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A Polysilicon Microhemispherical Resonating Gyroscope

Peng Shao, Curtis L. Mayberry, Xin Gao, Vahid Tavassoli, and Farrokh Ayazi

***Abstract*— This letter reports, for the first time, an integrated polysilicon microhemispherical resonating gyroscope (μHRG) with self-aligned drive, sense, and tuning electrodes, all fabricated using a single wafer process. The polysilicon hemispherical shell is 700 nm in thickness and 1.2 mm in diameter, resulting in a 1:3000 aspect ratio three-dimensional (3-D) microstructure. The quality factor of the wineglass mode is measured to be 8500 at 6.7 kHz with an as-fabricated frequency mismatch of 105 Hz between the two $m = 2$ degenerate modes. The modes are electrostatically matched and aligned using the tuning electrodes with a resulting mode-matched quality factor of 11 100. Initial characterization of the sensitivity of the μHRG shows a scale factor of 4.4 mV/°/s. [2014-0005]**

***Index Terms*— Gyroscopes, hemispherical shell resonator, microelectromechanical system (MEMS), mode matching, quality factor, frequency mismatch.**

I. INTRODUCTION

Successful fabrication and operation of micro-hemispherical shell resonators (μHSR) [1]–[4] have provided great potential for low-cost fabrication of integrated micro-hemispherical resonating gyroscopes (μHRG). Inspired by the macro-scale HRG, one of the most successful and widely used navigational gyro designs [5], μHRGs are aimed at low cost, high-performance microgyroscopes that offer higher levels of integration. The state-of-the-art micro-fabrication technologies used in MEMS inertial sensors enable miniaturization of the conventional HRGs to chip scale μHRGs. Similar to other MEMS axisymmetric gyroscopes, the operation is based on energy transfer between two degenerate resonance modes caused by the Coriolis effect. Therefore, matching the degenerate modes is essential to maximize the rate sensitivity through quality factor amplification of the transferred energy.

Axisymmetric structures such as ring [6], cylinder [7] and disk [8] have been successfully used for MEMS gyroscopes. The curved three dimensional structure of μHRGs allows low resonance frequencies (<10 kHz) at extremely small sizes compared to its planar counterparts [9]. It also has the potential of higher mechanical quality factor and higher degree of symmetry compared to the prior art, ring structures [6]. Furthermore, the structure is expected to demonstrate low stiffness, which would enable large reference vibration amplitudes with large capacitive gaps, resulting in an improved mechanical noise floor and sensitivity. A large electrostatic tuning range will be another outcome of the low stiffness of the μHRG structure.

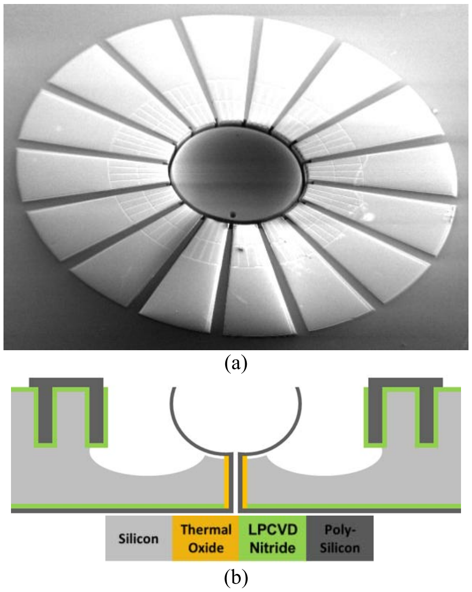

Fig. 1. (a) SEM image of a fabricated polysilicon μHRG. (b) Schematic illustration of a polysilicon μHRG with self-aligned polysilicon electrodes for driving and sensing the device.

This letter reports, for the first time, the rate gyro operation and characterization of a polysilicon μHRG with high quality factor and highly symmetric structure as a potential candidate for high performance MEMS gyroscopes. It is shown that with an open loop operation and a quality factor that has yet to reach its full potential, the device has strong rotation rate sensitivity. The ability to fabricate the μHRG with a small frequency split between the degenerate modes, and then to electrostatically tune the μHRG using integrated electrodes to align and match the two degenerate modes is also demonstrated. In section II the structure of the fabricated polysilicon μHRG is briefly reviewed. The resonator characterization is presented in section III, and then apreliminary gyro performance characterization is given in section IV.

II. POLYSILICON μHRG STRUCTURE

Fig. 1(a) shows a bird's eye view SEM of a fabricated polysilicon μHRG, and Fig. 1(b) illustrates schematically the cross-section of the device. It consists of a high Q polysilicon hemispherical shell resonator surrounded by 16 polysilicon electrodes for electrical driving, sensing and tuning. The electrodes are created by etching high aspect ratio trenches in a silicon wafer and then refilling them with a silicon nitride insulation layer and in-situ boron-doped polysilicon. A hemispherical shell is then created by isotropic etching of silicon, deposition of sacrificial and polysilicon layers and then removing the surrounding silicon and sacrificial materials [1]. In this process, the trenches for the electrodes and the openings for isotropic etching are defined by the same mask, thus the electrodes and hemispherical shell

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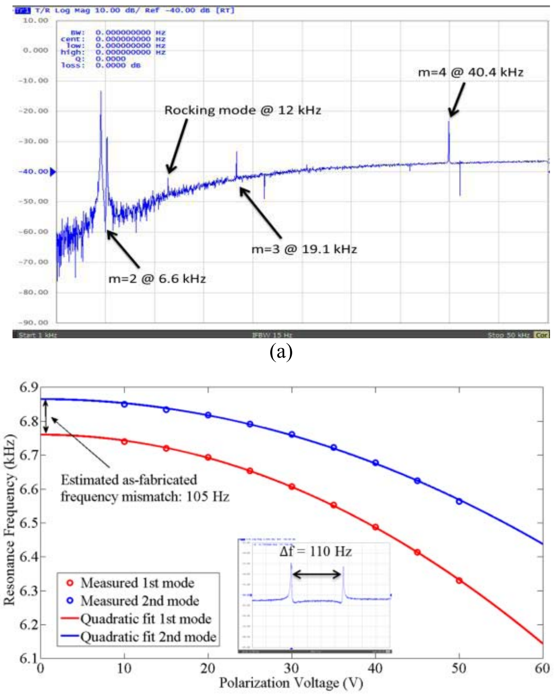


(a)

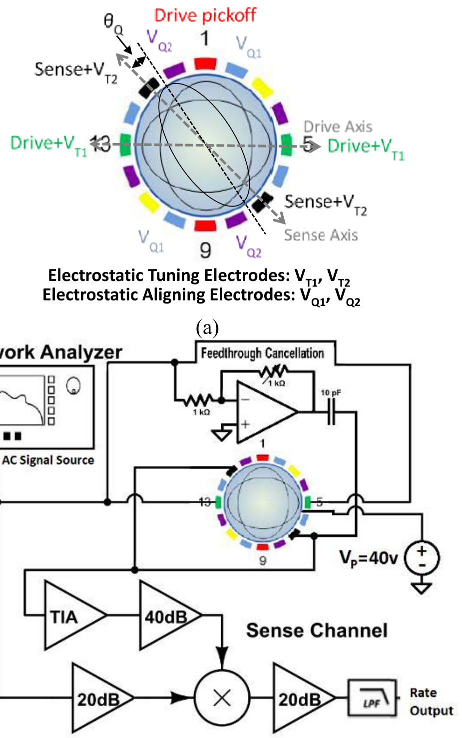
(b)

Fig. 2. (a) Frequency response of a polysilicon μHRG, showing different resonance modes. (b) Tuning curve of both modes, the as-fabricated frequency mismatch between the m=2 degenerate modes is estimated to be 105 Hz by quadratic curve fitting. The inset shows the measured frequency mismatch of 110 Hz at polarization voltage of 10V.

are self-aligned. The depth of the polysilicon electrodes is 300 μm and is scalable to improve the efficiency of capacitive transduction and robustness of the electrode structure during release. The gap size between the electrodes and the hemispherical shell is 20 μm to enable drive vibration amplitude of a few micrometers. A hole is also etched through from the backside to allow a DC bias to be applied to the hemispherical shell.

III. RESONATOR CHARACTERIZATION

The fabricated μHRG is mounted on an evaluation board and wirebonding is performed on the polysilicon electrodes. Resonator performance is characterized using a network analyzer (E5061B) while the board is placed inside a vacuum chamber with ∼5 μTorr vacuum pressure. Figure 2(a) shows the resonance peaks of the m=2, m=3, m=4 elliptical modes, and the rocking mode for a polysilicon μHRG with a shell thickness of 700 nm and a shell diameter of 1200 μm. The m=2, m=3 and m=4 resonances are measured to be at 6.7 kHz, 19.1 kHz and 40.2 kHz with quality factor 8,500, 7,000, and 10,400, respectively. Fig. 2(b) shows the electrostatic tuning curve of two degenerate m=2 modes. Polarization voltage is applied on the hemispherical shell from 10V to 50V. By quadratic curve fitting, the as-fabricated frequency mismatch without any tuning effect is estimated to be 105 Hz with $\Delta f/f = 1.56\%$. In the current polysilicon μHRG design, the m=2 mode is selected as the working resonance modes due to its low resonance frequency and small frequency mismatch. The m=2 resonance mode shows a quality factor of 8,500. The measured quality factor does not represent its limit for a polysilicon μHRG, which is believed to be in the hundreds of thousands. A thermoelastic damping (TED) analysis shows much lower material dissipation (Q_{TED} ∼1 million), so there is room for Q optimization and improvement. Current device Qs are believed to be limited by surface roughness and anchor loss. Due to the extremely small stiffness of this structure (∼1N/m), the drive amplitude can be as high as a few micrometers with large capacitive gaps of 20 μm. Nonlinearity of resonance peaks can be easily observed if input RF power exceeds −20 dBm. COMSOL multi-physics simulation confirms that with an RF power of −24 dBm and a DC polarization voltage of 26 V, drive vibration amplitude of 3 μm can be achieved. The testing results demonstrate a highly symmetrical hemispherical shell resonator with high quality factor that shows promise to be a high performance μHRG.



(a)

(b)

Fig. 3. (a) Schematic illustration of the tuning electrodes and the position of the two modes before mode matching and balancing. θ_Q represents the angle of the misalignment of the sense mode before the electrostatic alignment of the modes. After electrostatic alignment the sense mode would be aligned with the sense axis. (b) Rate measurement circuit architecture.

IV. PRELIMINARY GYRO CHARACTERIZATION

Preliminary gyroscope characterization is performed on the same polysilicon μHRG measured in the previous section. Mode matching and balancing of the gyroscope is performed using the approach described in [10]. As Fig. 3(a) shows, two sets of tuning electrodes (V_{T1}, V_{T2}) and two sets of balancing electrodes (V_{Q1}, V_{Q2}) are used. Tuning electrodes for the drive mode and sense mode are at the anti-nodes of both the drive mode and sense mode, respectively. Balancing or aligning electrodes that are at 22.5º to the drive anti-nodes and its equivalent position align the resonance modes with their principal axes. Fig. 4(a) shows the two peaks as their being matched with 27 Hz and 5 Hz frequency split, and Fig. 4(b) shows the mode matched resonance peak with an effective quality factor of 11,100.

The mode-matched polysilicon μHRG is operated in an open loop configuration as shown in Fig. 3(b) by exciting the drive mode using an external sinusoidal signal at the exact resonance frequency and an RF power of −35 dBm. The device is polarized at 40V. The Coriolis-induced signal is then processed by a transimpedance amplifier (TIA) with a gain of 500kΩ and post amplification of 60 dB.

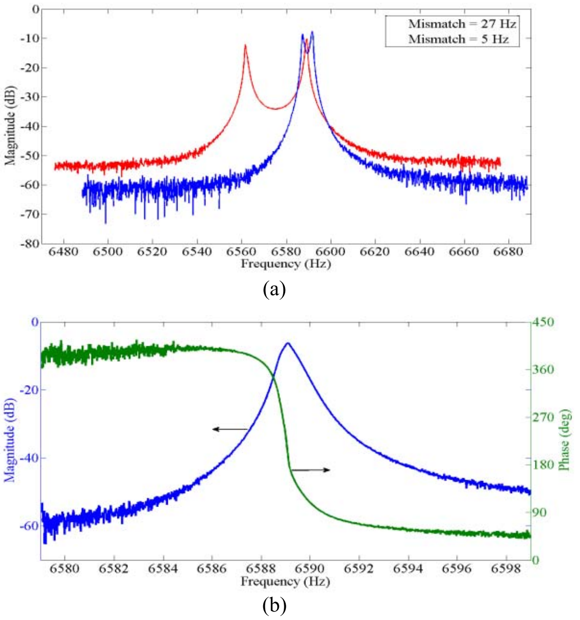


Fig. 4. A polysilicon μHRG with thickness of 700 nm and a diameter of 1.2 mm (a) shows the two peaks as their being matched with a 27 Hz and 5 Hz frequency split; (b) shows mode matching at 6.6 kHz with an effective quality factor of 11,100. Tuning and balancing are done by the polarization voltage and four sets of tuning and balancing electrodes.

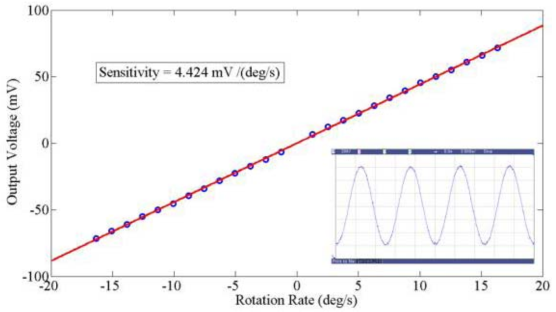


Fig. 5. Output voltage as a function of rotation rate, showing a sensitivity of 4.4 mV/(°/s). (inset) Rate output by running rate table at 200 mHz with a 14°/s rotation rate.

After demodulation with the drive signal and low-pass filtering, the rotation rate information can be detected. The vacuum chamber is mounted on a rate table with a vacuum hose connected to the pump. The rate table is programmed to run at 200 mHz with an incremental rotation amplitude for different rotation rates. Fig. 5 inset demonstrates the transient response to a 14°/s rotation rate measured using an oscilloscope. It shows a very clean and linear sinusoidal output. Sensitivity is also measured by applying a rotation rate of up to 16°/s. By linear regression, the scale factor of the polysilicon μHRG is extracted to be 4.4 mV/(°/s). The preliminary characterization demonstrated a polysilicon microscale hemispherical resonating gyroscope working in rate mode. This motivates further research in improving the mechanical quality factor, decreasing the noise level, optimizing the fabrication process, and improving the interface circuit.

V. CONCLUSION

This letter introduces a batch fabricated polysilicon hemispherical resonating gyroscope that works in rate mode. The gyroscope is operated under a mode-matched condition at 6.6 kHz with an effective quality factor of 11,100. Open loop operation of a mode-matched polysilicon μHRG demonstrates a sensitivity of 4.4 mV/(°/s). Further improvement of the quality factor will make the device suitable for operation in whole angle mode.

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