The Concept of “Collapsed Electrodes” for Glassblown Spherical Resonators Demonstrating 200:1 Aspect Ratio Gap Definition

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***Abstract*—We report a technique for defining high aspect ratio electrostatic gaps in micromachined glassblown spherical resonators. The approach is based on intentionally allowing a physical contact between the resonator and electrode structure, hence “collapsed electrodes”, then releasing and metalizing the electrodes and resonator. We utilized 500 um SOI electrodes in the glassblowing fabrication process, allowing to define narrow (2 um) and thick (400 um) electrostatic actuators (200:1 aspect ratio). We demonstrated a spherical resonator integrated with electrodes, blurring the boundary in complexity of fabricating conventional (2D) and glassblown (3D) resonators. The test resonator demonstrated 866kHz, 1.46MHz and 1.59MHz for N=1, N=2, and N=3 modes and the corresponding Q-factors of 1500, 1300 and 1600, all in vacuum of 0.4mT.**

Keywords—3D MEMS, Spherical Resonator, Glassblowing

I. INTRODUCTION

MEMS resonators are desirable for a wide variety of applications, including signal processing, timing, frequency control, and inertial sensing [1]. An increasing number of 2D silicon resonators are currently on the market [2], and the majority of products are fabricated using the silicon as a structural material, utilizing photolithography and DRIE-based techniques for defining the features. The structural precision of 2D resonators is limited by fabrication tolerances introduced by etching, such as DRIE-induced scalloping, and the intrinsic limits of the aspect ratio of features. As a result, the fabrication of devices with high quality factors and high aspect ratio electrostatic actuators become challenging. These factors have motivated the investigation of fabrication approaches that allow the development of 3D MEMS resonator architectures with increased symmetry, environmental robustness, and increased aspect ratios—all accomplished simultaneously.

In the recent years, there has been an increasing interest in the development of 3D MEMS spherical and hemispherical resonators for use in timing and inertial sensing applications. Conventional semiconductor fabrication processes have been used to fabricate silicon oxide hemispherical resonators, resulting in quality factors (Q) as high as 20,000, at a resonant frequency of 22kHz [3] and polysilicon resonators with Q's around 8,000, at a resonant frequency of 416kHz [4]. Plastic deformation of metallic glasses to achieve spherical structures has been explored by using a blow-molding technique [5]. The use of low Thermo-Elastic Damping (TED) materials, such as Fused Silica (FS), have also been explored [6]. Processing of such materials requires a development of dedicated infrastructure and tools operating at 1600°C. A batch fabrication glassblowing process developed at the UC Irvine Microsystems Laboratory allows shaping of FS glass and Pyrex to create symmetric structures with resonant frequencies in the range of kHz [7] achieving Q factors on the level of 1M [8] and axial symmetry with Δf less than 1Hz.

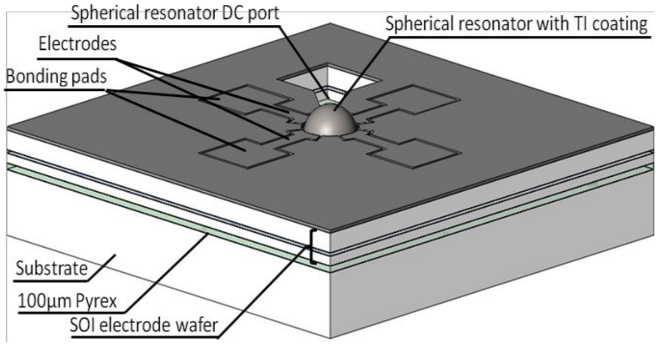

Fig. 1. Diagram of a spherical resonator with integrated SOI electrods and top-side metallization.

MEMS resonators for stable timing applications require higher frequencies of operation in order to reject, among other reasons, the effect of external accelerations. The use of spherical shapes provides higher stiffness and hence higher resonant frequencies. We fabricated quasi-spherical structures using micro glass-blowing techniques [10], demonstrating low order resonant frequencies about 1MHz [11] for resonators with improved thermal stability[12]. In [9], a new fabrication process is introduced combining batch-mode micro ultrasonic machining (µUSM), lapping, and micro electro-discharge machining (µEDM) for creating FS spherical structures with operation frequencies on the order of MHz and Q factors in air of 350.

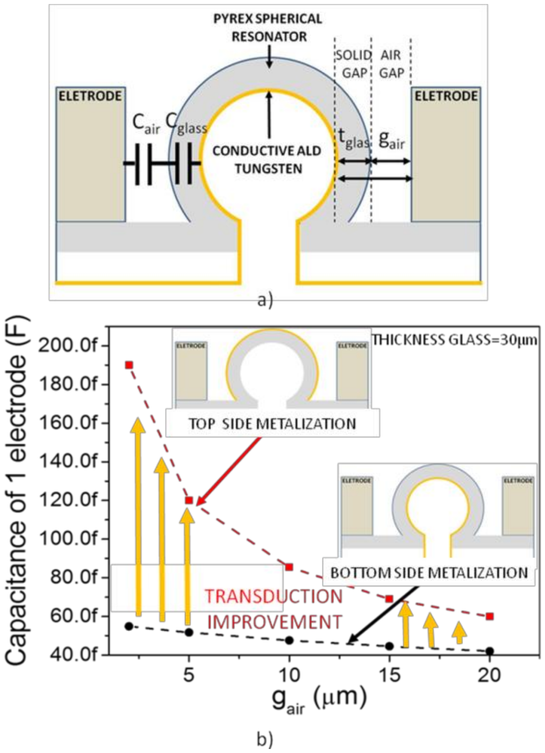

Fig. 2. a) Diagram of the cross-section of spherical resonator with integrated electrode and backside coating. b) Modeling of the transduction capacitance variation with the air gap between the shells and one of the four electodes, shown in Figure 1. Capacitance calculated using a shell of 500um radius, 400um electrode thickness, and an angular section of 35°.

Electrostatic actuation and sensing of spherical resonators present a challenge. The current approaches use either assembled out-of-plane [11] or in-plane [12] electrodes, and in some cases, integrate sputtering [3] or doping [4] of electrode features in the process. The former requires an extra assembly step reducing the yield and symmetry of structures. The electrodes as thick as several microns have been demonstrated, however they still do not take the full advantage of the large transduction area that the 3D spherical shells provide. We have recently demonstrated an integrated approach for fabrication of wafer-thick electrodes integrated in the glassblowing fabrication process, using back-side coating of the shell with ALD of conductors, enabling electrostatic transduction and effective electric isolation of electrodes from the resonator [13].

In this paper we present the design, fabrication, and test of high aspect ratio integrated SOI electrodes for quasi-spherical glass-blown Pyrex resonators with high aspect ratio symmetric electrostatic gaps. The approach presents narrower and more symmetric gaps than in our previous work. The SOI electrodes are designed to allow a shell to collapse with electrodes during the glassblowing process. Subsequently, the gaps are defined using the XeF_2 release. The under-etching of the SOI using wet etching enables the top-side coating to increase the transduction coefficient and reduce the motional resistance.

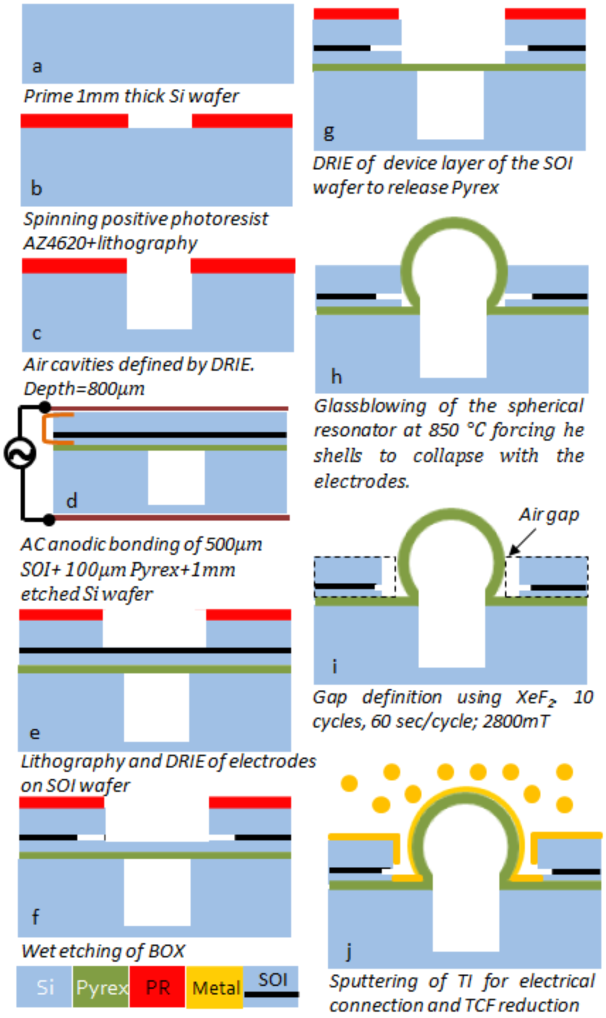

Fig. 3. Fabrication flow for ―collapsed electrode” and front-side metalization process

II. DEVICE

The device in Figure 1 consists of a g_r=500μm radius micro glassblown Pyrex spherical resonator with four electrodes with thickness of 400μm, for differential excitation and detection. The actual electrode structure is formed by 100μm device layer, 2μm BOX, and 400μm handle wafer. To generate the electrostatic force and to drive vibrations, the resonator is polarized with a DC voltage, while an AC voltage is applied to excitation electrodes. When the frequency of AC signal corresponds to the resonance frequency of the shell, the electrostatic force induces a mechanical vibration in the resonator. The shells and the electrodes are coated, providing both an electrical conductivity for the shell and an electrical isolation of the spherical shell from electrodes.

III. COMPARATIVE ANALYSIS

The process introduced in this paper is an improvement of our earlier results reported in [13], where we utilized a back side ALD metallization process for defining a capacitive gap. In [13], the gap was formed by thickness of the glass of the

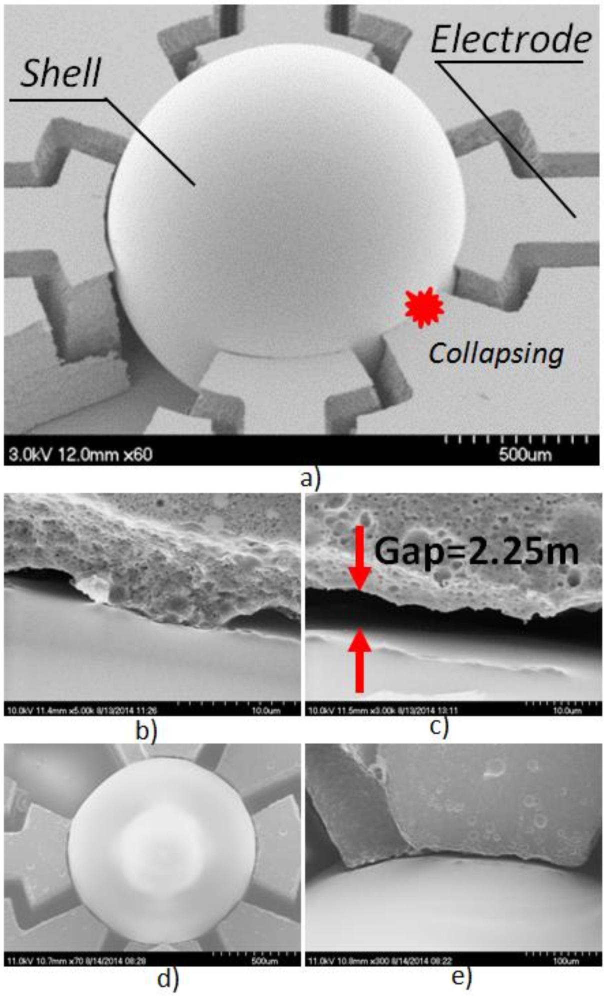

Fig. 4. a) SEM image of a collapsed spherical resoantor. b)close up of a collapsed gap before etching process using XeF_2, and after (c). d) Spherical resonator with integrated electrodes after definiton of gaps. d) clouse-up of an electrode after releasing

spherical resonator and an air gap between the resonator and an electrode (Figure 2a). The maximum achievable gap in the process was limited by thickness of the shell. Figure 2 b shows the modeling result of the static capacitance between the electrode formed by a circular section of silicon electrode with a thickness of 400 µm and a section of 35° of 500µm radius spherical shell. The capacitance of a back side ALD coating approach and a top side coating approach are shown by the black line and the red line, respectively. For the air gaps of 2µm, the static capacitance of the top side approach is 4x larger than capacitance of the back side approach. In section IV, we discuss our new process.

IV. FABRICATION PROCESS

The fabrication of a spherical resonator with integrated electrodes (Figure 3) starts with etching of circular cavity in a 1mm thick bare silicon wafer using a 24µm AZ4620 positive photoresist (a-c). The cavity, with 265nm radius and a depth of 800µm, traps the ambient air at atmospheric pressure that subsequently facilitate the glassblowing process. The volume of cavity defines the size and, thus the resonant frequency of the spherical resonator. After stripping off the photoresist, we cleaned all wafers utilizing an RCA-1 solution (to remove any contaminants), including the etched handle wafer, a 100 µm Pyrex wafer, and an SOI wafer (with a device layer of 100µm, a handle wafer of 400µm and buried oxide (BOX) of 2µm thickness). Wafers are stacked together in a way that the device layer of the SOI wafer contacts the Pyrex wafer leaving the thicker handle wafer of the SOI as a functional layer (d). The wafer stack is placed under weight to assure a uniform contact at the interfaces. Then, AC anodic bonding with a 0.1 Hz frequency and 800 V_{pp} at 400 °C are used to bond the three wafers. In order to generate a voltage difference between the device layer, that is in contact with the Pyrex wafer and the silicon substrate, a copper tape is used to electrically connect the two silicon parts of the SOI wafer (d). An electrode mask is patterned on the 400 µm handle silicon wafer (e) using the BOX as an etch stop. Then, the wafer is submerged in Hydrofluoric acid, a 20% Hydrogen Fluoride (HF) solution for 30minuts. The HF is used to remove the oxide on top of the device layer and to introduce under-etching of the BOX to define a discontinuity between the two silicon parts of the SOI wafer (f). The concentration of HF and the etching time have been obtained experimentally, and necessary to protect the initial photoresist mask that will be used for the subsequent DRIE steps. The device layer is etched using DRIE and the photoresist mask to reach the Pyrex underneath (g). The glassblowing process is carried out inside the annealing furnace in the nitrogen environment at 880 °C (h). Surface

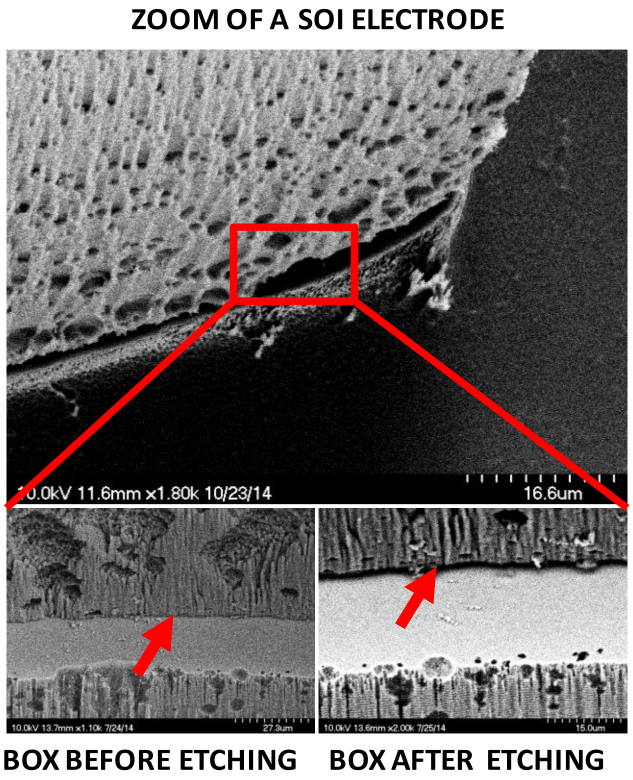

Fig. 5. SEM image of the SOI electrode structure, showing the gap between the two silico wafer after HF releasing. The gap ensures electical isolation between the device and handle silicon.f

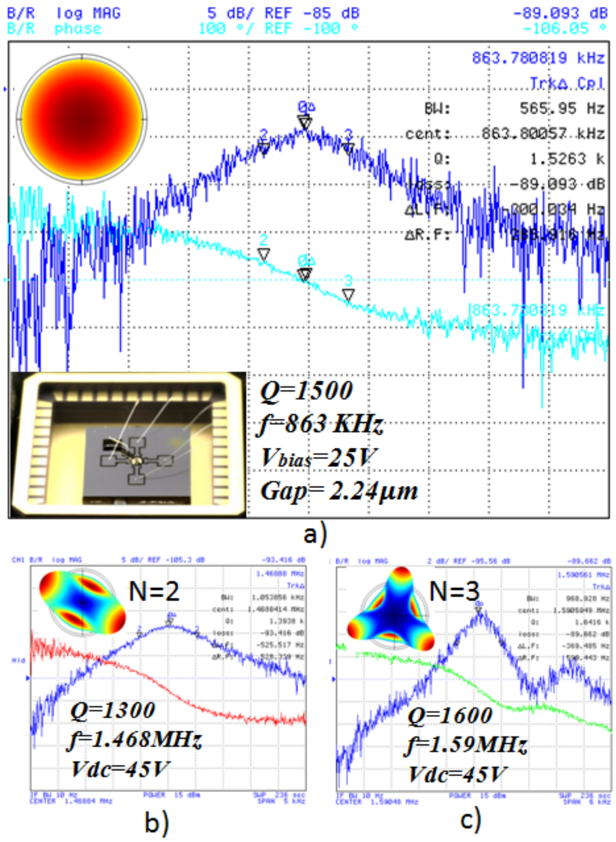

Fig. 6. a) Experiemental results (magnitude and phase) of the optical characterizatioin of the spherical resoantor with integated electrode in N=1 (Bouncing mode). b) and c) show the resuls for the N=2 and N=3 modes at 1.46MHz and 1.59MHz, respectively

tension forces and pressure gradients facilitate the glass-blowing of the spherical resonator with 40µm shell thickness around the equator. After 2.5 minutes of glassblowing the shell collapses to the electrodes. Then, 10 cycles of 60 second at 2800mT of pressure in a custom build XeF_2 vapor etcher are needed to define a 2.25µm air gap, consistently, between the electrode and the resonator (i). Finally, 50nm of Titanium are deposited via sputtering (j).

V. CHARACTERIZATION

The packaged device (inset Figure. 6 a) is characterized in a custom built vacuum chamber with an optical port at 0.4 mT. For experimental characterization, the input AC signal of 1.4 V_{pp} is generated with a network analyzer (Agilent 4395A) and applied to electrodes of the resonator. A DC voltage (V_{bias}) of 25 V is applied to the resonator though the opening at the top of SOI layer (Figure 1). AC and DC voltages generate an electrostatic force required to drive vibration modes of the shell. The frequency response is optically measured using a Polytec OFV5000 single-point Laser Doppler Vibrometer. The operational frequency for rocking mode is 863Khz, using a polarization voltage of only 25V. Frequencies of 1.468MHz and 1.59MHz, with Q factors of 1300 and 1600 have been measured for the N=2 and N=3 mode, respectively.

VI. CONCLUSION

We have demonstrated a new fabrication process for co-integration of SOI electrodes with a glass-blown spherical resonator. The use of collapsed shell and XeF_2 release allowed to obtain a high aspect ratio (200:1) actuators.

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REFERENCES

[1] [1] C. T. C. Nguyen, ―MEMS technology for timing and frequency control.” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 54, pp. 251–270, 2007.

[2] S. Tabatabaei and A. Partridge, ―Silicon MEMS Oscillators for High-Speed Digital Systems,” *IEEE Micro*, vol. 30, no. 2, pp. 80–89, 2010.

[3] P. Pai, F. K. Chowdhury, H. Pourzand, and M. Tabib-Azar, ―Fabrication and testing of hemispherical MEMS wineglass resonators,” *IEEE 26th Int. Conf. on Micro Electro Mechanical Systems (MEMS), 2013* pp. 677–680.

[4] L. D. Sorenson, X. Gao, and F. Ayazi, ―3-D micromachined hemispherical shell resonators with integrated capacitive transducers,” *IEEE 25th Int. Conf. on Micro Electro Mechanical Systems (MEMS), 2012*, pp. 168–171.

[5] B. Sarac, G. Kumar, T. Hodges, S. Ding, A. Desai, and J. Schroers, ―Three-Dimensional Shell Fabrication Using Blow Molding of Bulk Metallic Glass,” *IEEE/ASME Journal of Microelectromechanical Systems,* vol. 20, pp. 28–36, 2011.

[6] J. Cho, J. Yan, J. A. Gregory, H. Eberhart, R. L. Peterson, and K. Najafi,―High-Q fused silica birdbath and hemispherical 3-D resonators made by blow torch molding,” *IEEE 26th Int. Conf. on Micro Electro Mechanical Systems (MEMS)*, 2013, pp.177–180.

[7] D. Senkal, J. M. Ahamed, A. A. Trusov, and A. M. Shkel, ―Demonstration of Sub-1Hz Structural Symmetry in Micro-Glassblown Wineglass Resonators with Integrated Electrodes,” *IEEE Transducers Conference*, 2013.

[8] D. Senkal, M. J. Ahamed, S. Askari, and A. M. Shkel, ―1MillionQ-Factor Demonstrated On Micro-Glassblown Fused Silica Wineglass Resonators With Out-Of-Plane Electrostatic Transduction,” *Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head, 2014, pp. 68–71.*

[9] Visvanathan, Karthik, Tao Li, and Yogesh B. Gianchandani. "3D-SOULE: A fabrication process for large scale integration and micromachining of spherical structures." (MEMS), *IEEE 24th International Conference on. Micro Electro Mechanical Systems (MEMS, 2011*.

[10] E. J. Eklund and A. M. Shkel, ―Glass Blowing on a Wafer Level,” *IEEE/ASME Journal of Microelectromechanical Systems* vol. 16, no. 2, pp. 232–239, 2007.

[11] I. P. Prikhodko, S. A. Zotov, A. A. Trusov, and A. M. Shkel, ―Microscale Glass-Blown Three-Dimensional Spherical Shell Resonators,” *IEEE/ASME Journal of Microelectromechanical Systems* vol. 20, no. 3, pp. 691–701, 2011.

[12] J. *Giner*, L. Valdevit, A. M. Shkel, ―*Glass-Blown Pyrex resonator* with Ti Coating for Reduction of TCF”, *IEEE* Int. Symp. of Inertial Sensors and Systems *2014.*

[13] J. Giner, J. M Gray, J. Gertch, V.M. Bright, A.M. Shkel ―Design, Fabrication, And Characterization Of A Micromachined Glass-Blown Spherical Resonator With In-Situ Integrated Silicon Electrodes And Ald Tungsten Interior Coating”, *IEEE 25th Int. Conf. on Micro Electro Mechanical Systems (MEMS), 2015.*