MICROMACHINED POLYCRYSTALLINE DIAMOND HEMISPHERICAL SHELL RESONATORS

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ABSTRACT
The hemispherical resonator gyro (HRG) is low loss and high stability, spurring recent interest in micro-scale hemispherical resonators. To achieve mode-matching and high-Q performance in a hemispherical resonator, geometric symmetry in combination with low thermoelastic damping structural material are critical. In this work, we describe the development of millimeter scale 3D hemispherical shell resonators fabricated from polycrystalline diamond, a material with low thermoelastic damping and very high stiffness. The relation between the fourth harmonic (4θ) and frequency mismatch (Δf) of the 20 elliptical vibration modes of the shell resonator is demonstrated.

KEYWORDS
Gyroscope, Electro Discharge Machining, Diamond, Microfabrication.

INTRODUCTION
The commercial hemispherical resonator gyro (HRG) is a high-precision and highly reliable solid state gyroscope that meets the inertial grade performance [1]. The topology of an axisymmetric shell mounted on a stem minimizes unwanted coupling to the base substrate and, along with the use of high-purity fused-quartz materials, results in high Q operation. By operating these structures in a rate integrating mode, the sensor can continue to integrate the applied rotation during power interruptions allowing for robust long-term operation.

These characteristics have spurred recent interest in the development of microscale HRGs that can be mass manufactured in a wafer scale level to achieve low-cost inertial grade sensors with a small volume and large dynamic range. To achieve mode-matching and high-Q performance in a hemispherical resonator, geometric uniformity and symmetry in combination with low thermoelastic damping structural material are critical. Many different methods such as wafer scale glass blowing [2], traditional silicon etching [3, 4] and integrating precision machining with standard silicon microfabrication [5, 6] have been employed to create 3D spherical or hemispherical shells. Materials such as polysilicon, and glass have also been used as the isotropic structural material for the shell itself.

In this work, we describe the development and characterization of millimeter scale 3D hemispherical shell resonators. Micro-electro discharge machining is first employed to fabricate the silicon mold from which the shell structure can be built. Using traditional silicon micromachining techniques to carry out the subsequent polish, deposition and release steps, we realized a 1 mm diameter 3D shell resonator. Polycrystalline diamond is used as the structural material due to its unique material properties such as high stiffness and low thermoelastic damping. The effect Si mold radius variation on frequency mismatch (Δf) of the 20 elliptical vibration modes of the shell resonator is studied both with FEM and experimentation.

FABRICATION OF HRG
Resonators are fabricated through a combination of micro electro discharge machining (EDM) and silicon micromachining techniques (Figure ). A low resistivity (0.008-0.2 Ω-cm), silicon substrate is first deposited with a metal hard mask. The 1 mm diameter hemispherical shell mold is then formed via EDM process, after which a HNA (HF/Nitric/Acetic acid) etch chemically polishes the inside surface of the machined hemispherical mold while the metal hard mask protects the top surface of the silicon substrate. Image analysis demonstrates that the finished shell mold exhibits high symmetry, having a radial standard deviation below 6 µm for a 500 µm radius shell [3] and a surface roughness of 4 nm measured at the inside of the silicon mold.

Figure 1: Fabrication process flow for creating CVD diamond hemispherical shell resonators.

After stripping the etch mask, a 2 µm thick SiO₂ sacrificial layer is grown conformally on the shell mold via CVD. The shell mold is then seeded using an ultrasonic seeding suspension containing nanocrystalline diamond powder with diameter from 5-50 nm. Using a methane (CH₄) concentration of 1.5% and a relative tetramethyl boron/CH₄ concentration of 444 ppm, a 1 µm
thick boron-doped diamond structural layer is deposited via hot-filament chemical vapor deposition (HFCVD, SP3 Diamond Technologies). A 5 µm thick plasma enhanced tetraethyl-orthosilicate (PE-TEOS) oxide layer is deposited to mask the topside of the wafer. PE-TEOS is selected to ensure conformal oxide mask coverage on the rough microcrystalline diamond surface. A chemical mechanical polishing (CMP) step (Strausbaugh) removes the oxide mask at a rate of ~3000Å/min from the wafer surface but retains the mask within the mold. Subsequent diamond plasma etching (SPTS Inc., APS etcher) is carried out to define the shell. Backside silicon and oxide etches are used to open the required hole for the anchor which is later filled with LPCVD Si3N4 to form the anchor. The diamond shells are released in 49% HF and the top surface of the silicon mold is etched back in HNA to facilitate non-contact optical characterization of the shell structure. SEM micrographs in Figure show an array of totally released 1 mm diameter hemispherical shells.

Figure 2: SEM micrograph shows an array of totally released diamond shells attached to the silicon substrate with LPCVD Si3N4 anchors.

**POLYCRYSTALLINE DIAMOND**

Thin-film polycrystalline diamond offers enhanced mechanical properties, including significantly higher stiffness, strength, hardness, thermal conductivity, and chemical robustness, versus silicon and most other thin-film materials commonly used in microfabrication technologies. The excellent strength to density ratio and diamond’s superior surface properties make this an ideal material for low surface losses and ultra-low thermoelastic damping, both significant properties required for a resonator.

In this work, the diamond film deposited during the HFCVD process is microcrystalline diamond (MCD). Through control of the deposition conditions, either micro- or nano-crystalline diamond (NCD) films can be deposited. The selection of MCD as the structural material is motivated by the higher sp³ content of the MCD films and reduced density of grain boundaries; both translate into the high Q-factors of 71,400 at 299.86 MHz for a diamond disk resonator [7] and 81,646 at 473.3 kHz for a diamond double ended tuning fork [8].

**TESTING AND CHARACTERIZATION**

Preliminary prototypes of the diamond hemispherical shell are characterized using a Laser Doppler Vibrometer (LDV) (Polytec) both in air and in vacuum. Figure (a) shows a schematic of the testing setup, where the diamond shell is mounted onto a glass substrate. Since the probe and shell resonator are in horizontal plane, the LDV laser spot is focused using a 45° prism on the shell rim to directly measure the displacement of the vibrating shell in air. The whole setup was also mounted in a vacuum probe station (MMR Technologies Inc.) to allow measurement at sub-mPa pressures. Figure (b) shows the laser spot focused on the shell rim in vacuum chamber.

![Vacuum Chamber](image)

Figure 3: (a) Schematic of the drive/sense method for the shell resonator (b) The mounted shell in vacuum chamber.

The resonator was excited electrostatically using a probe tip placed close to the shell rim and driven with an amplified AC voltage (Vpp ~25.4 V). The frequency response of the hemispherical shell in vacuum at 4.3 mPa is shown in Figure . Resonance peaks at \( f_1 = 18.316 \text{ kHz} \) and \( f_2 = 18.321 \text{ kHz} \), corresponding to the two 20 elliptical modes, were observed. The frequency mismatch between these two modes, an important parameter for resonating gyroscopes, is \( \Delta f/f = 0.03\% \).

![Frequency Response](image)

Figure 4: Measured frequency response showing the 20 elliptical modes with \( \Delta f=5 \text{ Hz} \) frequency mismatch in 4.3 mPa vacuum.

A ring-down test is performed in order to obtain the
decay time of the shell resonator in vacuum and confirm the measured $Q$ using a swept-frequency Network Analyzer (NA). The shell is excited at a single frequency of $f_0 = 18318$ Hz. The excitation stops and the vibration amplitude is recorded (Figure ). The decay time is 110 mSec ($Q \sim 6300$) which is approximately 10% lower than the $Q$ measured with swept spectrum measurements with NA.

![Figure 5: Ring-down test following excitation at $f_0 = 18318$ Hz ($\tau = 110$ mSec, $Q = 6300$ @4.3 mPa).](image)

**EFFECT OF RADIUS VARIATION**

The performance of a resonating gyro is affected by the frequency mismatch between the gyro’s two degenerate resonance modes which, in a ring, disk, or hemispherical gyro, are usually low-order 20 or 30 radial modes [1,4]. Mode-matching is particularly important in rate integrating gyros, where the frequency mismatch cannot be distinguished from an input rotation rate and mode-matching on the order of 0.01% (100 ppm) or better may be required to achieve sufficiently low bias error. In this work, the deviation from true circularity in the gyro’s hemispherical mold is one of the main sources of frequency mismatch ($\Delta f$). As a result, a quantitative understanding of the effects of these small deviations on natural frequencies and mode shapes of the shell resonator is essential.

Here we use an approach developed for ring gyros where Fourier analysis is used to study the impact of radial deviations on frequency mismatch [9-11]. In ring gyros, it has been shown that fourth harmonic radial deviations, $|r(40)|$, has the largest effect on the frequency mismatch of the 20 elliptical modes. To apply this result, Fourier analysis was performed on images of machined silicon molds used for hemispherical resonator fabrication. Image acquisition was carried out using a microscope with a 5X objective (Mitutoyo M Plan APO). A Matlab™ image processing code was developed to process the individual images and extract quantitative measurements of the finished features. Figure shows an optical image, where the red curve traces the actual rim and the blue, green and magenta lines show circles corresponding to the average, minimum and maximum radius of the mold, respectively.

![Figure 6: Quantitative evaluation of EDM top edge finishing before HNA polishing. The average, minimum, and maximum radius is 498.8 µm, 493.2 µm and 504.7 µm, respectively.](image)

FEM simulation (COMSOL™ Multiphysics) was used to model the frequency mismatch as a function of the amplitude of the fourth harmonic component $|r(40)|$. In order to generate the 3D shell geometry in SolidWorks®, a 2D circular profile was generated with desired $|r(40)|$ deviation which resemble the shell edge. Then, a quarter-circular arc was revolved about the rotation axis while sweeping along the 2D circular profile. Thickness of the shell (1 µm) was added to the generated shell surface and the final geometry is transferred to COMSOL™ for FEM analysis. Figure shows the linear relationship between $|r(40)|$ and frequency mismatch.

To verify the simulation results, three batches of resonators were fabricated using different processing conditions and Si wafer crystalline orientations in order to realize resonators with different levels of radius variation. For the EDM process conditions used for all batches, a rough operation was first applied with adequate energy setting to reduce electrode wearing (5µm ON time, 4 A current and 120 V), followed by finishing which used low energy setting (0 µm ON time, 1 A current and 90 V), in conjunction with electrode orbiting of 40 µm/side (EDM conditions are more described in [6]). Batch 1 used [100] wafers, while batches 2 and 3 used [111] wafers. In batches 1 & 2, the same electrode was used to EDM all features on a given wafer, whereas in batch 3 a new electrode was used to machine each mold. After fabrication and testing of the shells from each batch, a good correlation between FEM and experimental results was achieved (Figure ), showing that $|r(40)| = 100$ nm results in $\Delta f = 17$ Hz in air.
Figure 7: Measured and simulated frequency mismatch $\Delta f$ versus fourth harmonic of radius variation, $|r(4\theta)|$.

The main source of higher $|r(4\theta)|$ deviations (and as a result, higher frequency mismatch) in batch 1 is that the [100] wafers are etched anisotropically by the post-EDM HNA polishing etch (step 3, Figure ). Using [111] wafers rather than [100] wafers in batch 2 eliminated this problem, and the remaining asymmetry is only related to the EDM. Using one electrode per mold in batch 3 also improved the EDM process, improving overall symmetry, reducing $|r(4\theta)|$ and more than 5x reduction in frequency mismatch when compared to batch 2.

CONCLUSION

We developed 3D hemispherical-shaped microcrystalline diamond shell structures, and demonstrated the shells as mechanical resonators. Using a combination of EDM and silicon machining technologies, 3D axisymmetric hemispherical molds were created in silicon wafers. The silicon molds were subsequently used to form hemispherical resonators from high Q-factor microcrystalline diamond. The resulting diamond shells are characterized using electrostatic excitation applied through a probe tip and optical detection at the rim of the shell to determine the natural frequencies and mode shapes of the shell structure operating at the wineglass mode. Resonance peaks at $f_1 = 18.316$ kHz and $f_2 = 18.321$ kHz corresponding to the 2θ elliptical modes were observed, showing a frequency mismatch $\Delta f/f \sim 0.03\%$. The experimental results agree with the FEM simulation that the fourth harmonic $|r(4\theta)|$ of Si mold is linearly related to the frequency mismatch of the shell resonator.

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REFERENCE


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