ULTRA CONFORMAL HIGH ASPECT-RATIO SMALL-GAP CAPACITIVE ELECTRODE FORMATION TECHNOLOGY FOR 3D MICRO SHELL RESONATORS

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ABSTRACT

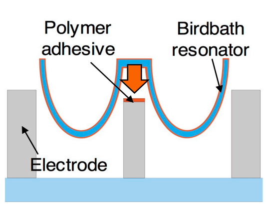
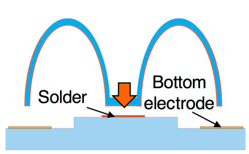
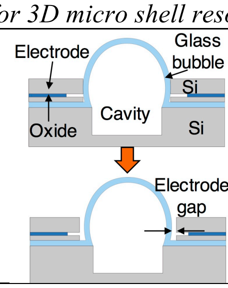
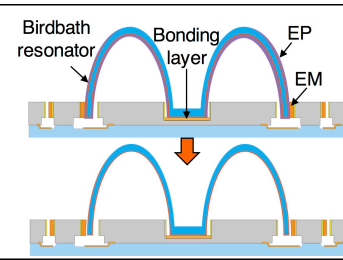
We report a new fabrication technology to form capacitive sense/drive electrodes with large area and narrow, uniform, and controllable gaps around a three-dimensional (3D) micro shell resonator. The process utilizes electroplated photoresist (EP) to form a conformal sacrificial layer on the 3D shell and electroplated metal (EM) to grow drive/sense electrodes towards the resonator until they touch the sacrificial layer and stop. Once the sacrificial layer is removed, extremely well defined and uniform capacitive gaps are formed. EP provides many desirable features as a sacrificial layer, including uniform coverage, excellent electrical insulation and chemical stability, wide thickness range, low deposition temperature, and easy removal. This post-processing technique can be applied to a variety of 3D micro devices. We demonstrate a birdbath resonator gyroscope (BRG) with ~7 µm gap and high mechanical quality factor (Q = 225,000). The development of this process is an important step toward the commercialization of high-performance 3D micro sensors and actuators.

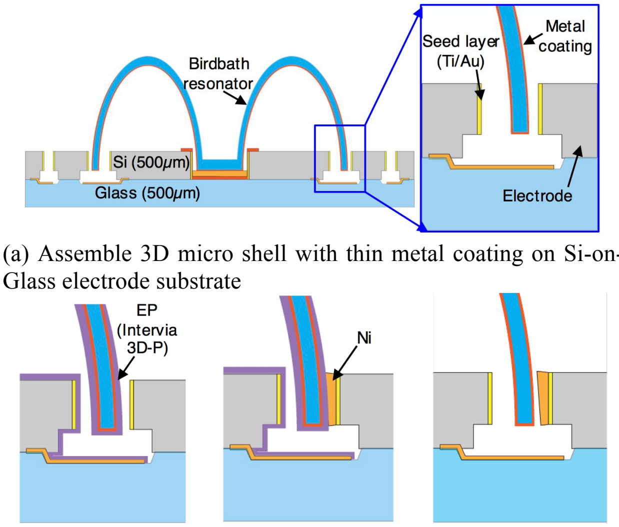
INTRODUCTION

Fused silica (FS) 3D micro shell resonators have great potential for a high performance vibratory gyroscope due to high Q, a long decay time constant (τ), and high frequency (f) and τ symmetry for the wine-glass modes [1]. However, one of the key challenges for 3D shell resonators is the difficulty in integrating capacitive electrodes around the resonator. A fabrication process for integrating electrodes needs to satisfy many requirements: 1) a uniform sacrificial layer with user-definable thickness controlled over a wide range (1–20 µm), low residual stress to prevent shell deformation, and easily removable without contaminating the shell and 2) multiple electrodes whose capacitive gaps to the shell are well defined and uniform, and that can be formed after the shell is attached and integrated onto the supporting substrate. These requirements render most conventional sacrificial layer materials such as polysilicon and metals incompatible.

A number of electrode formation techniques for 3D resonators have been proposed (Table I). We previously reported the mechanical assembly of a micro birdbath shell near silicon (Si) side electrodes (Table Ia) [2]. The drawback of this approach was limited gap uniformity (5–10 µm), low yield, low repeatability, and outgassing from an organic adhesive, which makes this approach incompatible with low-pressure (< 10 mTorr) vacuum packaging. Planar electrodes have also been proposed for micro hemitoroidal resonators in [3] (Table Ib). This method is also used in a macro-scale hemispherical resonator gyroscope from Sagem [4] and in a micro Si multi-ring cylindrical gyroscope [5]. In this method, the vertical motional components of the rim of a shell in the wine-glass modes are actuated and sensed. However, this technique has low sensitivity and a limited frequency tuning range because the sensing area is limited by the small width of the rim and the out-of-plane motion amplitude is smaller than the in-plane motion amplitude (the ratio of out-of-plane motion amplitude to lateral motion amplitude is approximately 1/3 for a shell with a radius-to-height ratio of around 1). Si side electrodes are formed after Pyrex glass blowing and isotropic Si etching in [6] (Table Ic); however, this method suffers from poor gap

Table I. Comparison of electrode integration approaches for 3D micro shell resonators.

			
(a) Assembly near side electrodes. Attachment using organic adhesive [2].	(b) Assembly near planar electrodes [3].	(c) Pyrex glass blowing + isotropic etching [6].	(d) *Current work*: assembly near side electrodes + EP sacrificial layer deposition on shell + metal electroplating on electrodes.
Drawbacks: alignment inaccuracy, low yield, low repeatability, incompatibility with vacuum packaging.	*Drawbacks*: small frequency tuning range, small capacitance.	*Drawbacks*: incompatibility with reflow molding FS, bad electrode gap controllability.	*Advantages:* good electrode gap uniformity and controllability, and compatibility with vacuum packaging.



(a) Assemble 3D micro shell with thin metal coating on Si-on-Glass electrode substrate

(b) Coat EP on the shell (c) Electroplate metal from side electrodes (d) Dissolve EP

Figure 1. Fabrication process steps.

controllability and is not compatible with FS shell resonators due to the high softening temperature of FS.

In this paper, we present a simple and very effective method for forming uniform electrodes around a shell resonator by depositing a conformal EP sacrificial layer and growing EM to touch and stop at the sacrificial layer (Table Id). This process is capable of providing small capacitive gaps for a variety of 3D structures with any shape, is simple and is performed after shell fabrication.

ELECTRODE FORMATION PROCESS

Process Step Overview

The electrode formation process is shown in Figure 1. First, a micro birdbath resonator gyroscope is fabricated (Figure 1a). This is done by a FS micro resonator using the micro blow-torch reflow process [7] and assembling it on a Si-on-Glass substrate with pre-fabricated arrays of tall Si electrodes with a large initial distance to the edge of the shell (initial distance = 20–40 μm, variation = 5–10 μm). The resonator is attached to the electrode substrate using AuRoFuse™ from Tanaka Precious Metals, which is an ultra-high-concentration gold paste that allows low temperature bonding (< 200 ºC) due to the sintering of sub-micron gold particles [8]. The sidewalls of the Si electrodes are covered with a Ti/Au (= 100/1000 Å) electroplating seed layer. Electrical connection between the metal coating layer on the shell and a Si electrode is also established. Second, the surface of the resonator is coated conformably with EP (MicroChem Intervia 3D-P) with a thickness of 10–15 μm (Figure 1b). Third, Ni is electroplated out from the sidewalls of the Si electrodes until all electrodes touch and conform to the sacrificial layer (i.e., the electrodes are grown out towards the shell, Figure 1c). Fourth, the EP is selectively removed to release the shell (Figure 1d).

Deposition of Electroplated Photoresist (EP)

EP is highly attractive due to its low process temperature, a wide thickness range (1–15 μm), low residual stress, high electrical insulation, high chemical stability, and high selectivity for removal with organic solvents [9]. The deposition of Intervia 3D-P is a simple, voltage-controlled process. The thickness of this photoresist is self-limited due to the increase in the resistance between the seed layer and the solution as the thickness of the deposited layer increases. Its final thickness is controlled by the peak voltage and the solution temperature.

Intervia 3D-P was mixed with DI with a volume ratio of 1:1. The temperature was controlled to be 20–30 °C. A characterization sample (unreleased FS birdbath shell) was coated with Ti/Pt (50/500 Å) and then treated with O_2 plasma. The sample was soaked in the EP solution for longer than 5 minutes before applying the plating voltage. The plating voltage was ramped up to 80 V. The current

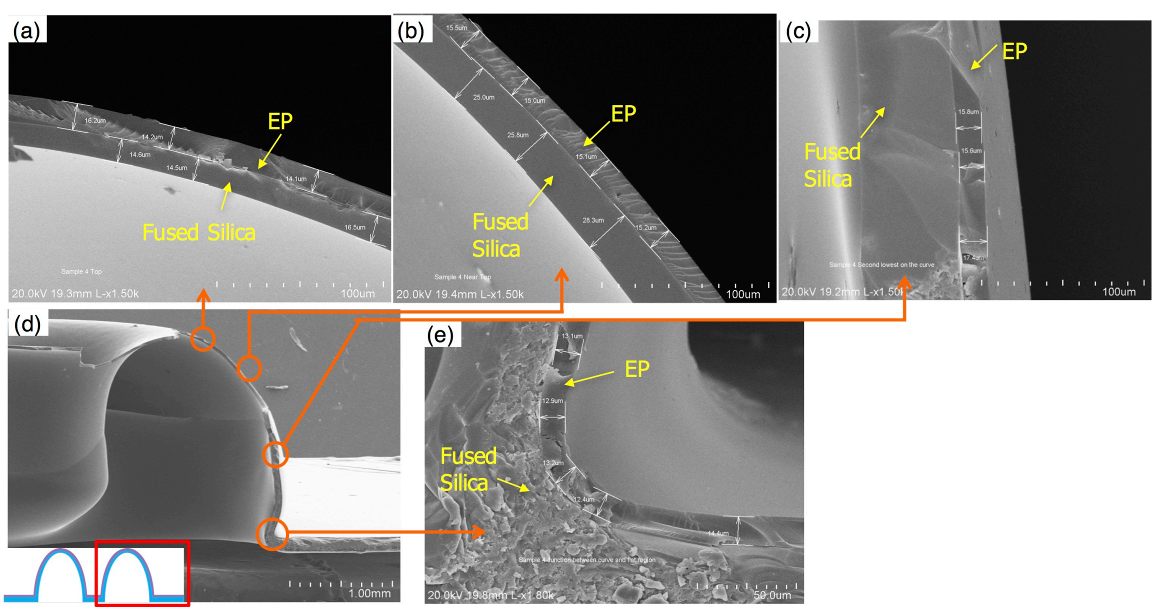


Figure 2. Cross-sectional SEM images of birdbath shell coated with EP. Thickness nonuniformity < 5 μm.

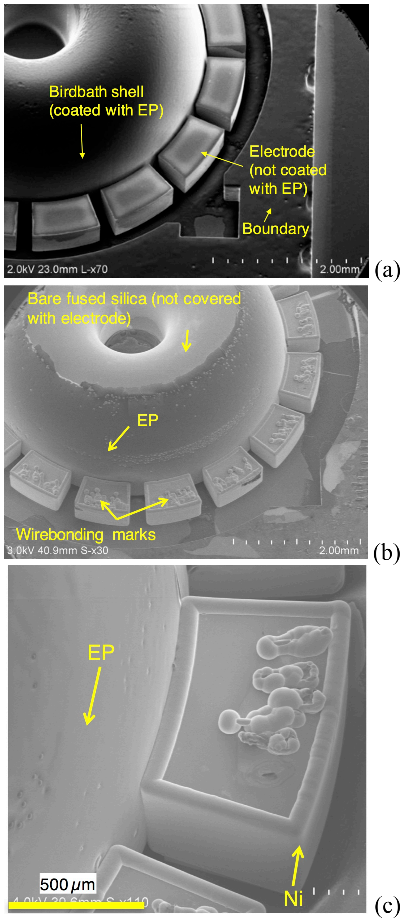


Figure 3. SEM images of a FS birdbath resonator gyro. (a) after the deposition of EP on the shell, (b) after the deposition of Ni on the Si electrodes, (c) close-up image near a single electrode.

flow dropped to zero less than 30 seconds after reaching the peak voltage. After the current dropped to zero, the sample was left for another 30 seconds before turning the voltage off. The overall duration for the electroplating step was less than 5 minutes. The sample was then rinsed in DI, air dried, and soft-baked on a 90 °C hot plate for about 10 minutes.

Figures 2a through 2e show cross-sectional scanning electron microscope (SEM) images of different portions of the birdbath shell. Excellent coverage of the EP on all sections of the shell is clearly visible. The thickness is large in convex regions (Figure 2c, Thickness: 15.6–17.4 µm) and small in the concave regions (Figure 2e, Thickness: 12.4–14.4 µm). The difference in the thicknesses of the EP layer in those regions is believed to be due to the difference in the electric field and solution concentration during electroplating.

Electrode Formation for Birdbath Resonator Gyroscope

Electrode formation for the BRG was performed at the die level. Individual BRG dies were attached on a support glass substrate covered with Ti/Pt = 100/1000 Å using a polymer adhesive. The electrical connections to the birdbath resonators were made by bonding wires from the

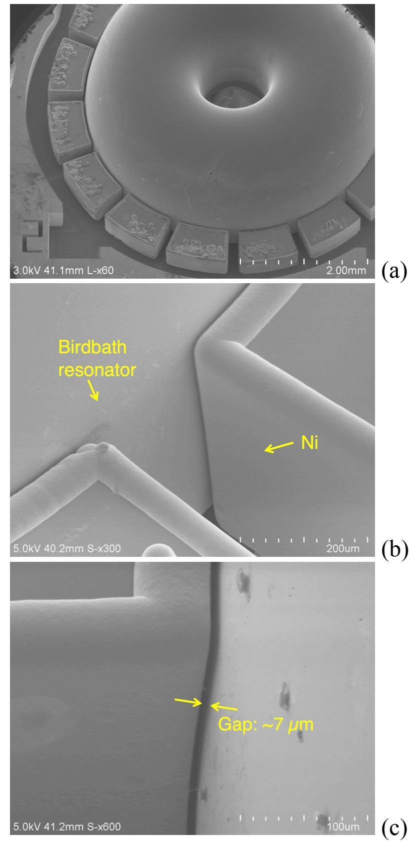


Figure 4. SEM images of a FS birdbath resonator gyro after removing the EP sacrificial layer. Small (5 ~ 8 µm) and uniform gaps between electrode and shells were realized.

metal layer on the glass substrate to the Si electrodes that are connected to the metal layer on the shell. Figure 3a shows an SEM image of the BRG after the deposition of EP on the gyroscope, demonstrating very high conformality of the EP. The surrounding electrodes were either not coated or coated by EP but with a much smaller thickness than on the shell. Any EP on the electrodes was removed using downstream O_2 plasma (800 W, 80 sccm, 80 ºC).

A standard Ni electroplating solution was used to grow the electrodes [10]. A moderate deposition rate (~4 nm/s) was chosen in order for the electrodes to cover the sidewalls of the EP layer uniformly. Figures 3b and 3c show SEM images of the BRG after Ni electroplating and a close-up image near a single electrode, respectively. The EP layer showed minimal degradation. The gap between the sacrificial layer and the electrode was completely filled with Ni.

After Ni electroplating, the BRG was released by dissolving the EP layer using organic solvents. Figures 4a through 4c show the SEM images of a released BRG. A highly conformal and uniform electrode gap of 5–8 µm was measured. Small spots of Ni residues were electroplated on the shell through the pinholes in the EP sacrificial layer. This issue will be addressed by improving the deposition conditions of EP to reduce the number of the pinholes.

DEVICE CHARACTERIZATION

The resonant characteristics of the BRG were evaluated by measuring its decay time constant. Figure 5 shows the ring down plot of one of the $n = 2$ wine-glass modes of the BRG (shell radius = 2.5 mm, height ≈ 2 mm, shell rim thickness ≈ 80 μm) at $f = 16.659$ kHz, which has $\tau = 4.3$ seconds and $Q = 224{,}930$. The other $n = 2$ wine-glass mode had $f = 16.522$ kHz, $\tau = 3.8$ seconds, and $Q = 197{,}140$. The Q of the current gyroscope is believed to be limited by the Ni residue on the resonator surface.

A high electrostatic frequency tuning efficiency was measured ($\Delta f \approx 10$ Hz for a tuning voltage of ~10 V). This will allow us to electronically match the mode frequencies and cancel the quadrature errors using practically low DC voltages. The electroplated Ni did not degrade after heating the sample at 350 ºC for 3 hours. The resonance quality was also maintained after the thermal cycling test. The current test results indicate great potential for this process to create a low-cost high-performance micro birdbath resonator gyroscope.

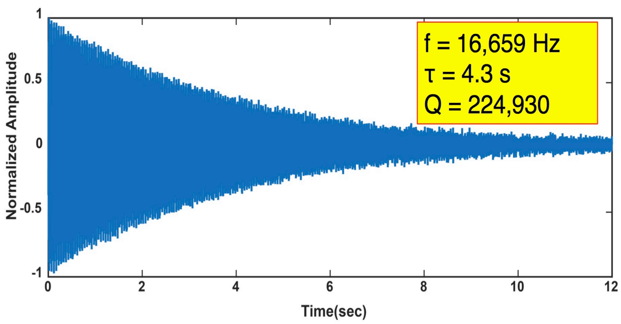


Figure 5. Decay time plot of the n=2 wine-glass mode of the birdbath resonator gyroscope. $f_{wg} = 16.659$ kHz, $\tau = 4.3$ s, $Q = 224{,}930$.

SUMMARY

We reported a new, simple, and highly effective method for creating conformal capacitive electrodes around a 3D micro shell resonator. This process utilized EP as a sacrificial layer and EM to grow electrodes towards the resonator until they touch the sacrificial layer and stop. EP is highly conformal and has a wide and controllable thickness range (1–15 μm). EP also can be deposited at room temperature and has great chemical stability and etch selectivity. This process is a post-processing technique that can be applied to a variety of 3D micro devices. We demonstrated the fabrication of a BRG with a ~7 μm gap and high Q (= 225,000). The development of this process is an important step toward the commercialization of a high-performance 3D micro sensors and actuators.

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REFERENCES

[1] T. Nagourney *et al.*, "130 Second Ring-Down Time and 3.98 Million Quality Factor in 10 kHz Fused Silica Micro Birdbath Shell Resonator", in *Proc. Hilton Head 2016*, Hilton Head Island, SC, June 2016, pp. 408-411.

[2] J. Cho *et al.*, "Fused-Silica Micro Birdbath Resonator Gyroscope (μ-BRG)", *J. Microelectromech. Syst.*, vol. 23, no. 1, pp. 66-77, 2014.

[3] D. Senkal *et al.*, "Demonstration of 1 Million-Factor on Microglassblown Wineglass Resonators with Out-of-Plane Electrostatic Transduction", *J. Microelectromech. Syst.*, vol. 24, no. 1, pp. 29-37, 2015.

[4] A. Jeanroy *et al.*, "HRG by SAGEM From Laboratory to Mass Production," in *Proc. IEEE Inertial Sensors 2016*, Laguna Beach, CA, Feb. 2016, pp. 1-4.

[5] J. Cho *et al.*, "High-Q, 3KHz Single-Crystal-Silicon Cylindrical Rate-integrating Gyro (CING)," in *Proc. 25th IEEE International Conference on Micro Electro Mechanical Systems (MEMS'12)*, Paris, France, January 2012, pp. 172-175.

[6] J. Giner *et al.*, "Design, Fabrication, and Characterization of a Micromachined Glass-Blown Spherical Resonator with In-Situ Integrated Silicon Electrodes and ALD Tungsten Interior Coating," in *Proc. IEEE MEMS 2015*, Estoril, Portugal, Jan. 2015, pp. 805-808.

[7] J. Cho *et al.*, "3-Dimensional Blow Torch-Molding of Fused Silica Microstructures", *J. Microelectromech. Syst.*, vol. 22, no. 6, pp.1276-1284, 2013.

[8] T. Ogashiwa *et al.*, "Hermetic Seal Bonding at Low-Temperature with Sub-Micron Gold Particles for Wafer Level Packaging", in *Proc. IMAPS 2015*, Orlando, FL, Oct. 2015, pp. 73-78.

[9] M. Heschel and S. Bouwstra, "Conformal coating by photoresist of sharp corners of anisotropically etched through-holes in silicon", *Sensors and Actuators A*, vol. 70, no. 1, pp. 75-80, 1998.

[10] A. Peczalski and M. Rais-Zadeh, "Temperature compensated fused silica resonators using embedded nickel-refilled trenches", in *Proc. Transducers'15*, Anchorage, Alaska, June 2015, pp. 157-160.

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