Design and Simulation of a MEMS Based Dual Axis Capacitive Accelerometer

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Abstract- Micro Electro Mechanical Systems (MEMS) based multi axis accelerometers are embedded in many modern technological applications. These sensors are widely used in smart electronics, bio-medical uses, automobiles and aeronautics. The work followed herewith is focused on designing of a 2 degree of freedom (D.O.F) MEMS based capacitive accelerometer which can be used with such vibration detection modules. The 2mm x 2mm x 100µm sensor has a working range of up to ±16g and a failure limit of 20g The movement of a proof mass which is 74.5% of the sensor area is used to generate amplified voltage signals based on the theory of capacitance using a series of capacitive comb elements mounted on the perimeter of the sensor. Process simplification is achieved with the use of a single Silicon-on-Insulation (SOI) wafer and minimum masking material. The paper contains details on structural and motion analysis performed on the design and also contains techniques which can be used for the fabrication of the sensor and electrical contacts needed for the successful implementation of the sensor into electrical circuitry.

Keywords—, Capacitive accelerometer, MEMS, SOI, Comb drive

I. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) based sensors are widely used for various industrial and domestic applications. MEMS technology is used in the design and fabrication of a variety of sensors to measure acceleration, pressure, force, humidity and temperature. This is due to low weight, compactness and economical nature of these types of sensors.

One of the most common mechanical sensing principles is the analysis of the change in parameters associated with the movement of a mass. This principle is predominantly used in accelerometers. The design of accelerometers can be done based on principles of, piezo-resistivity and capacitance.

With the increasing trend of using accelerometers for smart devices i.e. mobile phones and tablet PCs, the demand for MEMS based sensors is constantly on the rise. An overall compound growth rate of 6.6% in MEMS based accelerometers has been predicted over the years leading up to 2019 [1]. The challenge however is to create sensors of high sensitivity while keeping its size and weight to a minimum.

This paper looks at the design and simulation of a 2 D.O.F. MEMS based capacitive accelerometer with dimensions of 2mm X 2mm X 100µm. The proposed design optimally utilizes the single crystal silicon wafer of a thickness of 100µm. Fabrication can be done with use of minimum masking material and process simplification in mind. The micromachining of the sensing structure can be done with the use of a single mask, thus further simplifying the fabrication process.

The device is fabricated on single crystal silicon using bulk micro machining technology. An 'X' shaped symmetric proof mass with capacitive Comb fingers is suspended via serpentine springs is act as the sensing elements. The change in capacitance in comb drive is used to measure the relevant acceleration

II. PROPOSED SENSOR

The main principle behind the operation of accelerometers is the conversion of inertial displacement of a proof mass into an electrical signal [2]. The proposed sensor is designed to detect the capacitance of attached comb drive mechanism as the proof mass exerts any displacement due to the acceleration.

The proposed 2 D.O.F capacitive accelerometer in Fig.1 consists of a proof mass of 0.656 mg, suspended using four serpentine spring structures attached at the centers of its four faces. The accelerometer has dimensions of 2 mm X 2 mm X 100 µm where the critical dimension has been selected as 10 µm (Table 1). The thickness has been selected as the same value as the minimum thickness of Silicon wafer proposed for the use of fabrication; 100µm. The proof mass has been spread over an area of 1.8 mm X 1.8 mm with an effective area of 2.98 mm^2. Since the total area of the sensor has been utilized for the proof mass of the accelerometer, the effectiveness of the sensor has been maximized and the sensitivity has been improved compared with the design suggested by Kaya [2].The proof mass features an array of holes with a diameter 12µm, distributed throughout its face with a distance between centers of 24µm (see Fig. 2). This array of holes has been used to remove the layer of SiO_2 to free the proof mass from the insulator layer during the fabrication process.

A serpentine spring design has been selected to improve the flexibility of the proof mass as it allows maximum displacement of the proof mass [3]. The thickness of the cross beams of the spring structure (see Fig. 3) is kept at 10µm to ensure an enhanced structural stiffness. The thickness of the spring beam is kept to 10µm to ensure the stiffness of the spring is lower than that of the beam, thus sufficient deflection during linear acceleration is provided from the set of four springs. The springs are integrated inside the proof mass thus maximizing the utilization of sensor area in order to enhance the sensitivity of the designed accelerometer.

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The capacitance of the sensor is measured at each face along the outer perimeter of the proof mass with the use of 8 separated comb drives which are coupled accordingly to cancel out noise generation. The proof mass itself acts as one terminal of the capacitor. A comb drive consists of 81 individual elements with dimensions of 3μm X 40μm X 100μm mounted on the fixed structural members. The comb on the proof mass has 80 individual elements.

A similar capacitive MEMS based accelerometer as suggested by T. Kaya [2] uses a chip area of $4mm^2$ with an effective area utilization of 3.9%. The proposed design, uses the same chip dimensions and wafer thickness yet reaches an effective area utilization of 74.5%. The main reason behind this is the configuration of the serpentine springs used to connect the proof mass to the outer structure. The mass has been designed in such a way that it surrounds the four springs to a greater extent than in previous designs thus resulting in an increase in proof mass. This increase in mass produces greater sensitivity. The capacitance achieved per 1 μm of the comb drive is 13.82μF which is 70 times greater than the work of Kaya. This natural intensity in signal strength negates the necessity of further amplification circuitry.

Furthermore the mode frequency of the spring arrangement is higher than that of [2]. Due to this the working range of the sensor is increased where it is believed as a rule of thumb, that the maximum working frequency of the sensor should be one third of the first mode frequency of the sensor.

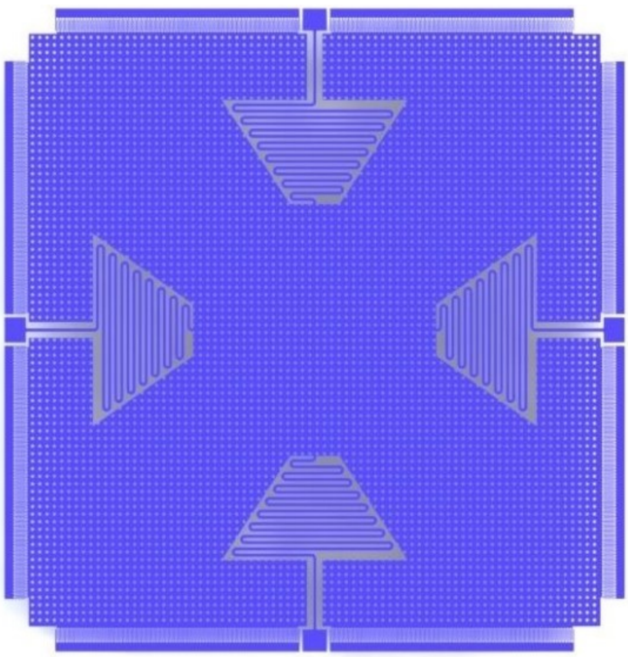

Fig. 1. Proposed capacitive accelerometer, the proof mass, serpentine springs and integrated fin structures

TABLE 1: BASIC PARAMETERS OF THE SENSOR

Size of the sensor	2 mm X 2 mm
Area of proof mass	2.98 mm^2
Weight of the proof mass	0.656 mg
Thickness of the wafer	100 μm
Thickness of the spring	10 μm
Diameter of the hole	12 μm

Dassault SolidWorks has been used for both the design of the accelerometer and the basic structural analysis of the accelerometer. *COMSOL 4.3a Multiphysics* has been used for further analysis of the accelerometer in terms of structural stability and performances under several linear accelerations

III. STRUCTURAL ANALYSIS

During structural analysis, the design of the accelerometer was subjected for several magnitudes of linear accelerations. For each of these cases, the response, i.e. the displacement of the proof mass in the DESIRED DIRECTION and the developed stresses were measured and graphed.

IV. WORKING PRINCIPLE

The motion of the proof mass is converted to a voltage signal based on the principle of capacitance. Neglecting the fringing effect near the edges, the parallel-plate capacitance is can be expressed as eq (1)

$$c = \varepsilon\frac{A}{d} = \varepsilon_0 A \tag{1}$$

Where $\varepsilon_0 = \varepsilon/d$ and A is the area of the electrodes, d the distance between them and ε the permittivity of the material separating them. The change in these parameters will be measured as a change in capacitance and variation of these three variables has been used in MEMS sensing.

A typical MEMS accelerometer is composed of a movable proof mass with plates that is attached through a mechanical suspension system to a reference frame. These movable plates and fixed outer plates represent capacitors. The deflection of proof mass is measured using the difference in capacitance. The free-space (air) capacitances between the movable plate and two stationary outer plates C1 and C2 are functions of the corresponding active capacitive area.

$$c_1 = \varepsilon_0(A + A_x) = c_0 + \Delta c\,, \tag{2}$$
$$c_2 = \varepsilon_0(A - A_x) = c_0 - \Delta c$$

If the acceleration is zero, the capacitances C1 and C2 are equal because Δc= 0. The proof mass displacement (x) results due to acceleration. If $x \neq 0$, the capacitance difference is found to be:

$$c_1 - c_2 = 2\Delta c = 2\varepsilon_0 x \tag{3}$$

Measuring ΔC, one finds the displacement x by solving linear algebraic equation:

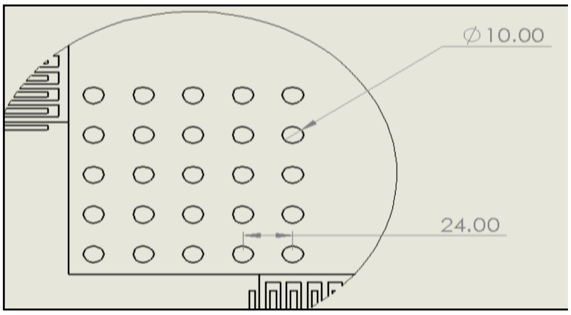

Fig. 2. Arrangement of the array of holes

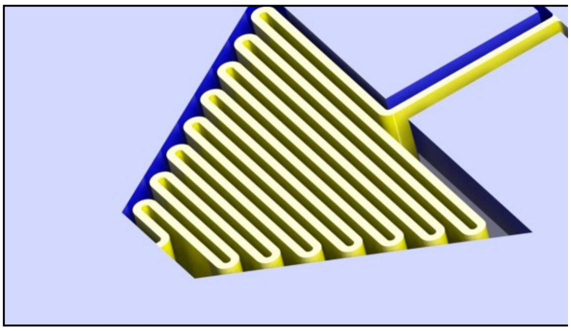

Fig. 3. The design of serpentine spring structure (each sensor has four of them)

$$x = \frac{\Delta c}{\varepsilon_0} \tag{4}$$

V. Arrangement of Sensing Element

Since the proposed accelerometer consists of a proof mass suspended by four serpentine springs, the maximum displacement under the application of linear accelerations is observed at the respective faces at the boundary. The sensing element and comb drive structure should be integrated at these faces where maximum displacement can be observed.

The comb drive structure has been integrated to two adjacent edges of the structure in order to get the required signal output.

The integration of the comb drive structure to each four corners of the proof mass has been done to reduce internal noise. In this case, feedback is taken from both parallel sensing elements for each directional acceleration. Thus a strong signal will reduce noises of deformations due to angular accelerations and gravitational forces [4, 5].

Integration of the comb drives with the designed structure is also easier as it can be obtained with the same manufacturing process.

VI. Electrical Circuit Designing

A simple Operational amplifier biased to the model will generate a sensible output relative to acceleration.

Here 4 separate comb drives used to get 4 different capacitive effects due to X, Y or XY combination of accelerations. There proof mass act as a single plate of a typical acceleration which surface area increased by a comb drive. Other plate of capacitor from sides of the proof mass steadily fixed to the die.

When considering Fig. 4 C1, C2, C3, C4 are capacitance generated by the acceleration or displacement of the proof mass. Cp1 and Cp2 are bias capacitors.

Voltage divider through capacitance difference enhance the sensitivity over a small change of acceleration.

Electrically isolated zones of proof mass have used to detect the separate capacitance

VII. Fabrication

The proposed fabrication process for the accelerometer is discussed in this section. The fabrication process starts with an SOI (Silicon-On-Insulation) wafer. The SOI wafer is used to fabricate the sensing element while an Al metal wafer is used as a substrate for metal interconnectors and signal inputs and outputs. The SOI wafer is in <100> orientation and has three layers;

- The device layer: This is used to build the sensing element and hence has the thickness of 100 µm.
- Oxide layer: This is used to separate the moving parts of sensing element from the holding layer and has the thickness of 2 µm.
- Handle wafer: this is used to handle the fixed parts of sensing element and has the thickness of 300 µm

A. Wafer Cleaning:

Cleaning the wafer with appropriate solvent, before use, is essential to remove any impurities that can disturb the fabrication process and overall function of the device.

B. Oxidation:

In order to grow a thin film of SiO_2 on the SIO wafer with 1 µm of thickness, dry oxidation is recommended.

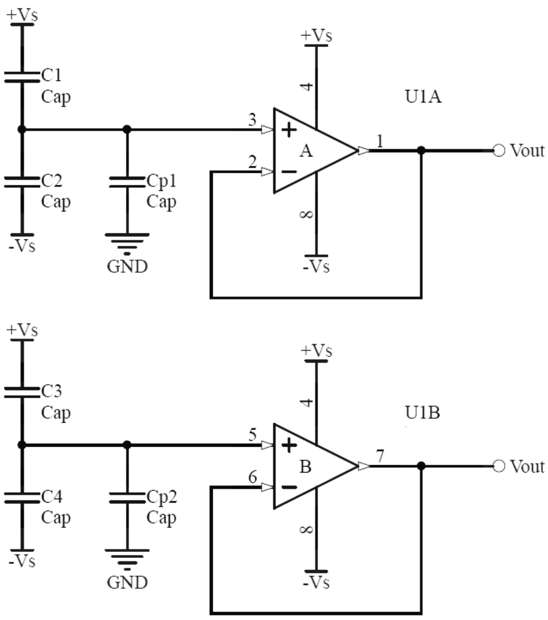

Fig. 4. Electrical Circuitry for Capacitance Measurements

C. Photolithography:

- Spin the positive photoresist material on the wafer surface to form a layer of photoresist with the thickness of 1 µm.
- Use the mask shown in Fig. 5 and expose it to UV light to transfer the pattern into the photoresist layer.
- Etch the SiO_2 layer by using wet etching method and use the KOH etchant. KOH etching rate on SiO_2 is 8 nm/min [6]. Therefore to etch 1 µm oxide layer the etchant should apply 2 hours and 5 minutes.
- Remove the photoresist.

The oxide layer which was in the SOI wafer should be removed from under the moving mass of our design (see Fig.6). The proposed method of doing so is to use small holes in the moving mass to pass the solvent into the oxide layer for dissolving. A proper predetermined dissolving time will ensure that no excess material from the oxide layer will be removed other than the materials under the moving mass and also no excess material remaining after the dissolving process directly under the moving mass.

The proposed etchant for this process is 5:1 BHF Oxide Ion-Mill and the etch rate at room temperature is set as 82 nm/min [6]. As the maximum wall thickness to be dissolved is 12 µm and it is in between holes of the moving mass body, the suggested etching time is 146 min.

D. Metallization

Electrical contacts which are needed to build the circuitry of the sensing parts is to be done by deposition of Al material on top of the sensing element. By using a separate mask, deposition of the Al connection on the Si layer at about 650 ^{0}C can be done.

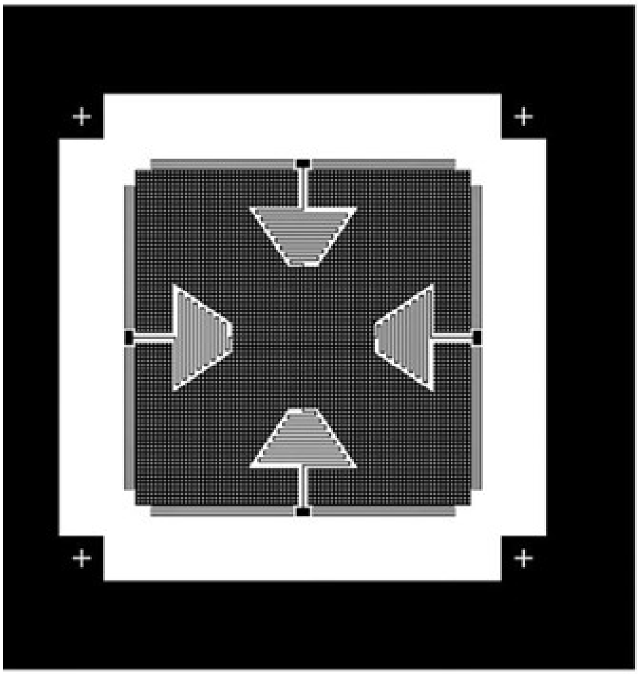

Fig. 5. Mask for photolithography

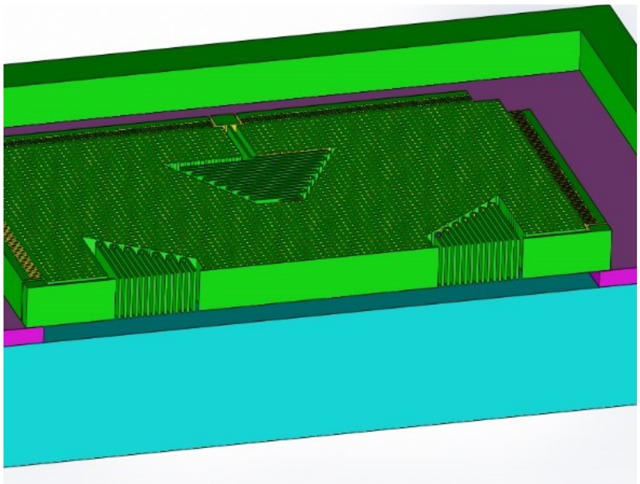

Fig. 6. After removing the oxide layer to form the moving mass (sliced)

VIII. Results and Discussion

From the simulation data we can obtain that the accelerometer exhibits a displacement of 2.1094 µm when it is subjected to an acceleration of 25 g (Fig. 7 & Table 2). but the minimum distance between the fingers of the comb drive is just 2µm thus implies that the displacement greater than that is quite impossible or not practical with the structure. There might be short circuiting or structural failures in the accelerometer with this amount of acceleration.

Therefore, the maximum possible acceleration should be limited to 16-g (156.96 ms^{-2}) to avoid any failures of the structure due to collisions and short circuits

Fig. 8 illustrates the variation of capacitance of the comb capacitors in one side of the accelerometer with respect to the acceleration values expressed in gravitational acceleration (g) terms. The capacitance is in the scale of Pico farads and the change of acceleration is in the scale of Femto farads.

TABLE 2: Variation of displacement of the proof mass w.r.t. acceleration

Acceleration (g)	Displacement (µm)
1	0.0844
2	0.1688
4	0.3349
6	0.5063
8	0.675
10	0.8438
16	1.35
20	1.6875
25	2.1094

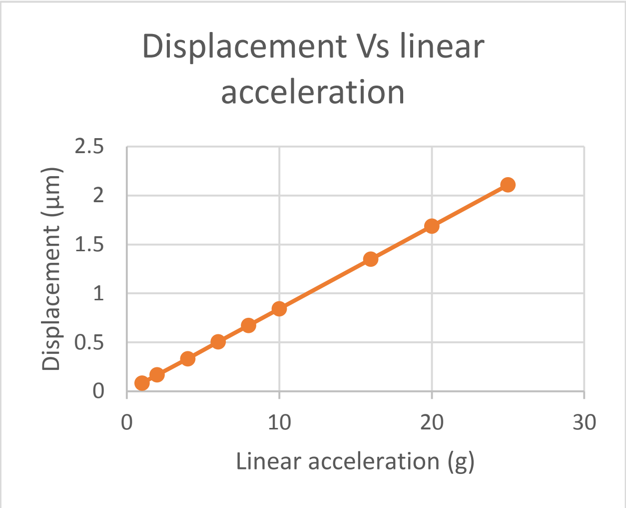

Fig. 7. Variation of the displacement vs. linear acceleration

The designed capacitive accelerometer was simulated for its first six mode frequencies and expressed in Table 3. The first mode frequency of the accelerometer is 1384.33 Hz and hence the accelerometer well suits to be used for vibrations of frequencies below that point.

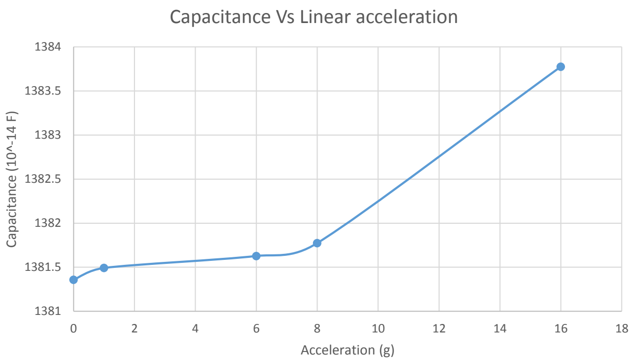

Fig. 8. Relationship between capacitance and linear acceleration

TABLE 3: FIRST 6 MODE FREQUENCIES

Mode	Frequency (Hz)
1	1384.88
2	1634.44
3	1637.17
4	2690.53
5	2691.91
6	3156.52

IX. CONCLUSION

From the simulation data we can obtain that the accelerometer exhibits a displacement of 2.1 µm when it is subjected to an acceleration of 25 g. but the minimum distance between the fingers of the comb drive is just 2µm thus implies that the displacement greater than that is quite impossible or not practical with the structure. There might be short circuiting or structural failures in the accelerometer with this amount of acceleration.

Therefore, the maximum possible acceleration should be limited to 16-g (156.96 ms^{-2}) to avoid any failures of the structure due to collisions and short circuits

The proposed design of capacitive accelerometer can be used as a vibration detecting module of a wireless sensor network of disaster preventing system. The suggested sensor is well suited for landslide prevention system since it has an operating range of ±16g. In addition to that the mode frequency of the sensor is well beyond the maximum frequency of a landslide [7] ensures more reliable and accurate results.

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