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Design and Analysis of 3D Capacitive Accelerometer for Automotive Applications

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Abstract: Accelerometer which detects rapid collisions with the ability to sustain wide range of shock is suitable for airbag deployment systems in automobiles. This issue can be met using prototype 3D capacitive accelerometers which are less prone to noise and temperature variations. They reduce the severity of the accident by sensing the sudden increase in negative acceleration and deployment of the airbags. The objective of this paper is to bring out the responsiveness of the capacitive accelerometer with changes in the input acceleration. The testing is done with 100g acceleration which is real time accident condition. Nanomaterials are used to enhance the shock survivability. The performance analysis of the device is done using COMSOL MULTIPHYSICS 4.1.It is analyzed that when the capacitance reaches a threshold value, amplifying the electric signal the air bag could be initiated.

Keywords: Air bag deployment, Capacitance, Proof mass.

1. Introduction

In the modern day to day world with increasing number of accidents, air bags are a necessity in the automobiles. An airbag is a vehicle safety device that consists of flexible envelope that prevents occupants from striking interior objects. Various devices such as accelerometers, gyroscopes, impact sensors are required to detect the impact of the collision. As the signal in the sensing device reaches a threshold value the deployment of the air bag should occur in few milliseconds. Thus rapid detection and sensitivity of the sensing device are an essential requirement.

The most common method to trigger an air bag system is to use MEMS accelerometers. It senses the sudden negative acceleration using changes in capacitance, voltage or resistance depending on the type of accelerometer used such as capacitive, piezoelectric or piezoresistive types.

Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications.

Various accelerometers based on piezoelectric and piezoresistive principles have already been in the market. Tri axial PZT accelerometer has been developed [1].Piezoelectric accelerometers have been designed in [1]. A capacitive sensor provides an upper hand to the above in various ways. Capacitive accelerometers are ideal enough since they are less prone to noise and temperature as compared to piezoelectric accelerometers. Other advantages include low power consumption, excellent bias and scale factor stability. Moreover, it's possible that self-testing and force-balancing techniques are realized by utilizing the electrostatic force. In most micromachining technologies no or minimal additional processing is needed. Capacitors can operate both as sensors and actuators. They have excellent sensitivity and the transduction mechanism is intrinsically insensitive to temperature. Capacitive sensing is independent of the base material and relies on the variation of capacitance when the geometry of the capacitor is changing.

Our research mainly focuses on the development of 3D capacitive accelerometers. These are designed and simulated using COMSOL MULTIPHYSICS 4.1. The dependency between the acceleration and the capacitance has been analysed. The sensitivity of the device with respect to forces in real time accident conditions is observed. The design for the interface between the sensor and the electronic circuitry to initiate the air bag has also been provided.

2. Background

The development of airbags began with the idea for a system that would provide safety for automobile drivers and passengers in an accident, whether or not they were wearing their seat belts.. Today, airbags are mandatory in new cars and are designed to act as a supplemental safety device in addition to a seat belt. Airbags have been commonly available since the late 1980's; however, they were first invented in 1953 [3].The automobile industry started to research airbags in the late 1950's and soon discovered that there were many more difficulties than expected. Crash tests indicated that for an airbag to be useful as a protective device, the bag must deploy and inflate within few milliseconds. The system must also be able to detect the difference between a severe crash and a minor one.

Timing is critical in the airbag's ability to save lives in a direct collision. An airbag should be able to deploy in a matter of milliseconds from the initial collision impact. Whereas it must also be prevented from deploying whenever there is no collision. Hence, the first component of the airbag system is a sensor that can detect head-on collisions and immediately trigger the airbag's deployment. The most common designs employed for the crash sensor is a steel ball that slides inside a smooth bore. The ball is held in place by a permanent magnet or by a stiff spring, which inhibit the ball's motion when the car drives over bumps or potholes. However, when the car decelerates very quickly, as in a head-on crash, the ball suddenly moves forward and turns on an electrical circuit, initiating the process of inflating the airbag [2].

3. Structural Design

It is apparent that the proposed accelerometer needs to sense the acceleration in the range of ±100g while able to maintain a 10 kHz (20 times higher than the required bandwidth) frequency response. The accelerometer should be also able to survive a maximum shock of ±150 g in case of extreme condition. Stability in extreme temperature condition is also essential.

The mechanical component of an accelerometer is equivalent to a second order mass-spring-damper system. The main component of the accelerometer is a spring-supported mass, usually linked with the dampers, which provide the necessary damping effect. Springs and dampers were connected to a shell. The mass will produce displacement x(t) when there is acceleration role. For inertial accelerometer, a mechanical sense element converts the initial acceleration into force, which will be shifted as a displacement and causes a change in capacitance that is then detected and converted into an equivalent electrical signal. The inertia of the proof mass restrains the motion of this element in the presence of external force acting on a reference frame to which the proof mass is attached by means of a spring. The proof mass is further subject to damping from the surrounding gas ambient or from internal dissipation in the spring [4].

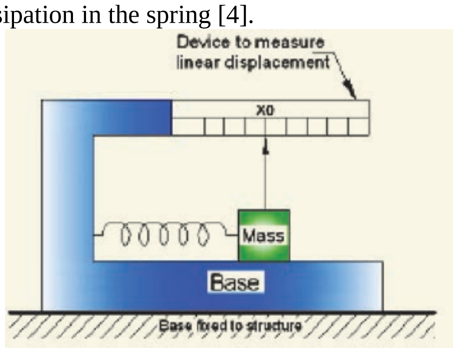

Figure 1: Basic accelerometer

4. Proposed model

This novel accelerometer has the following features 1.A central mass with large density and size as maximum as possible for a greater displacement. 2. Fixed fingers which act as electrodes 3.movable electrode which is placed between the fixed fingers. 4. Glass substrate for the support. Sensing electrodes could also be placed to sense the displacement of the central mass.

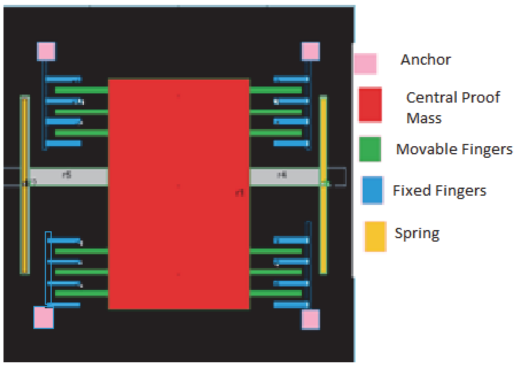

Figure 2: 3D capacitive accelerometer with springs in horizontal direction

This accelerometer is mainly made up of central movable fingers fixed to the proof mass and several fixed fingers. Fixed electrode plates are fixed on the substrate made up of glass. The sense capacitance is between the movable and the fixed fingers parallel to them. Sense organ is a bilateral comb, and the sense direction in lateral comb-finger microaccelerometers is in the proof-mass plane (x-y directions). For the condition of no acceleration input, the central proof of mass is in a state of balance, capacitance C1 is equal to C2, and the voltage of output is zero. When acceleration is effective, the movable fingers have a displacement by the action of inertial force. At this moment, the space between movable fingers and fixed plate is changed, that is, C1≠C2.

The moving and fixed fingers form a parallel plate capacitor and the capacitance can be estimated using Equation 1

$$C = \in A/d \tag{1}$$

Where $\in$ is the permittivity, A is the total overlap area between all the fingers in the sensing region, and d is the separation between adjacent fingers. Since the change in capacitance is proportional to the area (A), in order to achieve higher signal it is necessary to increase the area or number of fingers.

Electrostatic Force on the proof mass can be achieved by applying a DC voltage to the capacitor. The amount of force as a function of supplied voltage (Vs) can be estimated using the stored energy (W) on the capacitor is given below:

$$\boldsymbol{E} = \frac{\mathbf{1}}{\mathbf{2}(\boldsymbol{CV^2})} \tag{2}$$

As the mass gets displaced through the acceleration a, and the capacitance is changed.

3.1 Design of preliminary parameters

As the accelerometer represents a second order damper system, springs are important components. The springs are attached to an anchor and the force given to the springs will cause displacement of the proof mass. The displacement of proof mass will cause stretching of one spring and compression of the other spring [4].The spring constant can be calculated using equation as given in [3]

$$K = \left(\frac{\pi^4}{6}\right)\left[\frac{EWH^3}{(2L_1)^3 + (2L_2)^3}\right] \tag{3}$$

Where E is the Young's modulus of polysilicon, W is the beam width, H is the beam thickness and L1, L2 are the beam lengths.

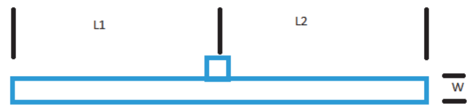

Figure 3: Folded spring structure

where
E= 131 ×10 ^{9} for silicon
W= 100nm
H=40 nm
L1=L2= 500 nm

The spring constant was calculated to be 13.5829 N/m
When springs are used in vertical direction the spring constant was found to be 54.3364 N/m
Using this value the resonant frequency can be calculated using

$$\omega_0 = 2\pi f = \sqrt{\frac{K}{m}} \text{ or, } m = \frac{K}{\omega_0^2} \tag{4}$$

Here the mass represents the mass of the central proof mass along with the mass of the fixed and the movable fingers. They have been calculated using the formula:

$$m = \rho V \tag{5}$$

Density of the silicon = 2330 kg/m^3

Mass of central proof mass= 9.69×10 $^{-17}$ Kg
Mass of fixed and movable fingers = 2.8705 ×10^{17} Kg
Total mass= 12.5605 ×10^{-17} Kg

Using equation (2) the stiffness of the accelerometer is found to be

2K = 13.5829N/m

Relating force and acceleration we know that

$$f = ma = kx \tag{6}$$

From the above equation the displacement for 100g acceleration can be calculated.

Theoretically it was found to be 924fm

For the above approximate parameters the capacitance can be derived using the software and it can be related to voltage using the equation using [2] and [3]

$$Vout = \frac{C1-C1}{C1+C2} \times Vs \tag{7}$$

Where C1 and C2 are the two capacitances between electrodes which are equal when there is no acceleration and vary when there is acceleration [3].

$$Vout = \left(\frac{\Delta x}{d}\right) Vs \tag{8}$$

Where Δx is displacement, Vs is input voltage, d is original gap between electrodes.

$$\Delta x = ma/k \tag{9}$$

Using the equation (8) and (9) V_{out} can be calculated

4. Use of COMSOL Multiphysics

The accelerometer designed was simulated using COMSOL MULTIPHYSICS 4.1.These simulations are necessary for the following reasons 1. It is mandatory to find out the maximum amount of g force the device will be able to withstand. 2. The variation in the capacitance with respect to the displacement can be analysed successfully.

4.1 Model definition

The simulations were done using the Electrostatics and solid mechanics physics in the MEMS module.

4.1.1 Domain Equations

The Capacitance is calculated using the equation

$$C = \frac{\varepsilon_r \varepsilon_0 A}{g_{ap}}$$

Electrical field (E) and electric displacement (D) vectors can be defined according to the expressions:

$$\mathbf{E} = -\nabla V$$
$$\mathbf{D} = \varepsilon_0 \varepsilon \mathbf{E} \tag{10}$$

The Capacitance can also be calculated using the energy relation [3]

$$W = \frac{1}{2} C V_s^2 \tag{11}$$

Knowing the electrostatic energy we could easily relate it with the capacitance.

4.1.2 Boundary conditions

The boundary conditions are given to the fixed and movable electrodes. For movable electrodes a potential of 1V is applied and the fixed electrodes are kept at ground to simulate a 1 V potential gradient across the electrodes.

4.1.3 Calculation of Capacitance

After the computation of the model, from the derived values using the global evaluation option the capacitance is calculated. One another way of calculating the capacitance is to use the electrostatic energy which also varies with the acceleration.

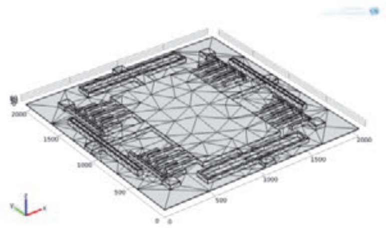

Figure 4: Meshed structure of accelerometer: 2302 elements

5. COMSOL Multiphysics Simulations

The variation of the capacitance with the input acceleration is easily visualized.When there is no acceleration applied the capacitance value obtained is 4.7735 $\times 10^{-28}$ F. For an acceleration of 100g which will occur during the displacement obtained is 600 fm and the corresponding capacitance is 1.4656×10^{-27}F. The output voltage signal calculated theoretically is 8.333V.This voltage signal is set as the threshold above which the airbag will be initiated.

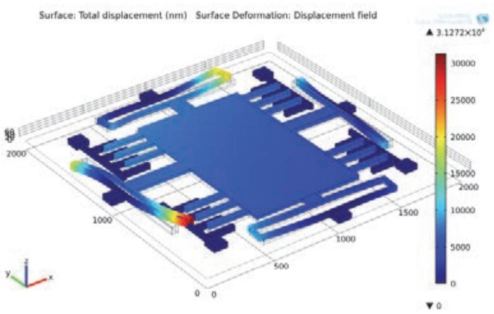

Figure 5 : Displacement for 100g acceleration in horizontal direction

The stress exerted on the device when 100g is applied is shown in the following figure

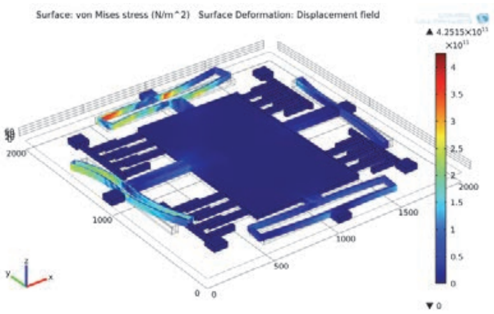

Figure 6: Stress under 100g acceleration

When springs are used in vertical direction as well the spring constant is 54.3364 N/m. The displacement is 12fm.The Capacitance obtained is 5.9331×10-28 F.

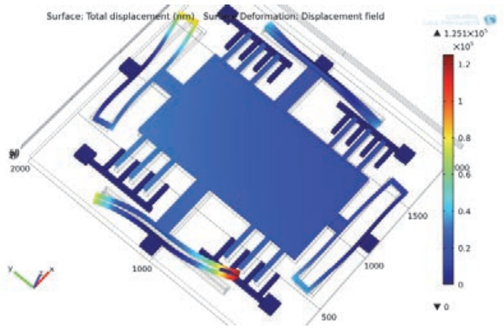

Figure 6: Displacement when acceleration is applied in vertical direction

The maximum stress limit is shown below

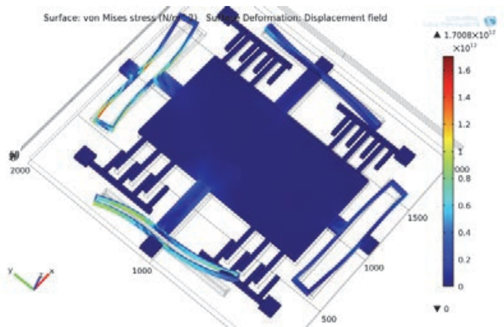

Figure 7: Stress limit when 100g applied in vertical direction

The various simulation results are tabulated below

S.No	Acceleration (100g)	Capacitance(F)	Max stress(N/m^2)
1.	13.58291N/m-> Edge load in horizontal direction	1.4656×10^{-27}.	4.5125×10^{11}
2	54.3364 N/m→ Edge load in vertical direction	5.9311×10^{-28}	1.7008×10^{12}

Table 1: Simulation results

For the nanometer dimensions the stress limit that the device will be able to withstand exceeds the elastic limit of silicon which is 0.4×10^{12} N/m^2

The Variation in the displacement along the spring is shown in fig 8.

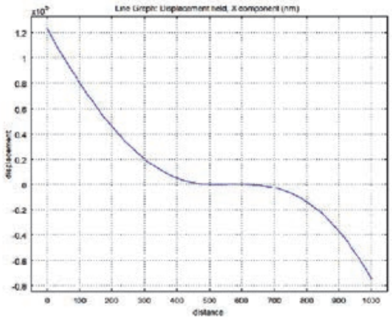

Figure 8: Displacement along the spring length

The Variation of acceleration with input voltage is shown in fig 8.which establishes a linear relationship between acceleration and the output signal.

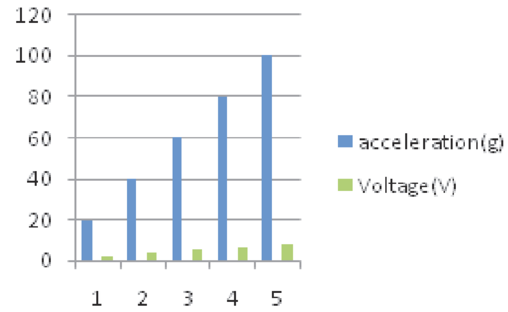

Figure 9: Relation between acceleration and voltage

6. Conclusion

This study was primarily intended to design an accelerometer for air bag deployment applications in automobile industries. The materials are chosen are in the nano dimensions since they exhibit higher tensile strength and Young's modulus. This will enable them to withstand real time accident conditions. With change in the acceleration which is applied in terms of body load, visible changes in the capacitance are seen. This change in Capacitance value is given as an electric signal input to the air bag deployment system and is amplified. Once the Capacitance reaches the threshold level (the value obtained when 100 g force is applied), the air bag system is initiated using electronic circuitry. Further improvements could include simulating the accelerometer using carbon nanotube as the material which might be able to withstand the stress. And finally fabricating the device in the nanometer regime appears to be another task

7. References

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