High-Frequency AlN-on-Silicon Resonant Square Gyroscopes

Roozbeh Tabrizian, Mojtaba Hodjat-Shamami, and Farrokh Ayazi

Abstract—This letter reports, for the first time, on a high-frequency resonant square micro-gyroscope using piezoelectric transduction. Degenerate pairs of orthogonal flexural resonance modes are used to provide energy exchange paths for the Coriolis-based resonant gyroscope in response to \( z \)-axis rotation. Aluminum nitride thin films have been used to provide highly efficient electromechanical transduction for drive and sense modes without requiring any dc polarization voltage for operation. A proof-of-concept design consisting of a 300 \( \mu \text{m} \times 300 \mu \text{m} \) square gyro shows linear rate sensitivity of 20.38 \( \mu \text{V}/\text{°}/\text{s} \) when operating in its first flexural mode at \( \sim 11 \text{ MHz} \). [2013-0116]

Index Terms—Resonant gyroscopes, high frequency gyroscope, square resonator, square gyroscope.

I. INTRODUCTION

Silicon bulk acoustic wave (BAW) resonant disk microgyroscopes operating in mode-matched condition at high frequencies have been recently considered as a viable miniaturized solution for rotation-rate sensing [1]–[3]. Capacitive signal transduction through nano air-gaps has been used for BAW silicon disk gyroscopes [3]. However, since such disk resonators operate in their high-order elliptical (\( m \geq 2 \)) BAW resonance modes with distortional in-plane stress fields [4], thin-film transverse-piezoelectric transduction is not very efficient for excitation and sensing of the drive and sense resonance modes. The purpose of this letter is to introduce a novel resonant square gyroscope along with a group of its inherently-orthogonal degenerate mode pairs which can be efficiently excited and sensed by thin-film piezoelectric transducers deposited on the top surface of the structure. Proper electrode configuration can be used for simultaneous, yet independent, transduction of these resonance pairs, enabling the operation of the silicon square resonator as a mode-matched gyroscope. Owing to highly efficient and linear piezoelectric transduction, such high frequency and high \( Q \) gyroscopes can potentially offer very large dynamic range (10^5–10^6) by simultaneously improving the full scale linear range while reducing the noise equivalent rotation rate [1].

II. SQUARE GYROSCOPE CONCEPT

Rectangular bar silicon resonators can be considered as acoustic waveguides with finite dimensions. Hence, several resonance modes of these structures can be approximately attributed to the Lamb modes of an infinitely long waveguide. Such a consideration facilitates a qualitative study of the resonance modes of a microstructure using dispersion characteristics of Lamb modes in acoustic waveguides. Fig. 1 shows several dispersion curves of guided waves propagating in \( X \)-direction of an infinitely long silicon waveguide aligned to <110> crystallographic direction with characteristic width (\( W \)) of 300 \( \mu \text{m} \) and a thickness (\( H \)) of 20 \( \mu \text{m} \). (c) Lamb mode shapes with similar wavelength in the waveguide and their corresponding resonance mode shapes in square resonator.
attributed to the Lamb modes propagating in X direction with a wave-length of \( \lambda_X = \frac{2L}{(2n - 1)} \), while those with X-axis symmetry can be attributed to the Lamb modes propagating in Y direction with a wave-length of \( \lambda_Y = \frac{2W}{(2n - 1)} \).

For a square resonator, identical Lamb modes exist at the same frequency propagating in X and Y directions. However, while symmetric (Si) modes couple together acoustically to form one single extensional resonance mode (such as Lamé or square-extensional modes), such a coupling cannot happen for anti-symmetric Lamb modes (Ai) thus resulting in degenerate flexural mode pairs. Such orthogonal mode pairs can be used for Coriolis-based resonant rotation rate sensing.

Based on this concept, a prototype square gyroscope has been designed and fabricated. Fig. 2 shows the SEM picture of a 300 \( \mu \text{m} \times 300 \mu \text{m} \times 20 \mu \text{m} \) silicon square resonator transduced with a thin (< 1 \( \mu \text{m} \)) AlN layer using COMSOL Multiphysics simulation tool. The single-crystal silicon resonator is aligned to the <110> direction of a (100) silicon plate. A quality factor (\( Q \)) of 3000, obtained from the measured results of a fabricated sample operating in air, was assumed for the resonance modes.

**III. FINITE ELEMENT MODELING**

The gyroscopic coupling between the two orthogonal flexural mode pairs (Ai) has been verified for a 300 \( \mu \text{m} \times 300 \mu \text{m} \times 20 \mu \text{m} \) silicon square resonator transduced with a thin (< 1 \( \mu \text{m} \)) AlN layer using COMSOL Multiphysics simulation tool. The single-crystal silicon resonator is aligned to the <110> direction of a (100) silicon plate. A quality factor (\( Q \)) of 3000, obtained from the measured results of a fabricated sample operating in air, was assumed for the resonance modes.

**IV. PRELIMINARY CHARACTERIZATION**

The resonator was actuated by applying a 1.6 V (peak) harmonic signal to the drive electrode, resulting in the antinode displacement of \( \sim 32 \text{ nm} \) at the resonance frequency, which in turn induces Coriolis-induced current [1] at the sense electrode when a finite rotation rate is applied. The simulated rate response of the square gyroscope shows a sensitivity of 250 pA/°/s per electrode (Fig. 3). The resonator was actuated by applying a 1.6 V (peak) harmonic signal to the drive electrode, resulting in the antinode displacement of \( \sim 32 \text{ nm} \) at the resonance frequency, which in turn induces Coriolis-induced current [1] at the sense electrode when a finite rotation rate is applied. The simulated rate response of the square gyroscope shows a sensitivity of 250 pA/°/s per electrode (Fig. 3).

Fig. 4 shows the interface circuit architecture used to detect the angular rate information. The gyroscope was operated in an open-loop configuration by applying an external sinusoidal voltage at resonance frequency to the drive electrode. The current generated at the sense electrode is processed in the sense channel of the interface circuitry to extract the Coriolis signal. The sense channel consists of a current-to-voltage converter and a synchronous demodulator to detect the applied rotation rate.
Fig. 5 shows the measured frequency response of the gyroscope operating in $A_0$ mode (i.e. first flexural mode), observed from Drive_In to Sense_Out electrode. The observed frequency split of $\sim$10 kHz ($\sim$1000 ppm) between the two modes is attributed to process non-idealities. Such a split can potentially be compensated by using the piezoelectric-stiffening tuning [6], [7] or post-fabrication trimming [8].

The response of the piezoelectric gyroscope to $Z$-axis rotation rates was measured using a rate table. The readout circuit was implemented on a printed circuit board using discrete electronic components. The gyroscope was excited in its first flexural mode ($\sim$11 MHz) and characterized for different input rotation rates resulting in a sensitivity of 20.38 $\mu$V/°/s (Fig. 6) for a sinusoidal drive voltage of 1.6 V (peak). The measured rate sensitivity is in close agreement with the value extracted from simulation (19.6 $\mu$V/°/s), considering the 680 kΩ current-to-voltage gain of the trans-impedance amplifier and taking into account the frequency split of 10 kHz at the resonance frequency of 11.279 MHz versus mode-matched simulated response shown in Fig. 3. Our preliminary implementation and characterization result demonstrates the feasibility of rotation rate sensing using orthogonal degenerate flexural modes in silicon square resonant structures excited with thin piezoelectric films. This motivates further optimization work on the resonator design, structure/transducer thicknesses, and proper resonance pair selection to achieve higher sensitivity, higher $Q$ and sufficient electrical tuning of the modes to compensate for process-induced mismatches.

V. CONCLUSION

This letter introduced a novel resonant square gyroscope based on a group of orthogonal degenerate modes that can be efficiently transduced and operated using thin piezoelectric films. A proof-of-concept AlN-on-Si square micro-gyroscope operating in one of these modes at 11 MHz shows a linear $Z$-axis rotation rate sensitivity of 20.38 $\mu$V/°/s, which is comparable to capacitive BAW disk micro-gyroscopes with similar resonance frequency and drive/sense modes frequency split [9], [10]. The process-induced frequency split between the drive and sense modes of these gyroscopes can potentially be compensated by using piezoelectric stiffening effect, which is currently under investigation.

REFERENCES