THE RESONATING STAR GYROSCOPE
M.F. Zaman, A. Sharma, B.V. Amini, and F. Ayazi
Integrated MEMS Laboratory
Georgia Institute of Technology, Atlanta, Georgia, USA

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/º/s. The Brownian noise floor of the sensor with a quality factor (Q) of 1500 and drive amplitude of 100nm is 0.03º/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 microgyrosopes 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 45º 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 45º away. This consequential motion is sensed capacitively at the sense electrodes.
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 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.

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.
Rate test from the polysilicon RSG under matched
operation yields an open-loop sensitivity of 1.6mV/º/s
using discrete PCB electronics ($C_{parasitics} \approx 5pF$), 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/º/s.

In order to increase sensitivity and achieve better rate
resolutions, it is imperative for the degenerate rate flexural
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 utilize 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.

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

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

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).

<table>
<thead>
<tr>
<th>Device Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary flexural mode frequency</td>
<td>39.6 kHz</td>
</tr>
<tr>
<td>Drive amplitude</td>
<td>100 nm</td>
</tr>
<tr>
<td>Polarization voltage</td>
<td>4.8 V</td>
</tr>
<tr>
<td>0º / 45º Balancing voltages</td>
<td>- 6.6 V / 11 V</td>
</tr>
<tr>
<td>Quality factor</td>
<td>1500</td>
</tr>
<tr>
<td>Mechanical resolution</td>
<td>0.03 º/s/Hz</td>
</tr>
<tr>
<td>Rate sensitivity</td>
<td>1.6 mV/º/s</td>
</tr>
<tr>
<td>Measured bias stability</td>
<td>&lt;0.3 º/s</td>
</tr>
</tbody>
</table>

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 90º apart.

![Figure 8: Higher-order flexural modes of RSG (Mode shapes have been exaggerated for clarity)](image)
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 1.6 mV/°/s and has a Brownian noise floor of 0.03°/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 8.5°/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 1°/h/√Hz while substantially reducing the operating voltage and power.

ACKNOWLEDGEMENTS

This work is supported under the DARPA HERMIT program. The authors wish to thank the staff at the Georgia Tech’s Microelectronics Research Center for their support.

REFERENCES