Design, Modelling and Fabrication of a 40-330 Hz Dual-Mass MEMS Gyroscope on Thick-SOI Technology

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Abstract

This work reports the design, modelling, fabrication and preliminary functionality testing of a dual-mass MEMS vibratory gyroscope for application in medical instrumentation, among others. The two-framed gyro has drive and sense mode resonance frequencies of 2500Hz and 2830Hz, with its bandwidth tunable between 40-330Hz. Adopted design and technological features such as the use of double-folded springs, quadrature-error-compensation electrodes and 50µm thick-SOI mechanical layer enable high resolution sensing. The designed sensor characteristics have been validated using FEM simulation and equivalent circuit modelling.

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Keywords: gyroscope, angular rate sensor, SOI MEMS, modal decoupling, medical instrumentation

1. Introduction

Certain applications in medical instrumentation require small sized and high resolution gyroscopes which can be realised in MEMS technology. Interestingly, gyroscope can be used as a part of an inertial measurement unit (IMU) for detecting physiological hand tremors of surgeons, and for tracking the orientation and position of micro-surgical tools in minimal invasive surgery [1,2]. For this application, typically a– sensitivity of 20 mV°/s, resolution of 0.01°/s, bandwidth of 40-330 Hz and dynamic range of 500°/s are required [2]. In this paper, we present a two-mass decoupled gyroscope that was designed in a collaborative research study carried out in [2] towards implementation in a post-CMOS high aspect ratio thick-SOI MEMS technology realised by backside micromachining described in [3] and developed later.

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2. Sensor Design and Modelling

A decoupled gyro design was chosen as it offers higher resolution, improved robustness, opportunity for bandwidth tuning and reduced cross-axis mode coupling, which are essential for achieving high performance angular rate sensing [4,5]. The designed gyro structure (Fig. 1a) features an outer drive mass, \(m_1\), coupled to an inner sense mass, \(m_2\), via the sense springs. Modal decoupling of the drive and sense mode motion is achieved in the design by addition of separate drive and sense masses and by including robust double-folded springs. The force-deflection curves revealing linear spring characteristics for the drive and sense springs are shown in Fig. 1b. The electromechanical design parameters are summarised in Table 1.

![Image of dual-mass MEMS gyroscope structure](image)

![Image of drive and sense spring characteristics](image)

**Table 1. Electromechanical design parameters of the 2-framed MEMS gyroscope**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Dimension</td>
<td>3x3 mm(^2)</td>
</tr>
<tr>
<td>Mechanical Layer Thickness</td>
<td>50 (\mu)m</td>
</tr>
<tr>
<td>Bandwidth (tunable)</td>
<td>40-330 Hz</td>
</tr>
<tr>
<td>Drive Mode Resonance Frequency</td>
<td>2500 Hz</td>
</tr>
<tr>
<td>Sense Mode Resonance Frequency</td>
<td>2830 Hz</td>
</tr>
<tr>
<td>Nominal Sense Capacitance per Side, (C_0)</td>
<td>5.89 pF</td>
</tr>
<tr>
<td>Sense Capacitance Change per Side, (\triangle C)</td>
<td>0.546 pF</td>
</tr>
<tr>
<td>Sense Tuning/ Quadrature-error Correction Comb Capacitance</td>
<td>1.41 pF</td>
</tr>
<tr>
<td>Mechanical Resolution</td>
<td>0.01 °/s</td>
</tr>
<tr>
<td>Electrical Sensitivity (ideal case)</td>
<td>73 mV/°/s</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>96 dB</td>
</tr>
<tr>
<td>Pull-in &amp; Tuning Voltage</td>
<td>41 V &amp; 1.5 V</td>
</tr>
</tbody>
</table>

To validate the gyro design and obtain its characteristics, finite element simulations using COMSOL and equivalent electrical circuit modelling with Agilent ADS were performed. The resonance characteristics were firstly obtained from the electrical equivalent circuit model of the electromechanical gyro, based on analytical modelling. The drive and sense mode resonance frequencies (Fig. 2a) were found to be 2500Hz and 2830Hz, respectively. The gyro design was then layouted and the structure was simulated using finite element method, in order to validate the spectral responses for the drive and sense modes. The simulation results presented in Figs. 2b and 2c confirm the resonance frequency values obtained using the electrical model. In the gyro design, the bandwidth is made tunable from 40-330Hz by applying a DC tuning voltage to the sense mass. The tuning electrodes can also be used for sense quadrature correction or self-test. However, quadrature-error compensation is preferably done on the drive mass, as the large amplitude drive mass motion transfers the vibrations into the sense mass including the quadrature. The sensor achieves an estimated theoretical resolution and sensitivity of 0.01°/s and 73 mV/°/s (~1.08 fF/°/s), respectively.
3. Microfabrication

The gyroscope was implemented in a custom 50µm thick-SOI MEMS technology (Fig. 3a) that allows CMOS-compatible MEMS post-processing, as described in [3]. In this work however, the starting material was a 100mm low ohmic SOI wafer on which a layer of Al-1%Si metal was sputtered for electrical contacts. This layer could be patterned, optionally, to define electrical bond pads at specified locations. Later, a thin layer of PECVD SiO₂ hard mask was deposited and patterned. A 3µm thick photoresist layer was then spun and lithographically patterned. The gyroscope structure was defined by etching the underlying oxide and aluminium hard mask materials to expose the device silicon layer. The silicon layer was then micromachined using the Bosch deep reactive ion etching (DRIE) RIE process optimised in [6] for creating the high aspect ratio 3D MEMS structure, landing on the buried oxide (BOX) etch-stop layer. The buried oxide was sacrifically wet etched in 73% HF solution to release the microstructures. Subsequently, a MEMS release step using freeze-drying process with Cyclohexane was performed in order to minimise stiction of released microstructures.

4. Results and Discussions

The scanning electron micrograph of the fabricated device is shown in Fig. 3b. The insets show the spring details. The large structural thickness leads to a higher inertial mass and larger spring constant in the vertical direction. This implementation translates into a direct increase in the mechanical sensitivity, while reducing the influence of external $a_z$ accelerations. A large number of sense electrodes were included, aiming at improving the electrical device sensitivity and the signal to noise ratio. Consequently,
severe lateral stiction was observed after fabrication that limited the device yield. Preliminary electrical test was performed on a released device to check device functionality. The CV plot in Fig. 4a was obtained by moving the sense mass away from the sense electrodes by applying drive voltage on the opposite side. The nominal capacitance is different from the designed value due to observed stiction and broken combs. The CV plot from the sense tuning cum quadrature compensation electrodes in Fig. 4b indicates a nominal capacitance of 1.39pF that is in agreement with the designed value of 1.41pF.

![Fig. 4](image)

Fig. 4. (a, left) CV response plot obtained from the sense electrodes with stiction by moving the sense mass away from the fixed sense electrodes; (b, right) CV response plot obtained from the sense tuning cum quadrature compensation electrodes.

5. Conclusions and Future Work

The design, modelling and fabrication aspects of a two-framed thick-SOI MEMS gyroscope were presented. Preliminary device characterisation confirms functionality. Currently, the encountered stiction issue is being solved and a newly fabricated set of devices will be released. Future work includes detailed device characterisation and its comparison with a three-mass gyroscope design [7]. Suitable applications for the presented device include medical instrumentation, robotics, and platform stabilisation and control.

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References