SINGLE PROOF-MASS TRI-AXIAL PENDULUM ACCELEROMETERS OPERATING IN VACUUM

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ABSTRACT

This paper reports on the design, fabrication and characterization of single proof-mass tri-axial capacitive accelerometers coexisting in a low-pressure environment with high-frequency gyroscopes, for the implementation of monolithic 6-degree-of-freedom inertial measurement units. The accelerometers are designed to operate as quasi-static devices (i.e. non-resonant sensors) in mid vacuum levels (1 – 10 Torr) by increasing squeeze-film air damping through the use of capacitive nano-gaps (< 300 nm). Reduced die area is achieved utilizing a pendulum-like structure composed of a 450x450x40 µm³ proof-mass anchored to the substrate by a cross-shaped polysilicon spring. The small capacitive gaps, allow for the design of devices with high resonance frequency (~ 15 kHz) that provide large shock and vibration immunity.

INTRODUCTION

Micromachined accelerometers have played a critical role in the commercialization of almost all MEMS devices [1]. Their success in both the automotive industry and consumer electronics motivated the development of fabrication and integration techniques necessary for the implementation of other types of micromachined structures, such as resonators, microphones and gyroscopes, among others. Today—after almost twenty years since the first commercial product—sales projections for standalone MEMS accelerometers in the consumer space are starting to show a slow decline in market share due to the demand of highly integrated multi-degree-of-freedom sensors [2]. This new breed of devices incorporate accelerometers, gyroscopes and magnetometers on the same package, indicating that for further reductions in size, monolithic single-die implementations of inertial sensors will be necessary [3].

Conventionally, accelerometers and vibratory gyroscopes required different pressure levels to attain optimal operation conditions. Gyroscopes are implemented under high vacuum environments to achieve increased quality factors (Q), which are essential for large scale-factor and low noise performance. On the other hand, accelerometers are packaged at levels close to atmospheric pressure (760 Torr) in order to increase squeeze-film damping; this prevents the devices from experiencing overshoot and long settling times associated with a high Q response. The critical difference in pressures necessary for each type of sensor indicates that, in order for them to coexist in the same package, a paradigm shift in the design methodology of either accelerometers or resonant gyroscopes is necessary.

Methods to operate MEMS accelerometers by monitoring the change in their resonance frequency as a function of acceleration have been suggested as a possible solution [4]. If implemented as resonant sensors rather than quasi-static devices, accelerometers can then be integrated in the same pressure levels with gyroscopes. However, this comes at the expense of higher power consumption (required to operate them in an oscillator configuration), strong dependency on temperature (due to the temperature coefficient of frequency), and increased system complexity.

As an alternative, the use of deep-submicron capacitive gaps has been proposed and demonstrated as a technique for the reduction of Q values in accelerometers operating at low pressures [5]. In this paper, this technique is utilized for the implementation of single proof-mass tri-axial capacitive accelerometers co-integrated in the same wafer-level package with bulk-acoustic wave (BAW) tri-axial gyroscopes in a moderate vacuum environment (1 – 10 Torr). The pressure range is optimized to achieve maximum Q for the high-frequency gyro without compromising accelerometer performance.

Acceleration sensors with proof-mass areas of 450x450 µm² were implemented on 40 µm-thick SOI wafers using the high-aspect-ratio poly and single-crystal silicon (HARPSSTM) process [6]. Out-of-plane capacitive nano-gaps (< 300 nm) provide high scale-factor and increased squeeze film damping (SFD) to guarantee stable behavior. The devices have been interfaced with front-end electronics to characterize their performance.

ACCELEROMETER DESIGN

![A schematic diagram of the proposed tri-axial accelerometer is shown in Fig. 1. The design consists of a pendulum-like structure composed of a 450x450x40 µm³ single-crystal silicon proof-mass anchored to the substrate by a cross-shaped polysilicon spring (Fig 2) [7]. The tethers that compose the spring are attached to the mass using a self-aligned process that prevents offsets in the center-of-mass, which would result in cross-axis sensitivity. Four pick-off electrodes placed on top of the moving structure are multiplexed to read out...](image-url)
changes in capacitance generated by the $x$-, $y$- and $z$-axis acceleration components. In presence of acceleration along the $x$-axis, the tethers act as torsional springs, allowing the mass to tilt. This causes a differential change in capacitance $\Delta C_x = (C_1 + C_2) - (C_3 + C_4)$, where $C_1$ through $C_4$ correspond to the individual capacitances between the proof-mass and fixed electrodes (Fig. 2). Similarly, acceleration along the $y$-axis causes a differential change of $\Delta C_y = (C_1 + C_3) - (C_2 + C_4)$. Lastly, $z$-axis acceleration produces out-of-plane translation of the proof-mass, causing an effective capacitance variation $\Delta C_z = (C_1 + C_2 + C_3 + C_4) - 4C_0$, where $C_0$ is the zero-input acceleration rest capacitance. Figure 3 shows the simulated displacement response in the presence of acceleration along each individual axis.

![Figure 2. Top and side SEM view of single-proof mass tri-axial accelerometer. Electrodes over pendulum mass are multiplexed to detect acceleration along all 3 axes.](image)

In a parallel-plate capacitive accelerometer, the overall scale-factor can be expressed as:

$$SF = \frac{\Delta C}{a_{in}} = \frac{n \varepsilon A_{elec}}{\omega_n^2 g_0^2}$$

(1)

where $\omega_n$ is the resonance frequency of the structure and $n$, $A_{elec}$ and $g_0$ are the number of electrodes, the electrode area and rest gap of the parallel plate capacitors, respectively. Therefore, the use of narrow capacitive gaps (~ 300 nm) between the top electrodes and the pendulum proof-mass provides large electromechanical coupling. This allows for the design of much smaller structures with larger resonance frequencies (~ 15 kHz) as compared to other commercial accelerometers (1 – 6 kHz), making them less prone to stiction during fabrication and more immune to shock and vibration. For instance, it takes up to 8,000 g to bring the proof-mass in contact with the electrodes separated by a 300 nm gap.

![Figure 3. Displacement simulation response to $x$, $y$- and $z$-axis input acceleration in ANSYS (electrodes not shown and displacements greatly exaggerated for clearer visualization).](image)

Capacitive nano-gaps also provide increased squeeze-film air damping to avoid high quality factors that could cause overshoot and ringing in the accelerometer response. In a parallel-plate moving capacitor, the damping coefficient $b$, which is inversely proportional to $Q$, can be expressed as [8]:

$$\frac{1}{Q} \propto b = n \mu_{eff} \frac{l}{w}$$

(2)

where $l$ and $w$ are the electrode length and width ($A_{elec} = w*l$) and $\mu_{eff}$ is the effective viscosity of the gas inside the package. The strong dependency of $b$ with respect to $g_0$ indicates that for gaps of only a few hundreds of nanometers, $Q$ can be reduced by 3 to 4 orders of magnitude in comparison with devices implemented with conventional capacitive gaps of 2 to 5 µm in the same pressure environment.

Equation (2) serves as a starting guideline for the initial selection of the required capacitive gaps. However, a more complete expression should be utilized to capture the effects of fluid-wall interactions, presence of release holes and non-trivial boundary conditions [8-10]. For the particular case of non-uniform wall displacements—such in the case of the $x$- and $y$-axis acceleration tilt response (Fig. 3)—close-form expressions are challenging to derive, thus finite element analysis (FEA) tools provide a much better estimation of $Q$.

Figure 4 shows the pressure distribution in the electrode gaps for the $x$-axis and $z$-axis response. $Q$ values of 0.5 and 0.6 were extracted at 10 Torr for the $x/y$- and $z$-axis response, respectively.

![Figure 4. Pressure distribution of squeeze-film damping simulation for (a) $x$-axis and (b) $z$-axis acceleration response. $Q_{xy} = 0.5$, $Q_z = 0.6$ at 10 Torr, and $Q_{xy} = 4$, $Q_z = 5$ at 1 Torr.](image)

FABRICATION

The single-proof mass tri-axial accelerometers were batch-fabricated with bulk-acoustic wave (BAW) tri-axial gyroscopes on a 40 µm-thick silicon-on-insulator (SOI) substrate utilizing a modified version of the HARPSS™ process [11]. Lateral trenches were etched through DRIE to define the proof-mass and electrodes in the device layer by the use of a thermal oxide mask. A 300 nm layer of sacrificial oxide was grown to define the lateral gaps required for the gyro. Trenches were filled with polysilicon and TEOS oxide to implement side electrodes. By growing an additional 300 nm thermal oxide layer, out-of-plane gaps were defined, followed by the deposition and patterning of polysilicon for top electrodes. The devices were then fully released in hydrofluoric acid (HF).

A capping wafer, which is processed independently, was bonded to the base wafer in order to provide hermetic wafer-level packaging (WLP). Figure 5 shows a visual image of a 6-degree-of-freedom inertial sensor consisting of the single proof-mass accelerometer co-integrated with high-frequency tri-axial gyroscopes [11, 12].
MEASUREMENT RESULT

The resonance response of the tri-axial accelerometer was first measured by probing an uncapped wafer inside a vacuum probe station with adjustable pressure. Electrodes C1 and C4 were tied to excite the device, whereas C2 and C3 were connected together to the input of a network analyzer; the proof mass was biased at the same potential as the electrodes, thus the measured peak frequencies are twice the value of the device resonances. This is attributed to the quadratic relation between the drive voltage and the generated excitation force. In this configuration, the x-axis and z-axis modes are primarily excited (Fig. 6), but small capacitance mismatches cause a minor response of y-axis mode. Measured values of 12 kHz and 14 kHz are in good agreement with designed frequencies of 13 kHz and 16 kHz for the x/y- and z-axis modes, respectively.

Figure 7 shows the Q values for the z-axis response at different vacuum levels. It is seen that for pressures above 200 mTorr, the device starts approaching a desired over-damped condition, which guarantees stable operation at the WLP pressure levels in the range of 1 to 10 Torr.

Accelerometers were mounted on an evaluation board and interfaced with a front-end switched-capacitor integrated circuit to verify functionality. Since mismatch between the parasitic capacitances translates into offset that limits or saturates the operation range of the electronics, additional compensation circuitry was implemented with discrete components to calibrate the system. A programmable voltage \( V_{cal} \) is switched between amplification phases to cancel the DC differential charge generated by the static capacitance offset (Fig. 8) [13].

Acceleration sensitivities of 5 mV/g, 6 mV/g and 11 mV/g measured for the x-, y- and z-axis response, respectively (Fig 9). Higher z-axis sensitivity is observed due to larger change in capacitance during out-of-plane translation as compared to in-plane tilting. Differences between x and y responses are attributed to alignment inaccuracies between the evaluation board and the shaker table. Higher sensitivity can be achieved by having larger gain through circuit optimization. Similarly, cross-axis sensitivity levels in the order of 1 to 3% shown in Fig. 10 can be further reduced by proper alignment methods the measurement setup in order to reach the simulated cross-axis value of < 0.1% (Table 1).

The measured output noise of the system (MEMS+IC) is in the order of 3 to 6 mg/\( \sqrt{Hz} \), with a bias drift of 20 mg. This is attributed to the discrete electronics added for the offset calibration scheme (Fig. 11). Adding the calibration on-chip and further optimization will make the response Brownian noise limited, which is designed to be 30 \( \mu g/\sqrt{Hz} \) at 10 Torr.
**CONCLUSIONS**

A new single proof-mass tri-axial capacitive accelerometer, co-integrated with high-frequency BAW gyroscopes, was designed and fully characterized. Capacitive nano-gaps were used to achieve increased sensitivities using small form-factor structures, which provide high immunity to shock and vibration. Additionally, the small gaps provide optimal squeeze-film damping to stabilize accelerometer response in low-pressure environments, preventing the device from undergoing overshoot and long settling times.

**Table 1. MEMS and system specifications**

<table>
<thead>
<tr>
<th>Accelemer Design Parameters</th>
<th>Dimensions</th>
<th>Brownian noise</th>
<th>Resonance Frequency</th>
<th>Bandwidth</th>
<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>450 μm x 450 μm x 40 μm (proof mass)</td>
<td>13 μg/√Hz (x/y-axis), 30 μg/√Hz (z-axis) @ 10 Torr (worst case)</td>
<td>12 kHz (x/y-axis), 14 kHz (z-axis)</td>
<td>6 kHz (x/y-axis), 10 kHz (z-axis) @ 10 Torr (worst case)</td>
<td>3.0 fF/g (x/y-axis), 8.0 fF/g (z-axis)</td>
</tr>
<tr>
<td>Cross-axis Sensivity (% of FS)</td>
<td>Simulation @ 20 g</td>
<td>Measured @ 6 g</td>
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| Nonlinearity (% of FS) | 0.5% (x/y-axis), 1.0% (z-axis) |

**MEMS + Interface IC**

| C/V gain | ~ 2 mV/μF |
| Sensitivity | 6 mV/g (x), 5 mV/g (y), 11 mV/g (z) |
| Noise floor | -90 dBVrms/√Hz @ 1 Hz |

**REFERENCES**


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