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MEMS micro-glassblowing paradigm for wafer-level fabrication of fused silica wineglass gyroscopes

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Abstract

In this paper, we report latest developments in wafer-level micro-glassblowing paradigm for fabrication of highly symmetric, high Q-factor fused silica wineglass gyroscopes. Q-factors over 1 million have been demonstrated on both n = 2 wineglass modes with a high frequency symmetry (Δf/f) of 132 ppm. High Q-factor is enabled by a high aspect ratio, self-aligned glassblown stem structure, careful surface treatment of the perimeter area, and low internal loss fused silica material. Low frequency split is provided by the self-correcting behavior of the surface tension based micro-glassblowing process. Micro-glassblowing may enable batch-fabrication of high performance fused silica wineglass gyroscopes on a wafer surface at a significantly lower cost than their precision-machined macro-scale counterparts.

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Keywords: MEMS wineglass gyroscope; high-Q resonator; micro-glassblowing of fused silica.

1. Introduction

Coriolis vibratory gyroscopes (CVGs) can be divided into two broad categories based on the gyroscope 's mechanical element [1]: degenerate mode gyroscopes which have x-y symmetry (Δf = 0 Hz ideal for a z-axis gyro) and non-degenerate mode gyroscopes which are designed intentionally to be asymmetric in x and y modes (Δf of 10 to 100 Hz for a z-axis gyro). Despite potential advantages of degenerate mode operation (high rate sensitivity and whole-angle operation), historically, most high-performance MEMS CVGs have been designed to operate as non-degenerate mode devices, whereas degenerate mode operation was reserved for precision machined macro-scale CVGs, such as the Hemi-spherical Resonator Gyroscope (HRG) [2]. This is mainly due to the high structural symmetry, or equivalently high frequency symmetry (Δf) required for degenerate mode operation, making large-scale fabrication of these devices challenging due to large relative tolerances and low aspect ratios (2.5-D) associated with

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conventional micro-machining processes. Factors such as mold non-uniformity, high surface roughness and granularity of deposited thin films have so far prevented the integration of 3-D wineglass structures with MEMS techniques.

For example, Q-factor of 19.1k have been demonstrated on poly-silicon shell structures deposited in pre-etched cavities [3]. Q-factors up to 24k [4] were measured on poly-diamond wineglass shells. Blow molding was used to demonstrate Q-factors as high as 7.8k on bulk metallic glass shells [5] and above 1 million on fused silica shells [6].

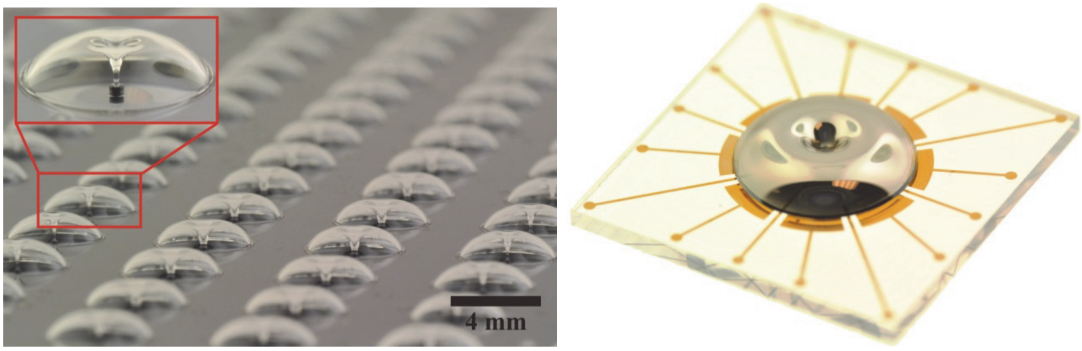


Fig. 1. (left) Array of over 100 wineglass structures simultaneously glassblown on a 100 mm wafer. (right) Fused silica wineglass resonator.

We explore an alternative fabrication paradigm under the hypothesis that surface tension and pressure driven micro-glassblowing process may serve as an enabling mechanism for wafer-scale fabrication of extremely symmetric and atomically smooth degenerate mode CVGs, Fig 1. Micro-glassblowing process relies on viscous deformation of the device layer under the influence of surface tension and pressure forces to define the 3-D shell structure as opposed to conventional deposition, molding, or etching techniques, this leads to levels of smoothness and structural symmetry that is not available through conventional fabrication techniques. In addition, current MEMS fabrication techniques limit the maximum achievable Q-factor by restricting the material choice to a few materials. Available materials such as single-crystal silicon have relatively high coefficient of thermal expansion (CTE) and consequently high thermo-elastic dissipation (TED) at typical CVG operation frequencies (20-100 kHz). Materials with low CTE, such as fused silica (0.5 ppm/°C) or ultra low expansion titania silicate glass, provides a dramatic increase in fundamental Q_{TED} limit. Micro-glassblowing allows the use of bulk fused silica material on a wafer-level without the need for challenging dry etching techniques, Fig 1.

2. Design

To understand the impact of quality factor (*Q*) and frequency split between two degenerate vibratory modes (Δf) on the performance of a CVG, one can look at the fundamental noise limit of the mechanical element. For a degenerate mode CVG operating in force rebalance mode the equation for angle random walk is given as [7]:

$$\Omega_{\mathrm{ARW}} \approx \sqrt{\frac{k_B T \omega_y}{A^2 M \omega_x^2 Q_y}\left(1+\frac{\omega_d^2}{\gamma^2}\right)} \times 3437.7^{\circ}/\sqrt{hr} \tag{1}$$

In this equation k_B is the Boltzmann constant, T is the temperature (300 °K), $\omega_d = (\omega_y^2 - \omega_x^2)/(2\omega_x) \approx \Delta f$ and $\gamma = \omega/(2Q_y) = 1/\tau$. For a 7 mm OD, 500 µm thick wineglass structure operating at $\omega_x \approx \omega_y$ =100 kHz central frequency, with an effective modal mass of M = 8 µg, angular gain factor of ~0.3 and driven to A = 1 µm amplitude. The angle random walk (ARW) of the gyro with respect to Q-factor and Δf is given in Fig. 2. Two important observations can be made based on Fig. 2: (1) it is possible to obtain significantly lower thermo-mechanical noise at higher Q-factors, (2) a cross-over point does exist for quality factor at $\Delta f \approx 1/\tau = \gamma$, where higher quality factors become detrimental to gyro performance and result in higher thermo-mechanical noise. This shifts the emphasis on to frequency symmetry, as a frequency split of $\Delta f < 1/\tau$ is required to be able to utilize high Q-factors on degenerate mode CVGs, else the high Q-factor becomes a liability.

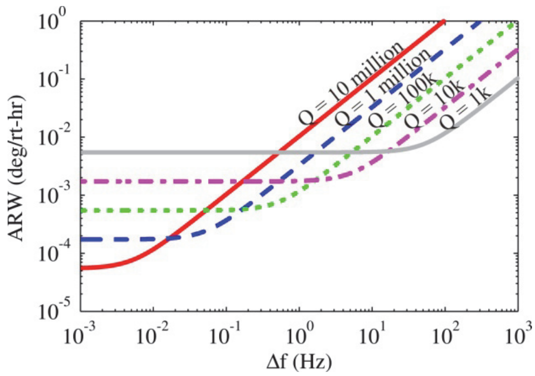


Fig. 2. Effect of quality factor and frequency split on angle random walk (ARW). Higher quality factor helps reduce ARW only if the frequency split is sufficiently low.

3. Fabrication & Results

Fabrication process starts with wet etching cavities onto a fused silica substrate, Fig 3. The next step of the fabrication process is plasma assisted fusion bonding of the fused silica or ULE TSG device layer onto the fused silica substrate and micro-glassblowing the device layer at > 1600 °C. This is followed by back-lapping the wafer stack to release the inverted wineglass structures and metallization of the interior surface of the wineglass. For the electrode structures, separate fused silica wafers are patterned with Cr/Au and covered with a thin layer of sacrificial layer (photoresist). Subsequently, lapped and metalized wineglass wafer is bonded to electrode wafer at the stem of each wineglass. Once the bonding is complete the sacrificial layer is removed to release the wineglass structure around its perimeter, creating capacitive gaps between the metalized wineglass structure and the Cr/Au electrodes.

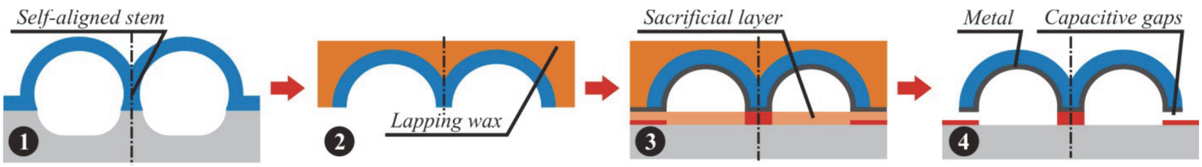


Fig. 3. Process flow for fused silica wineglass fabrication: (1) glassblowing, (2) lapping, (3) bonding and (4) removal of sacrificial layer.

3.1. Frequency symmetry and surface roughness

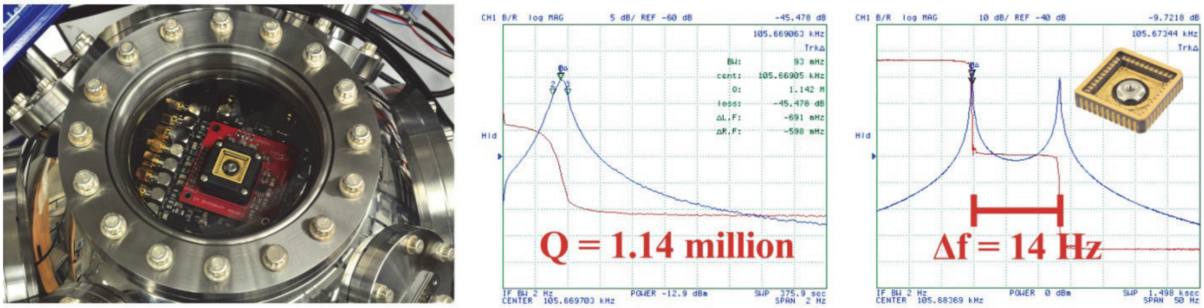
During the brief duration, while the device layer is still viscous, surface tension forces act on the 3-D shell structure to minimize surface roughness and structural imperfections. This leads to atomically smooth surfaces (0.23 nm Sa measured on glassblown shells using AFM [8]) and frequency splits (Δf) that are uniformly low across the wafer. Table 1, shows summary of 5 borosilicate glass wineglasses on the same wafer, demonstrating ppm level frequency symmetry between the two degenerate n = 2 wineglass modes [9].

Table 1. Frequency symmetry of n = 2 wineglass mode on 5 borosilicate glass wineglass structures fabricated on the same wafer.

Device #	**Center Freq.**	**Δf (Hz)**	**σ (Hz)**	**Δf/f (ppm)**
1	27388.65	0.16	0.04	5.67
2	28889.18	4.69	0.05	162.18
3	29227.60	1.76	0.05	60.30
4	29090.38	21.08	0.06	724.65
5	29442.98	9.61	0.07	326.40

3.2. Quality-factor

Fused silica shells were fabricated and integrated with out-of-plane electrodes using the process described in Fig 3 [10]. Frequency sweep using out-of-plane electrodes revealed Q factor of 1.14 million and frequency split of 14 Hz at a center frequency of 105 kHz ($\Delta f / f$ = 132 ppm) and 20 µTorr pressure, Fig. 4.



(a) Fused silica shell inside vacuum chamber (b) Freq. sweep showing Q > 1 million (c) Frequency split of 14 Hz.

Fig. 4. Frequency response of a 7 mm fused silica shell structure, demonstrating over 1 million quality factor at 20 µTorr pressure.

4. Conclusions

Frequency splits as low as Δf < 1 Hz has been demonstrated on borosilicate glass wineglass structures. In addition, Q-factors above 1 million have been demonstrated on fused silica wineglass structures. These results demonstrate the feasibility of surface tension driven micro-glassblowing process as a means to fabricate extremely symmetric and smooth high-Q 3-D wineglass resonators. Low internal dissipation of fused silica material combined with extremely high structural symmetry of MEMS micro-glassblowing paradigm may enable a new generation of low-cost, high performance (ARW < 0.001 deg/rt-hr) fused silica CVGs.

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References

[1] A. M. Shkel, "Type I and Type II Micromachined Vibratory Gyroscopes," IEEE ION 2006, pp. 586–593.
[2] D.M. Rozelle, "The hemispherical resonator gyro: From wineglass to the planets", Proc. AAS/AIAA Space Flight Mechanic, Feb. 2009, pp. 1157–1178.
[3] P. Shao, V. Tavassoli, L. Chang-Shun, L. Sorenson, and F. Ayazi, "Electrical characterization of ALD-coated silicon dioxide micro-hemispherical shell resonators," IEEE MEMS 2014, pp. 612–615.
[4] P. Taheri-Tehrani, T. Su, A. Heidari, G. Jaramillo, C. Yang, S. Akhbari, H. Najar, S. Nitzan, D. Saito, L. Lin, and D. A. Horsley, "Micro-scale diamond hemispherical resonator gyroscope," Hilton Head Workshop, pp. 289–292, 2014.
[5] M. Kanik, P. Bordeenithikasem, J. Schroers, D. Kim, and R. T. M'Closkey, "Microscale Three-Dimensional Hemispherical Shell Resonators Fabricated from Metallic Glass," in *IEEE ISISS*, 2014, pp. 9–12.
[6] J. Cho, T. Nagourney, A. Darvishian, B. Shiari, J. Woo, and K. Najafi, "Fused silica micro birdbath shell resonators with 1.2 million Q and 43 second decay time constant," Hilton Head Workshop, pp. 103–104, 2014.
[7] R. P. Leland, "Mechanical-thermal noise in MEMS gyroscopes," IEEE Sensors Journal, vol. 5, no. 3, pp. 493–500, Jun. 2005.
[8] D. Senkal, M. J. Ahamed, A. A. Trusov, and A. M. Shkel, "High temperature micro-glassblowing process demonstrated on fused quartz and ULE TSG," Sensors and Actuators A:Physical, vol. 201, pp. 525–531, Dec. 2012.
[9] D. Senkal, M. J. Ahamed, A. Trusov, and A. M. Shkel, "Achieving Sub-Hz Frequency Symmetry in Micro-Glassblown Wineglass Resonators," *JMEMS.*, vol. 23, no. 1, pp. 30–38, 2014.
[10] D. Senkal, M. J. Ahamed, S. Askari, and A. M. Shkel, "1 million q-factor demonstrated on micro-glassblown fused silica wineglass resonators with out-of-plane electrostatic transduction," Hilton Head Workshop, pp. 68–71, 2014.