

VACUUM PACKAGED SILICON MEMS GYROSCOPE WITH Q -FACTOR ABOVE 0.5 MILLION

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We report a vacuum sealed silicon MEMS gyroscope with a measured Q -factor of 0.64 million. The z -axis sensor utilizes a novel mechanical design which suppresses substrate energy dissipation and maximizes the sense-mode Q -factor. A silicon-on-insulator device was fabricated and sealed in a sub-mTorr vacuum, demonstrating Q -factors several times higher than any other MEMS gyroscope reported in literature. By achieving Q -factors on the order of 1 million, the technology promises to introduce silicon micromachined devices for demanding inertial sensing applications previously limited to precision-machined quartz hemispherical resonator gyroscopes.

Architecture of the novel z -axis mechanical sensing element [1,2] comprises two identical symmetrically-decoupled tines, in which the x - y mobile proof masses are suspended by a system of independent drive and sense shuttles, Fig. 1. The drive-mode of the gyroscope is formed by the two tines forced into anti-phase, anti-parallel motion synchronized by the mechanical lever system, Fig. 2. The sense-mode is formed by the two linearly coupled tines moving in anti-phase to each other in response to the anti-phase Coriolis input, Fig. 3. Devices were fabricated using an in-house SOI process and robustly sealed in sub-mTorr vacuum using a custom technology [3]. The packaging procedure comprises the attachment of a gyroscope die to a ceramic package followed by the vacuum sealing of the cavity, Fig. 4. Both the die and lid attachment rely on fluxless gold-tin eutectic solder bonding in order to minimize outgassing of the bond material and to eliminate flux residue. A getter material deposited on the lids was activated in 1 μ Torr before the lid sealing to provide long-term stability of vacuum.

A vacuum packaged gyroscope with a 1.7 kHz drive-mode operational frequency was characterized using ring-down tests to determine its Q -factors, Fig. 5. The measured Q -factor of the momentum balanced drive-mode was 0.31 million, providing very low phase noise and allowing actuation with just 0.2 mV ac with a 5 V dc polarization voltage. While the drive-mode is balanced in linear momentum, its Q -factor is limited by the energy loss due to the non-zero torque. In contrast, the measured sense-mode Q -factor of the sense-mode is twice higher at 0.64 million, confirming the high- Q design hypothesis. The sense-mode Q -factor enabled by the energy dissipation optimized mechanical design combined with the sub-mTorr vacuum sealing is several times higher than for any other silicon MEMS gyroscope reported in literature. Maximization of the gyroscope sensitivity is the main advantages of increasing the sense-mode Q -factor while maintaining a relatively low operational frequency. The ultra-high Q -factor of the vacuum packaged gyroscope translates into mechanical sensitivity of 2 nm/($^{\circ}$ /h) when operated mode-matched. This provides a path to eliminate the noise of the detection electronics, since it is not unprecedented for state-of-the-art integrated electronics to detect 10^{-5} nm displacements. At the same time, the fundamental mechanical-thermal resolution limit of the gyroscope is 0.02 $^{\circ}$ /h/ $\sqrt{\text{Hz}}$.

To achieve the best performance, the vacuum packaged gyroscope should be operated under a close matching between the drive- and the sense-modes, Fig. 5 inset. The measured frequency-temperature characteristics of the drive- and sense-modes are linear, Fig. 6, which makes the silicon gyroscope more amendable to electrostatic compensation than quadratic dependency of similar high- Q quartz gyroscopes [4]. Unlike most high- Q silicon devices, the gyroscope can also be ovenized [5] without a significant sacrifice in resolution since a Q -factor on the order of 0.5 million is sustained up to 50 $^{\circ}$ C. Open loop rate characterization of the gyroscope was performed under a 7 Hz frequency mismatch, Fig. 7. The measured resolution was 0.4 $^{\circ}$ /s/ $\sqrt{\text{Hz}}$ with bias stability of 70 $^{\circ}$ /h. From gain-bandwidth analysis in Fig. 5, the expected resolution for mode matched operation is 0.2 $^{\circ}$ /h/ $\sqrt{\text{Hz}}$, which can be further improved by controlling quadrature. In order to take complete advantage of the high- Q sense-mode without sacrificing the rate bandwidth, closed loop control is currently in development.

References:

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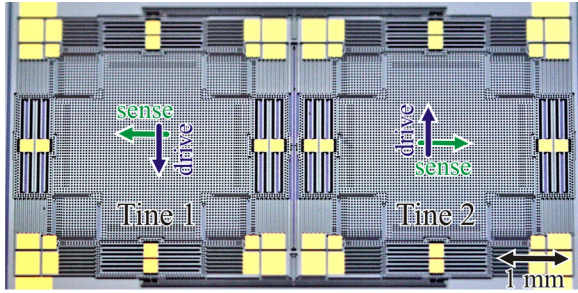


Figure 1: Photograph of a z-axis in-house fabricated SOI levered tuning fork gyroscope with two coupled tines.

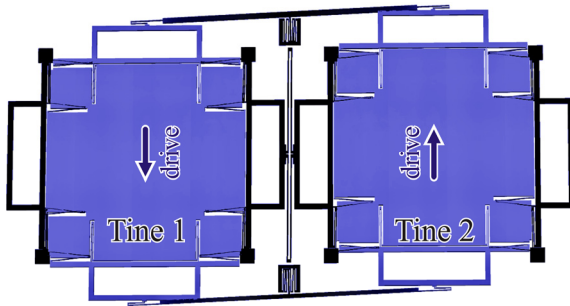


Figure 2: Levered drive-mode with anti-phase synchronization and linear momentum balancing, modeling.

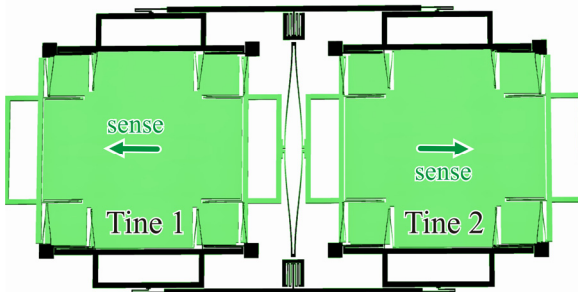


Figure 3: Linearly coupled anti-phase sense-mode with complete dynamic balancing for Q maximization, modeling.

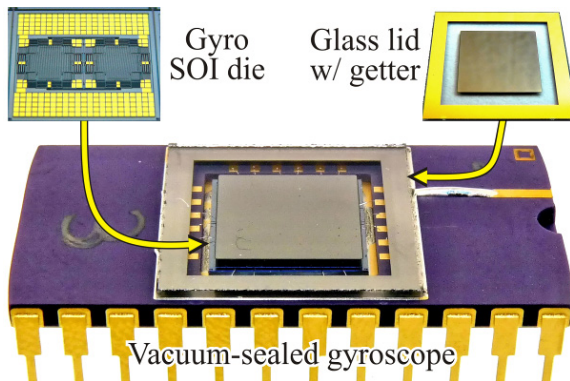


Figure 4: Photograph of a high-vacuum packaged gyroscope, showing the fabricated gyro die, ceramic DIP-24 package, and custom made glass lid with getter material.

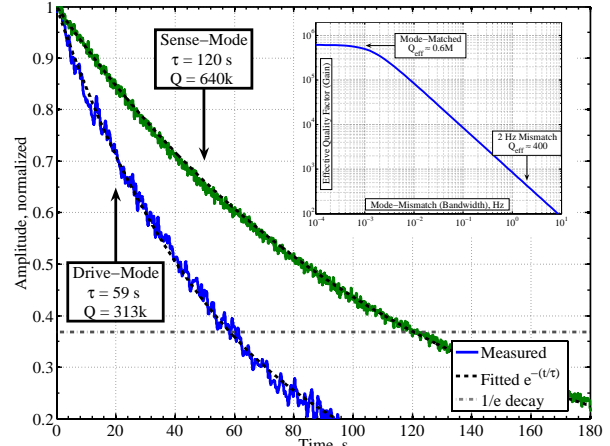


Figure 5: Measurement of vacuum packaged gyroscope Q -factors using ring-down tests. Drive-mode Q is 313,000, and sense-mode Q is 640,000. Inset: gain-bandwidth characteristic of the gyroscope, modeling.

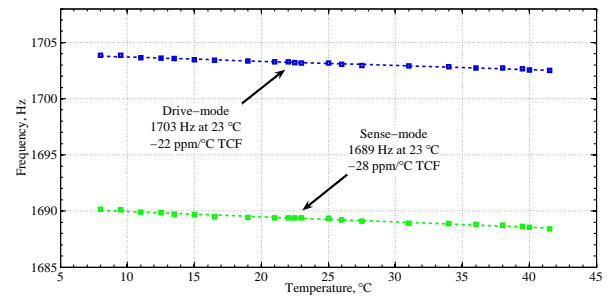


Figure 6: Measured frequency versus temperature for the drive- and sense-modes of the vacuum packaged gyroscope. For both modes, the dependency is linear with temperature coefficients of frequency below 32 ppm/°C TCF of silicon.

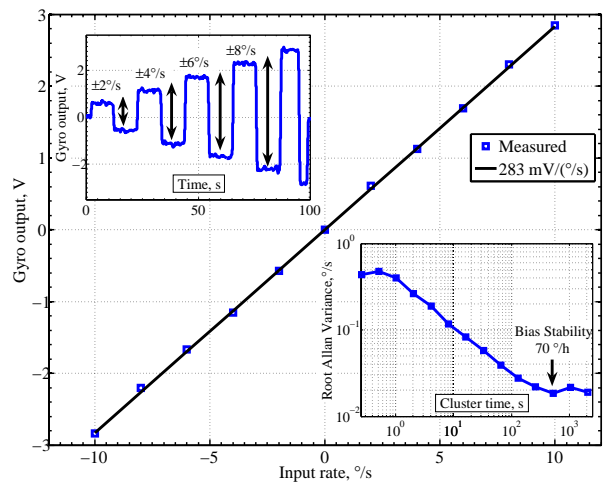


Figure 7: Experimental characterization of the gyroscope rate performance. Drive-mode is 7 Hz mismatched from the sense-mode for a 5 Hz bandwidth. Expected sensitivity improvement is +40 dB for 0.1 Hz matching (and +60 dB for 10 mHz). Insets: response time history, root Allan variance.