THE RESONATING STAR GYROSCOPE

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ABSTRACT

This paper introduces the Resonating Star Gyroscope (RSG), a new vibratory shell-type structure for rate sensing. The structure formed as a merged superposition of two square shells, yields in-plane degenerate flexural modes that are used to sense z-axis rotation. A high aspect ratio polysilicon implementation utilizing the primary degenerate flexural modes of the gyroscope exhibits an open-loop rate sensitivity of 1.6mV/°/s. The Brownian noise floor of the sensor with a quality factor (Q) of 1500 and drive amplitude of 100nm is 0.03°/s/√Hz. The RSG may also function at higher-order flexural modes. A single crystal silicon design explores such an operation. Preliminary characterization results yield matched-mode operation and very high-Q higher-order degenerate flexural modes (Q~100k).

1. INTRODUCTION

Low power vibratory microgyroscopes are needed in numerous consumer applications due to their small size, low power and ease of fabrication. Vibratory gyroscopes, which are based on transfer of energy between two vibration modes of a structure, can operate in either *matched-mode* or *split-mode* condition. Under *matched-mode* condition, the sense mode is designed to have the same (or nearly the same) resonant frequency as the drive mode. Hence, the rotation-induced Coriolis signal is amplified by the Q of the sense mode (which can be high in vacuum). In *split-mode* condition, the drive and sense modes are separated in resonant frequency. Due to Q amplification, gyroscopes operated under matched-mode configuration offer higher sensitivity and better resolution. Resonant matched devices are themselves broadly classified into two types depending upon the nature of their operating modes. *Type I* devices rely on *non-degenerate* vibration modes for driving and sensing. The tuning fork gyroscope is an example of a type I gyroscope. As reported in [1] it is often difficult to achieve and maintain mode matching in these devices. *Type II* devices on the other hand function with *degenerate* vibration modes and are invariably easier to match and operate under matched condition. A shell type gyroscope such as the vibrating ring gyroscope [2] is an example of a type II gyroscope. In this work, a novel type II resonant matched vibratory gyroscope is introduced and characterized.

2. THE STAR GYROSCOPE DESIGN

As illustrated in Fig. 1, the star gyroscope can be visualized as a merged superposition of two identical square shells that are spatially 45° apart. This ensures pairs of degenerate flexural vibratory modes in the resulting eight-fold star shell, which is anchored to a central post through flexural springs. Eight optimally designed springs are necessary to maintain degeneracy of the resonant modes. Rotation-induced Coriolis acceleration causes energy to be transferred between two flexural modes of any degenerate resonant pair. The nodes of each mode are located at the anti-nodes of its degenerate counterpart. The schematic diagram of the RSG is illustrated in Fig. 2.

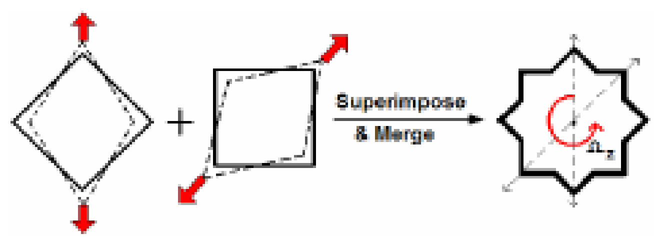

Figure 1: Concept illustration of the star gyroscope

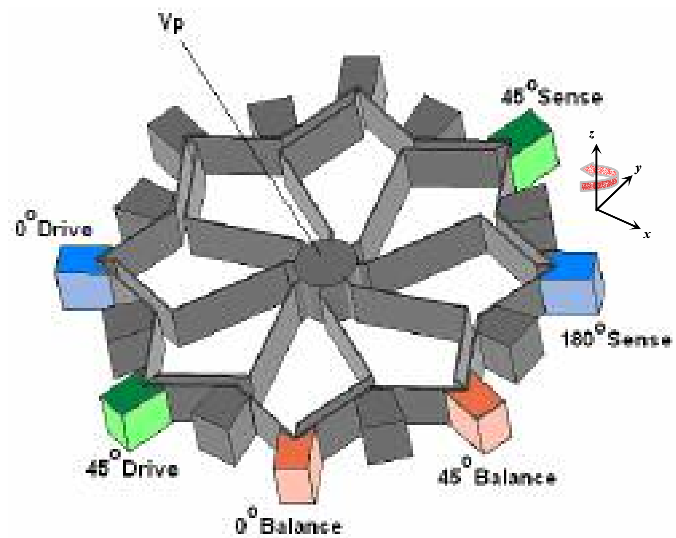

Figure 2: Schematic diagram of the resonating star gyroscope.

The star gyroscope is a fully symmetric and balanced structure that offers differential sensing capability. The shell is surrounded by capacitive drive, sense and balancing electrodes. Electrode placement schemes enable frequency matching of both primary and higher-order flexural modes.

The primary degenerate modes shown in Fig.3 are analogous to the elliptical mode shapes observed in the vibrating ring gyroscope [2]. The star is electrostatically driven into resonance at the primary flexural mode. When the device is subjected to rotation, Coriolis force causes energy to be transferred to the secondary degenerate mode located 45° away. This consequential motion is sensed capacitively at the sense electrodes.

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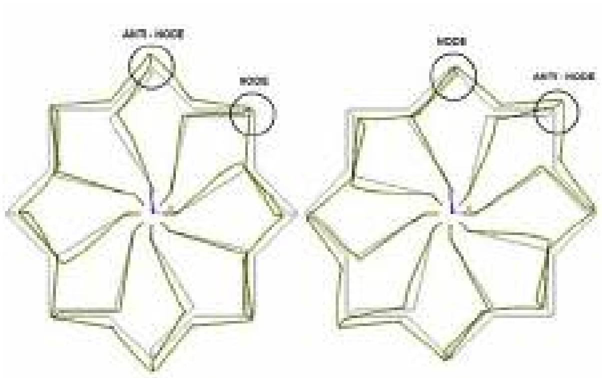


Figure 3: Primary degenerate flexural modes of RSG (Mode shapes have been exaggerated for clarity)

HARPSS Implementation

Figure 4 illustrates the essential steps of the HARPSS fabrication process flow [3] used to fabricate thick polysilicon versions of the RSG.

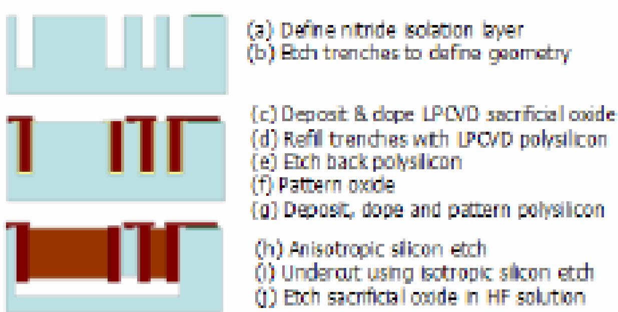


Figure 4: Fabrication process flow for polysilicon RSG.

Mechanical structures are created by refilling trenches with polysilicon deposited over a sacrificial oxide layer. The structural polysilicon layer is doped to make it conductive. Silicon sense electrodes as tall as the ring structure are released from the substrate using a two-step dry release process.

SEM pictures of fabricated 1mm diameter, 65µm thick HARPSS RSG can be viewed in Fig. 5(a). High aspect ratio actuation gaps are shown in Fig. 5(b). These small capacitive gaps (1µm) enable low voltage operation of the gyroscope.

Primary Degenerate Mode Operation

A prototype polysilicon RSG was tested open loop under vacuum. A sinusoidal drive signal was applied at the drive electrode and output signals, monitored at the 0˚ and 45˚ electrodes, were amplified using external amplifiers. The primary flexural mode frequency of the prototype device was measured to be 39.6 kHz which is in agreement with ANSYS simulations. Electronic tuning allows compensation of any fabrication imperfections that may cause a frequency separation (~ 100 – 400 Hz) between the two degenerate resonant modes. Frequency splits as great as 430 Hz have been matched by applying less than 11V tuning voltages to the balancing electrodes which are located 90˚ from the primary drive and sense electrodes. Figure 6 illustrates the two modes before and after balancing. After balancing, the two peaks merge together and the sense and drive mode frequencies become equal.

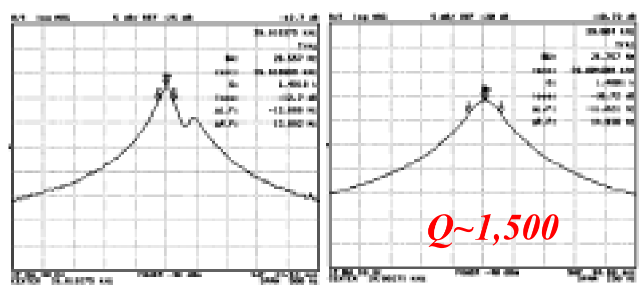
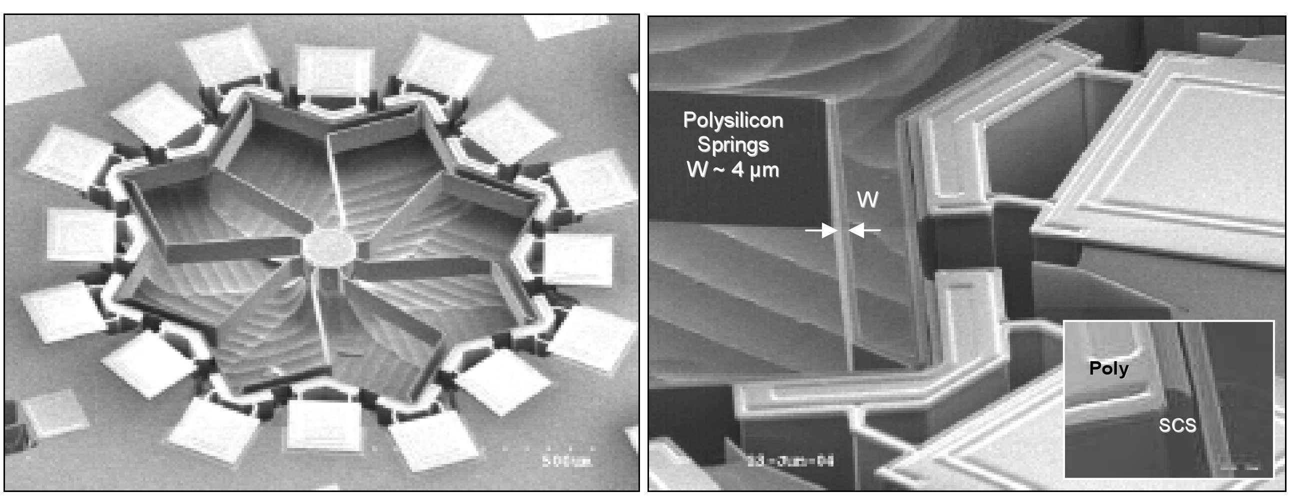


Figure 6: Electronic balancing: (Left) Before balancing the two flexural modes are 50Hz apart. (Right) After balancing the two peaks are merged together and frequencies are equal.



(a) *(b)*

Figure 5(a): SEM of a HARPSS 1mm diameter 65 µm thick polysilicon RSG. Figure 5(b): View of SCS electrodes (Inset) Close-up of the 1µm sense/actuation gap defined through sacrificial oxide.

Rate test from the polysilicon RSG under matched operation yields an open-loop sensitivity of 1.6mV/°/s using discrete PCB electronics ($C_{parasitics}$ ~ 5pF), as shown in Fig. 7. The measured Q of 1mm, 65µm-thick polysilicon RSG was 1500 under matched mode operation. This low Q-factor is attributed to anchor and bulk TED losses (voids inside poly) [4] and can be improved by optimizing the design. At present, the maximum measured bias drift after 2 hours was less than ±0.3˚/s.

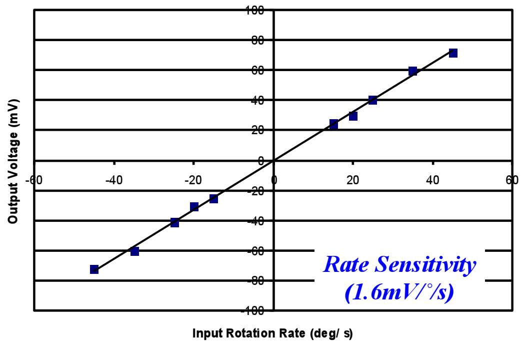


Figure 7: Measured rate results obtained from the polysilicon RSG indicates a rate sensitivity of 1.6mV/°/s.

Table 1: Specifications of 1mm polysilicon RSG.

Device Parameter	Value
Primary flexural mode frequency	39.6 kHz
Drive amplitude	100 nm
Polarization voltage	4.8 V
0˚ / 45˚ Balancing voltages	- 6.6 V / 11 V
Quality factor	1500
Mechanical resolution	0.03 ˚/s/√Hz
Rate sensitivity	1.6 mV/°/s
Measured bias stability	< 0.3 °/s

A single crystal silicon (SCS) implementation of the current design will significantly improve the quality factor which has been verified by an SOI version.

3. HIGHER-ORDER DEGENERATE MODE OPERATION

The pair of higher-order degenerate modes, shown below, may also be used to detect rotation. In this degenerate pair the nodes and antinodes are located 90˚ apart.

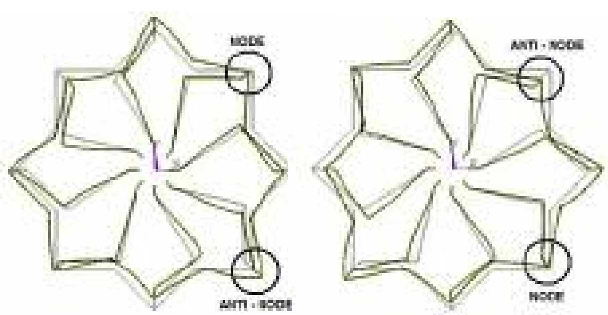


Figure 8: Higher-order flexural modes of RSG (Mode shapes have been exaggerated for clarity)

In order to increase sensitivity and achieve better rate resolutions, it is imperative for the degenerate flexural modes to have high quality factors, greater drive amplitudes and larger mass. In an effort to achieve this, a SCS implementation of the RSG was considered. A high Q of 47,000 was measured for the primary flexural mode. However, due to the anisotropic nature of (100) SCS substrate, the primary drive and sense flexural modes occur 3.6 kHz apart (as predicted by ANSYS and verified experimentally). This is almost impossible to tune electrostatically. The use of (111) silicon wafer is an alternative [5], but cost intensive. An interesting solution is to operate the device using its higher-order degenerate flexural modes. As predicted by ANSYS these higher-order degenerate modes occur within close proximity of one another (<1 kHz) and may be tuned electronically.

Single Crystal Silicon Implementation

SCS RSGs were fabricated on 40µm thick low resistivity SOI. SEM pictures of fabricated 1mm, 40µm thick SCS RSG can be viewed in Fig. 9. Actuation gaps between the electrodes and the vibrating shell is defined through DRIE trench etching step and is therefore aspect ratio limited.

The higher-order flexural mode frequency of the prototype device was observed at 49.2 kHz as predicted by ANSYS simulations. Frequency split between the two secondary flexural modes is compensated using a similar scheme described to tune the primary order flexural modes of the polysilicon RSG. Figure 10 shows the two resonant modes before and after balancing.

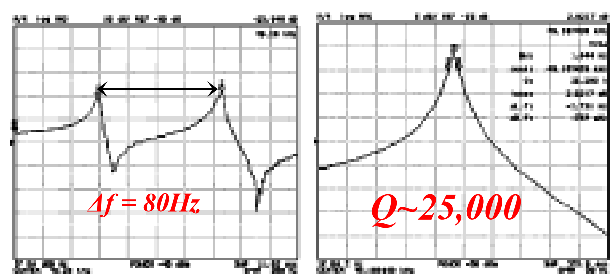
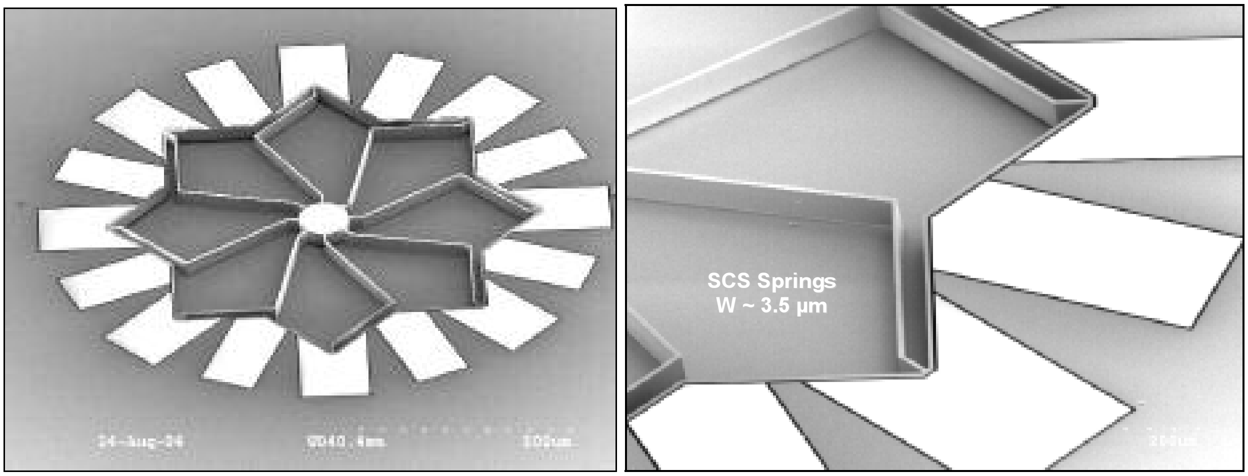


Figure 10: Electronic balancing: (Left) Before balancing Frequency split of the secondary flexural mode is 80Hz. (Right) After balancing Matched operation w/ Q~25k.

Wider capacitive gaps (3µm) reduce device capacitance and consequently increases required operating voltages. Polarization and balance voltages (to compensate 330Hz frequency split) for the SCS RSG are 20V and 26V respectively. Table II summarizes the key parameters of the SCS implementation of the RSG. Subsequent testing of other SCS RSG devices have yielded quality factors in excess of 100,000 for these higher-order degenerate modes (Fig. 11).



(a) *(b)*

Figure 9(a): SEM view of 1mm diameter 40µm thick SCS RSG. Figure 9(b) DRIE trench-defined 3µm sense/actuation gap.

Table II: Specifications of 1mm SCS RSG.

Device Parameter	Value
Flexural mode frequency	49.2 kHz
Drive amplitude	300 nm
Polarization voltage	20 V
0˚ / 45˚ Balancing voltages	22 V / -26 V
Quality factor	25000
Temperature Coeff. Factor (TCF)	-23 ppm/˚C
Expected mechanical resolution	8.5 ˚/h/√Hz

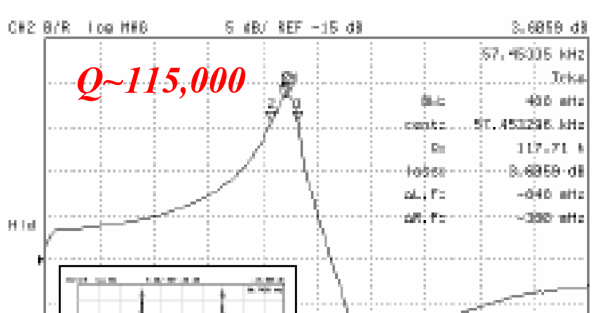


Figure 11: High-Q higher-order flexural mode (Inset) Pair of degenerate higher-order flexural modes.

4. Conclusions And Future Direction

This paper introduces the resonating star gyroscope. Two modes of operation are presented using two distinct fabrication processes. The polysilicon HARPSS implementation of the RSG was used to demonstrate the primary degenerate mode operation. The HARPSS fabrication process facilitated high-aspect ratio sense and actuation gaps. This increased the sensitivity and enabled operation at low voltages. The polysilicon RSG demonstrated a sensitivity of 1.6mV/˚/s and has a Brownian noise floor of 0.03º/s/√Hz. The SCS SOI implementation of the RSG verified higher-order degenerate mode operation. High-Q and higher frequency resonant modes were achieved in this implementation which improves the Brownian noise floor. The theoretical Brownian noise floor for the SCS RSG is 8.5º/h/√Hz.

Type II shell gyroscopes suffer from low mass per-unit area. By designing for high-Q and higher operating frequency it is possible to alleviate the mass requirements and achieve high resolution. Current effort is focused on a SCS HARPSS implementation of the RSG. By consolidating the positives of both approaches it is possible to achieve resolutions better than 1º/h/√Hz while substantially reducing the operating voltage and power.

Acknowledgements

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