

# Design and Packaging of Ultra-High Q-Factor MEMS for Inertial Applications

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The paper discusses challenges, opportunities, and progress in design and packaging of ultra-high quality factor vibratory MEMS. Stand-alone, vacuum packaged single and dual axis silicon MEMS resonators with measured quality (Q) factors on the order of 1 million are reported. Unprecedentedly low energy dissipation in these microstructures is enabled by dynamically balanced design, high aspect ratio SOI fabrication, and vacuum packaging with getters. These MEMS transducers allow implementation of very sensitive vibratory gyroscopes. Similar ultra-high Q-factor architectures are also developed to enable several new types of inertial MEMS, such as angle measuring and FM gyroscopes.

Maximization of the quality factors is key to enhancing performance of micromachined vibratory devices<sup>1</sup>. The sensitivity of high-Q gyroscopes is further enhanced by closely matching the natural frequencies. The trade-offs, however, are open loop restricted input range and rate measurement bandwidth. These constraints of rate gyroscopes can be eliminated by operating a high-Q structure in the rate integrating (whole angle) mode<sup>2</sup>. However, previously investigated rate integrating MEMS gyroscopes suffered from anisoelectricity, anisodamping, and short energy dissipation constants (<1 sec). This presentation reports silicon micromachined ultra-high Q mode-matched gyroscopes with measured isotropic dissipation constant of 1 minute demonstrating operation in both rate and rate integrating modes.

Prototypes of the new gyroscopes utilizing symmetrically decoupled tines synchronized by anti-phase lever mechanisms<sup>3</sup> were fabricated using an in-house SOI process, Fig. 1. Characterization of a vacuum packaged dual mass gyroscope revealed drive- and sense-mode Q-factors of 0.31 million and 0.64 million, respectively, Fig. 2. Operated in rate measuring mode the gyroscope can provide mechanical sensitivity of up to 2 nm/(°/h) and mechanical-thermal noise limit as low as 0.02 °/h/√Hz, Fig. 3. While this dual mass gyroscope can be instrumented for rate integration, the 50 % Q-factor mismatch characteristic of MEMS tuning forks is a source of angle drift. To address the damping anisotropy a new completely symmetric quadruple mass architecture was developed, Fig. 4. Experimental characterization in vacuum, Fig. 5, demonstrated isotropic drive- and sense-mode Q-factors of 0.45 million, dissipation time constant in excess of 1 minute, and measured isotropic temperature coefficient of frequency of  $-22.5 \pm 0.25$  ppm/°C. Characterization of a mode-matched device in free vibrations regime revealed wide bandwidth, large dynamic range measurement of rate integrating (whole angle) operation, Fig. 6.

Based on achievements in ultra-high Q-factor silicon MEMS transducers, we investigated a new class of ultra-high resolution and stability quasi-digital acceleration sensors based on frequency modulation. The approach is based on tracking the acceleration-induced change of frequency in an ultra-high quality factor silicon MEMS resonator optimized for g-sensitivity. Similarly to the inherently FM gyroscope<sup>4</sup>, the new accelerometer provides stable, digital output with potential performance beyond the capabilities of conventional capacitive MEMS sensors. The presented ultra-high quality factor transducers may enable new classes of inertial MEMS, including angle measuring gyroscopes and high-gain FM accelerometers.

<sup>1</sup> M. Weinberg, R. Candler, S. Chandorkar, J. Varsanik, T. Kenny, A. Duwel, "Energy Loss in MEMS Resonators and the Impact on Inertial and RF Devices," TRANSDUCERS 2009, Denver, Colorado, USA, 2009.

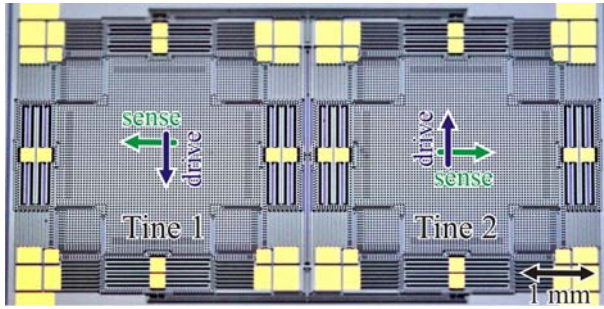
<sup>2</sup> I.P. Prikhodko, S.A. Zotov, A.A. Trusov, A.M. Shkel, "Foucault Pendulum on a Chip: Angle Measuring Silicon MEMS Gyroscope," IEEE MEMS 2011, Cancun, Mexico, 2011.

<sup>3</sup> 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, US Patent Application 20100313657.

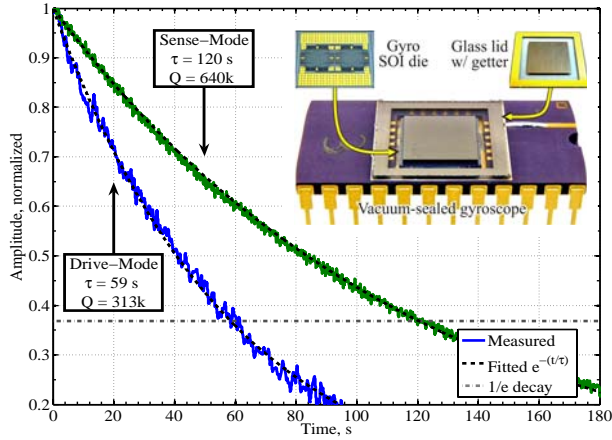
<sup>4</sup> S.A. Zotov, I.P. Prikhodko, A.A. Trusov, A.M. Shkel, "Frequency Modulation Based Angular Rate System," IEEE MEMS 2011, Cancun, Mexico, 2011.

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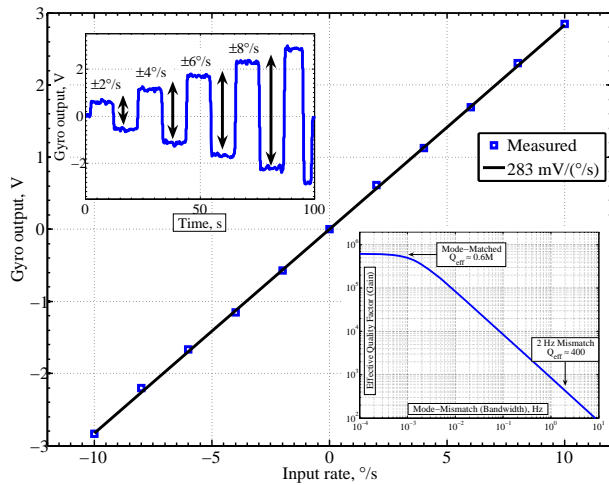
IMAPS 7<sup>th</sup> International Conference and Exhibition on Device Packaging, Scottsdale, AZ, March 8-10, 2011



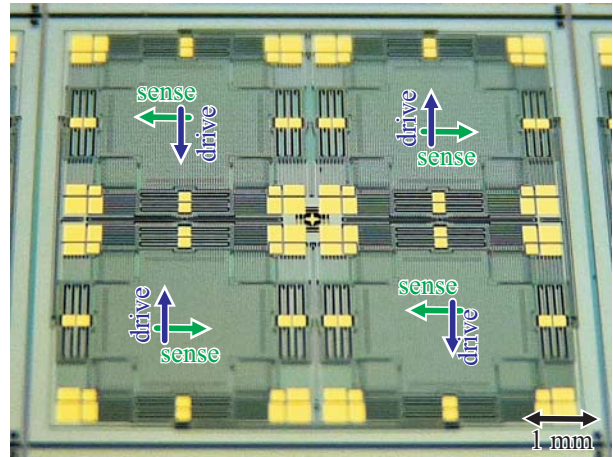
**Fig. 1:** Photograph of a fabricated 50  $\mu\text{m}$  thick SOI tuning fork gyroscope with two coupled tines.



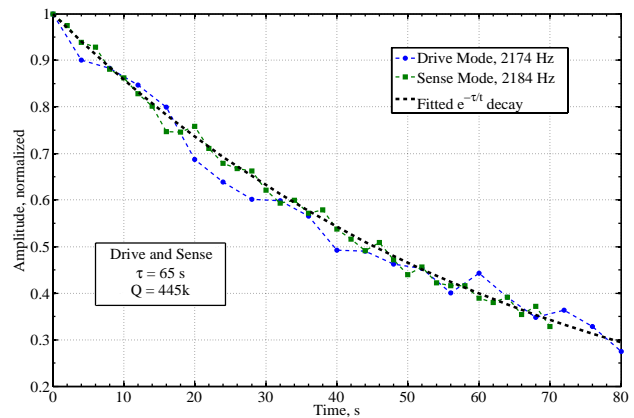
**Fig. 2:** Ring-down characterization of a vacuum packaged two mass gyroscope. Drive- and sense-mode  $Q$  is 313,000 and 640,000, respectively. Inset: gyroscope packaged at sub-mTorr vacuum level.



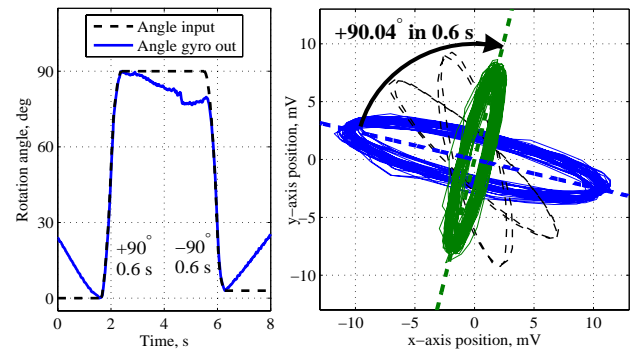
**Fig. 3:** Experimental characterization of a two mass gyroscope operated in rate measuring mode. Drive-mode is 7 Hz mismatched from the sense-mode for a  $\sim 5$  Hz bandwidth. Complete mode matching improves sensitivity by 60 dB at the cost of limiting the angular rate bandwidth to less than 10 mHz.



**Fig. 4:** Photograph of a fabricated 100  $\mu\text{m}$  thick SOI tuning fork gyroscope with four coupled tines.



**Fig. 5:** Ring-down characterization of a four mass gyroscope in vacuum. Both operational modes have  $Q$  of 445,000, demonstrating complete frequency and damping symmetry of the four mass gyroscope.



**Fig. 6:** Experimental characterization of a mode-matched four mass gyroscope operated in rate integrating (whole angle) mode for fast  $\pm 90^\circ$  rotation. The elliptical pattern of free vibrations remains fixed in inertial space, providing direct angle measurement.