INTERACTION EFFECTS OF TEMPERATURE AND STRESS ON MATCHED-MODE GYROSCOPE FREQUENCIES

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ABSTRACT

We present our initial results toward understanding the interaction of temperature and stress on resonant frequencies of a matched-mode SOI-MEMS gyroscope. We also validate a new electrostatic frequency tuning design for gyroscopes that works over large displacements. A stress and temperature gradient is formed on the gyroscope die by using on-chip silicon heaters, affecting the gyroscope frequencies. Simulation and measurements of the gyroscope frequencies under different gradient conditions are compared. We also show that the orientation of the die with respect to an asymmetric package plays an important role in frequency response of the gyroscope to environmental conditions.

KEYWORDS

gyroscope, matched-mode, Young's Modulus, stress and temperature effects, frequency tuning, shaped combs

INTRODUCTION

Bias characterization of MEMS gyroscopes requires understanding the device behavior under temperature and external stress variations. These tests are typically performed on a packaged system rather than on chip, as a result the actual temperature and stress state of the MEMS structure is generally not well known [1]. However, on-chip stress and temperature sensors can monitor the device state in real time and potentially improve compensation. Past studies that characterize the gyroscope frequency with temperature [2, 3] assume the frequency change is only due to the temperature; however inevitable stress due to the material difference between the package and chip also affects the frequency [1]. [1-3] use a measurement-only methodology and lack simulation results that distinguish between stress and temperature induced effects.

Tuning the gyroscope frequencies is vital for vacuum operated mode-matched gyroscopes, since inevitable microfabrication tolerances result in a split in the frequencies. We propose a new tuning structure using shaped combs [4] that enables tuning of each mode with displacement up to 12 µm, and provides on-chip compensation to support FM gyroscope operation [5]. In contrast to the conventional gap-tuning combs, which limit the displacement [6], shaped combs allow the design of gyroscopes without any practical displacement limitation.

As a first step towards a gyroscope with on-chip stress and temperature sensing and bias compensation, this paper presents our initial results on understanding the effect of environmental factors on gyroscope frequencies. We designed and fabricated a SOI-MEMS gyroscope with on-chip resistive silicon heaters to induce temperature gradients, enabling the measurement of temperature induced effects on gyroscope frequency. These measured effects are compared with the simulation results that are obtained by coupling Joule heating, thermal expansion, and modal FEM. The tuning capability of the proposed shaped combs is also demonstrated.

DEVICE DESCRIPTION

Figure 1 shows an SEM image of the fabricated gyroscope and close up views of the mode decoupling springs and shaped combs for frequency tuning. The chip periphery includes heater resistors (marked red and labeled Heater1-4) and temperature sensors (marked blue and labeled T1-4). The gyroscope is fabricated by an in-house 2 mask SOI-MEMS process. Starting with SOI wafers having a 15 µm device layer, Cr/Au pads are defined by lift off and then the device is formed by DRIE (deep reactive ion etching). Finally devices are released by a timed buffered HF etch. The gyroscope is mirror symmetric in x, y and diagonal axes. The shaped combs enable retention of all three symmetries while enabling with tuning of x and y modes independently. The operation of the shaped combs relies on its curved shape that provides a quadratic capacitance with respect to comb engagement [4]. The two modes of the gyroscope are labeled as Mode 1 and 2, and both modes can be used either for driving or sensing for AM gyroscope operation.

We inserted a 500 µm glass substrate between the die and the package to thermally isolate the gyroscope so that heaters can create thermally induced stress gradients. Heating efficiency without the glass would be low since silicon and package are both thermally conductive, and the thickness of the SOI oxide layer (2µm) is small enough that it inadequately isolates the device from the package. Figure 2 shows the cross section and top view of the tested gyroscope after the gyroscope is mounted on the package, and explains how the device is heated. When the heater is activated, heat energy goes through the SOI oxide and creates a temperature gradient in the handle layer, which is then transferred back to the device through the anchors.

SIMULATIONS

A three-step simulation procedure (electrothermal, thermomechanical and modal) allows extraction of the environmental effects on the modal resonance frequencies. The first step captures the electrothermal effects of the system in Figure 2 by running a Joule heating simulation with a voltage applied to one of the heaters.

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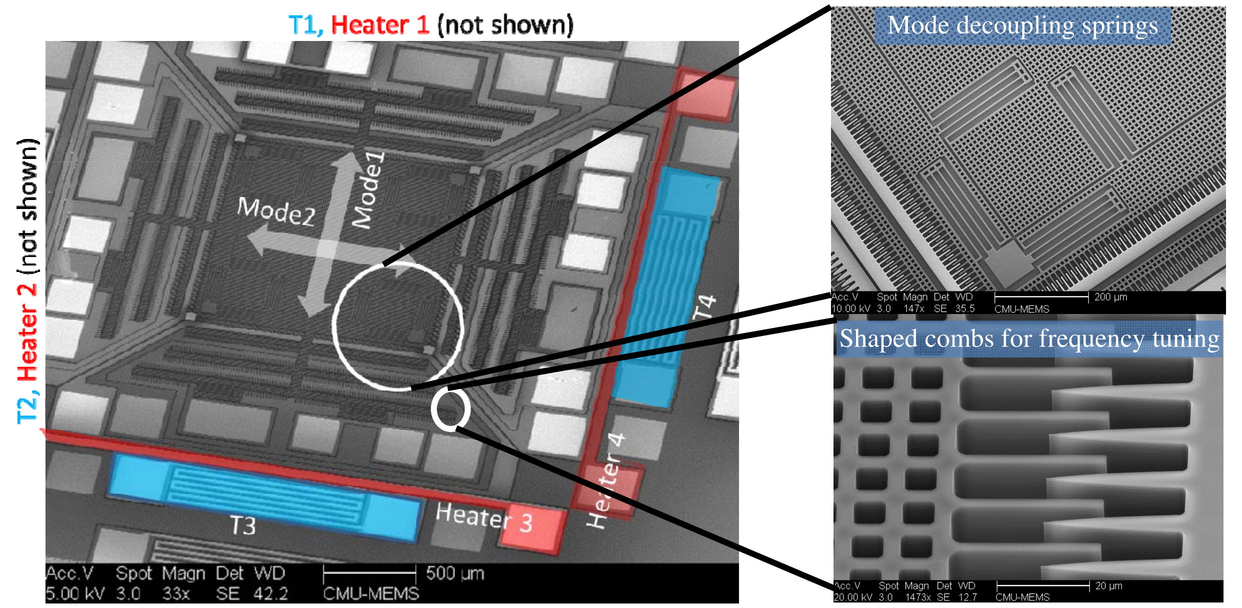

Fig. 1: SEM image of the fabricated gyroscope and close up views of the mode decoupling springs and shaped combs for frequency tuning. Heaters are marked with red (Heater 1-4) and temperature sensors are marked with blue (T1-4).

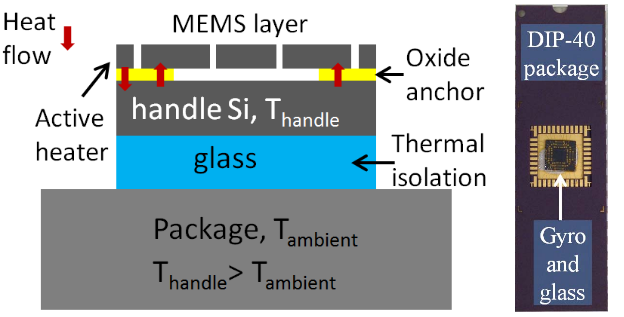

Figure 2: Cross section (left) and top view (right) of the tested gyroscope. Glass thermally isolates the die resulting in a sensitive stress and temperature change on the gyroscope as a function of heater power.

Figure 3 shows the temperature distribution in the die when 500 mW of power is applied to one of the heaters. The glass layer thermally isolates the device layer from the package as expected. The thermal and mechanical characteristics of the die are dominated by the glass and the handle silicon since their combined thickness is 60 times that of the device layer. Thus, the actual mechanical structure does not need to be simulated at this stage; only anchor regions are included to obtain the necessary boundary conditions for the modal simulation.

The output of the Joule heating simulation is coupled with a thermal expansion solver. Figure 4 shows the displacement results due to the heater generated temperature distribution. Additional package stress can be modeled at this step. In the experimental characterizations in the next section, this temperature-induced deflection induces a stress gradient on the device. Anchor displacements are extracted from Figure 4 and then used as boundary conditions for the modal simulations of the actual mechanical structure. Modal simulations also take into account temperature dependence of Young's Modulus (E) [7]. Springs are assumed to have the same temperature as anchors. The mechanical system follows Hooke's law ($F=kx$), since the displacements are small enough. In other words, not only temperature differences but also anchor displacements vary linearly with respect to the heater power. These characteristics are then used to obtain frequency characteristics for different stress and temperature levels.

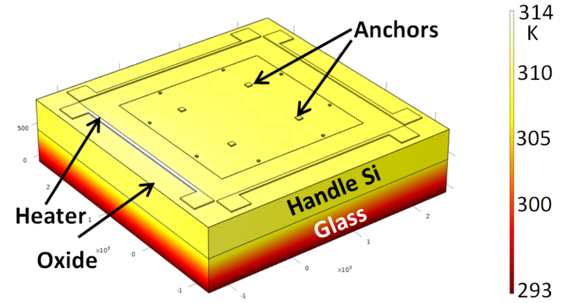

Figure 3: Simulated temperature distribution on the die with 500 mW heater power.

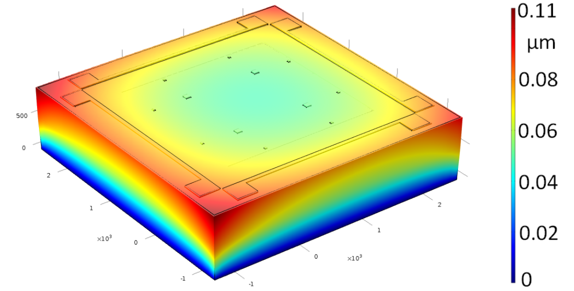

Figure 4: Simulated thermal expansion displacement results due to the temperature distribution in Figure 3. Anchor displacements are used as boundary conditions for the modal simulation.

MEASUREMENT RESULTS AND COMPARISON WITH SIMULATIONS

Figure 5 shows the measured tuning curve for the gyroscope. The initial frequency split between the two modes is 140 Hz, which is believed to be caused by a 30 nm beam offset (within specs of the laser mask writer [8]). Shaped combs can tune this frequency difference with 50 V DC. These combs are located symmetrically on the gyroscope with the DC tuning voltage applied across the higher frequency mode (in this case, mode 2).

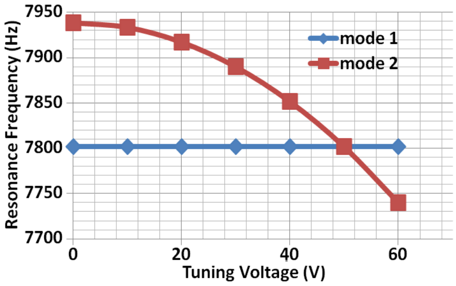

Figure 5: Measured tuning curve for the gyroscope. DC tuning voltage is applied across mode 2.

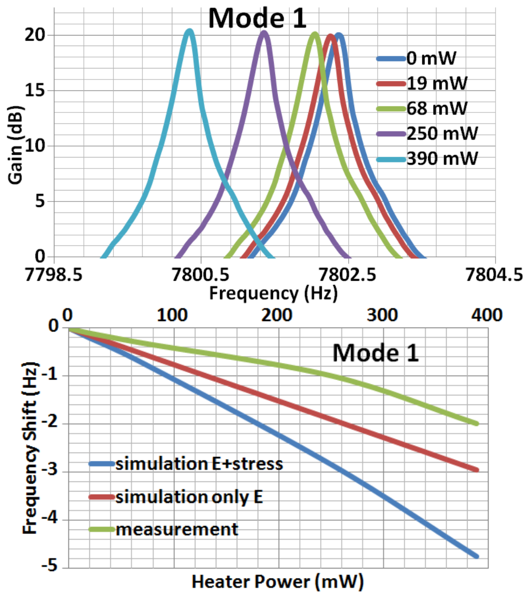

Figure 6: Measurement and simulation results for the frequencies of mode 1 with one of the heaters activated. Upper figure shows the measured resonance curve under 50 mTorr for different heater power levels. Lower figure of resonant frequency shift (Δf_r) vs. heater power (P) enable comparison of simulation and measurement.

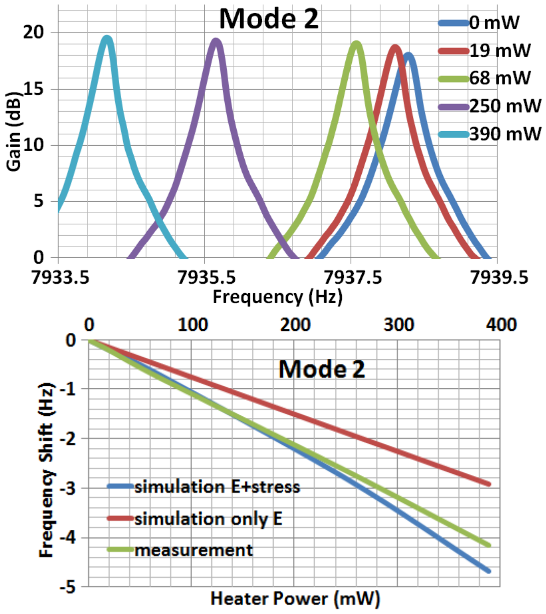

Figure 7: The same graphs as in Figure 6 plotted for mode 2.

Figures 6 and 7 compare simulated and measured resonant frequencies for different heater power levels at 50 mTorr for mode 1 and 2, respectively. The frequencies decrease due to the -60 ppm/˚C change in E [7] and the temperature-induced stress. In order to understand how stress affects the gyroscope, one needs to examine how the anchors and springs are located on the device. Figure 8 shows gyroscope anchor positions. The folded-flexure suspensions are anchored at the inner beams. When the heater is activated, the die expands as in Figure 4, and the anchors move from Position 0 to +. This movement creates a tensile stress on the inner beams increasing the y spring constant and creates a compressive stress on the outer beams decreasing the y spring constant. Since inner and outer beams are connected in parallel, anchor displacement results in a decrease in the effective spring constant. The effective spring constant always decreases whether the anchor moves inwards or outwards because inner and outer beams will always see the stress in opposite directions as shown in the lower graph in Figure 8. The transverse stress (y directed) is not taken into account since it has very little effect on spring constant compared to axial stress (x directed).

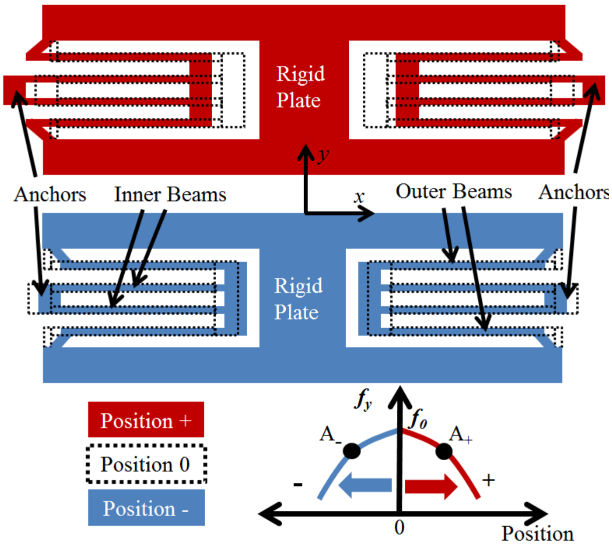

Figure 8: Three states of the device for different stress levels. Position 0 shows the initial state, Position + shows when an outwards directed stress is applied, and Position − shows when an inwards directed stress is applied to the device. The frequency always decreases when the spring moves from the Position 0.

Simulations in Figures 6 and 7 show that the chip-level stress effects (*i.e.*, through anchor displacements) are significant and add a nonlinear component to the Δf_r–P (resonant frequency shift–heater power) characteristics. The assumption that frequency only changes due to temperature [2, 3] is not accurate, because the frequency shift is a combination of both stress and temperature and is still linear up to a certain level according to our simulations. The simulations and experiments agree for mode 2 (Figure 7) but not for mode 1 (Figure 6). This difference occurs in multiple gyroscope samples and remains the same when a heater on an adjacent side is heated. Shifting the heater does not affect frequency characteristics, because the handle layer conducts the heat uniformly.

Figure 9 shows test results of another gyroscope for which we continued test up to a higher power level for mode 1. The frequency behavior of mode 2 is close to simulation results, but for mode 1 the frequency increases up to 300 mW and then decreases. We think there is a certain amount of stress coming from mounting the die and glass on to the package. Mounting was performed at 150°C with epoxy. When the sample cools to room temperature, the stress state of mode 1 is Position − in Figure 8 and then as more power is applied to the heater it first comes to Position 0 and the frequency increases during this stage, and when it passes Position 0 and goes to Position +, the frequency starts decreasing again. This corresponds to moving from point A_- to A_+ in Figure 8.

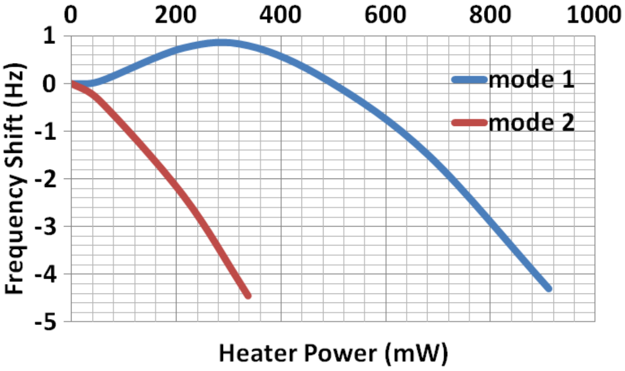

Figure 9: Test result of another gyroscope for which the test continued up to higher power levels for mode 1. We think the difference in the frequency characteristics is coming from mounting the die and glass on to the package.

The DIP-40 (dual-in-line package) used for mounting the gyroscope is asymmetric as shown in Figure 2. We think this asymmetry creates directionally different stresses on the modes of the gyroscope. To test this theory, we mounted one of the gyroscopes with a 45° angle with respect to the package edge, and ran the resonance tests again. Figure 10 shows the frequency shift vs. heater power for the 45° mounted gyro. The frequency shift for the two modes are almost the same in this case and very close to simulation, which validates that the way the die is mounted on the package is important especially for asymmetric packages.

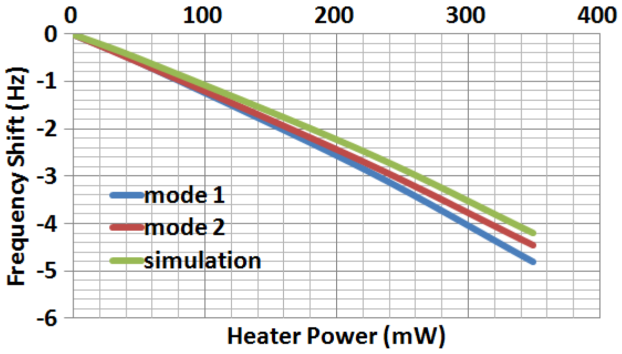

Figure 10: Frequency shift vs. power for the 45° mounted gyroscope. The frequency shift is almost the same for the two modes and very close to simulation.

CONCLUSIONS

We successfully showed that the effect of stress and temperature on gyroscope frequencies can be simulated by coupling Joule heating, thermal expansion and modal FEM. A stress gradient on the die can be experimentally induced by thermally isolating the die and applying heat through an on-chip heater. The frequency varies with temperature and stress due to the negative temperature dependence of Young's Modulus and to anchor displacements, which affect the spring constant. We also demonstrated that asymmetries in the package create mismatch in the frequency behavior of the gyroscopes, which can be solved by mounting the gyroscope into the package symmetrically. In addition, we validated the shaped-comb tuning structure for the gyroscope and successfully showed that it can tune the frequency offsets due to process imperfections.

ACKNOWLEDGEMENTS

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