Fabrication Process and Structural Characterization of Fused Silica-on-Silicon Toroidal Ring Gyroscope

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Abstract—This paper reports a micro-scale Toroidal Ring Gyroscope (TRG) fabricated from Fused Silica (FS) material. To overcome the Thermo-Elastic Damping (TED) limitation of micro-resonators manufactured out of silicon, we developed a Fused silica-On-Silicon (FOS) process to utilize FS as the structural material. In the process, a 4-inch FOS wafer-stack, comprised of a 100- μm device layer and a 500- μm handle layer, was used. The TRG structure was defined in the FS device layer using inductively coupled plasma etching and subsequently released through isotropic etching of silicon. The TRG design architecture was successfully fabricated using the process to operate in the n=2 degenerate wineglass modes. The TRG devices were characterized electrostatically, revealing a quality factor as high as 539k and a frequency split as low as 8 Hz. Experimental results were reported on the effect of metal coating on quality factor of the FS-TRGs. This study indicates that despite a relatively high surface-roughness in plasma etching of FS material and quality factor degradation due to metal coating, FS micro-resonators with a high quality factor can be realized, exceeding that of conventional silicon resonators. We also demonstrated that optimization of the metal coating process is key to reach the TED limit of pristine FS material.

I. INTRODUCTION

Fused Silica (FS) is a desirable material for fabrication of micro-scale optical, mechanical, and fluidic systems. An exceptionally low Thermal Expansion Coefficient (TEC), chemical inertness, transparency, and isotropy of mechanical properties make FS a favorable candidate to substitute the conventional Single-Crystalline Silicon (SCS), as the structural material, in fabrication of vibratory Micro-Electro-Mechanical Systems (MEMS).

Due to a low TEC of FS, the Thermo-Elastic Damping (TED) of FS resonators is expected to be an order of magnitude lower than SCS-based resonators, [1]. High quality factors have been reported for macro and micro-scale 3-dimensional FS resonators, such as the milli-Hemispherical Resonator Gyroscope (HRG), [3], and the Precision Shell Integrating (PSI) gyroscope, [4]. Adapting conventional micromachining techniques to fabricate high quality factor FS micro-mechanical resonators would directly benefit applications, including inertial sensing, [2], time referencing, chemical and biological sensing, and acoustic sensing.

While attempts have been made to realize 2-dimensional FS resonators through conventional micromachining techniques, the quality factors reported for plasma-etched FS resonators have been well below the theoretical TED limit of the material,



Fig. 1. Schematics of the Fused silica-on-Silicon (FOS) process which was utilized for fabrication of TRGs.

[5, 7, 8]. Currently, the highest quality factor reported for a 2-D FS resonator is around 120k as compared to the TED limit of 1M, [8]. To reach the intrinsic quality factor limit of FS resonators, the limiting energy dissipation mechanism needs to be identified, understood, and eliminated. Among more conventionally studied energy loss mechanisms are air damping, anchor loss, and surface losses, [9], while the losses specific to processing of FS still need to be studied. A robust process for fabrication of 2-D FS micro-resonators is key for identifying and studying energy dissipation mechanisms.

For fabrication of 2-D FS micro-resonators, two common approaches have been explored. In one approach, an FS or an SCS substrate with pre-etched cavities is bonded to the FS device layer, and the device layer is later etched using high-density plasma. Once the etch is completed, the resonator would be free to vibrate above the pre-etched cavities. In the case of using an FS substrate, the cavities are defined through wet etching, [5], and for an SCS substrate, cavities are defined using Reactive Ion Etching (RIE), [6].

One of the main challenges with the pre-etched cavity approach is the TEC mismatch between different layers. During plasma etching, a high temperature is experienced by the structure, and due to the TEC mismatch between the masking layer, device layer, and the substrate, the FS device layer goes through high thermo-mechanical stress. Once the device layer is partially released, the TEC mismatch would cause deformations in the device layer, which would adversely affect the etch profile. Furthermore, after plasma etching, since the structure is released, it is fragile and it is prone to breakage in subsequent steps of the process, reducing the yield.

In another approach, reported in [7], an FS device layer is bonded to an SCS substrate. The device layer is patterned using plasma etching and the structure is released in the

This material is based on work supported by the Defense Advanced Research Projects Agency (DARPA) and U.S. Navy under Contract No. N66001-16-1-4021.



Fig. 2. SEM images of a FOS test structure prior to release. In (a), a fully etched fused silica layer with rectangular channels of different opening sizes, ranging from 20 μ m to 500 μ m, is demonstrated. In (b) and (c), cross-section images are shown, demonstrating etched features with 3.3:1 and 5:1 aspect-ratios and near vertical sidewalls.

last step through isotropic etching of the silicon material underneath the resonator. In this approach, since the device layer is fully bonded to the silicon substrate up until the last step of releasing, a higher yield is expected.

In this paper, we utilized the second approach, which we refer to as the Fused silica-On-Silicon (FOS) process, to fabricate Toroidal Ring Gyroscopes (TRG) out of FS material. Details of the fabrication process and characterization results on quality factor and frequency split of the fabricated FS-TRGs are reported.

II. FABRICATION PROCESS

The fabrication process for the Fused Silica Toroidal Ring Gyroscope (FS-TRG) is illustrated in Figure 1. Initially, a 4-inch 500- μm thick SCS substrate wafer was bonded to a 100- μm thick FS wafer through plasma-activated fusion bonding, as illustrated in step (b). For bonding, the wafers were immersed in an RCA-1 solution (NH_4OH : H_2O_2 : H_2O = 1 : 1 : 5) at 75-80 $^{\circ}C$. Using Plasma-Therm RIE, the wafers were exposed to O_2 plasma for 150 seconds to increase the initial bonding strength. In the plasma treatment, we used an O_2 flow rate of 24 sccm, process pressure of 90 mtorr, and antenna power of 25 W. After surface activation, the wafers were rinsed with DI water and blow-dried with nitrogen. Subsequently, the wafers were manually brought into contact and were annealed on a hot plate for 8 hours at 200 $^{\circ}C$. To provide enough time for thermal relaxation and partial stress release for both the SCS and FS layers, the temperature was increased to 200 $^{\circ}C$ with a ramp rate of 30 $^{\circ}C$ /hour.

In step (c), using e-beam Physical Vapor Deposition (PVD), a 10 nm chromium thin film and a 100 nm gold layer were deposited onto the FS device layer. The chromium layer served as an adhesion layer, and the gold layer was used as the seed layer for nickel electroplating. Nickel has been reported to be a desirable masking material for plasma etching of FS material, [11]. The chemically amplified Az-12xT positive photoresist was used to create 15 μm thick molds for nickel plating, as described in [10]. An HT-2 Ready-to-Use (RTU) nickel plating solution by Techni was used for electroplating 11 μm of nickel on top of the gold layer with a deposition rate of 50 nm/min. After electroplating, the photoresist was removed by acetone, and the nickel layer was used as masking material for plasma etching. In step (d), the FOS wafer-stack was etched using UCI's SPTS APS PM oxide etching system. The APS etcher is an Inductively Coupled Plasma (ICP)-based high-density plasma source, which we utilized for deep etching of FS. Through an optimization procedure, process parameters summarized in Table I were found to provide an etch rate of 0.53 μ m/min and near-vertical sidewalls.

 TABLE I

 PROCESS PARAMETERS USED FOR PLASMA ETCHING OF FUSED SILICA.

Parameters	Values	Parameters	Values
Antenna power	1500 W	Plate power	400 W
C_4F_8 gas flowrate	65 sccm	O_2 glas flowrate	15 sccm
Ar gas flowrate	25 sccm	Platen temperature	40 °C

Despite a mismatch in the TEC of SCS and FS, due to a helium backside cooling mechanism along with a relatively high thermal conductivity of the SCS substrate, we observed that both the die-level and the wafer-level plasma etching of FOS structures were successful. After plasma etching, the nickel mask and Cr/Au layers were removed through wet etching. Using FEI Quanta 3D Scanning Electron Microscopy (SEM), cross-section images of FOS test structures were used for characterization, as shown in Figure 2 (a). In Figure 2 (b) and (c), 100- μ m deep etched channels with aspect-ratios of 3.3:1 and 5:1 are demonstrated.

In step (e), the FOS devices were put in a XeF_2 pulse etcher for isotropic etching of the silicon, releasing the FOS structure. In step (f), piranha cleaning was used to remove polymers left from the plasma etching process and residues from the wet etching agents. The cleaning was followed by metal coating of the FS structures for conductivity, required for electrostatic actuation and detection.

III. TOROIDAL RING GYROSCOPE DESIGN

The Toroidal Ring Gyroscope (TRG) design architecture consists of concentric rings which serve as both the inertial mass and suspension elements of the resonator, [12]. The rings are connected through spokes and anchored at the outer ring, as shown in Figure 3.

The TRG in this paper was designed to operate in the n=2 wineglass modes. Based on balanced dynamics of the wineglass modes along with the isotropic mechanical properties



Fig. 3. Design of the TRG used for demonstration of the FOS process. The modal deformation of n=2 wineglass modes in a TRG is illustrated.

of FS, the energy loss through anchors of the FS-TRG was anticipated to be minimal. 16 electrode pads were designed facing the innermost ring for electrostatic actuation, detection, and frequency tuning.

As an initial demonstration, 18 rings with a width size of 40 μm and a gap size of 30 μm were used in design of the FS-TRG. To minimize the quality factor degradation, the number of rings, anchor size, and ring width were chosen to have a minimum frequency separation of 2 kHz between the operational n=2 wineglass modes and the parasitic modes, [13]. Through Finite Element Analysis (FEA), the resonant frequency and TED quality factor of the FS-TRG were calculated to be on the order of 10.38 kHz and 3.9 M, respectively.



Fig. 4. SEM images showing the cross-section of the FS-TRG and a closeup cross-section of the concentric rings. Faceting and high surface-roughness, due to charging of the nickel mask [14], on the top portion of features are evident.

IV. EXPERIMENTAL RESULTS

SEM cross-section images of an FS-TRG fabricated through the FOS process are shown in Figure 4, taken prior to the releasing step. After releasing, the TRG was uniformly coated with a 5 nm thick chromium layer using Denton sputter coater. The device was temporarily attached and wire bonded to a chip carrier for electrostatic actuation and detection.

The FS-TRG devices were tested in a vacuum chamber at a pressure below 30 $\mu torr$. Using a Zurich HF2Li lock-in amplifier, the TRG was excited using a combination of DC and AC voltages which were applied to the drive electrodes, while the displacement of the inner ring was electrostatically measured. By utilizing the frequency response and ring down response, we characterized the frequency split and quality factor of two FS-TRG devices in both the n=2 wineglass modes, summarized in Table II.

 TABLE II

 EXPERIMENTAL CHARACTERIZATION RESULTS ON TWO FS-TRGS.

Parameters	TRG #1	TRG #2
Resonant frequency 1	10.453 kHz	10.648 kHz
Resonant frequency 2	10.466 kHz	10.656 kHz
Frequency split	13 Hz	8 Hz
Quality factor 1	539k	488k
Quality factor 2	511k	436k

Based on results in [15], we anticipated that the metal coating was potentially reducing the quality factor of the TRG. To characterize the effect of metal coating on quality factor, we coated an FS-TRG device with different thicknesses of chromium varying from 5 nm to 30 nm. Before deposition of a thicker chromium layer, we removed the previously deposited metal layer through wet etching. The device was then cleaned using piranha solution and dehydrated for 4 hours at $120 \,^{\circ}C$. The quality factors of both modes were characterized and the results are shown in Figure 5. By increasing the thickness of the metal layer, we observed an increase in sensitivity of capacitive detection. However, as shown in Figure 5, by increasing the thickness from 5 to 30 nm, a quality factor reduction of more than 50% was observed.



Fig. 5. Experimental data demonstrating the effect of metal coating on quality factor of FS-TRG devices. As shown, by increasing the metal thickness from 5 to 30 nm, a quality factor reduction of more than 50% was observed.

V. CONCLUSIONS

In this paper, we presented results on fabrication and structural characterization of a fused silica toroidal ring gyroscope. The dynamically balanced TRG device was successfully fabricated using the FOS process with a 100- μm thick device layer and characterized at $\mu torr$ pressure vacuum. While a relatively high roughness on the sidewalls due to the plasma etching process was observed, we measured a high quality factor on the order of 539k for the metal-coated FS-TRG. Based on structural characterization results, a high correlation between quality factor and thickness of metal coating was noted, indicating that metal coating of 2-D FS resonators is a major source of energy dissipation which needs to be accounted for. Further experiments will be conducted to characterize the quality factor of the FS-TRG, without any metal coating, to identify other mechanisms limiting the quality factor.

REFERENCES

- Y. Sun, D. Fang, and A. K. Soh, "Thermoelastic Damping in Micro-Beam Resonators," in International Journal of Solids and Structures vol. 43, no. 10, pp. 3213-3229, May 2006.
- [2] R. P. Leland, "Mechanical-Thermal Noise in MEMS Gyroscopes," in IEEE Sensors Journal, vol. 5, no. 3, pp. 493-500, May 2005.
- [3] A. A. Trusov, M. R. Phillips, A. Bettadapura, G. Atikyan, G. H. McCammon, J. M. Pavell, Y. A. Choi, D. K. Sakaida, D. M. Rozelle, and A. D. Meyer, "mHRG: Miniature CVG with Beyond Navigation Grade Performance and Real Time Self-Calibration," IEEE International Symposium on Inertial Sensors and Systems (INERTIAL), CA, USA, February 2016.
- [4] J. Y. Cho, S. Singh, J. Woo, G. He, and K. Najafi, "0.00016 deg/\sqrt{hr} Angle Random Walk (ARW) and 0.0014 deg/hr Bias Instability (BI) from a 5.2M-Q and 1-cm Precision Shell Integrating (PSI) Gyroscope," IEEE International Symposium on Inertial Sensors and Systems (INERTIAL), Hiroshima, Japan, March 2020.
- [5] E. Song, S. Kang, H. Kim, Y. K. Kim, J. E. An, and C. W. Baek, "Wafer-Level Fabrication of a Fused-Quartz Double-Ended Tuning Fork Resonator Oscillator Using Quartz-on-Quartz Direct Bonding," in IEEE Electron Device Letters, vol. 34, no. 5, pp. 692-694, April 2013.
- [6] S. Grousset, P. Lavenus, L. Benaissa, R. Taibi, E. Augendre, T. Signamarcheix, O. Le Traon, and S. Ballandras, "Quartz-Based Vibrating MEMS Fabricated Using a Wafer-Bonding Process with Sealed Cavities," IEEE International Frequency Control Symposium (FCS), Taipei, Taiwan, May 2014.
- [7] Y. S. Hwang, H. K. Jung, E. S. Song, I. J. Hyeon, Y. K. Kim and C. W. Baek, "Fabrication of Electrostatically-Actuated, In-Plane Fused Quartz Resonators using Silicon-on-Quartz (SOQ) Bonding and Quartz Drie," IEEE International Conference on Micro Electro-Mechanical Systems (MEMS), Sorrento, Italy, January 2009.

- [8] A. D. Challoner, H. G. Howard, and J. Y. Liu, "Boeing Disc Resonator Gyroscope," IEEE/ION Position, Location and Navigation Symposium (PLANS), CA, USA, May 2014.
- [9] Y. Wang, Y. W. Lin, J. Glaze, G. D. Vukasin, D. D. Shin, H. K. Kwon, D. B. Heinz, Y. Chen, D. D. Gerrard, T. W. Kenny, and A. M. Shkel, "Quantification of Energy Dissipation Mechanisms in Toroidal Ring Gyroscope," in IEEE Journal of Microelectromechanical Systems, vol. 30, no. 2, pp.193-202, January 2021.
- [10] D. Hii, D. Vatanparvar, and A. M. Shkel, "Optimization of Photoresist Plating Mold Fabrication for Metal Mask Patterning," in Journal of Vacuum Science and Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, vol. 39, no. 2, March 2021.
- [11] Z. Cao, B. VanDerElzen, K. J. Owen, J. Yan, G. He, R. L. Peterson, D. Grimard, and K Najafi, "DRIE of Fused Silica," IEEE International Conference on Micro Electro Mechanical Systems (MEMS), Taipei, Taiwan, January 2013.
- [12] D. Senkal, S. Askari, M. J. Ahamed, E. J. Ng, V. Hong, Y. Yang, C. Hyuck Ahn, T. W. Kenny, and A. M. Shkel, "100K Q-factor Toroidal Ring Gyroscope Implemented in Wafer-Level Epitaxial Silicon Encapsulation Process," IEEE International Conference on Micro Electro-Mechanical Systems (MEMS), CA, USA, January 2014.
- [13] D. Vatanparvar and A. M. Shkel. "Effect of Fabrication Imperfections on Energy Loss Through Mechanical Mode Coupling in MEMS," IEEE International Symposium on Inertial Sensors and Systems (INERTIAL), Lake Como, Italy, March 2018.
- [14] M. Huff and M. Pedersen, "Electrical Field-Induced Faceting of Etched Features Using Plasma Etching of Fused Silica," in Journal of Applied Physics, vol. 122, no. 2, July 2017.
- [15] T. Nagourney, J. Y. Cho, A. Darvishian, B. Shiari, and K. Najafi, "Effect of Metal Annealing on The Q-factor of Metal-Coated Fused Silica Micro Shell Resonators," IEEE International Symposium on Inertial Sensors and Systems (ISISS), HI, USA, March 2015.