Design and Simulation of SOI-MEMS Z-axis Capacitive Accelerometer

O. Sidek, M. Afif and M.A. Miskam

Abstract—The outstanding mechanical properties of silicon on insulator (SOI) wafers make it popular for high-performance MEMS sensors such as accelerometers. Other advantages include the fabrication of structures at a very high aspect ratio using deep reactive ion etching, facilitation of the integration of MEMS and integrated circuit on the same wafer, exhibition of superior electrical performances by effective electrical isolation between two silicon layers, and reduction of process complexity and costs using SiO2 as an etch stop. The current work demonstrates the design and simulation of a capacitive Z-axis accelerometer based on the SOI-MEMS technology.

Index Term—Capacitive accelerometer, silicon on insulator, MEMS, silicon on insulator, simulation

I. INTRODUCTION

Recently, there has been a gradual increase in the fabrication of MEMS accelerometers on SOI wafer [1]–[6]. This is due to various advantages of SOI wafer, namely, its superior material properties, capability to reduce process complexity and cost, and feasibility of MEMS and IC integration [6], [7]. Several SOI-MEMS accelerometers have been successfully designed and fabricated. However, few of them actualize a Z-axis accelerometer with differential capacitive sensing [2]. Thus, the demand for high-performance SOI-MEMS accelerometers (high sensitivity, high resolution, low noise, etc.) for various applications remains.

The majority of commercial MEMS accelerometers are presently used as capacitive-type sensing mechanisms due to their high sensitivity, low noise, low temperature sensitivity, and low power dissipation characteristics [8]. The design and simulation of an SOI-MEMS capacitive Z-axis accelerometer using the architect module in CoventorWare2010 is presented in this work. The main goals of this study are to achieve high sensitivity and wide bandwidth in an SOI-MEMS capacitive z-axis accelerometer.

II. MATERIAL AND METHODS

The capacitive accelerometer converts the displacement signal into an electrical signal. Figure 1 shows the layout of an SOI-MEMS capacitive Z-axis accelerometer. The proof mass is suspended by four compliant beams anchored to a fixed frame. The physical parameters of the beam in this device, such as the shape, geometry, and materials used, need to be carefully considered because they will influence the stiffness of the beam. Lowering the spring stiffness means reducing the natural frequency of the accelerometer, thereby reducing the operating bandwidth [9], [10]. To achieve the desired performance, it is necessary to ensure that the proof mass moves smoothly and the cross-axis sensitivity is low. To minimize the off axis deflection, the L-beam is designed and adjusted to be at the center of the device mass, so that when the force is acting on the device mass, the motion of the device mass is corresponding to the centre of gravity.

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The physical dimensions employed in the simulation are listed in Table I. The architect model is shown in Fig. 2. The steps of the fabrication process are illustrated in Fig. 3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Variable Name</th>
<th>Value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Width</td>
<td>W_P</td>
<td>1000</td>
</tr>
<tr>
<td>Plate Length</td>
<td>L_P</td>
<td>1000</td>
</tr>
<tr>
<td>Beam length:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam A</td>
<td>L_{Ba}</td>
<td>300</td>
</tr>
<tr>
<td>Beam B</td>
<td>L_{Bb}</td>
<td>380</td>
</tr>
<tr>
<td>Beam Width</td>
<td>W_B</td>
<td>50</td>
</tr>
<tr>
<td>Hole Width</td>
<td>W_h</td>
<td>50</td>
</tr>
<tr>
<td>Hole Length</td>
<td>L_h</td>
<td>50</td>
</tr>
<tr>
<td>Device Thickness</td>
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</tr>
<tr>
<td>Oxide Thickness</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Handle Thickness</td>
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<td>625</td>
</tr>
<tr>
<td>Aluminum Thickness</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

The SOI wafer used was produced using the SIMOX method [11]. The wafer consists of three layers: the handle layer located in the bottom, the silicon dioxide (SiO_2) layer in the middle, and the device layer at the top (Fig. 4). The middle layer separates the device layer and handle layer, and acts as a gap when the SiO_2 layer is etched in order to release the structure. The 1 µ gap between the device and handle layers has been controlled and optimized, ensuring that the gap is uniform when the SOI wafer is produced in the manufacturing stage. Thus, the optimized gap can be easily archived without compromising the masking design, which can be very costly. The process of fabrication can be simplified as well. The device layer at the top comprises beams, mass, and a plate that will couple with the handle layer at the bottom. These two layers then function as a sensor capacitance. Holes in the device plate have two purposes: (1) to ease the fabrication process when releasing the structure, enabling the SiO_2 layer in the middle layer to be conveniently etched through the holes, and (2) to repress the squeezed-film effect so that the accelerometer has a good frequency response.

The fabrication process begins with coating the device layer with 0.5 µm thick aluminum. The aluminum surface is then patterned using a positive photoresist. The patterned surface is sequentially etched by wet–etching, followed by DRIE etching of silicon. DRIE is used because of the high aspect ratio requirement for the device [6]. Finally, the device is released by etching away some of the oxide under the device layer using a buffered oxide etchant [12]. The 3D model is shown in Figure 4.
The capacitive sensitivity of the z-axis accelerometer is given by Equation (1).

\[ S = \frac{\Delta C}{a} = \left( \frac{C}{d} \right) \left( \frac{x}{a} \right) \]  

(1)

where \( C \) is the capacitance, \( a \) is the acceleration, \( d \) is the air gap, and \( x \) is the displacement of the proof mass.

III. RESULTS AND DISCUSSION

In this study, the length of multiple beams was varied to obtain the optimum and linear capacitance increment without lowering the sensitivity, and to easily develop the readout circuit. The effect of \( L_{bB} \) length is shown in Figure 6 and the physical parameter is listed in Table 1. From the results, the \( L_{bB} \) with a length of 380\( \mu \)m was choosing. Figure 5 shows the result of displacement and capacitance during a steady state condition at Time 0. The initial capacitance of the accelerometer was found to be approximately 7.325 pF, and the displacement at z, x, and y axis was very small. The length of the beam can greatly influence the total sensitivity and the performance of the device (Fig. 6). The performance required in terms of mechanical sensitivity can be raised to the desired performance by manipulating the length of the beam. The effort to increase the sensitivity by increasing the beam length will result in a complex readout circuitry. In addition, it will reduce the operating range of the accelerometer.

The resonant frequency for the z-axis is approximately 4.1 kHz (voltage pulse is set to 1 volt), whereas it remains the same in the x and y-axis, as shown in Fig. 7. In this simulation, the device is given an input from 0 until 50 g (1 g is equal to 9.98 ms\(^{-1}\)), as shown in Fig. 6. The output will then be in terms of capacitance, where the capacitance gradually increases when acceleration is increased. Capacitance is therefore directly proportional with acceleration in this case. The maximum capacitance observed at 50 g was measured to be approximately 26.133 pF. In the sensitivity analysis, the input acceleration was varied in from 0 to 1 g at a linear range with a step increment of 1 mg along the sense direction. In this condition, the sensitivity was found to be 103.551 fF and the displacement was found to be 14.622 nm, as shown in Fig. 9.
Table 2 below exhibits the summary of results from the simulation.

**TABLE 2**  
**SUMMARY OF THE RESULT**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Capacitance (pF)</td>
<td>7.325</td>
</tr>
</tbody>
</table>

Natural frequency (kHz):

- Z 4.1  
- X 4.1  
- Y 4.1  

Sensitivity per 1 g acceleration:

- Displacement 14.622 nm/g  
- Capacitance 103.55 fF/g

![Fig. 5. DC operating point analysis.](image1)

![Fig. 6. Simulation data for varied beam length](image2)
Fig. 7. Frequency response for the Z-axis accelerometer

Fig. 8. Acceleration vs. capacitance and displacement of the proof mass
IV. CONCLUSION

A design and simulation of SOI-MEMS capacitive z-axis accelerometer is examined in this paper. The designed accelerometer was found to be capable of actuating up to 50 g acceleration with sensitivity of approximately 103.551 fF. The beam length has significant influence on the sensitivity and operating bandwidth of the accelerometer. Therefore, the required performance and manufacturing capability can be achieved by compromising the structural design and fabrication process.

REFERENCES


