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Design and Simulation of MEMS-based Z-Axis Capacitive Accelerometer

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ABSTRACT

In this paper, a MEMS-based Z-axis capacitive accelerometer is designed and simulated. An out-of-plane Z-axis accelerometer designed for 8 µm UV-LIGA technology for an acceleration range of ±10g. The operating voltage is 5 V DC. Simulation results show good linear characteristics in the operating range of DC-400 Hz, which is the bandwidth of the accelerometer. The simulations of the device were carried out using CoventorWare®. By using modal analysis in CoventorWare® the resonating frequency of 3.1 kHz is obtained.

Keywords: MEMS, Accelerometer, UV-LIGA, CoventorWare®.

I. INTRODUCTION

Accelerometers are used to measure the linear acceleration along its sensitive axis and transduce this inertial force into a measurable electrical signal. Accelerometers can measure tilts, shocks and vibrations [1]. They have a numbers of applications of such inertial sensors. Around 90% of the applications of accelerometers are in automotive industry used in the deployment of air bag systems, 8% in inertial navigation and guidance systems. Some other applications of the accelerometer are biomedical applications, vibrating monitoring, and seismic activities, etc. [2-3].

There are various types of accelerometers based on their fabrication or working principle like piezoresistive, piezoelectric, capacitive, tunnelling, etc. [4]. Since there are various sensing mechanisms with their advantages and limitations, capacitive accelerometers have several advantages such as good DC response, high voltage sensitivity, low noise floor, low drift, low power consumption and low temperature dependency, which make them very attractive for various high performance applications [5].

Accelerometer measure linear acceleration along its sensitive axis. This acceleration can be converted into capacitance change by using capacitive accelerometers. Most of the MEMS capacitive accelerometers are single axis, and the integration of two or three accelerometers is required to measure three-dimensional acceleration [6]. Accelerometer consists of a large proofmass, connected to anchors via suspension beams and a bottom electrode. When there is acceleration, the proofmass deflects from its initial position, gap between proofmass and electrode changes and there is a change in capacitance. This change in capacitance can easily be measured by using capacitance to voltage convertor circuit.

II. METHODS AND MATERIAL

Theoretical Background

Accelerometer consists of a square size proofmass, four anchors attached to suspension beams and a bottom electrode. Fig. 1 shows the schematic of the accelerometer. When there is z-axis acceleration, the gap between proofmass and bottom electrode changes and thereby, capacitance changes. This change in capacitance can be measured by converting it into voltage by using a capacitance to voltage convertor. This output voltage is proportional to acceleration at the input.

The sensitivity of the accelerometer is directly proportional to the displacement of the proofmass from its mean position and inversely proportional to the resonant frequency of the structure.

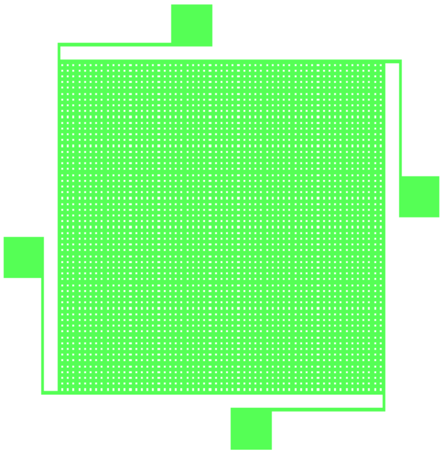

Figure 1 : Schematic of the accelerometer

The accelerometer model is same as the second-order spring-mass-damper system as shown in Fig. 2 [7]. When there is an external acceleration, proofmass displaces and the motion of proofmass is opposed by spring and damper. The inertial force is given in equation (1).

$$m\ddot{z} + b\dot{z} + kz = F_{electrical} \qquad (1)$$

Where, m is the mass of the system, z is the displacement, b is the damping force coefficient, and k is the spring constant.

Considering z-axis as the sensing direction, the equation for the out-of-plane accelerometer is

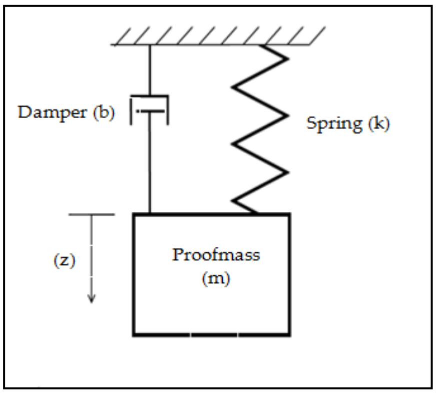

Figure: 2 Dynamic model of out-of-plane accelerometer

shown in equation (2),

$$m\frac{d^2}{dt^2}z(t) + b\frac{d}{dt}z(t) + k\,z(t) = ma(t) \qquad (2)$$

Where a(t) is the acceleration on the proofmass. Let, C_1 is the original capacitance and C_2 is the capacitance after change in the gap between proofmass and bottom electrode. ΔC is the total change in capacitance after deflection as shown in equation (3).

$$C_1 = \frac{\epsilon_\circ A}{d}, \qquad C_2 = \frac{\epsilon_\circ A}{d-z} = \frac{\epsilon_\circ A}{d}\left(1+\frac{z}{d}\right)$$

$$\Delta C = C_2 - C_1 = \frac{\epsilon_\circ A}{d}\left(1+\frac{z}{d}-1\right) = \frac{\epsilon_\circ A}{d}\left(\frac{z}{d}\right)$$

$$\Delta C = C_1\left(\frac{z}{d}\right) \qquad (3)$$

Total energy in the capacitive structure is calculated by using equation below, and force in the z-direction is calculated by partial differentiation of energy w.r.t. z. After solving, the force is obtained as shown in equation (4).

$$F = \frac{1}{2} \times \frac{-2}{2}\frac{\epsilon_\circ A}{(d-z)^2}V_{dc}{}^2 - \frac{1}{2}\frac{\epsilon_\circ A}{(d-z)^2}(2V_{dc}V_{ac}) \qquad (4)$$

Where,
d = original gap between electrodes
z = displacement from mean position
V_{dc} = applied dc voltage
V_{ac} = applied ac voltage

The design specifications of the accelerometer are given in Table I.

Table I : Design Specifications Of The Accelerometer

Specification	**Value**
Acceleration range	±10g
Bandwidth	DC-400 Hz
Operating voltage	5 V
Resonant Frequency	3.1 kHz
Nominal Capacitance	2 pF

The physical dimensions calculated for the optimized accelerometer design to meet the above specifications are given in Table II.

Table II : Physical Dimensions of the Accelerometer

Parameter	**Size (units)**
Proofmass size	1150 µm × 1150 µm

Size of perforations	10 µm × 10 µm
Beam width	8 µm
Small beam length	50 µm
Large beam length	400 µm

III. RESULT AND DISCUSSION

A. Simulation Results

Simulations of the accelerometer were carried out by using MEMSCAD tool CoventorWare®. Resonant frequency of the structure was observed using modal analysis in CoventorWare®. By using modal analysis first resonant mode of the structure was in Z-axis, which is the dominant mode of out-of-plane accelerometer, as shown in Fig. 3.1. Second mode was torsional across X-axis, as shown in Fig. 3.2, and third mode was torsional across Y-axis, as shown in Fig. 3.3.

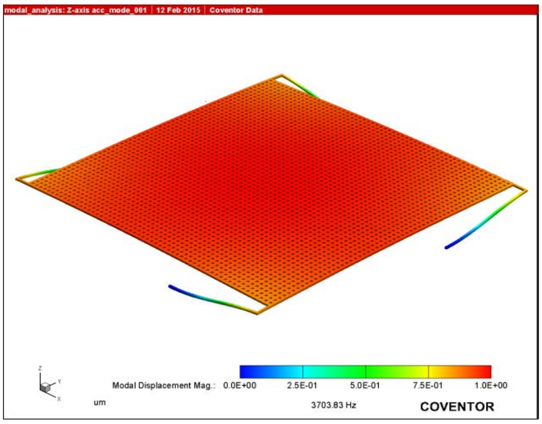

Figure: 3.1 First resonant mode of the accelerometer

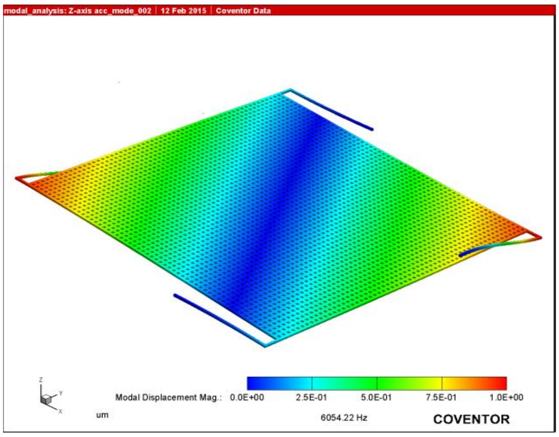

Figure: 3.2 Second resonant mode of the accelerometer

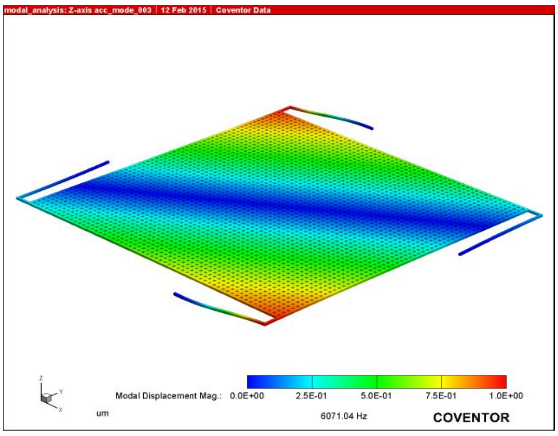

Figure: 3.3 Third resonant mode of the accelerometer

Modal harmonic analysis is done in CoventorWare®. Amplitude response and phase response of the structure are observed. In amplitude response, maximum displacement observed at the resonant frequency of 3.1 kHz as shown in Fig. 3.4. Device behaves linearly between DC to 400 Hz, which is the bandwidth of the accelerometer.

In phase response, phase of the accelerometer is changed by –π/2 at the resonant frequency as shown in Fig. 3.5.

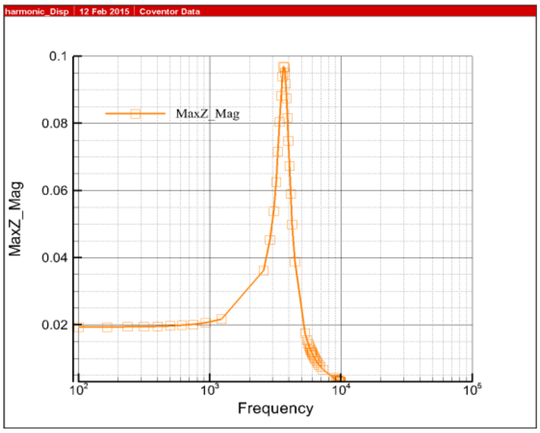

Figure: 3.4 Amplitude response of the accelerometer

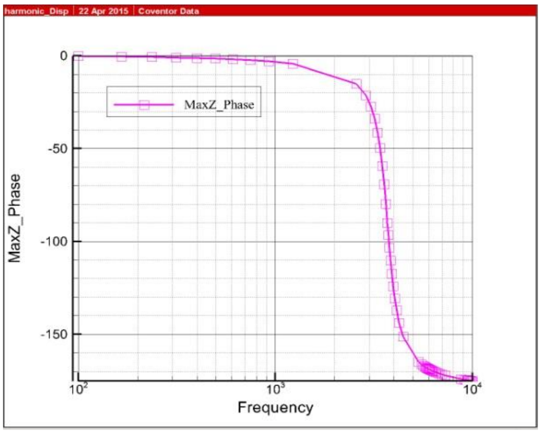

Figure: 3.5 Phase response of the accelerometer

The structure dimensions were decided optimally based on this analysis and the layout of the structure was generated using L-Edit, layout editor tool from Tanner EDA. Then 3-level masks were designed for the fabrication of the accelerometer.

B. Proposed Device Fabrication

The accelerometer device is to be fabricated by using 8 μm UV-LIGA technology [8-9]. The process flow is shown in Fig. 4. It is a three mask process. Gold is used as a seed layer and chromium is used with gold for the adhesion purpose. Copper is used as sacrificial layer which acts as an excellent undercoat for the structural layer which is to be made of nickel material, has a high mechanical strength. The mould for the structural layer, nickel, is made by using SU-8 negative photoresist. Final device thickness will be of 8 μm.

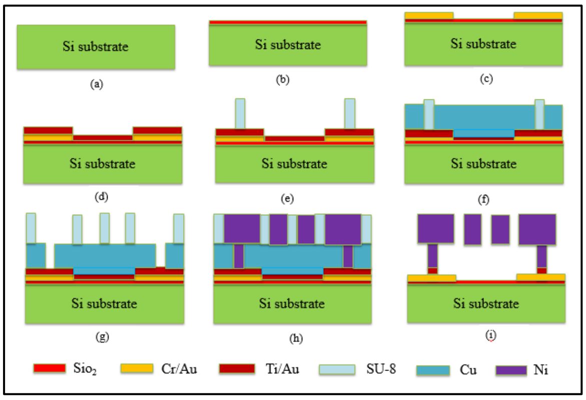

Figure : 4 Fabrication methodology of Accelerometer fabrication process: (a) Silicon substrate (b) oxidation on substrate (c) formation of anchors and contact pads of gold in 1st lithography (d) sputtering of Au seed layer (e) coating of SU-8 using 2nd level mask (f) Electroplating of copper (g) coating of SU-8 using 3rd level mask (h) Electroplating of Nickel (i) Released structure after etching of SU-8, copper and Au seed layer.

First of all, anchors and electrodes of gold are formed, than by protecting anchors by using SU-8 negative photoresist, copper is electroplated. Then mould is formed for nickel structural layer, and final nickel structural layer is electroplated. Final step is to release the structure by etching SU-8, copper and gold seed layer.

IV. CONCLUSION

In this paper, design and simulation of a single axis, out-of-plane capacitive accelerometer using CoventorWare® have been presented for 8 μm UV-LIGA technology. Masks layout for the fabrication of the device has been designed and fabricated. The fabrication flow for the device is also discussed. The device resonating frequency of 3.1 kHz is achieved.

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