Design and Analysis of a Novel MEMS Dual Axis Accelerometer

Zijun He¹, Xingguo Xiong², Wei Quan³

Abstract – Due to their small size, low weight, low cost and low energy consumption, MEMS (Microelectromechanical Systems) devices have achieved great commercial success in recent decades. MEMS accelerometers have been widely used in automobile airbag deployment systems, inertial navigations, etc. In this paper, the design and simulation of a novel bulk-micromachined capacitive MEMS dual axis accelerometer based on Silicon-on-Glass (SoG) structure is proposed. Theoretical model is used to analyze the working principle of the accelerometer. Based on analysis, a set of optimized design parameters are suggested. ANSYS simulation is used to verify the function of the device. The device has Silicon-on-Glass compound structure based on silicon-glass anodic bonding, which can reduce parasitic capacitance and ease the signal detection. DRIE is used to pattern the silicon device structure. The fabrication flow of the MEMS accelerometer is also suggested. The proposed accelerometer can be used for 2-axis inertial navigation applications.

Keywords: Microelectromechanical Systems (MEMS), Accelerometer, Dual-axis Accelerometer, Silicon-on-Glass (SoG), Inertial Navigation.

INTRODUCTION

Micro-electro-mechanical systems (MEMS) are devices and systems integrated with mechanical elements, sensors, actuators, and electronic circuits on a common silicon substrate through microfabrication technology. As a newly developed interdisciplinary field, MEMS have achieved tremendous progress in recent decades. Due to their small size, low cost, low energy consumption and high resolution, MEMS have found applications in many different fields. As an example, MEMS accelerometers have been used in airbag deployment systems in automobiles, inertial navigation system, consumer products, etc. MEMS accelerometers based on different working principles have been reported, such as piezoresistive accelerometers [1], piezoelectric accelerometers [2], capacitive accelerometers [3], and optical accelerometers [4], etc. MEMS accelerometers are generally designed to sense acceleration only along one certain sensitive direction. If acceleration sensing along multiple axes is needed, several MEMS accelerometers with different sensitive directions are integrated. However, a more efficient solution is to fabricate a single MEMS accelerometer which can simultaneously sense accelerations along multiple axes (e.g. 2-axis or 3-axis accelerometers). Such multiple-axes accelerometers lead to more compact design and better signal integration. However, the design of multiple-axis accelerometers is more challenging due to signal coupling issue among different axes in the working mode. Some research work on multiple-axis MEMS accelerometer has been reported [5]-[10]. As shown in Fig.1 (a), a MEMS dual-axis accelerometer integrating two individual MEMS single-axis accelerometers in a single chip is reported [9]. It simply integrates two single-axis MEMS comb accelerometers in perpendicular to each other, with one sensing the acceleration along X direction and another one sensing the acceleration along Y direction. The two devices are independent from each other with separate beam, mass and comb fingers. As a result, the device design is simple, and there is no signal coupling issue.

¹ Department of Electrical Engineering, University of Bridgeport, CT 06604, Email: hzj422@hotmail.com
² Department of Electrical Engineering, University of Bridgeport, 221 University Avenue, Bridgeport, CT 06604, Email: xxiong@bridgeport.edu
³ Department of Electrical Engineering, University of Bridgeport, Bridgeport, CT 06604, Email: weiquan@bridgeport.edu
between two devices. However, such a simple design is not efficient and compact. As shown in Figure 1(b), a MEMS dual-axis accelerometer based on a single device structure is reported [10]. It utilizes differential capacitive sensing of comb finger groups attached to a single proof mass. The proof mass is supported by 8 folded beams properly arranged so that the mass can move along both X and Y directions. The 8 folded beams are located in the four corners of the square mass, with each corner containing 2 folded beams. If there is acceleration inputs along X and Y directions, the resulted inertial forces lead to bending of the folded beams, hence the proof mass move for a certain displacement along X and Y directions. There are four set of movable fingers extruding from the top, bottom, left and right sides of the square mass. For each movable finger, there are fixed fingers in its left/right (or top/bottom) sides, and together they constitute differential capacitance. When there is no acceleration input, the movable fingers stay in the middle between left/right (or top/bottom) fixed fingers, hence left/right (or top/bottom) capacitances are equal. If the movable fingers move due to inertial force, the capacitance gaps change and the resulted differential capacitance change can be measured, hence the input acceleration along X and Y directions can be determined. Various other dual-axis MEMS accelerometers have been reported. Due to their functional efficiency and compact structure design, MEMS dual-axis accelerometers have attracted interest from researchers and will continue to improve in the future.

![Figure 1](image1.png)

(a) Integration of separate devices in a single chip  
(b) Dual-axis accelerometer with single device structure

Figure 1. Reported research work of MEMS dual axis accelerometers [9][10]

In this paper, a dual-axis MEMS accelerometer based on differential comb capacitance sensing is reported. The device utilizes silicon DRIE (Deep Reactive Ion Etching) bulk-micromachining technique to increase the device thickness to more than 100µm. Compared to poly-Si surface-micromachined device, the device capacitance can be greatly increased, which makes the differential capacitance signal sensing easier. Further, the device utilized silicon-on-glass (SoG) compound structure. By using glass (insulator) as substrate, the parasitic capacitance can be greatly reduced compared to accelerometers using silicon as substrate. The device utilizes a single proof-mass for sensing of acceleration along both X and Y directions, which greatly improves the functional efficiency and leads to more compact structure design. The proposed MEMS dual-axis accelerometer can be used for inertial navigation system where acceleration sensing along two different directions is required.

**DUAL-AXIS ACCELEROMETER DESIGN**

The proposed bulk-micromachined MEMS capacitive dual-axis accelerometer structure is shown in Fig. 2. As seen in Figure 2, an H-shape central mass is connected to four vertical folded beams, which are in turn connected to two horizontal straight beams with one end anchored to substrate. There are 32 horizontal and 32 vertical movable fingers extruding from side and central mass respectively. Vertical movable fingers constitute differential capacitance with left/right fixed fingers on the top/bottom, and horizontal movable fingers constitute differential capacitance with top/bottom fixed fingers. The designed vertical folded beams and horizontal straight beams can bend along horizontal and vertical directions separately. As a result, if there is a horizontal acceleration, the resulted
inertial force on central mass causes the vertical folded-beams to bend. The vertical movable fingers move and by measuring the resulted differential capacitance change of vertical fingers, the input horizontal acceleration can be derived. If there is vertical acceleration input, the resulted inertial force on central mass causes the horizontal straight beams to bend. The horizontal movable fingers move and by measuring the resulted differential capacitance change of horizontal fingers, the input vertical acceleration can be derived. This is the working principle of the dual-axis MEMS accelerometer.

![Figure 2. Structure design of the MEMS dual-axis accelerometer](image1)

The differential capacitance sensing for MEMS comb accelerometer is shown in Figure 3. For simplicity, only a single capacitance group with one movable finger and its left/right fixed fingers is shown in the figure. The movable finger constitutes differential capacitance \( C_1 \) and \( C_2 \) with its left and right fixed fingers. When there is no acceleration \( (a=0) \), the movable fingers stay in middle between left and right fixed fingers. As shown in Figure 3(a), left capacitance \( C_1 \) equals to right capacitance \( C_2 \) and it can be expressed as

\[
C_1 = C_2 = C_0 = \frac{N \varepsilon_r \varepsilon_0 S}{d_0} = \frac{N \varepsilon_r \varepsilon_0 L_f}{d_0}
\]

where \( N \) is the number of comb finger groups, \( \varepsilon_r \) is the relative dielectric constant of air, \( \varepsilon_0 \) is the dielectric constant of vacuum \( (\varepsilon_0=8.85\times10^{-12} \text{F/m}) \), \( S \) is the overlap area between movable finger and fixed finger, \( t \) is device thickness, \( L_f \) is the length of movable fingers, and \( d_0 \) is static capacitance gap between movable and fixed finger (when \( a=0 \)).

![Figure 3. Differential capacitance sensing in MEMS accelerometer](image2)

When there is acceleration input along horizontal direction, the movable fingers move toward left or right due to the inertial force (see Figure 3(b)). As a result, the differential capacitance changes. If input acceleration is toward left direction, the movable fingers move toward right with displacement \( x \) along right direction, under small deflection approximation (assume \( x<<d_0 \)), then
In order to sense the differential capacitance change \( \Delta C = C_0(x/d_0) \), modulation voltages \(+V_s\) and \(-V_s\) are applied to the left and right (or top and bottom) fixed fingers separately, as shown in Figure 4, which has been discussed in many reference books.

Assume the voltage output in the movable finger is \( V_o \). According to charge conservation law, the charge stored in capacitance \( C_1 \) and \( C_2 \) should be equal. That is,

\[
(V_o + V_s)C_1 + (V_o - V_s)C_2 = 0
\]

Solving above equation, voltage output \( V_o \) in movable finger can be calculated as

\[
V_o = \frac{C_1 - C_2}{C_1 + C_2} V_s
\]

Based on Equations (1) and (2), we have:

\[
C_1 - C_2 = -2\Delta C
\]

\[
C_1 + C_2 = 2C_0
\]

Substituting Equations (5) and (6) to Equation (4), the output voltage \( V_o \) can be calculated as

\[
V_o \approx \frac{-\Delta C}{C_0} V_s = -\frac{x}{d} V_s
\]

From Equation (7), the output voltage is linearly proportional to the displacement of movable finger. Under small deflection approximation, the folded/straight beams can be treated as springs with effective spring constant \( k_{tot} \). In equilibrium state, the inertial force due to input acceleration and the restoring force of the beams are equal to each other. That is,

\[
F_{inertial} = M_s a = k_{tor} x
\]

Where \( M_s \) is the total sensing mass (including the proof mass, connectors and all the movable fingers), \( a \) is the input acceleration. Thus the input acceleration \( a \) can be calculated as

\[
a = \frac{k_{tor} x}{M_s}
\]

Then, making use of Equation (7), the acceleration is found to be proportional to voltage output:

\[
a = \frac{k_{tor} dV_o}{M_s V_s}
\]

As a result, the acceleration can be calculated by measuring the voltage output in the movable fingers. This is the working principle of most of the MEMS capacitive accelerometers.
DESIGN OPTIMIZATION AND SIMULATION

Assume the width, length and thickness of each section of the folded beams are \( W_{b1}, L_{b1} \) and \( t_{b1} \) separately, and the width, length and thickness of each straight beam are \( W_{b2}, L_{b2} \) and \( t_{b2} \) separately. The mass of H-shape mass is \( M_h \). Given Young’s modulus of Si material as \( E \), and gravity acceleration is \( g \).

Each section of the folded beam can be treated as double-clamped beam model. Its spring constant can be calculated as

\[
K_{b1} = \frac{12EI_{b1}}{L_{b1}^3} = \frac{Et_{b1}W_{b1}^3}{L_{b1}^3}
\]  

(11)

For each folded beam, two sections are connected in series. Thus, the spring constant of each folded beam is

\[
K_b = \frac{K_{b1}}{2} = \frac{12EI_{b1}}{2L_{b1}^3} = \frac{Et_{b1}W_{b1}^3}{2L_{b1}^3}
\]

The four folded beams are connected in parallel, thus the total spring constant \( K_{x,\text{tot}} \) of four folded beams along X axis is:

\[
K_{x,\text{tot}} = 4K_b = \frac{24EI_{b1}}{L_{b1}^3} = \frac{2Et_{b1}W_{b1}^3}{L_{b1}^3}
\]

(12)

where \( I_{b1} \) is moment of inertia of one section of the folded beam ( \( I_{b1} = \frac{1}{12}L_{b1}W_{b1}^3 \)).

The spring constant of one straight beam is \( K_{b2} \). Each straight beam can be treated as double-clamped beam model, with its spring constant

\[
K_{b2} = \frac{12EI_{b2}}{L_{b2}^3} = \frac{Et_{b2}W_{b2}^3}{L_{b2}^3}
\]

(13)

and the total spring constant of two straight beams ( \( K_{y,\text{tot}} \) ) along Y axis is

\[
K_{y,\text{tot}} = 2K_{b2} = \frac{24EI_{b2}}{L_{b2}^3} = \frac{2Et_{b2}W_{b2}^3}{L_{b2}^3}
\]

(14)

where \( I_{b2} \) is moment of inertia of one straight beam \( I_{b2} = \frac{1}{12}W_{b2}t_{b2}^3 \).

The X-axis displacement sensitivity of the accelerometer is defined as the displacement of movable fingers along X direction in response to \( 1g \) acceleration along X direction. It can be calculated as

\[
S_{dx} = \frac{F_{x,\text{inertial}}}{K_{x,\text{tot}}} = \frac{M_h g}{K_{x,\text{tot}}}
\]

(15)

Correspondingly, the Y-axis displacement sensitivity of the accelerometer is:

\[
S_{dy} = \frac{F_{y,\text{inertial}}}{K_{y,\text{tot}}} = \frac{M_h g}{K_{y,\text{tot}}}
\]

(16)

The resonant frequency of the accelerometer along X direction is

\[
f_x = \frac{1}{2\pi} \sqrt{\frac{K_{x,\text{tot}}}{M_h}}
\]

(17)

The resonant frequency of the accelerometer along Y direction is

\[
f_y = \frac{1}{2\pi} \sqrt{\frac{K_{y,\text{tot}}}{M_h}}
\]

(18)

Based on those equations, we plot the relationship between X-axis (Y-axis) displacement sensitivity and the width of folded beams (straight beams) respectively, as shown in Fig. 5. As shown in the figures, the X-axis (Y-axis) sensitivity is very sensitive to the width of folded beams (straight beams). If the beam width is reduced, the sensitivity increases very rapidly. The curves can guide us in the device design optimization. Based on the analysis,
we derived a set of optimized design parameters of the MEMS accelerometer, as shown in Table 1. The gap between two neighboring movable fingers is 20μm, the thickness of the device is 80μm.

![Relationship between the width of folded beam and Sensitivity](image1.png)

![Relationship between the width of straight beam and Sensitivity](image2.png)

Table 1. The optimized design parameters of the MEMS accelerometer

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
<th>Length(μm)</th>
<th>Width(μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central mass</td>
<td>1</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Side mass</td>
<td>4</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Movable Fingers</td>
<td>32</td>
<td>160</td>
<td>4</td>
</tr>
<tr>
<td>Folded beams</td>
<td>4</td>
<td>500 (1 section)</td>
<td>4</td>
</tr>
<tr>
<td>Straight beams</td>
<td>2</td>
<td>300 (1 section)</td>
<td>4</td>
</tr>
<tr>
<td>Connection mass</td>
<td>2</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>Connector1</td>
<td>4</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Connector2</td>
<td>2</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 5. Displacement sensitivity versus the width of beams

All of above analysis and calculation are based on theoretical model. In order for more accurate analysis, ANSYS FEM simulation is used verify the function of the device. Note that in ANSYS model, only the movable parts and the anchors are displayed. The fixed comb fingers only contribute to the differential capacitance of the device, but do not contribute to the displacement sensitivity analysis, resonant frequency analysis and stress distribution of the movable parts, thus they are not shown in the simulation.

**Sensitivity Simulation**

Displacement sensitivity of the accelerometer is simulated in ANSYS. Input acceleration (1g) is applied to the device in X direction and Y direction separately. Figure 6 shows ANSYS simulation result of displacement sensitivity when experiencing 1g (1g=9.8m/s²) acceleration along X or Y directions. From ANSYS simulation results, it is shown that the displacement sensitivity along X direction is $S_d=x=2.05\text{nm/g}$, and the displacement sensitivity along Y axis is $S_d=y=7.64\text{nm/g}$. This is in good agreement with our hand calculation results.
Stress Simulation

Stress distribution analysis can tell which part of the device experiences the largest stress when device is in its working mode. This is very important for the long term reliability of the device. Stress distribution of the accelerometer under the deflection in driving and sensing modes is simulated in ANSYS. Figure 7 shows the ANSYS contour plot of stress distribution when the device experiences acceleration input of 5g along X and Y directions. From ANSYS stress contour plot, we can see that the maximum stress occurs on the beams close to the anchors or close to the connectors of the beam section. As a result, in the device design, we intentionally widen these parts so that they can withstand more stress without being broken.
DEVICE FABRICATION

The fabrication sequence of the bulk-micromachined comb accelerometer is shown in Figure 8(a-i). The device is based on Silicon-on-Glass (SoG) compound structure. Silicon-glass anodic bonding and DRIE etching are used in the fabrication.

![Fabrication sequence of the accelerometer](image)

**Figure 8.** The fabrication sequence of the accelerometer

CONCLUSIONS AND FUTURE WORK

In this paper, the design and simulation of a novel bulk-micromachined capacitive MEMS dual axis accelerometer is proposed. Due to the design of beams, the H-shape mass can move along X and Y direction separately under corresponding inertial forces. Hence, the input acceleration along X and Y directions can be measured by differential capacitance sensing. Based on the analysis, an optimized design is suggested. ANSYS simulation is used to verify the device performance. The fabrication flow of the device is also proposed. In the future, we will look into the signal coupling between X and Y axis of the device, and minimize its influence by improving the device design.

REFERENCES


BIOGRAPHIES

Zijun He is a master student in Department of Electrical and Computer Engineering at University of Bridgeport, CT. He obtained his B.S. degree in Electrical Engineering in Ocean University of China, Shandong, China in 2006. His research interests include VLSI and MEMS.

Xingguo Xiong is an associate professor in Department of Electrical and Computer Engineering at University of Bridgeport, CT. His research interests include MEMS (Microelectromechanical Systems), nanotechnology, as well as VLSI design and testing.

Wei Quan is a master student in Department of Electrical and Computer Engineering at University of Bridgeport, CT. He obtained his B.S. degree in Electrical Engineering in Shandong University, China in 2010. His research interests include VLSI and MEMS.