Compact Roll-Pitch-Yaw Gyroscope Implemented in Wafer-level Epitaxial Silicon Encapsulation Process

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***Abstract*—This paper presents for the first time the design and characterization of an ultra-compact 3-axis roll-pitch-yaw gyroscope which employs a single vibrational element with a torsional drive mode and a multi-directional sense modes. Implemented in wafer-level Epitaxial Silicon Encapsulation (Epi-Seal) process, device occupies an area of 1.2 mm^2. Initial characterization reported in this paper includes a scale factor, a noise level, and a cross-axis error measurement.**

Introduction

MEMS gyroscopes find a wide scope of applications as rotation sensors in consumer electronics and gaming devices, for example for activity detection, virtual and augmented reality, optical and electronic image stabilization.

In general, in order to determine the orientation of a moving platform, it is necessary to measure rotation around three perpendicular axes: roll, pitch, and yaw. The most conventional method to provide three axes of sensitivity is based on mounting of single-axis gyroscopes along the three non-collinear axes, [1]. Such discrete assembly approach usually results in increased size and weight of the system. Another common trend is to fabricate three single-axis sensors on a die, [2]. This approach allows for minimizing volume of the system, however miniaturization is still limited by the size of individual sensors.

During the last few years, several multi-axis solutions have entered the market, for example, [3]. An "all-in-one-sensor" approach, which involves measuring rotation around three axes using a single structural element, is very attractive for applications where low power and extremely small volume are required, such as, for example, wearable devices. In this paper, we report an ultra-compact three-axis angular rate sensor with a footprint of 0.8x1.49 mm^2, fabricated in wafer-level Epitaxial Silicon Encapsulation (Epi-Seal) process.

Design and Fabrication

We consider a design approach which employs a torsional drive and multi-directional sense modes. The single driving structure consists of two shuttles connected by means of the central rigid frame and four flaps linked to the frame, Fig. 1(a). Each of the shuttles is suspended relative to the anchors by four springs, restricting motion of the driving shuttles to their respective axes. The drive mode consists of a torsional motion of the single driving structure around the Z axis, Fig. 1(b).

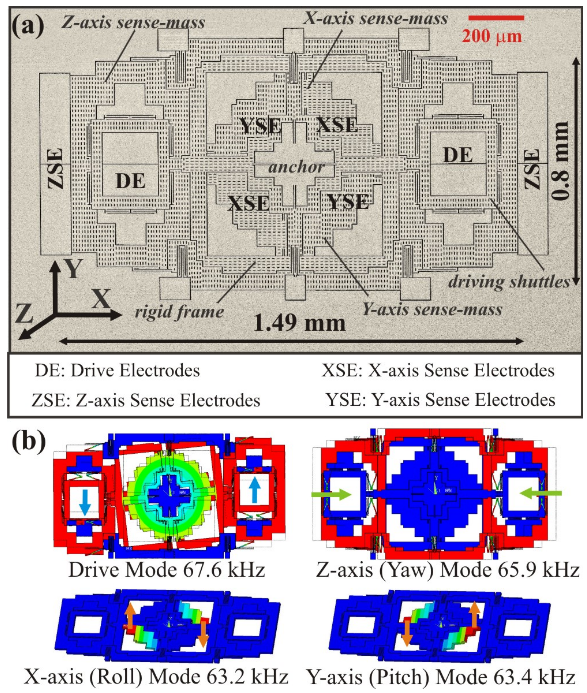

Fig. 1. (a) Microphotograph of a three-axis gyroscope; (b) Mode-shapes and frequencies.

The Z-axis sense structure is formed by two proof-masses connected to the drive shuttles and mechanically coupled by means of the corner springs and a lever. In the yaw mode, the Z-axis proof-masses move in-plane, in anti-phase. The XY-axis proof-masses are formed by the four flaps suspended inside the central rigid frame. The roll (X-axis) and pitch (Y-axis) sense modes consist of out-of-plane anti-phase motion of the two pairs of flaps.

A rigid frame connected to the center anchor separates the roll, pitch, and yaw sense-masses, effectively reducing the coupling between the three axes of sensitivity. This differentiates this design from the previously reported single-structure 3-axis gyroscopes, where the same portion of a proof-mass is often used for detection of rotation around more than one axis, for example [4] and [5].

Prototypes of a three-axis gyroscope were fabricated using a wafer-level Epitaxial Silicon Encapsulation (Epi-Seal) process, [6]. In this process, movable silicon microstructures are encapsulated with a layer of epitaxially deposited silicon,

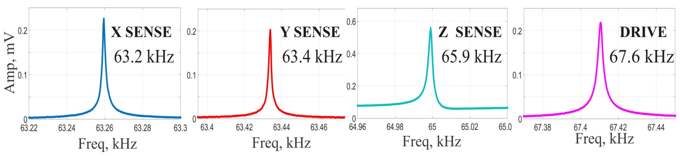

Fig. 2. Experimental sweeps of the sensor for roll, pitch, yaw, and drive modes.

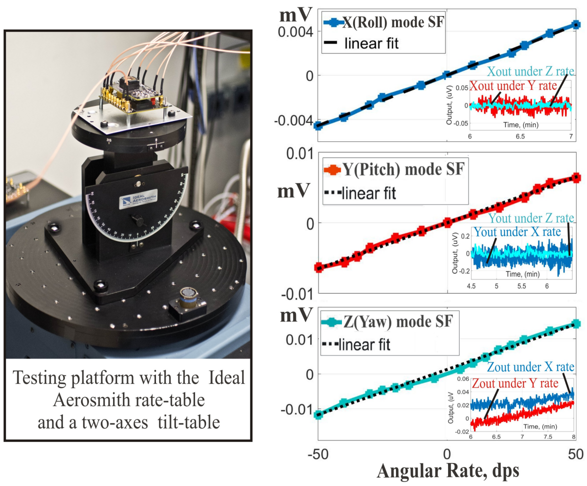

Fig. 3. Gyroscope scale factors along the three axes were derived using a testing platform with the Ideal Aerosmith rate-table and a two-axes tilt-table.

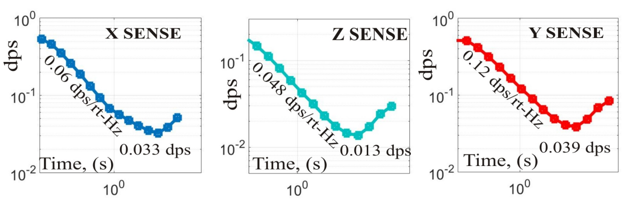

Fig. 4. Noise analysis of Z axis revealed in-run bias of 0.013 dps and ARW of 0.048 $dps/\sqrt{Hz}$; noise analysis of XY axes revealed in-run bias of <0.033 dps and ARW of <0.06 $dps/\sqrt{Hz}$.

allowing for an ultra-clean hermetic seal and resulting in a high vacuum environment. All devices were fabricated in a standard ("Hot Dog") Epi-Seal process with a 40 μm thick device layer and 1.5 μm capacitive gaps. The out-of-plane motion of the proof-masses was detected using the top-electrodes. In "Hot Dog" Epi-Seal process, out-of-plane electrodes were formed by portions of the top Si layer isolated using nitride plugs, [6].

Devices were designed to operate at relatively high resonant frequencies (>63 kHz) to improve the robustness to shock and vibrations.

Experimental Results

Frequency response characterization of the sensors was performed using electrostatic excitation with a DC voltage of 2 V applied to the proof mass and 100 mV AC signal applied to the drive electrodes. Resonant peaks were measured at 63.26 kHz (roll mode), 63.43 kHz (pitch mode), 65 kHz (yaw mode), and 67.41 kHz drive mode).

Gyroscope scale factors along three axes were derived using a testing platform with the Ideal Aerosmith 2102 series

TABLE I
Experimental tested parameters of the gyroscope

Area of the mechanical element, mm^2	1.2		
Drive mode Q-factor	34000		
	Roll	**Pitch**	**Yaw**
Sense mode Q-factor	53000	45000	36000
Scale Factor, μV/dps	0.12	0.09	0.3
Angle Random Walk, dps/rt-Hz	0.06	0.12	0.048
In-run bias, dps	0.033	0.039	0.013
Cross-axis sensitivity, %	0.2	0.3	0.12

rate-table and a two-axes Ideal Aerosmith tilt-table, Fig.3. A carrier signal at the frequency of 550 kHz was applied to the proof-mass, resulting in amplitude modulation of the sensor output. The output signal was then demodulated to reveal the low frequency changes in capacitance. The amplitude of the drive-mode motion was stabilized, using an Automatic Gain Control (AGC). All loops were realized using a Zurich Instruments HF2LI digital lock-in amplifier.

The gyroscope was calibrated to compensate for the mis-alignment relative to the testing platform. The experimentally derived scale factors were 0.12 μV/dps, 0.09 μV/dps, and 0.3 μV/dps for the roll, pitch, and yaw modes. The sensor responses to the angular rates along the directions perpendicular to the sensitivity axes are shown in the inserts of Fig. 3. After initial calibration was performed, a cross-axis sensitivity of less than 0.3% was measured for all three axes.

The Root Allan Variance Analysis (r-AVAR) was used for identification of random noise characteristics, Fig. 4. Experimental characterization of the yaw channel revealed in-run bias of 0.013 dps and ARW of 0.048 $dps/\sqrt{Hz}$; noise analysis of the roll and pitch channels revealed in-run bias of <0.033 dps and ARW of <0.06 $dps/\sqrt{Hz}$.

Conclusion

Consumer electronics market has an increasing demand for the multi-axis ultra-compact angular-rate sensors. Motivated by this demand, in this paper we presented a design of an ultra-miniature roll-pitch-yaw gyroscope. Thanks to the mechanical design with a decoupled sense modes and a small capacitive gap enabled by the Epi-Seal process, our three-axes solution allows for satisfactory performance in terms of a cross-axis error, scale factor, and noise level. The focus of our future work is on characterization of the environmental performance of a compact three-axis gyroscope.

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