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

A. A. Trusov, A. R. Schofield, and A. M. Shkel
MicroSystems Laboratory, University of California, Irvine, CA, USA

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 µTorr 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/(°/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 °/h/√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 °C. Open loop rate characterization of the gyroscope was performed under a 7 Hz frequency mismatch, Fig. 7. The measured resolution was 0.4 °/s/√Hz with bias stability of 70 °/h. From gain-bandwidth analysis in Fig. 5, the expected resolution for mode matched operation is 0.2 °/h/√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:

[1] A.A. Trusov, A.R. Schofield, A.M. Shkel, “Micromachined Tuning Fork Gyroscopes with Ultra-High Sensitivity and Shock Rejection," US Patent pending, UC Case No 2009-748-1.
[2] A.A. Trusov, A.R. Schofield, A.M. Shkel, “Gyroscope Architecture with Structurally Forced Anti-Phase Drive-Mode and Linearly Coupled Anti-Phase Sense-Mode,” Transducers 2009 Conference, Denver, CO, USA, June 21-25, 2009.
[3] A.R. Schofield, A.A. Trusov, A.M. Shkel, “Versatile Sub-mTorr Vacuum Packaging for the Experimental Study of Resonant MEMS,” IEEE MEMS 2010 Conference, Hong Kong, January 24-28, 2010.
[4] Y. Xie, S. Li, Y. Lin, Z. Ren, C. Nguyen, “1.52-GHz Micromechanical Extensional Wine-Glass Mode Ring Resonators,” IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol.55, no.4, pp. 890-907, April 2008.
[5] S. Lee, J. Cho, S. Lee, M.F. Zaman, F. Ayazi, K. Najafi, “A Low Power Oven-Controlled Vacuum Package Technology for High Performance MEMS,” IEEE MEMS 2009, Sorento, Italy, January 2009, pp. 753-756.

Corresponding author: Alexander A. Trusov, alex.trusov@gmail.com, www.alexandertrusov.com.
IMAPS 6th International Conference and Exhibition on Device Packaging, Scottsdale, AZ, USA, March 8 – 11, 2010.

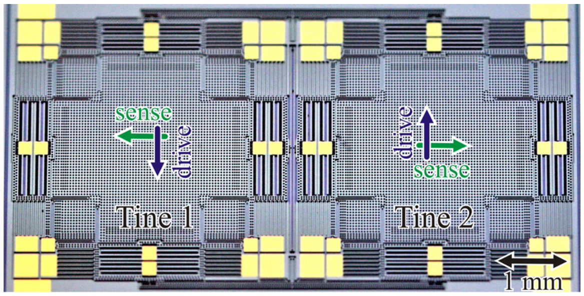

Figure 1: Photograph of a z-axis in-house fabricated SOI levered tuning fork gyroscope with two coupled tines.

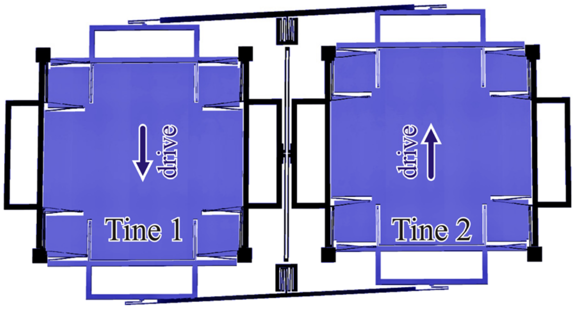

Figure 2: Levered drive-mode with anti-phase synchronization and linear momentum balancing, modeling.

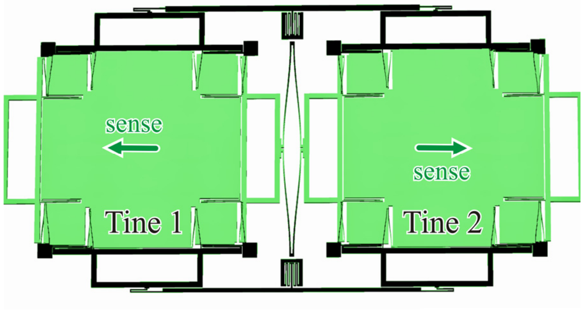

Figure 3: Linearly coupled anti-phase sense-mode with complete dynamic balancing for Q maximization, modeling.

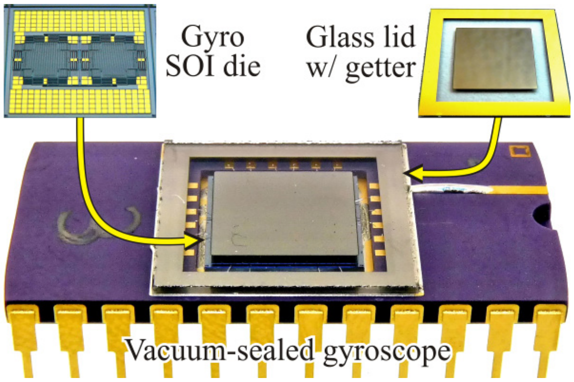

Figure 4: Photograph of a high-vacuum packaged gyroscope, showing the fabricated gyro die, ceramic DIP-24 package, and custom made glass lid with getter material.

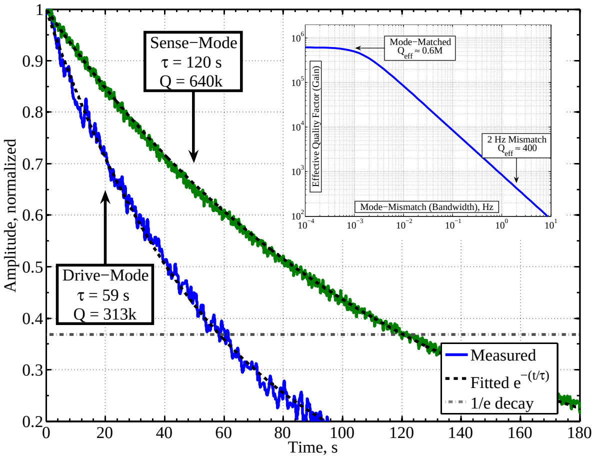

Figure 5: Measurement of vacuum packaged gyroscope Q-factors using ring-down tests. Drive-mode Q is 313,000, and sense-mode Q is 640,000. Inset: gain-bandwidth characteristic of the gyroscope, modeling.

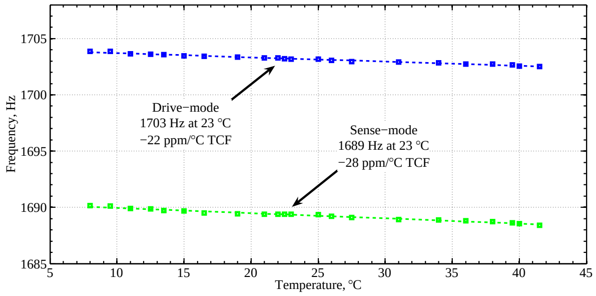

Figure 6: Measured frequency versus temperature for the drive- and sense-modes of the vacuum packaged gyroscope. For both modes, the dependency is linear with temperature coefficients of frequency below 32 ppm/°C TCF of silicon.

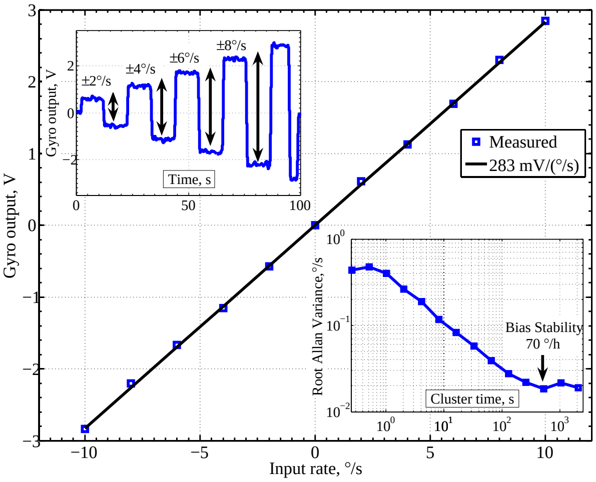

Figure 7: Experimental characterization of the gyroscope rate performance. Drive-mode is 7 Hz mismatched from the sense-mode for a 5 Hz bandwidth. Expected sensitivity improvement is +40 dB for 0.1 Hz matching (and +60 dB for 10 mHz). Insets: response time history, root Allan variance.