DESIGN, FABRICATION, AND CHARACTERIZATION OF A MICROMACHINED GLASS-BLOWN SPHERICAL RESONATOR WITH IN-SITU INTEGRATED SILICON ELECTRODES AND ALD TUNGSTEN INTERIOR COATING

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ABSTRACT

We propose a new approach for integration of electrodes as a part of the micro glass-blown spherical resonator fabrication process as well as an ALD metallization of the inner side of the spherical shell enabling electrostatic conduction. We use a 500µm thick silicon electrode whose electrostatic gap width, defined during the glass blowing process, is not limited by lithographic effect and enables sub-micron gap possibilities. In addition, we introduce a metallization technique based on ALD of tungsten on the inner side of the shell. 35:1 aspect ratio electrodes demonstrated to excite a 500µm radius spherical resonator with an operating frequency of 1.66MHz and a Q factor above 2700 in vacuum (0.4mT)

INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) resonators are desirable for a wide variety of applications, including signal processing, timing, frequency control, and inertial sensing [1]. Several silicon MEMS resonators are currently on the market [2], and the vast majority of MEMS resonators are fabricated using silicon as a structural material, photolithography and DRIE techniques for defining the features. The dimensional resolution is due to fabrication tolerances introduced by etching, such as DRIE-induced scalloping, surface roughness, and the intrinsic limits of the aspect ratio of features. As a result, the fabrication of highly symmetric, frequency-matched devices with high quality factors becomes extremely challenging. These factors motivate the investigation of alternative fabrication approaches that allow the development of 3D MEMS resonator architectures with increased symmetry, reduced roughness, and increased aspect ratios—all accomplished simultaneously.

Recently, there has been significant interest in the development of 3D MEMS spherical and hemispherical resonators for use in timing and inertial sensing applications. Photolithography and DRIE based approaches have been used to fabricate silicon oxide hemispherical resonators using silicon molds, resulting in quality factors (Q) as high as 20,000 at a resonant frequency of 22kHz [3]. The same fabrication approach was demonstrated to build polysilicon resonators for inertial application with Q's around 8000 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

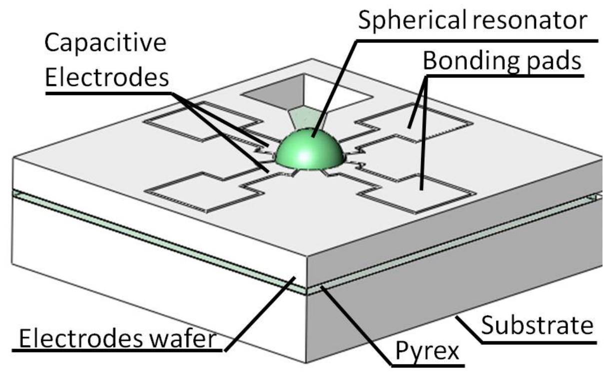

Figure 1 3D diagram of the spherical resonator with integrated silicon electrodes.

Thermo-Elastic Damping (TED) materials, such as Fused Silica (FS), as structural material has also being explored; Q factors above 100,000 at frequencies around 10kHz have been demonstrated [6]. Processing of these materials requires temperatures in excess of 1,600°C. A highly parallel batch fabrication glass-blowing process developed at the UC Irvine Microsystems Laboratory allows shaping of fused silica glass and Pyrex to create highly symmetric structures with resonant frequencies in the range of kHz [7] achieving outstanding Q factors on the level of 1M and axial symmetries with Δf less than 1Hz.

MEMS resonators for stable time applications require higher frequencies in order to reject the effect of the external acceleration. We fabricated quasi-spherical structures using micro glass-blowing techniques [8] in our implemented 3D spherical resonators demonstrated low order resonant frequencies about 1MHz for resonators [9] with improved thermal stability[10]

Instrumentation of spherical vibratory elements requires fabrication of electrostatic electrodes for actuation and sensing. For instance, assembled out-of-plane fold electrodes are used to actuate a 1.2M Q factor wine-glass shell [11]. In-plane assembled silicon electrodes are also used to excite SiO_2 hemispherical shells at 113KHz [12], however assembly approaches require extra fabrication steps that increase process complexity. Others developed integrated alternatives by sputtering and etching metal electrodes around the shell [3] or doping some areas of the silicon handle wafer [4]. With these techniques, electrodes as thick as several microns can be fabricated, but they do not take advantage of the large transduction area that the use of 3D spherical and hemispherical shells provide.

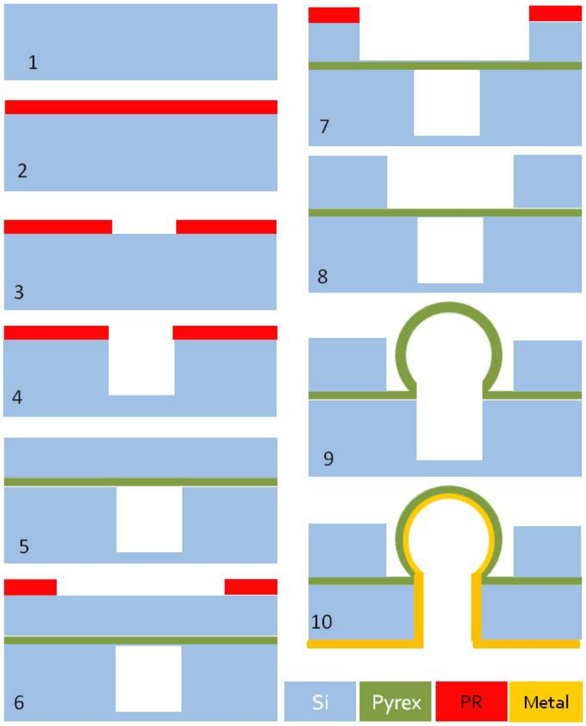

Figure 2 Fabrication flow of the spherical resonator with integrated electrode.

In this paper we present the design, fabrication and test of high aspect ratio integrated silicon electrodes for quasi-spherical glass-blown Pyrex resonators. The silicon electrodes are designed according to the glass blowing dynamics to enable narrow-gap, high aspect ratio electrodes. Electrical connection to the shell is provided by Atomic Layer Deposition (ALD) of tungsten inside the shell, providing a homogeneous thin metal layer to preserve the geometric advantages of the spherical resonator.

DEVICE

The device (Figure 1) consists of a g_r=500µm radius micro glass-blown Pyrex spherical resonator with four electrostatic electrodes with thickness T_e=500, two for differential excitation and two for differential detection.

The distance from the sidewall of the electrode to the center of the shells is 520µm and is defined by applying the equation of the dynamics of the glassblowing process that defines the radius of the shell as a function of the air cavity size and environmental conditions such as temperature and pressure. After the glassblowing process the inner part of the shell is coated with ALD metal. To generate electrostatic force and to drive vibration, the resonator is polarized with a DC voltage while an AC voltage is applied to the excitation electrodes. When the frequency of the AC signal corresponds to the natural frequency of the shell, the electrostatic force induce mechanical vibration in the resonator. The shells is coated in the inner side by ALD. The atomic layer deposition coating from the back side proves to be the effective method to electrically separate the electrodes from the shell and to allow for electrostatic actuation. The transduction takes advantage of the large area of the

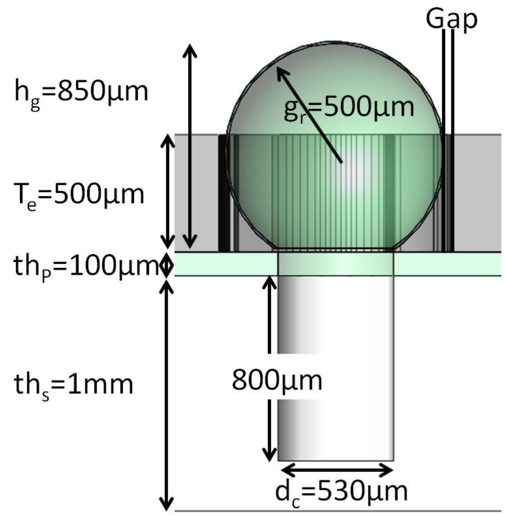

Figure 3 Cross-section diagram of the spherical resonator with the electrostatic gap between the shell and the electrode with the design parameters.

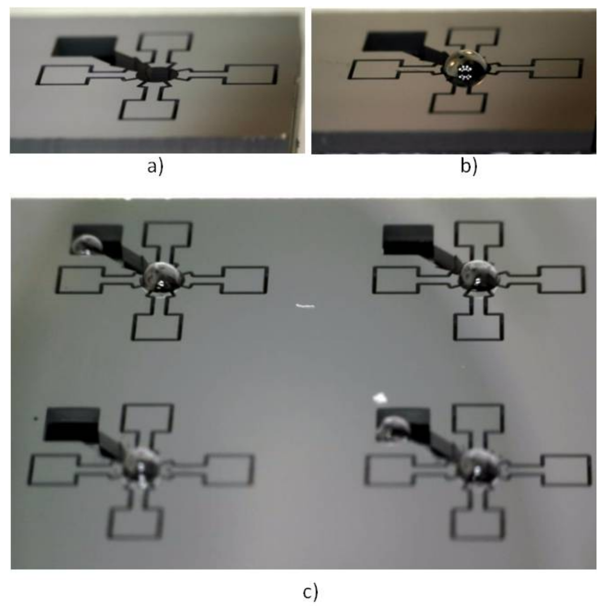

Figure 4 a) shell before glassblowing, b) shell after glass-blowing. c) Wafer level process.

spherical resonator significantly increasing the aspect ratio compared with conventional 2D approaches.

FABRICATION

Spherical Resonator with integrated electrodes

The fabrication of the spherical resonator with integrated electrodes (Figure 2) starts with the etching of circular cavities in a 1mm thick bare prime silicon wafer using a 24µm AZ4620 positive photo resist mask. The cavities, with 265nm radius and a depth of 800µm, contain the air at atmospheric pressure that facilitates the glass-blowing of the shell; therefore its volume will define the size and thus the resonant frequency of the spherical resonator. Figure 3 shows the schematic of the cross-section of a spherical shell with integrated electrodes showing the design parameters used to

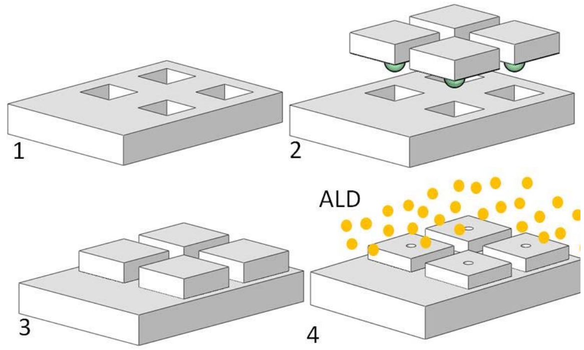

Figure 5 Diagram of the fabricated device holder used for backside etching and ALD deposition.

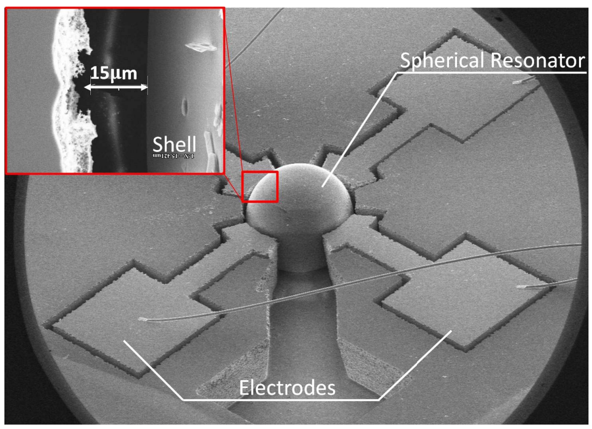

Figure 6 SEM micrograph of the 500um radius spherical shells with integrated electrodes.

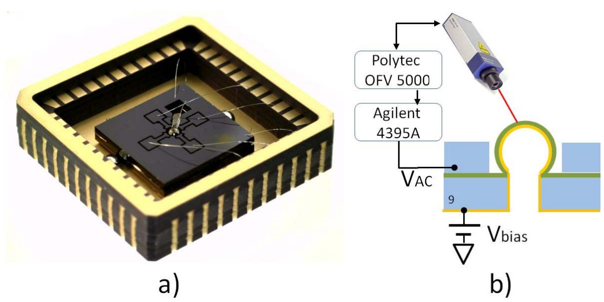

Figure 7 a) Packaged spherical resonator and characterization set-up schematic for electrostatic actuation and optical detection(b).

fabricated the spherical resonator. Deep Reactive Ion Etching (DRIE) is used to open the air pocket on the silicon wafer. After striping the photoresist, the drilled handle wafer, a 100 µm Pyrex wafer, and a double-sided polished 500 µm silicon wafer are cleaned using an RCA-1 solution to remove any contaminants. Wafers are stacked together under weight to assure intimate contact of the interfaces. Then, AC anodic bonding with a 0.1 Hz frequency and 800 V_{pp} is used to bond the three wafers. The electrode mask is patterned on the 500 µm silicon wafer. The glass-blowing process is carried out inside the annealing furnace in a nitrogen environment at 880 °C. Figure 4 shows a single device before (a) and after the glassblowing process (b). After glassblowing, 500µm radius spherical shells with 40µm shell thickness around the equator were obtained. Figure 4 (c) shows the wafer

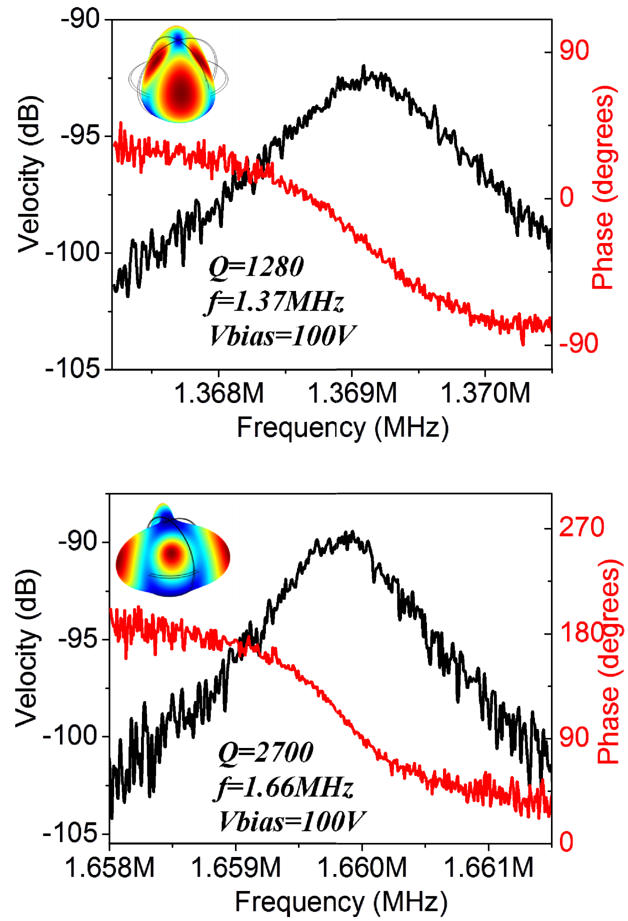

Figure 8 Characterization results of the electrostatic actuated spherical resonator. N=2 and N=3 resonant modes are shown.

level finalized fabrication process of spherical shells with integrated silicon electrodes. Note that the shells are not coated in the picture.

ALD Tungsten Deposition

After fabrication of the spherical resonator with integrated electrodes, metallization of the interior of the spherical shells has to be done in order to electrically connect the non-conductive glass shells. We do this in two steps. The first step consists of facilitating access to the inner side of the shell by back-side etching the silicon substrate. We fabricated a device holder (Figure 5). Squared cavities were dry etched in silicon (1), then shells are inserted in the cavities in order to expose the silicon substrate and to protect the shells during the dry etching step (2-3) Backside of the resonators is plasma etched until the air cavity is fully open. The same silicon holder is used to protect the top side of the shells from the ALD deposition sealing them using Van der Walls force. Atomic Layer deposition took place in a viscous flow ALD reactor at 130 °C with N_2 as the purge and carrier gas. A 3.6 nm aluminum oxide (Al_2O_3) ALD base layer, using trimethylaluminum and water precursors, was used to promote tungsten (W) nucleation. This was followed by a 20 nm deposition of ALD W using disilane (Si_2H_6) and tungsten hexafluoride (WF_6) chemistries. The metal film was capped with an additional 1.2 nm of Al_2O_3 to prevent

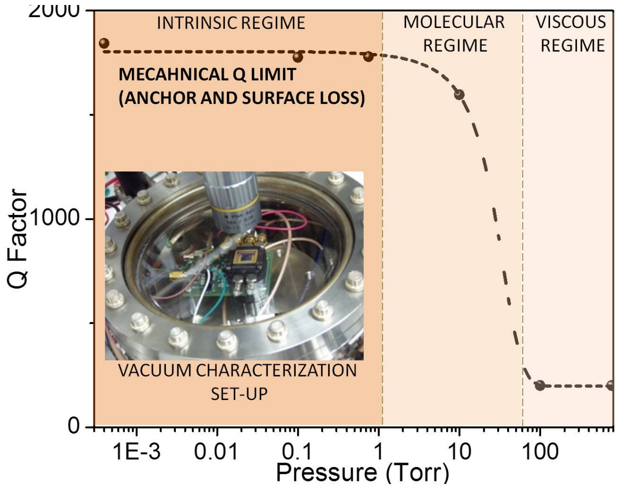

Figure 9. Measurement of the Q factor of the Pyrex spherical resonator as function of vacuum.

metal oxidation.

CHARACTERIZATION

Figure 6 shows a SEM micrograph of the coated spherical resonator with 15µm electrostatic gaps (inset in Figure 6). Resonators in Figure 7 a) were evaluated in a custom built vacuum chamber at 0.4mT with an optical port. For experimental characterization the input signal is generated with a network analyzer (Agilent 4395A) and divided in a balanced (0° phase shift) and unbalanced (180° phase shift). The frequency response was measured using a Polytec OFV5000 single-point Laser Doppler Vibrometer. Figure 8 shows the frequency response of the N=2 mode, and N=3 mode resonator frequency at 1.37 MHz and 1.66 MHz, respectively. Results on characterization of the shells in vacuum (Figure 9) show a maximum on the quality factor at the intrinsic regime (<1 Torr) and suggest that the Q factor is limited by material impurities and anchor losses, given that modeled thermoelastic dissipation Q factors (Q_{TED}) of Pyrex are around 10^8.

CONCLUSION

We have demonstrated the fabrication of operational integrated silicon transductors along with glass-blown spherical resonator fabrication. ALD of tungsten on the inner side of the spherical shells is used to electrically connect the non-conductive shell and to isolate it from the electrodes. The combination of the silicon electrodes and ALD enable 3D MEMS resonator transduction, taking advantage of the large transduction areas that such resonator. 35:1 aspect ratio electrodes have been fabricated to excite spherical resonators. Operational frequencies in the High Frequency range with Q factor around 2700 have been demonstrated.

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