A Novel Three-axis Comb Capacitive MEMS Accelerometer
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Abstract
Traditional MEMS (Microelectromechanical Systems) accelerometers generally can only sense acceleration input along certain direction. However, in reality, the measurement of acceleration inputs along all directions in 3-D space may be required for a complete inertial navigation system. In this project, a novel three-axis comb capacitive MEMS accelerometer is reported. By the ingenious structure design, the proposed three-axis MEMS accelerometer can simultaneously sense acceleration inputs from X, Y and Z axes. Differential comb capacitive sensing is used in the accelerometer. ANSYS simulation is used to verify the function of the designed accelerometer under different acceleration inputs. Simulation results verify the correct function of the designed accelerometer. The fabrication flow of the three-axis MEMS accelerometer is also proposed. The novel three-axis MEMS accelerometer can be used in gaming gesture sensing, complete inertial navigation system and other applications.

Introduction
MEMS accelerometers have been widely used in automobile air bag deployment system, aerospace inertial navigation, motion control, etc. Compared to traditional bulky accelerometer device, MEMS accelerometers have the advantages of small size, low weight, low cost, fast response, high sensitivity and low energy consumption. Most MEMS accelerometers are designed to sense acceleration input along one sensitive direction. However, in reality, acceleration in 3D space is a vector with components along all the X, Y and Z directions. For complete inertial navigation, acceleration measurement along all three axes is desired. One solution is to integrate three accelerometers in a single chip, with each accelerometer sensing acceleration along one axis. However, such hybrid integration is difficult to align the sensitive directions, and it may introduce larger parasitic effects. Some research work about dual-axis MEMS accelerometers have been reported. However, three-axis MEMS accelerometer which can simultaneously measure acceleration along all directions is very rare. Such single-device solution leads to more compact design without alignment error. It offers a more efficient solution for multi-axis acceleration sensing. In this research, we proposed a capacitive MEMS accelerometer which can simultaneously measure acceleration inputs along X, Y and Z direction. The design and working principle of the device is discussed. ANSYS simulation is used to verify the function of the accelerometer.

Design of MEMS Three-Axis Accelerometer
The structure design of the MEMS three-axis accelerometer is shown in Fig. 1. It consists of two sets of flexible beams: four outside L-shape beams and two straight torsional beams in center. The L-shape beam can bend along X and Y direction. This allows the central mass to sense acceleration input along both X and Y directions. Furthermore, the central torsional beams are connected to left and right plates which are not equal size. This asymmetric design is essential for Z-axis sensing. In case there is acceleration input along Z-axis, the left and right plates experience inertial force which is directly proportional to the sensing mass. Thus the larger plate experience larger inertial force than the smaller plate. This results in net torque and the sensing plates rotate along torsional beam. Left and right bottom electrodes are pre-deposited on the glass substrate below the plates. By sensing the differential capacitance change between the left/right plates and bottom Al electrodes, we can know the acceleration input along Z-direction. This is the working principle of the accelerometer. Part of comb finger group structure of accelerometer is shown in Fig. 2.

Design Optimization and ANSYS Simulation
Based on the analysis of the device, an optimized design of the three-axis MEMS accelerometer is shown in Figs 2-3. The detailed design parameters of the device is listed in Table 1. ANSYS modal simulation is used to verify the three working modes of the 3-axis MEMS accelerometer. The ANSYS model of the device is shown in Fig. 5.

Device Fabrication
The proposed three-axis MEMS accelerometer is to be fabricated with a typical CMOS-MEMS fabrication process. The single-crystalline silicon wafer is pre-etched from the bottom with a deep channel for releasing of movable microstructure. CMOS sensing circuitry is then fabricated on top of the silicon wafer. After that, surface-micromachining is used to fabricate the MEMS structure. The silicon DRIE (Deep Reactive Ion Etching) is then used to etch from the bottom to release the movable microstructure. This allows the MEMS device and signal sensing circuitry to be fabricated on a single chip, which greatly reduce the parasitic effects in hybrid integration. A typical commercial TSMC 0.35 CMOS fabrication technology through MOSIS is shown in Fig. 9.

Conclusions and Future Work
In this research, a novel monolithic tri-axis capacitive MEMS accelerometer is proposed. Due to the ingenious structure design, by utilizing a single proof mass, the acceleration along all three axes (X, Y and Z) can be measured. The device structure design and working principle analysis are discussed. Based on the analysis, an optimized design of the accelerometer is proposed. ANSYS simulation is used to verify the three working modes of the accelerometer. The accelerometer is to be fabricated with a typical Silicon CMOS-MEMS process, which allows the signal sensing circuitry to be monolithically integrated with the MEMS structure. The proposed accelerometer has low cross-axis sensitivity and less parasitic effects compared to the traditional three-axis accelerometer made by hybrid integration of single-axis accelerometers. In the future, we will have the device fabricated and test its performance.

Table 1. The design parameters of three-axis MEMS accelerometer

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Design Parameters</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>150×150</td>
<td>Anchor length, width (µm)</td>
<td></td>
</tr>
<tr>
<td>1500×1500</td>
<td>Elastic beams length, width (µm)</td>
<td></td>
</tr>
<tr>
<td>4500×7500</td>
<td>Central fixed mass (part I) length, width (µm)</td>
<td></td>
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<tr>
<td>1500×600</td>
<td>Central fixed mass (part II) length, width (µm)</td>
<td></td>
</tr>
<tr>
<td>4500×650</td>
<td>X-axis fixed mass length, width(µm)</td>
<td></td>
</tr>
<tr>
<td>4500×600</td>
<td>Y-axis fixed mass length, width(µm)</td>
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</tr>
<tr>
<td>1500×1500</td>
<td>Z-axis main mass (part I) length, width (µm)</td>
<td></td>
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<tr>
<td>1500×300</td>
<td>Z-axis main mass (part II) length, width (µm)</td>
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<tr>
<td>1200×750</td>
<td>Z-axis differential mass length, width (µm)</td>
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<tr>
<td>750×24</td>
<td>Fixed fingers length, width (µm)</td>
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</tr>
<tr>
<td>750×24</td>
<td>Movable fingers length, width (µm)</td>
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</tr>
<tr>
<td>1500×30</td>
<td>Electrode (µm)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Structure design of 3-axis MEMS accelerometer
Fig. 2. Comb capacitance sensing of the accelerometer
Fig. 3. Design parameters of accelerometer comb fingers
Fig. 4. Detailed design parameters of the accelerometer from Table 1
Fig. 5. ANSYS model of 3-axis MEMS accelerometer (3D view)
Fig. 6. ANSYS simulation of 1st working mode (f0=643.1Hz)
Fig. 7. ANSYS simulation of 2nd working mode (f0=685.147Hz)
Fig. 8. ANSYS simulation of 3rd working mode (f0=1209Hz)
Fig. 9. CMOS-MEMS fabrication process for the accelerometer

Design Parameters
Symbols
Dimensions
Anchor length, width (µm) 150×150
Elastic beams length, width (µm) 1500×1500
Central fixed mass (part I) length, width (µm) 4500×7500
Central fixed mass (part II) length, width (µm) 1500×600
X-axis fixed mass length, width(µm) 4500×650
Y-axis fixed mass length, width(µm) 4500×600
Z-axis main mass (part I) length, width (µm) 1500×1500
Z-axis main mass (part II) length, width (µm) 1500×300
Z-axis differential mass length, width (µm) 1200×750
Fixed fingers length, width (µm) 750×24
Movable fingers length, width (µm) 750×24
Electrode (µm) 1500×30