A High-Q In-Plane SOI Tuning Fork Gyroscope

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Abstract

This paper presents the design and implementation of an in-plane solid-mass single-crystal silicon tuning fork gyro that has the potential of attaining sub-deg/hr rate resolutions. A design is devised to achieve high Q in the drive and sense resonant modes (Q_{drive}=81,000 and Q_{sense}=64,000) with effective mode decoupling. The gyroscope was fabricated on 40µm thick Silicon-on-Insulator (SOI) using a simple two-mask process. The drive and sense resonant modes were balanced electrostatically to within 0.07% of each other and the measured rate results show a sensitivity of 1.25mV/°/s in a bandwidth of 12Hz.

Keywords

Tuning Fork, Gyroscope, High-Q, Silicon-on-Insulator

INTRODUCTION AND MOTIVATION

Vibratory micromachined gyroscopes rely on the Coriolis induced transfer of energy between two vibration modes to sense rotation. Micromachined gyroscopes are increasingly employed in numerous consumer and automotive applications, primarily due to their small size and low power. However, they are yet to achieve performance levels comparable to their optical and macro-mechanical counterparts in high-precision applications such as space and tactical/ inertial navigation.

The requirements for inertial grade devices are rate resolutions and bias stabilities better than 0.1°/h. The Brownian motion of the structure represents the fundamental noise-limiting component of a vibratory gyroscope [1]. By equating the Brownian motion to the displacement caused by the Coriolis force, one can derive the mechanical noise equivalent rotation (*MNEΩ*) of the microgyro. This is expressed as

$$MNE\Omega = \frac{1}{2q_{Drive}} \cdot \sqrt{\frac{4k_B T}{\omega_0 M}} \sqrt{BW} \qquad (1)$$

Eq. 1 indicates that the mechanical noise floor varies inversely with both, the drive amplitude (q_{Drive}), the square root of the resonant drive frequency (ω_0), and square root of the effective mass in the sense direction (*M*). Matching the resonant frequencies of the sense and the drive mode improves this resolution by a factor of $\sqrt{Q_{Sense}}$.

Therefore, to achieve sub-deg/hr rate resolutions, a vibratory gyroscope must attain very high quality factors (>30,000), large sense capacitances (>1pF), large proof mass (>100µg) and large drive amplitude (>5µm) [2,3]. This calls for innovative designs and radical advances in fabrication technology. In an effort to reach this goal, we have introduced an in-plane, solid-mass silicon tuning fork device that incorporates very high Q, large proof mass per unit area, and in-plane operation within a single framework – unlike previously reported tuning fork gyroscopes (TFG) [4,5].

DESIGN

The operating principle is based upon a standard tuning fork's response to rotation. In this design (see Fig.1) the proof-masses are driven at resonance along the x-axis, and the Coriolis acceleration induced by rotation around the z-axis is sensed capacitively along the y-axis.

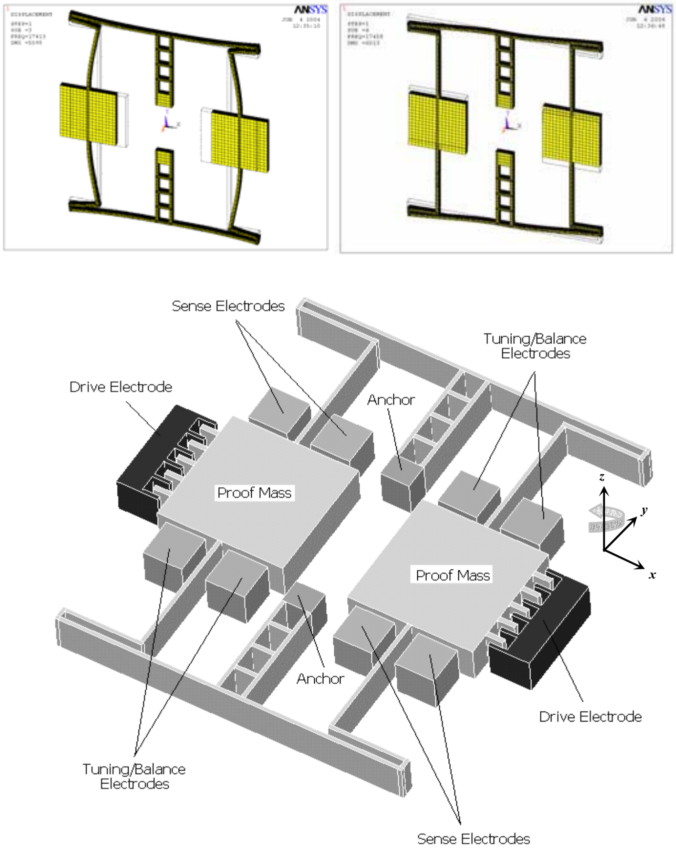

Figure 1. Schematic diagram of the gyroscope and resonant mode shapes as simulated in ANSYS® (exaggerated for clarity).

A major incentive in utilizing this symmetric tuning fork architecture as opposed to a frame-design or single-mass design [6] is the differential sensing capability. As a result, linear acceleration/shock signals are rejected as “common mode” without the need for complex electronics. The spring structure design makes it possible to drive the solid proof masses linearly with displacement amplitudes in the range of 4-6μm. A high Q in the drive mode is necessary to get large drive amplitudes using small drive voltages – a highly desirable feature required in low-power CMOS interfacing. A high Q in the sense mode is imperative to substantially increase sensitivity of the device and also lower the Brownian noise floor of the gyroscope. The anchor and the flexures were carefully designed to ensure minimal support loss and consequently high Q in the drive and sense modes through torque cancellation/reduction. Support loss [7] is the primary energy loss mechanism that leads to Q degradation.

FABRICATION

The prototype structures were fabricated on 40μm thick SOI wafers. SEM pictures of a fabricated device are shown in Figure 2.

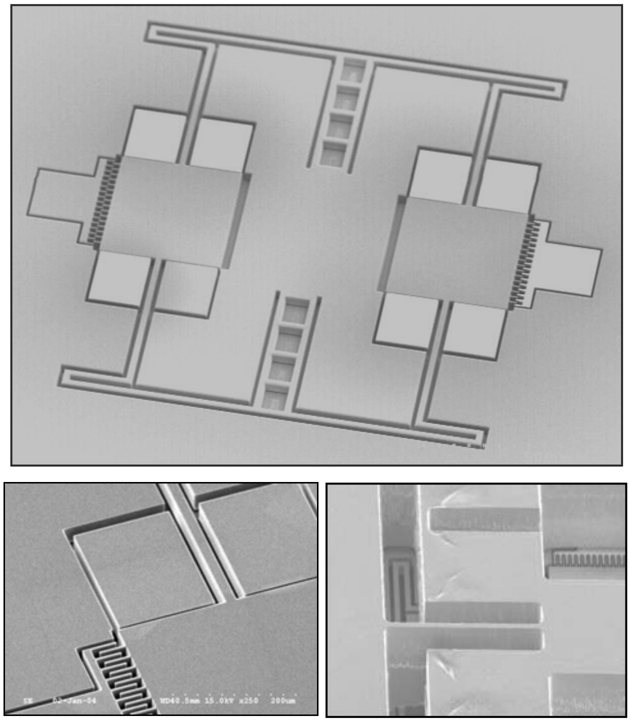

Figure 2. (Clockwise from top) In-Plane Solid-Mass Silicon TFG, support posts for anchor as seen from back-side, and close-up of 6μm comb & 2.5μm sense gaps.

The fabrication flow is shown in Figure 3. The moving sections of the structure and the areas under the comb drives are first released from the backside of the wafer by etching the handle silicon layer through to the buried oxide layer using the Bosch process [8]. The buried oxide is then removed in a reactive ion etching (RIE) system and finally the top layer is patterned all the way through, leaving behind a suspended structure whose anchors are supported to the handle substrate via several support posts. The final etch step involves a quick HF etch to release areas under these supports.

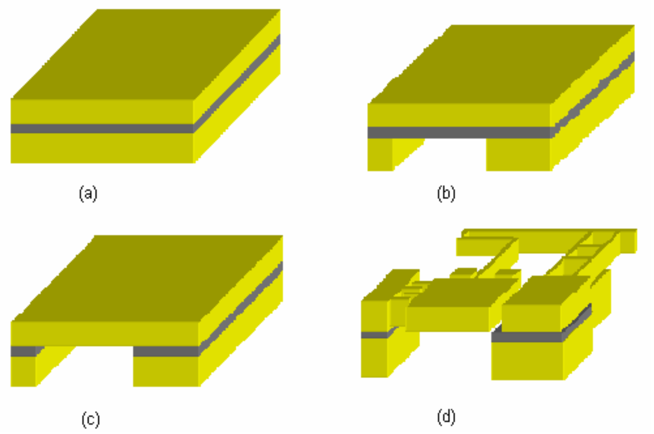

Figure 3. Fabrication process flow (a) 40μm thick SOI substrate (b) back-side etch (c) buried oxide etch and (d) top-side patterning and release.

The proposed fabrication process is very simple and precludes the requirement of any perforations in the proof mass, resulting in a larger mass per unit area. The simultaneous elimination of the ground plane under the comb drives prevents the excitation of the out of plane modes and detrimental effects of levitation.

EXPERIMENTATION

A prototype device was tested in vacuum and high Q operation was confirmed. Figure 4 shows the measured drive and sense resonant modes respectively with high Q values (~ 81,000 for drive and ~ 64,000 for sense).

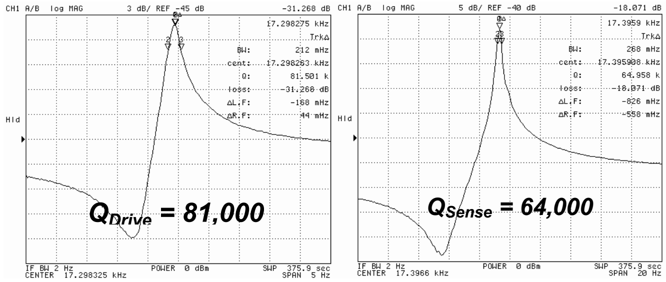

Figure 4. Measured drive and sense resonant modes.

As discussed earlier, such high Q’s are essential to achieve inertial grade performance in a small bandwidth. Larger bandwidth can be obtained by operating the device in closed loop at the expense of sensitivity.

Figure 5 shows the tuning characteristics of the sense resonant mode. This mode shows a variation of approximately – 1600 ppm/ V over a tuning voltage range of 20V. The tuning characteristics are crucial to obtain matched operation – which in turn is necessary to lower the Brownian noise floor.

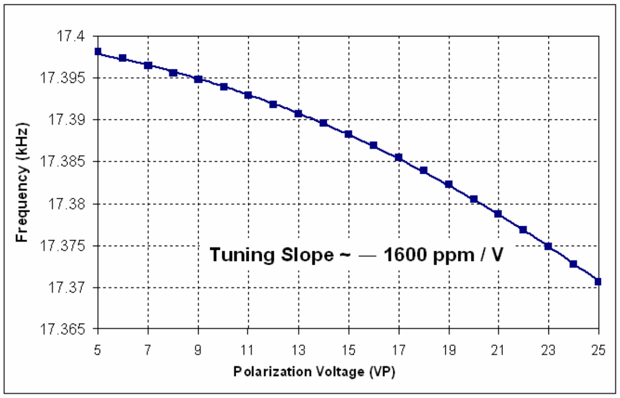

Figure 5. Variation of the sense resonant mode frequency as a function of the polarization voltage, V_P

From an initial separation of about 65 Hz, the drive and sense frequencies were matched to within 0.07% (12Hz over 17.38kHz) of each other (see Figure 6).

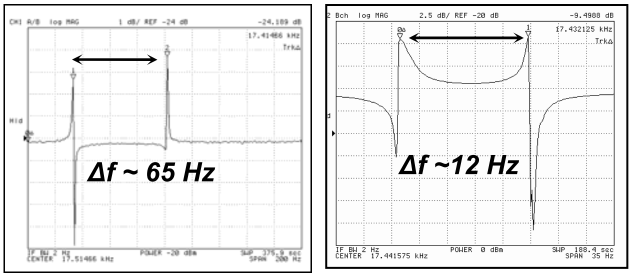

Figure 6. The resonant modes have been matched to within 12 Hz of each other.

Figure 7 below shows the measured temperature variation of the drive resonant frequency for a second tuning fork gyroscope with slightly different flexural widths. The drive mode temperature coefficient of frequency (TCF) is measured to be about – 22 ppm/ºC which is in agreement with the values reported in [9] for SCS resonators. The sense resonant mode also shows a similar TCF implying that mode matching can be maintained over temperature. Also, a single temperature compensation circuit will suffice to maintain mode matching over temperature.

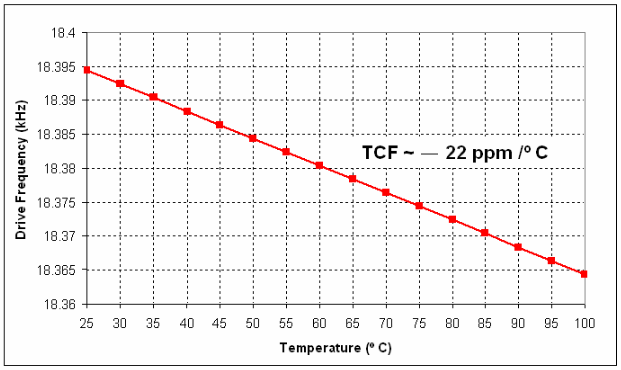

Figure 7. Temperature variation of the drive resonant frequency showing a TCF of – 22 ppm/ ºC.

Despite an optimized, mechanically decoupled design, in practice, fabrication imperfections can lead to non-zero off-diagonal elements in the spring stiffness and damping coefficient matrices [10] resulting in an undesirable zero-rate output (ZRO). This quadrature error prevents close matching of the drive and sense resonant modes [10]. Inertial grade performance requires that the high Q resonant modes be matched. This lowers the Brownian noise floor by a factor of $\sqrt{Q_{sense}}$ [2]. The Brownian noise floor is an order of magnitude greater than the electronic noise floor and is therefore the key factor in determining the resolution of the gyroscope. Additionally, any mismatch is undesirable as it reduces the sensitivity and makes it a function of the frequency of the input rotation signal.

Figure 8 shows the schematic of the set-up used to test the gyroscope. There are two resonant modes that occur along the x-axis. The first resonant mode involves the proof-masses vibrating along the same direction (*pseudo-drive mode*). The second resonant mode, which we have defined earlier as drive, involves the proof-masses vibrating along opposite directions. These two modes correspond to the symmetric and anti-symmetric modes of a tuning fork. This *pseudo-drive* mode has been designed to occur 300 Hz below the actual *drive* mode. Filtering this mode out electronically places stringent specifications on the filter characteristics and is not amenable to CMOS integration. However, this mode can be effectively suppressed by applying the sinusoidal drive signal to both the comb-drives simultaneously.

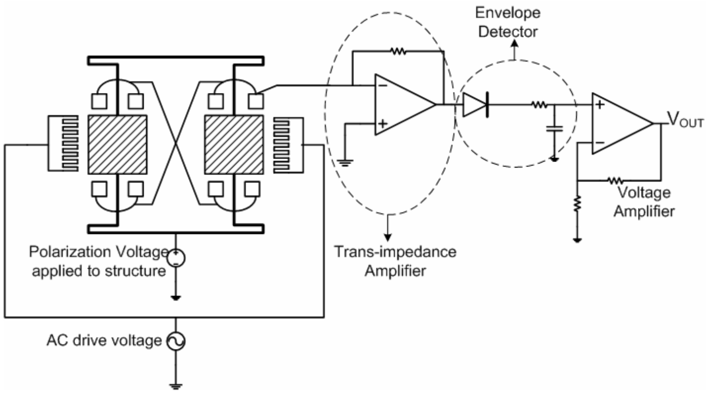

Figure 8. Test set-up used to measure the open loop characteristics of the gyroscope.

The sense electrodes have been cross-coupled so as to obtain a greater change in sense capacitance, and therefore a greater signal output. The tuning voltages are applied separately though an external DC power supply to electrostatically balance the drive and sense resonant modes. The coriolis response is sensed using a trans-impedance amplifier and demodulated using a simple envelope detector circuit before being passed to a final gain stage.

Measured rate results from the tuning fork gyro with a 12Hz resonant mode mismatch and 1μm drive amplitude yields an open-loop rate sensitivity of 1.25mV/º/s, as shown in

Figure 9. The inset shows the time-varying response of the system to an input 3Hz sinusoidal rotation at 150 °/s.

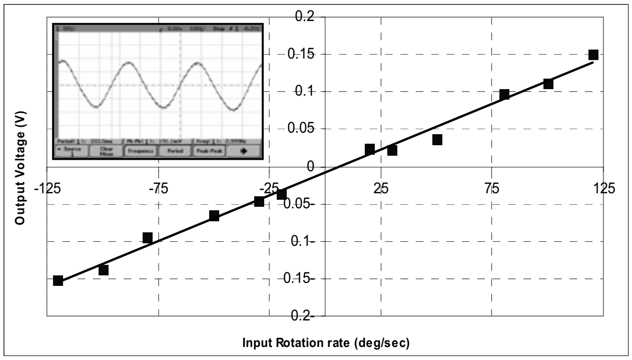

Figure 9. Output voltage vs. input rotation rate. Inset: The time-varying response of the sensor to an input of 150 °/s 3Hz signal.

Table 1 summarizes the key parameters of the proposed tuning fork gyroscope.

Table 1: Summary of the solid-mass Silicon TFG parameters.

Single proof mass dimension (in μm)	400x 400 x 40
Effective mass	30 μg
Drive mode resonant frequency (in kHz)	ANSYS: 17.413 Measured: 17.298
Sense mode resonant frequency (in kHz)	ANSYS: 17.458 Measured: 17.396
Split of drive and sense resonant frequencies	12 Hz
Rate sensitivity	1.25 mV/°/s
Resolution with 12 Hz freq mismatch	0.01°/s/√Hz
Theoretical Brownian noise floor with matched modes	0.3°/h/√Hz
Electronic noise floor (input ref. noise = 1μV/√Hz)	0.02°/h/√Hz
Measured temp. coefficient of freq. (TCF)	– 22 ppm/°C

CONCLUSIONS

An in-plane, solid-mass silicon tuning fork gyroscope has been designed and implemented on 40μm SOI. This design demonstrates high drive and sense mode quality factors, large drive amplitudes and increased mass – all critical requirements to lower the Brownian noise floor and thereby achieve sub-degree per hour angular rate resolutions.

However, the large capacitance requirements are restricted by the aspect ratio limitations of the current silicon etch systems (~ 50:1). Modifying the fabrication process to decrease the sense gap, for example by filling the gap with doped polysilicon [3] can help increase sensitivity. Strategic electrode placement schemes and electronic feedback control mechanisms are being investigated to achieve complete matching of the high-Q resonant modes and mitigate the quadrature error. The high Q operation calls for advancements in vacuum packaging technologies like those mentioned in [11].

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