SILICON BASED CAPACITIVE SENSORS FOR VIBRATION CONTROL

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ABSTRACT

Micromachined vibration sensors with high sensitivity and linearity are needed in many applications including aerospace and advanced automobiles. These sensors can also be used to monitor and control vibrations in a machine or any vibrating body, isolation of precision equipment and activation of safety systems. Capacitive sensors have the advantage of low noise, low temperature sensitivity and compatibility with CMOS readout electronics. In this paper, design calculations for vibration sensors based on capacitive detection technique for sensing vibrations in the vertical direction are presented. Results of vibration sensors developed at SSPL are also discussed.

Keywords: Sensor, Micromachining , MEMS technology, Vibration

1. INTRODUCTION

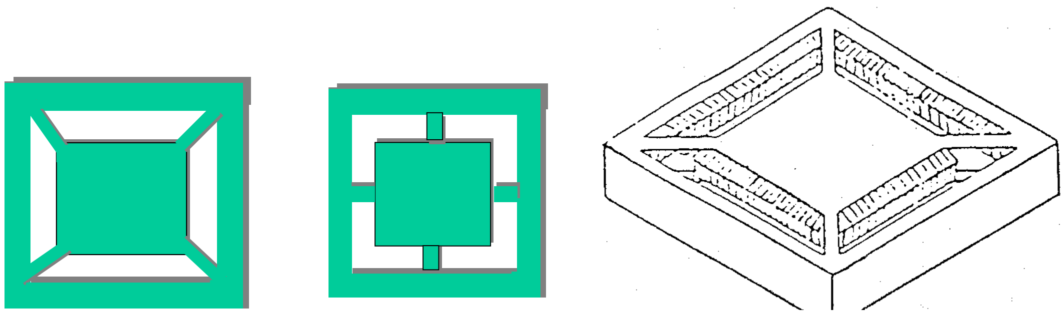
Low cost, small size vibration sensors with high resolution have been developed for various applications ranging from geophysical sensing, inertial navigation systems, vibration control & failure prediction of sophisticated machinery and isolation of precision equipment. Sensors fabricated using MEMS technology [1,2,3] can offer many advantages over traditional sensors in terms of small size, less weight and high performance. MEMS vibration sensors are being fabricated using a variety of surface micromachining and bulk micromachining technologies. In surface micromachined devices, the thickness of the deposited layer hence the proof mass is small causing limitation on the performance of the device. On the other hand, bulk micromachining provides larger proof mass and larger capacitive area, which gives higher resolution and greater sensitivity. In this study, design consideration and fabrication of silicon based capacitive sensors have been carried out. Sensors have been fabricated for sensing vibrations in the vertical direction using bulk micomachining and results are described

2. PRINCIPLE AND DESIGN CONSIDERATIONS

For sensing vibration, a mechanical element converts the vibration or acceleration into a displacement which is then detected and converted to an electrical signal. Various detection technique are used such as piezoelectric, piezoresistive, optomechanical and capacitive. Capacitive devices have several advantages over other techniques. Here movement of the seismic mass due to vibration changes the capacitance with the fixed electrodes. The change in capacitance can be measured using electronic circuitary. These sensors have high sensitivity, good dc response and noise performance, low temperature sensitivity, low power dissipation., compatibility with CMOS readout electronics and a simple structure. However, capacitive type of sensors can be susceptible to electromagnetic interference (EMI). This problem can be solved by proper packaging and by shielding the device and its interface circuits. The only thermal effect here is a change in the capacitance due to thermal expansion of the constituent elements. A symmetric sensor design reduces the effects of thermal expansion to a minimum; therefore, these sensors do not need any active temperature compensation.

The sensing element in a vibration sensor is a mechanical resonator consisting of a seismic mass supported by thin suspensions or springs anchored to a fixed frame. Main parameters that define the performance of a vibration sensor are sensitivity and frequency bandwidth. They depend on the stiffness of the spring and geometrical parameters. These were calculated for different configurations using analytical and finite element methods.

Fig.1- (A & B) shows the sensor top configurations used for vibration sensors in vertical direction. It is a highly symmetric structure and therefore desirable from technology point of view as well as to get a tilt free movement for getting linearity in capacitive measurement. Fig 1C shows the entire structure of the fabricated sensor mounted over a fixed electrode.



A B C

Sensor's top structures Complete geometry of sensor

Fig.1

Here, the main sensor element is a seismic mass suspended by four thin silicon hinges, which act like springs. Most of the sensor parameters are fixed once the masks are designed. However there are two parameters, hinge thickness and thickness of the seismic mass that can be varied during fabrication. The sensitivity S of the structure is given by

$$\mathbf{S=m/k=1/f_n^2=mL^3/4Ebh^3},$$

Where m=mass, k=stiffness constant, fn=natural frequency, L=hinge length, and b=hinge width.

However, the over all sensitivity is determined by $S_T = \delta C / C$ g i.e., the change in capacitance per unit acceleration. The entire structure is made in silicon using suitable micromachining techniques. This structure is mounted on a metallised glass plate forming a parallel plate capacitor. Deflection of the mass under acceleration along vertical axis changes the gap between movable and fixed electrodes. This changes the capacitance that is monitored to give a measure of vibration.

As shown in Table 1 design calculations were done for the parameters mentioned for a 1.6 mm x 1.6 mm chip size sensor for different hinge thickness. As shown sensitivity increases with decrease in hinge thickness where as value of resonant frequency decreases. This sensor is useful for operation at low frequencies below 500 Hz and gives high sensitivity with this type of structure. Tables 2 & 3 show the design calculations done for a smaller sensors (7 mm x 7mm ,8 mmx8mm)for different values of hinge thickness . This sensor is designed for operation at higher frequencies applications (i.e.100 –1 KHz). These analytical calculations were verified using ANSYS software and results are given in the tables showing good agreement. Fig 2 shows the displacement at each point of sensor at 10 g (maximum displacement~0.029 microns) Thus by choosing the proper dimensions desired operating frequency bandwidth could be obtained. As is clear from these calculations sensitivity and frequency are inversely proportional to each other. Therefore, design has to be optimized to get the desired parameters. The above analysis can be used to tailor the design of the sensor to specific requirements.

Table-1

Chip size: 1.6cm x 1.6cm, Seismic mass: 9mm x 9mm x 0.27mm, Hinge length: 2.12mm

S.No.	Hinge Thickness (µm)	Natural frequency (f_n) Hz	Sensitivity (S) =$(1/f_n^2)*10^{-6}$
1.	20	501.52	3.977
2.	25	700.90	2.035
3.	30	921.36	1.177

Table-2

Chip size: 7mm x 7mm, Seismic mass: 3mm x 3mm x 0.27mm, Hinge length: 1.0mm

S.No.	Hinge Thickness (µm)	Natural frequency (f_n) Analytically (KHz)	Natural frequency (f_n) by ANSYS (KHz)
1.	20	1.13	1.12
2.	25	1.5	1.47
3.	30	2.07	2.03

Table-3

Chip size: 8mm x 8mm, Seismic mass: 3mm x 3mm x 0.27mm, Hinge length: 1.5 mm

S.No.	Hinge Thickness (µm)	Natural frequency (f_n) Analytically (KHz)	Natural frequency (f_n) by ANSYS (KHz)
1.	20	2.07	2.05
2.	25	2.90	2.87
3.	30	3.81	3.76

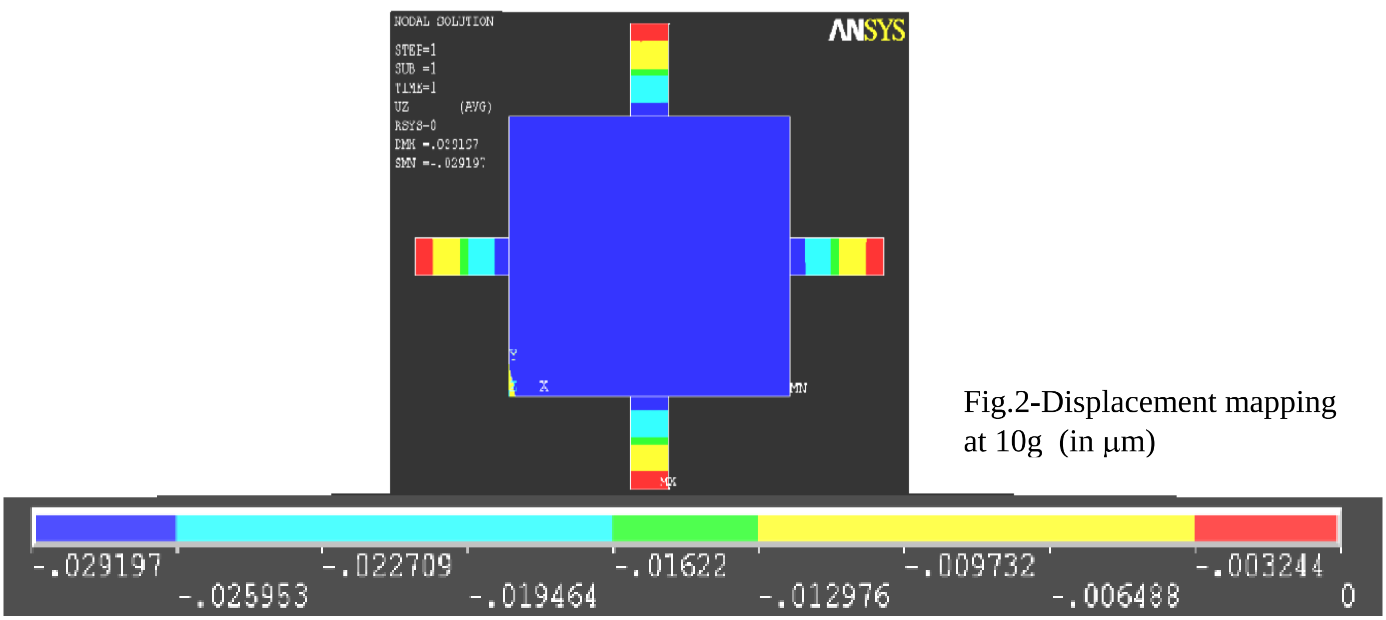


Fig.2-Displacement mapping at 10g (in µm)

3. FABRICATION PROCESS

Fabrication of vibration sensors was done using 1-ohm cm, p type, (100) silicon wafers. Geometry of the sensor was defined using standard photolithography techniques and thinning of the 4 hinges to about 25 –20 µm was carried out using bulk silicon micromachining . Fabrication of the bottom electrode was done by evaporating and patterning Aluminium thin film on glass. Sensor top structures were mounted using a special epoxy on the bottom electrode.. Technique for Anodic bonding using 7740 glass was also developed [4] and few sensors were bonded using that technique. Sensors with both the configuration were fabricated using anisotropic etching. In structure (A) slight non uniformity was observed at the corners due to under etching for small values of hinge widths < 1 mm where as in (B) rounding of corners of the seismic mass was observed which was later compensated by using new masks designed for corner compensation[5].For low frequency applications, sensors of 1.6cmx1.6 chip size were fabricated (Fig 3) and test results are described in the next section..

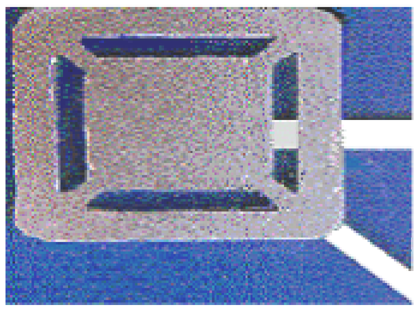


Fig.3 Sensor Photograph (Chip size: 1.6 cm x 1.6 cm)

4. TESTING AND MEASUREMENTS

Vibration sensors shown in Fig.3 were packaged in an Aluminium package and tested on a vibration shaker from M/s Saraswati Dynamics installed for these measurements. When the sensor is mounted on a vibrating table vibrating in the vertical direction, the vibrations are transferred to the seismic mass through thin hinges and the seismic mass moves up and down varying the gap between the two parallel plates. The change in capacitance was observed using an electronic circuit developed and fabricated for this purpose. Sensors were calibrated on the vibration calibration system using a reference accelerometer and the sinusoidal input in frequency range 1 – 500 Hz. Sensors showed a flat response in 30-200 Hz frequency range and linear variation from 1 to 25 g. Beyond 200 Hz a slight decrease in the output was observed because of the limitation of circuitry. Fig4 shows the variation in the sensor output as a function of g .As shown in the graph sensor response increases linearly with g. Fig -5 shows the output from sensors for the complete frequency sweep between 30-200 Hz. As shown the sensor is giving a flat response in this range.

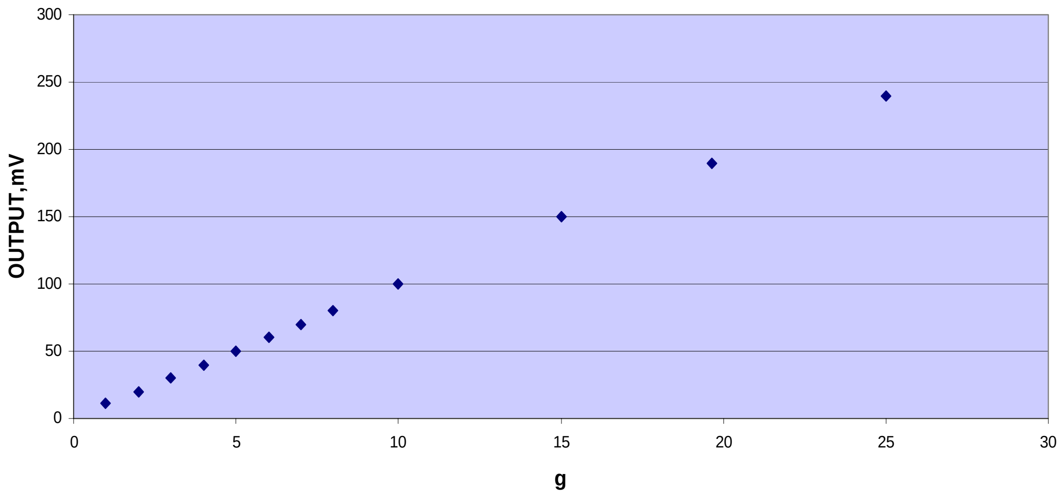


Fig.4: Sensor Output as a function of g

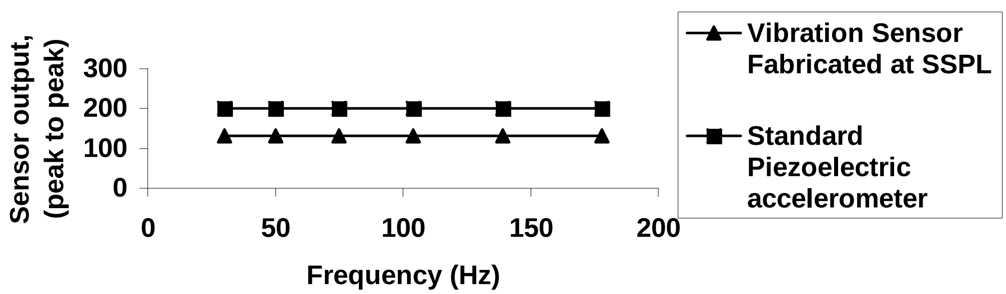


Fig 5: Frequency response of the sensor at 1g

Main sensor specifications are **:**

Sensor Chip Size : 1.6 cm x 1.6 cm , Linear response : 1 – 25g

Average Sensitivity : 10mV/g , Frequency band width : 1 Hz – 200 Hz

5. CONCLUSION

Development of Vibration Sensors based on MEMS technology has been carried out successfully. Sensors have been fabricated, packaged and tested at SSPL. The technology for fabrication and testing of Silicon vibration sensors based on capacitance detection technique has been established at SSPL. The sensor performance is matched with that predicted from the design calculations. Now, depending on the user requirements, vibration sensors can be fabricated. Sensors have also been designed for high frequency applications. They are being packaged with ASIC for testing.

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