchor. These features effectively trap the mechanical energy in the rim, greatly reducing dissipation through the anchor. Shell resonators such as those in [7] and [9]-[11] have less isolating anchor designs that could increase anchor loss.

Third, the blowtorch molding process can form BB resonators with an ultra-smooth surface out of fused silica, which has one of the lowest amounts of internal and thermoelastic dissipation (TED) of any material.

Other researchers used a variation of the blowtorch...
molding process to produce a similar 10.3 kHz fused silica shell resonator [12], but with a large $\Delta f$ of 427.3 Hz, low $\tau$ of 0.39 s ($Q = 12,558$), and high $\Delta r^{-1}$ of 2.26 Hz. Using a method of trapped gas expansion, [13] demonstrated a fused silica structure similar to the BB resonator that achieved a $Q$ of 1.05 million, but due to its high 105 kHz frequency it has a $\tau$ of only 3.18 s. A slightly longer 4.32 s $\tau$ but high $\Delta r^{-1}$ of $3.1\times10^{-3}$ Hz was reported in [7] for a cylindrical microcrystalline diamond shell resonator, with a frequency of 23.07 kHz and $Q$ of 313,100. A higher frequency 160 kHz hemispherical resonator gyroscope with a 9.0 s $\tau$ ($Q = 4.5$ million) was reported in [10]. Larger fused silica hemispherical resonator gyroscopes (HRG) fabricated from a solid mass of bulk fused silica with abrasive machining have demonstrated especially high $Q$s and long $\tau$s. Notably Sagem’s 20-mm-diameter 7 kHz HRG has $\tau > 500$ s ($Q > 11$ million) [14] and Northrop Grumman’s 30 mm HRG 130P has a $Q > 25$ million [15] and estimated $\tau > 1000$ s; however, achieving this performance for these machined resonators typically requires post-fabrication balancing and tuning. The BB resonator aims to match this performance in a smaller and more affordable package.

We initially reported the 2.5-mm-radius BB resonator (referred to as BB-2.5) (Figure 1, left) and accompanying blowtorch molding process (Figure 3) to form shell resonators with thermal reflow-molding at $> 1600$ °C in [16], [17]. In [18] we demonstrated the BB resonator as a gyroscope. The resonator operates in the $n = 2$ WG modes; in rate mode, the gyroscope is operated with force-rebalance control, while in whole-angle mode the vibrations are allowed to freely precess around the rim, their orientation indicating the rotated angle. More detail on the BB resonator gyroscope can be found in [5]. Here, we present a 5-mm-radius version of the BB resonator (Figure 1, right), referred to as BB-5, and the resulting performance improvements. The relevant dimensions for the BB-5 are shown in Figure 2. We also discuss trends in $Q$ in relation to WG mode damping asymmetry.

**FABRICATION**

Fused silica is an attractive resonator material, considering that its small TED and low internal friction give it the highest room temperature $Q$ of any known glass [19]. Unfortunately, conventional microfabrication does not lend itself to high aspect ratio devices, especially for fused silica. To overcome this challenge, we developed the blowtorch molding process, which is akin to micro-scale glass blowing and is designed to accommodate the material properties of fused silica and other exotic materials with a high softening temperature.

This technique precisely and rapidly defines structures by vacuum reflowing a thermally softened flat substrate into a graphite mold that can be affordably and rapidly machined in a conventional machine shop. This greatly reduces the time and cost of trying new designs, and reduces dependence on costly cleanroom processing.

Anchor alignment can be problematic for lithographically defined resonators, as alignment error can accumulate through successive layers. With the blowtorch molding process, millimeter-scale features can be aligned with micrometer-scale precision in a single step to replicate the geometry of the graphite mold.

In this paper, we report on the BB-2.5 and BB-5 resonators. Both are fabricated with the same technique, with the only major differences being that a larger mold and thicker bulk substrate are used for the BB-5.

**Reflow Molding**

The final shape of the BB resonator is formed from a flat fused silica substrate in ~10 seconds with thermal reflow molding. After placing a substrate atop a graphite mold, a propane-oxygen blowtorch is lowered, rapidly heating the fused silica to its softening point. Vacuum is applied to the mold cavity, causing the substrate to reflow and stretch over the center anchor post and circular outer wall (Figure 3). Most of the shell does not contact the graphite mold during reflow, leaving the surface with a low average roughness of 1.8 Å, as measured with atomic force microscopy (AFM) (Figure 4).

![Fuel-Oxygen Blowtorch Temperature > 1600 °C](image)

**Figure 3:** The blowtorch molding process forms fused silica shell resonators within a graphite mold in ~10 s.

![Atomic Force Microscopy](image)

**Figure 4:** Reflow molding smoothes the suspended fused silica surfaces to an average roughness of 1.8 Å.

**Shell Isolation**

Once formed, the BB resonator must be separated from the substrate from which it was molded. This is a batch process where twenty-four BB-2.5 or nine BB-5 resonators are released and polished simultaneously. The shell portion is set into a hole in a silicon wafer so that the flat bulk substrate rests on the wafer surface. Both sides of the shell are filled with a thermoplastic polymer to hold the shell in place and protect it while the flat substrate is removed with tapping (Figure 5), exposing the rim of the shell on the surface. The rim is then polished with chemical-mechanical planarization (CMP) (Figure 6). The process is
completed by dissolving the polymer in a solvent to release the shell. A detailed discussion on the blowtorch molding process can be found in [20].

RESULTS

A plot summarizing the dependence of $Q$ on $\Delta \tau^{-1}$ for BB-2.5 and BB-5 resonators is shown in Figure 8. Each data point represents the averaged $Q$ for one resonator. To provide an even comparison across frequencies, $Q$ is shown instead of $r$, as a lower frequency resonator with the same $Q$ will have a longer $r$.

This data reveals a correlation between high $Q$ and low $\Delta \tau^{-1}$. We have not observed any devices that have both a high $\Delta \tau^{-1}$ and high $Q$ or any with a low $\Delta \tau^{-1}$ and low $Q$. Rather, there appears to be an upper and lower envelope for this relationship, suggesting $\Delta \tau^{-1}$ is tied to the dominant energy loss mechanism for BB resonators. Large $\Delta \tau^{-1}$ is caused by asymmetry in the shell structure. While the WG modes theoretically have very low anchor loss, any small asymmetry may result in unexpected amounts of dissipation through the anchor. It is therefore critical to ensure the graphite mold is machined precisely with a high degree of circularity and concentricity, and that the lapping process does not create any imbalance.

We observe a tendency for higher $Q$ in BB-5 resonators compared to the BB-2.5 design. The larger size of the BB-5 provides two advantages over the BB-2.5 that may account for this observation. One is its larger volume-to-surface (V/S) ratio. FS has very low internal damping, but for resonators with a low V/S ratio, surface loss can become the dominant loss mechanism [21]. The BB-5 has an estimated ~44 $\mu$m V/S ratio, compared to ~24 $\mu$m for a BB-2.5. The other advantage pertains to geometric imperfections. If both resonator sizes were to be fabricated with the same slight imperfection, the effect on the larger resonator will be less significant. Regardless, both sizes achieve very high $Q$s and $r$s considering their size and that they are not balanced or tuned after fabrication.

The resonant characteristics of two exemplary BB resonators are summarized in Table 1. Although both have very low $\Delta \tau^{-1}$, the BB-5 resonator achieves considerably higher $Q$ and $r$. The ring-down plot for the 259.0 s $r$ mode of the BB-5 resonator is shown in Figure 9.
CONCLUSION

Using the blowtorch molding process, BB resonators of various sizes can be rapidly and affordably fabricated. Their high aspect ratio three-dimensional design and the automatic alignment afforded by blowtorch molding have helped us achieve the longest rs and highest Qs for any comparable resonators reported to date. We observed an increase in Q for BB resonators with a larger radius and V/S ratio, and found a correlation between Q and $\Delta r^{-2}$. We conclude that low $\Delta r^{-2}$ is critical for achieving high Q, and that for this thickness and frequency range, surface loss may become the dominant loss mechanism.

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