A 3-Axis MEMS Capacitive Accelerometer Free of Cross Axis Sensitivity

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Abstract—**This paper describes integrated multi-axis MEMS capacitive accelerometer by using a set of vertical and horizontal electrodes. The proposed device has only one silicon proof mass which all detecting electrodes were located on it. 3-axis acceleration was detected by using a set of newly proposed movable and fixed, vertical and horizontal comb electrodes of different lengths. The structure employs capacitive transduction mechanism which provides high reliability, low temperature sensitivity, low drift, and low power consumption. It is introduced a new technique to eliminate the cross-axis sensitivity based on orientation and location of the electrodes. The proposed method is suitable for multi axis, acceleration detection systems such as automotive. The total sensing area for sensing all axis acceleration was 1.85 mm^2. The ranges of measurable acceleration for in-plane (X and Y directions) and out plane (Z direction) are ±67g and ±18 g respectively. The resolution of all directions is 1g.**

Keywords-3-axis capacitive accelerometer, MEMS sensor, free cross axis sensitivity, comb electrode

I. Introduction

An accelerometer is a sensor that measures the physical acceleration experienced by an object due to inertial forces or due to mechanical excitation. Designing sensors with MEMS technology have advantages of miniaturization, low cost, low power and good dynamic characteristics. Accelerometers as a major member of MEMS sensors, have been broadly used in different applications such as: vibration checking systems, inertial guidance, mobile devices, biomedical and automotive applications [1-9].

The accelerometers are classified due to their sensing method for example: tunneling, piezoelectric, pizoresistive and capacitive [1, 2, 7]. The capacitive sensors are preferred in microelectronics because of their compatibility to CMOS technology, less thermal sensitivity, high accuracy, low power consumption and low noise [2, 3, 8, 9].

Capacitive position sensing is done by interdigitated comb electrodes. They have become an integral part of many MEMS devices such as pressure sensors, gyroscopes and accelerometers. However, lateral accelerometers have been developed using comb electrodes and differentially detecting parallel electrodes to obtain linear output. The use of vertical capacitance change between comb fingers is limited by parasitic capacitance among fixed and movable electrodes and electrical isolation difficulties. There are many reported accelerometers in literature but most of them are one or two axis sensors [3, 5] and usually they suffered from cross axis sensitivity which decrease device performance. For detecting acceleration in more than one direction, generally designers use more than one proof mass i.e. for each direction a proof mass is embedded [4, 6].

In this work to measure acceleration on 3-axis, it is proposed a unique configuration of electrodes which enables the sensor to measure acceleration in multi axis by one proof mass. The presented structure eliminate cross axis sensitivity in all directions of capacitive micro-machined accelerometer. Upcoming section describes the device operational principles and structural design. Next, simulation results are exhibited and then suggested fabrication process is explained. The paper is finalized by conclusion.

II. Operation principles and structural design

As the dimension of electrodes in MEMS sensors are in micron thus the fringing field has a noticeable effect on the total capacitance variation. The fringe capacitance is due to electrical field on the edge of electrodes, selecting electrodes shape is crucial in device performance. According to [1] rectangular shape is good choice due to its moderate displacement and capacitance variation compared to others. Consequently, it is choose for designing proposed sensor. The whole suggested design is shown in Fig.1. The vertical and horizontal comb electrodes are designed to sense acceleration in X and Y axis respectively. However, the central Square shape electrode is embedded to detect acceleration in Z axis direction. Capacitance variation in X and Y directions is due to area changing between fixed and movable electrodes but in Z axis is due to distance changing between them. As shown in Fig. 1 and 2 capacitance changing in 2 directions (X, Y) is differentially and is due to area changing among electrodes. This structure is free of cross axis sensitivity in all directions. The movable electrode fingers are smaller than their fixed counterparts which enable the device to detect 3-axis accelerations without any interface on each other. To the best of authors' knowledge, this is first time a 3-axis accelerometer is designed free of cross axis sensitivity.

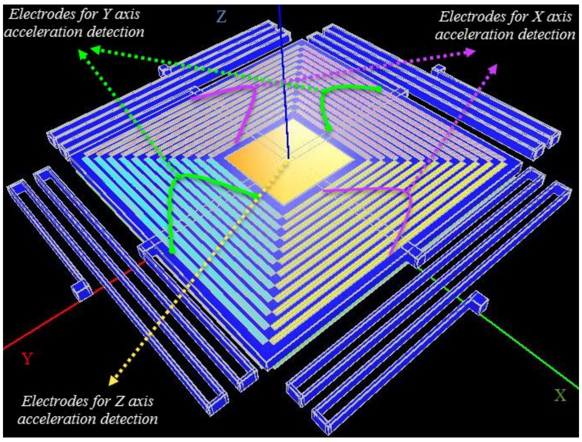


Figure 1. 3D view of Proposed Structure

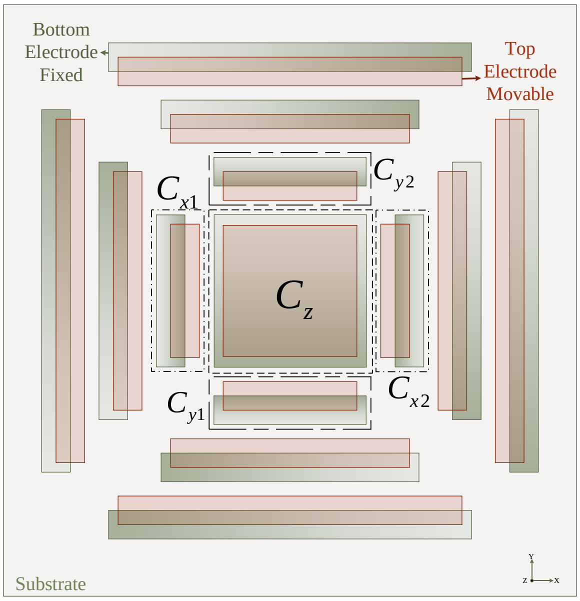


Figure 2. Arrangement of electrodes (2D top view)

To show eliminating cross axis sensitivity by new configuration, the simple capacitance relation (C=kA/D), is used. As the structure measures acceleration in 3-axis, so the investigation should be done for all directions separately. Calculations for applied acceleration in X and Y axis electrodes due to similarity is the same, thus calculation is done for X axis. The capacitance variation is calculated in 3 conditions:

- Applied acceleration is in plane (X or Y)
- Applied acceleration is in out plane (Z)
- Applied acceleration is in both out & in plane (Z&X or Z&Y)
- Applied acceleration is in three directions(X&Y&Z)

Since for each of mentioned states the capacitive changing is detected by separated electrodes, then the electronic circuit can easily detects acceleration orientation.

A. *Applied acceleration is in plane (X or Y)*

Figure 2 shows sample of electrodes embedded for acceleration detecting on 3-axis. Since movable electrodes are smaller than their fixed counterparts, then Y and Z electrodes do not sense applied acceleration in X axis. This results in eliminating cross axis sensitivity completely. In other words, displacement of movable electrodes in X orientation will not change capacitance between Y and Z embedded electrodes. If it is considered that the acceleration applied just in X axis in positive direction, then total capacitance changing before and after acceleration applying can be calculated as:

$$\Delta c = c_{x2} - c_{x1} = 0 \qquad (1a)$$

$$\Delta c = c_{x2,x} - c_{x1,x} = k\left(\frac{A+\Delta a}{D} - \frac{A-\Delta a}{D}\right) = k\frac{2\Delta a}{D} \qquad (1b)$$

Where in ($C_{\Delta⌂,\square}$), Δ defines the axis which capacitance is belong to, ⌂ shows number of capacitance and □ denotes the axis which acceleration is applied in. Since $C_{X2,X}$ is increased and $C_{X1,X}$ is decreased, the analyzing part can easily detect the acceleration orientation. According the symmetry of detection electrodes for Y and X axis, when the applied acceleration will be just on Y axis, calculation will be the same. Furthermore, Y axis acceleration will not changes capacitances for X and Z directions. If the acceleration is exerted to X and Y axis capacitance variation calculation will be same as one direction case.

B. *Applied acceleration is in out plane (Z)*

If the applied acceleration is in Z axis, then the capacitance changing can be derived as:

$$c_{x2x} = c_{x1x} = k\left(\frac{A}{D+\Delta d}\right) \rightarrow \Delta c = 0 \qquad (2)$$

For Y axis, it is like as X case. For the square electrode, C_Z is decreased if acceleration is in positive Z direction and increased if it is in negative Z direction. The governing equations for the capacitance variation due to the acceleration in positive direction will be:

$$c_Z = k\frac{A}{D}, \quad c_{Z,Z} = k\frac{A}{D+\Delta d} \qquad (3a)$$

$$\frac{1}{\Delta c_Z} = \frac{1}{c_{Z,Z}} - \frac{1}{c_Z} = \frac{D+\Delta d}{kA} - \frac{D}{kA} = \frac{\Delta d}{kA} \qquad (3b)$$

C. *Applied acceleration is in both out & in plane (Z&X or Z&Y)*

If the acceleration is exerted to two-axis (out & in plane), two circumstances occur, XZ and YZ.

For XZ case, capacitance calculations are as:

$$\Delta c_x = c_{x2,xz} - c_{x1,xz} = k\left(\frac{A+\Delta a}{D} - \frac{A-\Delta a}{D}\right) = k\frac{2\Delta a}{D} \qquad (4a)$$

$$\Delta c_y = c_{y2,xz} - c_{y1,xz} = 0 \qquad (4b)$$

$$\frac{1}{\Delta c_Z} = \frac{1}{c_{Z,XZ}} - \frac{1}{c_Z} = \frac{D+\Delta d}{kA} - \frac{D}{kA} = \frac{\Delta d}{kA} \quad (4c)$$

The YZ case is same as XZ.

D. *Applied acceleration is in three directions(X&Y&Z)*

If acceleration is applied in 3-axis i.e. XYZ, capacitance variation calculation in all orientations are as:

$$\Delta c_x = \frac{c_z}{c_{z,xyz}}(c_{x2,xyz} - c_{x1,xyz}) = k\frac{D+\Delta d}{D}\left(\frac{A+\Delta a}{D+\Delta d} - \frac{A-\Delta a}{D+\Delta d}\right) = k\frac{2\Delta a}{D} \quad (6a)$$

$$\Delta c_y = \frac{c_z}{c_{z,xyz}}(c_{y2,xyz} - c_{y1,xyz}) = k\frac{D+\Delta d}{D}\left(\frac{A+\Delta a}{D+\Delta d} - \frac{A-\Delta a}{D+\Delta d}\right) = k\frac{2\Delta a}{D} \quad (6b)$$

$$\frac{1}{\Delta c_Z} = \frac{1}{c_{Z,XYZ}} - \frac{1}{c_Z} = \frac{D+\Delta d}{kA} - \frac{D}{kA} = \frac{\Delta d}{kA} \quad (6c)$$

By comparing all states, it can be seen that capacitance variation for all of them in each axis is same. In other words the sensor is capable to eliminate cross axis sensitivity in all directions.

III. FABRICATION PROCESS

As suggested structure is design by the aim of automotive application, the dimensions should be accurate. Consequently surface micromachining is selected to fabrication process. Furthermore, Pyrex substrate is chosen instead of silicon in order to eliminate parasitic capacitance among electrodes and substrate.

Surface micromachining fabrication process for suggested device can be written as:

1. Thermal wet oxidation (200nm)
2. Al evaporation for bottom electrode (0.5um)
3. Al pattern (forming bottom electrodes)
4. Spin photoresist for air gap and lithography (2um)
5. Polysilicon deposition by LPCVD (proof mass, 5um)
6. Sio2 deposition by LPCVD (to form dielectric of proof mass)
7. Sio2 and polysilicon pattern (forming proof mass)
8. Al evaporation for top electrode (0.5um)
9. Al pattern (forming top electrode)
10. releasing the structure (plasma ashing)

The final 2D structure is depicted in Fig. 3. The Y orientation capacitances cannot be seen in cross section figure.

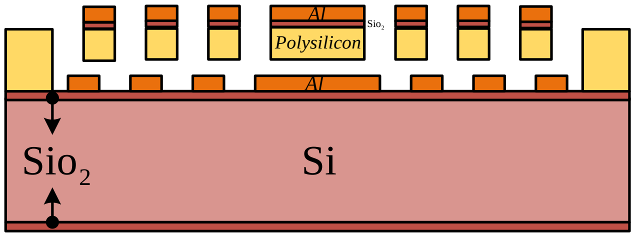


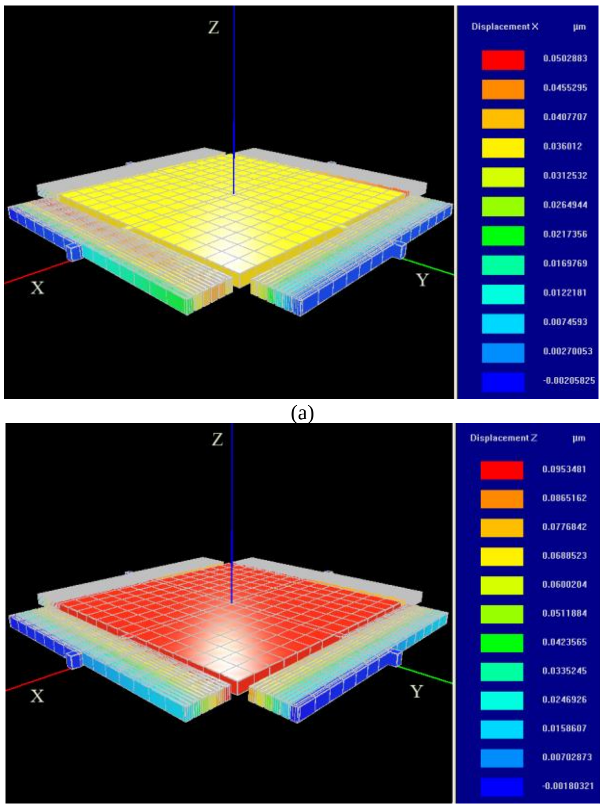
Figure 3. Cross section view of final structure

IV. SIMULATION RESULTS

The simulation of the designed accelerometer is done by a MEMS-specific CAD tool named IntelliSuite. Table I shows displacement versus applied acceleration in X, Y and Z axis. Fig. 4 shows displacement in X and Y and Z axis due to apply 1g acceleration. Fig. 5 and 6 depict displacement and capacitance variation versus applied acceleration for 3-axis, respectively.

TABLE I. ACCELERATION VERSUS DISPLACEMENT IN 3 AXIS

a (g)	**X Displacement (µm)**	**Y Displacement (µm)**	**Z Displacement (µm)**
1	0.036012	0.036012	0.09535
10	0.36012	0.36012	0.9535
20	0.72024	0.72024	1.907
40	1.44048	1.44048	-
60	2.16072	2.16072	-



(a)

(b)

Figure 4. Displacement in (a)X &Y, (b)Z axis due to 1g acceleration

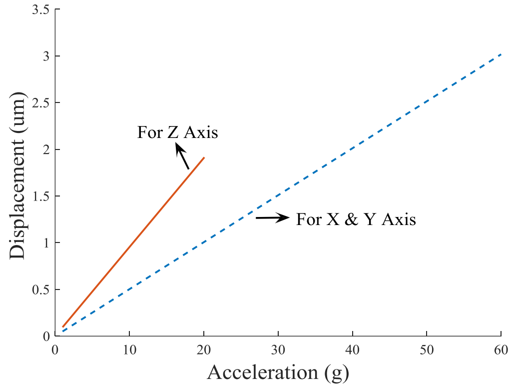


Figure 5. Displacement versus applied acceleration in 3-Axis

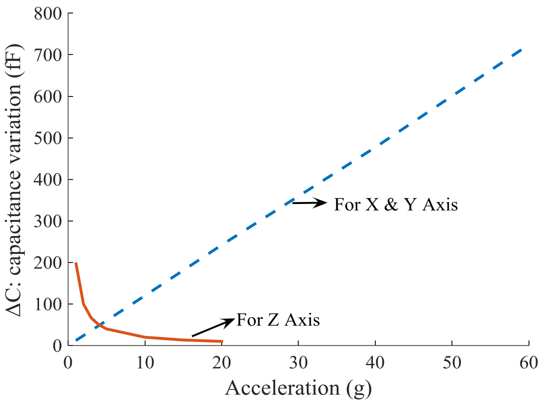


Figure 6. Capacitance Variation versus applied acceleration in 3-Axis

V. CONCLUSION

A new 3-axis acceleration's structure, fabrication process and simulation results are explained. The figure of merit of design was its entirely eliminating cross axis sensitivity. Furthermore, it could be measured acceleration in 3-axis with only one proof mass. On the other hand, in 3-axis, the applied acceleration has a linear relationship with the result of part II which is easily calculated by processing electronic circuits. The designed sensor is suitable for automotive application, therefore surface micromachining is chosen for fabrication process. The crucial characteristics of the accelerometer are given in table II.

TABLE II. ACCELEROMETER CHARACTERISTICS

Acceleration measuring axis		X, Y and Z
Mass		22.81 µgram
Range of measurable acceleration	X and Y	±67 g
	Z	±18 g
Spring constant in	X and Y	633.52
	Z	239.27
Sensitivity in	X and Y	12 fF/g
Total size		1.85 mm^2

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