Microscale PolySilicon Hemispherical Shell Resonating Gyroscopes with Integrated Three-dimensional Curved Electrodes

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Abstract. A novel approach for fabrication of polysilicon hemispherical resonator gyroscopes with integrated 3-D curved electrodes is developed and experimentally demonstrated. The 3-D polysilicon electrodes are integrated as a part of the hemispherical shell resonator’s fabrication process, and no extra assembly process are needed, ensuring the symmetry of the shell resonator. The fabrication process and materials used are compatible with the traditional semiconductor process, indicating the gyroscope has a high potential for mass production and commercial development. Without any trimming or tuning of the n=2 wineglass frequencies, a 28 kHz shell resonator demonstrates a 0.009% frequency mismatch between two degenerate wineglass modes, and a 13.6 kHz resonator shows a frequency split of 0.03%. The ring-down time of a fabricated resonator is 0.51 s, corresponding to a Q of 22000, at 0.01 Pa vacuum and room temperature. The prototype of the gyroscope is experimentally analyzed, and the scale factor of the gyro is 1.15 mV/°/s, the bias instability is 80 °/h.

1. Introduction
Micro-Electro-Mechanical Systems (MEMS) gyroscopes are electromechanical devices that measure rate or angle of rotation. They have been adopted in a large variety of applications, such as smartphone, car navigation, electronic toy and industrial robot [1]. A wide variety of surface and bulk fabrication approaches for MEMS gyroscopes have been investigated over the past decades, and various micromachined resonators are developed [2-4]. Among these vibrating elements, the shell-type gyroscopes are the most popular and favorable ones owing to their high axial symmetry and high possibility to operate in whole angle mode.

Shell type gyroscopes of multifarious shapes and different materials are developed. Polysilicon hemispherical resonators were fabricated using isotropically-etched molds in silicon, and for the one with a shell thickness of 700 nm and a diameter of about 1.2 mm, a Q factor around 8500 at a resonant frequency of 6.7 kHz was observed, and for the one with a long anchor, a Q factor of 40400 was obtained [5]. The gyroscope based on this kind of resonator showed a scale factor of 8.57 mV/°/s [6]. A prototype of polysilicon hemispherical resonator with integrated spherical electrodes was fabricated using isotropic silicon etching molds and ICP etching process [7]. The resonator possessed several attractive characters, including large transduction area, small and uniform capacitive gap, no assembly process and high axis symmetry. The radial deviation of the hemispherical shell was less than 1.22 μm.
for the 500 μm radius shell (0.24%), promising a small frequency split. Silicon oxide hemispherical resonators were produced and Q factors of resonators with 500 μm in diameter and 1μm in thickness were in excess of 10000 when operated in 50mT vacuum. The separation in the degenerate frequencies of wineglass modes was 5 Hz at a resonant frequency of 22 kHz [8]. Cylindrical resonators made of microcrystalline diamond were batch-fabricated using diamond deposited by hot filament chemical vapor. The Q factor of the fabricated resonator was 528000 at 19 kHz wineglass modes with the ring-down time 8.9 s [9]. Frequency split less than 1Hz was demonstrated on borosilicate glass wineglass structures, and Q factors above 1 million were demonstrated on fused silica wineglass structures [10]. Fused silica wineglass resonators with high Q factors were fabricated though a simultaneous process of micro blow-torching and microwelding. The resonator had a shell radius/height of about 2.8 mm, and a stem diameter of 1 mm. At < 10 μTorr vacuum, the frequency of the wineglass mode was 22.6 kHz, the value of the Q factor was 2.55 million [4]. For the gyroscope with a fused silica Birdbath Resonator demonstrated, a bias stability of 0.0391 deg/hr was obtained using a force-rebalanced control architecture without temperature control or additional compensation [11].

Microscale hemispherical resonator gyroscopes have exhibited several intriguing characters and are considered to be a viable solution for inertial navigation applications. During its way to commercial market, one of the most serious challenges is to make its fabrication process be compatible with traditional semiconductor process. In this way, the gyroscope will be suitable to mass production and the cost can be reduced. Gyroscopes with assembled electrodes face the problem of requiring extra fabrication steps which increases process complexity and cost, making a bottle-neck in batch-fabrication of the devices at wafer level. Some gyroscopes equipped integrated alternatives by sputtering and etching metal electrodes around the shell or doping some areas of the silicon handle wafer. With these techniques, electrodes as thick as several microns can be fabricated, but they do not take the advantage of the large transduction area that the use of 3-D spherical and hemispherical shells provides. Integrated 3-D glass blown electrodes and high aspect ratio silicon electrodes for spherical shell gyroscopes have been successfully demonstrated [9, 10]. However, the curved walls of the shell-type resonators make it challenging to obtain small, uniform capacitive gaps across the height of the structure.

An alternative wafer-level approach for the batch micromachining of polysilicon hemispherical resonators equipped with integrated 3-D curved silicon electrodes is introduced. Gaps between the electrodes and the shell resonator were shaped by a sacrificial layer, ensuring a small, uniform width of the gaps. Assisted by the 3-D curved electrodes, which are self-aligned located around the resonator and have a similar profile with the shell, the gyroscope owns a large initial capacitance. Low voltage (the amplitude of ~mV) is needed to drive these resonators, making them suitable candidates for very low-power applications.

2. Structure Design
Structure of the designed gyroscope is illustrated schematically in Figure 1. It is a three-layers sandwich structure, including a upper cap layer, a middle silicon layer, and a bottom glass layer. Among them, the middle silicon layer is the gyro’s main structure layer, it consists of a polysilicon hemispherical shell resonator and dozens of discrete three-dimensional electrodes. The number of the electrodes is variable according to the electrical connection design. The electrodes can be divided into two groups according to their functions. One group is named as functional electrodes which used for electrical driving, sensing and tuning the resonator. The other group is dominated supporting electrodes. All the electrodes in this group joined together to form a solid pedestal to support and provide electrical access to the resonator. Trenches between these electrodes are used as air passages when pumping vacuum. Metal pads are sputtered and patterned on the top surface of the electrodes. A shallow cave is fabricated in the upper cap glass layer, which is used to cover the shell resonator and make sure the resonator can vibrate freely and safely. Dozens of through holes are drilled in this layer and are aligned with the pads on silicon wafer. When the gyroscope chip is encapsulated in a ceramic
package, these holes are the aisles for gold lines to reach the pads. The bottom glass layer is just a flat glass wafer whose function is to protect the resonator from being contaminated.

![Figure 1. 3D diagram of the polysilicon hemispherical gyroscope with integrated 3-dimensional electrodes.](image)

The gyroscope offers several attractive features. Firstly, the resonator is made of polysilicon. Polysilicon is a very common material used in semiconductor industry. It is easy to be handled and processed, so the cost of the gyroscope is reduced. Secondly, the initial capacitance of the gyroscope is large. By using integrated 3-D curved electrodes, the transduction area of the gyro is greatly improved. Besides, the capacitive gaps between spherical electrodes and shell are formed by a thin sacrificial dioxide layer, the width of the gap can be very uniform and small. The driving voltage of the resonator is as low as less than 30 mV.

3. Fabrication Process

The fabrication process is schematically illustrated in Figure 2. The resonators are fabricated on a 400 μm low-resistivity p-type single-crystal <111> silicon wafer. First, a hemispherical silicon cave is formed using isotropic etching in hydrofluoric acid \ nitric acid \ acetic acid (HNA) system (Figure 2(a)). The mask of the HNA etching is a composite membrane which consists of a 0.2 μm thermal SiO₂ layer and a 2 μm low-stress LPCVD silicon nitride layer. Then the mask layer is stripped and a bottom cave is ICP etched at the bottom of the hemispherical silicon cave. Subsequently, a blanket sacrificial thermal oxide layer is grown on the wafer and an anchor mold is fabricated by stripping a part of sacrificial oxide from the bottom cave’s bottom, as shown in Figure 2(b). The anchor mold is the bridge which connects the hemispherical shell resonator and the pedestal mechanically and electrically. A 1-2 μm low-stress polysilicon shell layer is conformally deposited on the oxide layer. Then the polysilicon is doped with boron and annealed. After that, the shell layer on the top surface of the wafer is removed using chemical mechanical polishing (Figure 2(c)).
Figure 2. Fabrication process steps for the polysilicon hemispherical gyroscope with integrated 3-dimensional curved electrodes.

Subsequently, three-dimensional curved electrodes are ICP etched from the bottom side of the wafer using the step-shaped silicon oxide mask [12], as shown in Figure 2(d). The shell is then released in vapor hydrofluoric (VHF). Capacitive gaps between the resonator and the electrodes are formed simultaneously at this step (Figure 2(e)). Figure 3 shows a close-up scanning electron microscope (SEM) of the 1.7 μm gap between the resonator shell and electrodes. The capacitance between the resonator and each electrode is about 0.4 pF. The upper cap glass layer with through holes and shallow caves is bonded to the wafer using silicon-glass anodic bonding. Metal pads are patterned on the electrodes using sputtering with a mask. The mask is carefully aligned to make sure the pads are just located in the bottom of these holes and directly connected with the electrodes (Figure 2(f)). Finally, the bottom glass layer is bonded to the stack (Figure 2(g)).

Figure 3. SEM image of the gap between the shell and electrode (gap size = 1.7 μm).
Figure 4. Photograph of a gyroscope chip (a) and a completed gyroscope chip wire bonded into a ceramic package (b).

Figure 4 shows a finished resonator chip (Figure 4(a)) fabricated using the proposed approach and a chip packaged in a ceramic package (Figure 4(b)). It shows clearly that the metal pads are just under the glass holes and attached to the electrodes firmly. Compared with the pads used in [7], the electrical connection is 100% successful in here. The pads fabricated using the method introduced in [7] often fail because of the break of the metal layer, which usually occurs at the corners between glass holes and silicon electrodes. Figure 5 is the SEM picture of the polysilicon hemispherical shell resonator whose 3-D curved electrodes are stripped away. The resonator is anchored to the pedestal created by the supporting electrodes, and the functional electrodes stretch into the cave deeply (about 160 μm), ensuring a large transduction area.

Figure 5. SEM micrograph of a 0.78 mm diameter hemispherical shell resonator whose electrodes have been stripped away.

4. Experimental results
A series of experiments have been performed to characterize the fabricated polysilicon hemispherical shell resonators, in which the resonator $n=2$ wine glass vibration is measured using laser vibrometer Ploytec MSA-500 and Zurich Instrument’s HF2LI lock-in amplifier respectively. The laser vibrometer testing setup is shown in Figure 6. The device is fixed in a sealed chamber and actuated using the power that supplied through the electrical wires. A glass window is located on the top of the chamber, so the laser beam can translate into and out of the chamber. The gyro chip is mounted on the platform using glue with an angle in order that the laser beam can be focused on the edge of the shell where the vibration is much more violent, and a strong signal can be obtained.
After the chamber is pumped to vacuum, the resonator is actuated using electrostatic force and vibration information is obtained. Figure 7(a) is the frequency response of a polysilicon shell with a diameter of 0.78 mm and a thickness of 1.8 μm at 0.9 Pa and room temperature. The frequency of the n=2 wineglass mode are at 28.012 kHz and 28.0146 kHz, the frequency split is 2.6 Hz (Δf_n=2 / f_n=2 = 0.009%). The Q factors of these two frequencies are 14365 and 11435 respectively.

Figure 7. The frequency spectrum of a polysilicon shell with a diameter of 0.78 mm and a thickness of 1.8 μm (a), and a shell with a diameter of 1.3 mm and a thickness of 1.5 μm (b).

Frequency sweeps of a polysilicon hemispherical shell resonator with a diameter of 1.3 mm and a thickness of 1.5 μm are obtained using a Zurich Instrument’s HF2LI lock-in amplifier. Figure 7(b) shows the frequency spectrum of the shell. The n=2 modes frequency are 13.649 kHz and 13.653 kHz respectively. The test is implemented at 0.02 Pa vacuum and room temperature, the driving voltage is 20 mV, the bias voltage is 400 mV. The as-fabricated frequency difference of these two modes is 4Hz (Δf_n=2 / f_n=2 = 0.03%) , which is larger than the one with a diameter of 0.78 mm. The main reason is that the symmetry of the shell is becoming difficult to be maintained in the fabrication process as the diameter increases.

The Q factor is measured in time domain by ring-down method. The ring-down time constant τ is related to the quality factor by Q = πτf. Time series data was exported to MATLAB for curve fitting to extract τ. A hemisphere ring-down time of 0.51 s (corresponding to a Q of 22000) at 0.01 Pa vacuum and room temperature is shown in Figure 8.
Figure 8. Ring-down plot of a polysilicon hemispherical shell resonator with a diameter of 1.3 mm and a thickness of 1.7 μm.

A prototype of the polysilicon hemispherical gyroscope has been successfully excited and sensed. The gyroscope without any trimming and tuning operates in an open loop mode. The measured scale factor is about 1.15 mV/°/s and bias instability (BS) is 80 °/h, as shown in Figure 9. The primal experimental results indicate a promising future of polysilicon hemispherical gyroscopes and motivate further research in improving the mechanical quality factor, optimizing the fabrication process, and improving the interface circuit.

Figure 9. Measured Allan variance stability of a prototype of the designed polysilicon hemispherical gyroscope.

5. Conclusions
Micromachined polysilicon hemispherical shell resonating gyroscopes with integrated three-dimensional curved capacitive electrodes are fabricated and experimentally analyzed. 3-D curved electrodes are integrated as a part of the hemispherical shell resonator fabrication process, and are manufactured in company with the shell resonator in the same process, no extra assembly process is needed. The fabrication process and materials used are compatible with the traditional semiconductor process, indicating the gyroscope has a high potential for mass production and commercial development. Without any trimming or tuning of the n=2 wineglass frequencies, a 28 kHz shell resonator demonstrates a 0.009% frequency mismatch between two degenerate wineglass modes, and a 13.6 kHz resonator shows a frequency split of 0.03%. The Q factor of a fabricated resonator is measured using ring-down method. The ring-down time is 0.51 s, corresponding to a Q of 22000, at
0.01 Pa vacuum and room temperature. The prototype of the gyroscope is experimentally analyzed, and the scale factor of the gyro is 1.15 mV/°/s, the bias instability is 80 °/h. The process may inspire new classes of high-performance MEMS devices for inertial sensor applications.

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