



Analysis of 3D MEMS Accelerometer

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Abstract: The paper analyzes the theoretical and electrical design specifications of 3-D Micro-Electro-Mechanical Systems (MEMS) based Accelerometer that is designed and simulated using COMSOL Multiphysics. The design presented in this paper consists of a square shaped proof-mass with four serpentine springs supporting it. The device is most suitable for low-G applications.

Keywords: MEMS, Accelerometer, serpentine springs, COMSOL Multiphysics, low-G applications.

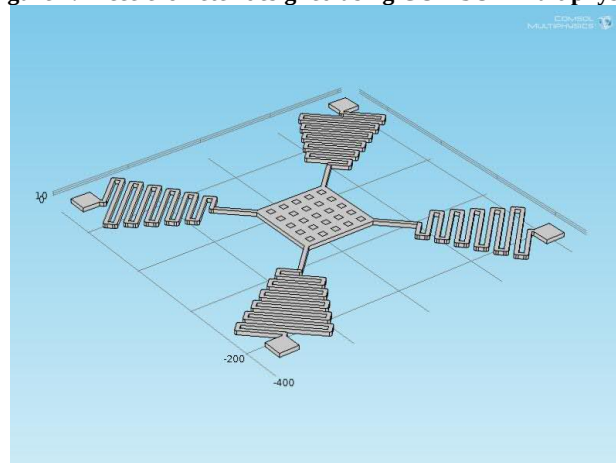
I. Introduction

Micromachining technologies have enabled a many fold increase in the functionality of the mechanical sensors and, at the same time have enabled a reduction in their size thus achieving unprecedented levels in miniaturization. New markets for MEMS (Micro Electro Mechanical Systems) Accelerometers have emerged owing to their enormous capabilities with respect to performance, miniaturization, reliability, low price, and low power consumption. For all MEMS devices, for achieving sufficient low cost, a high production volume must be achieved. The most important markets that provide high volume opportunities are consumer products, automotive, computers and peripherals, and medical and biological applications [1]. These include navigation, air bag control, motion sensing, roll over, GPS with E-compass for automotive market, camera stabilization, 3D gaming, motion dialling, text scroll, hard disk protection, free fall detection, image stability, motion detection in consumer applications, and motor stability, seismometers in industrial applications [2, 5].

II. Device design

Accelerometer operates by measuring the inertial force generated when a mass is accelerated. The force applied deflects the suspension of the proof mass. So, if the deflection of the structure can be measured, the acceleration can be easily determined. This accelerometer structure consists of a mass-spring-damper system which is used to interact with the inertia forces. The Fig. 2.1 shows the final mechanical design in 3D.

Figure 1. Accelerometer designed using COMSOL Multiphysics.



The structure is created using 2D geometrical workplane in COMSOL. After the initial design, Finite Element Analysis (FEA) is implemented using physics models in the COMSOL Multiphysics software. This design has the capability of multi-axis sensing, out of plane detection: rotation and has high shock survivability.

III. Material Selected

The material selected for the device is Single Crystal Silicon (100). Silicon has almost the same Young's modulus as that of steel but it is light like aluminum which makes it an ideal material for structures. Silicon is dimensionally stable at high temperatures due to its high melting point of 1400°C and a lesser thermal coefficient than that of steel. The material properties of single crystal silicon are shown in table 2.1.

Table 2.1 Material properties of Silicon.	
Material Property	Value
σ_y (Yield strength) 10^9 N/m ²	7
E (Young's Modulus) 10^{11} N/m ²	1.69
ν (Poisson's ratio)	0.28
α (Thermal expansion coefficient) 10^{-6} mt/mt°C	2.5
P (Density) g/m ³	2.3

Apart from the structural advantages, fabrication using silicon wafers is extremely advantageous and simplified owing to the present available technology. Silicon wafers, for building microstructures, can accept many coatings and additional thin film layers. Using standard etching techniques and photolithography, precise geographical features can be realized. Also, silicon does not exhibit mechanical hysteresis.

IV. Analytical Design

The structural parameters of the device that are considered for the design analysis are as follows:

- A. Proof-mass area (A)
- B. Proof-mass's mass (m)
- C. Maximum force on seismic mass
- D. Moment of inertia of the beams
- E. Deflection of beam
- F. Bending stress in beam
- G. Factor of safety
- H. Natural frequency

In order to acquire the required sensitivity and bandwidth, the structural parameters are thoroughly optimized. The device is assumed to be working in ambient pressure condition. The acronyms for proof-mass length, breadth and thickness are l_p , b_p , h_p respectively and for the beam they are l_b , b_b , h_b respectively.

While planning out the device design, the question of air gap dimensions aroused. Following the works of [23] and current availability of fabrication technology in India, the air gap was chosen to be 22 μ m. The dimensions of the proof-mass are (200 x 200 x 10) μ m.

The parameters are calculated as follows:

A. Proof-mass area (A)

The area is calculated as:

$$A = l_p \times b_p = 0.04 \times 10^{-6} m^2$$

B. Proof-mass's mass (m)

The mass is calculated as:

$$m = V \times \rho = (A \times h_p) \times \rho = 0.92 \times 10^{-9} Kg$$

Where, V is the volume of proof-mass and ρ is the density of silicon and equals 2300 kg/m³.

Also, Total mass of beams (m_b) is,

$$m_b = 4(l_b) \times b_b \times h_b \times \rho = 4.75786 \times 10^{-10} kg$$

C. Maximum force on seismic-mass

Let 'F' be the force that acts on the seismic-mass, sue to 1g of acceleration, therefore,

$$F = m_p \times a = 0.3924 \mu N$$

And, since the force is shared equally by the four beams, the force acting per beam is

$$W = \frac{F}{4} = 0.0981 \mu N$$

D. Moment of inertia of the beams

The moment of inertia is calculated as:

$$I = \frac{1}{12} (b_b \times h_b^2) = 8.33 \times 10^{-22} \text{ m}^4$$

E. Deflection of beam

The serpentine spring is rigidly fixed to the proof-mass on one side and to a frame on the other. The spring can be considered as multiple cantilevers joined in series. The equation to calculate deflection is as follows:

$$\delta = \frac{1}{12} \times \frac{W \times l_b^3}{E \times I}$$

Where, E is the Young's modulus and I is the moment of inertia of beam.

For beam with length l_1 ,

$$\delta_1 = \frac{W \times l_{b1}^3}{12 \times E \times I}$$

Similarly, for length l_2 ,

$$\delta_2 = \frac{W \times l_{b2}^3}{12 \times E \times I}$$

Therefore, total deflection:

$$\delta = \delta_1 + \delta_2 + \delta_3 + \dots + \delta_n = \delta_1 = \frac{W \times (l_{b1}^3 + l_{b2}^3 + \dots + l_{bn}^3)}{12 \times E \times I}$$

Calculating the above,

$$\delta = 29.1461 \text{ pico-m}$$

F. Bending stress in beam

The formula for determination of bending stresses in a beam is given as

$$\sigma_{beam} = \frac{M}{I} \times y$$

Where, σ_{beam} is the bending stress in beam, M is the banding moment that is acting on beam and y is the perpendicular distance to neutral axis.

At 1g,

$$M = W \times l_b \times 1 = 180.2097 \times 10^{-12} \text{ Nm}$$

For maximum σ_{beam} ,

$$y = \frac{h_b}{2}$$

Therefore,

$$\sigma_{beam} = 1.081690876 \text{ Mpa}$$

G. Factor of Safety

For calculating the factor of safety while using Silicon, the UTS (Ultimate Tensile Strength) value is used because Silicon is a brittle material. For ductile materials, yield strength is used. The formula therefore is

$$N = \frac{\text{Ultimate Tensile Strength}}{\text{Maximum stress}} = \frac{7000}{1.081690876} = 6471.349766$$

Therefore, Factor of safety is 6471.35 approximately.

H. Natural Frequency

The natural frequency is given as

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Where, k is the stiffness of spring and is given by

$$k = \frac{F}{\delta} = 13463.207 \text{ N/m}$$

Therefore, $f_n = 609.1450287 \text{ MHz}$

V. Electrical Design

The ability of a body to hold electric charge is known as capacitance. The capacitance in between two parallel plate conductors is calculated when the geometry of the conductors & the dielectric properties of insulator in between the plates is known. In order to study the electrical design, nominal capacitance and accelerometer sensitivity are calculated.

A. Nominal Capacitance

The nominal capacitance of the device is

$$C_o = \frac{\epsilon_r \times \epsilon_o \times a}{d}$$

Where,

ϵ_r is the relative permittivity of dielectric medium (for Air $\epsilon_r = 1$)

ϵ_o is the permittivity of free space = 8.85×10^{-12} F/m

a is the overlapping area of capacitor

d is the distance between the plates

Therefore,

$$C_o = 16.091 \text{ fF}$$

B. Accelerometer sensitivity

The initial air gap between the electrodes is 22 μm . Let C_1 be the capacitance between the proof-mass and top electrode and C_2 be the capacitance between the proof-mass and bottom electrode, under application of 1g acceleration. The system considered here is a differential capacitor therefore under the influence of 1g, the capacitance on one side increases and decreases on the other. Figure 2.3 shows the configuration. Therefore,

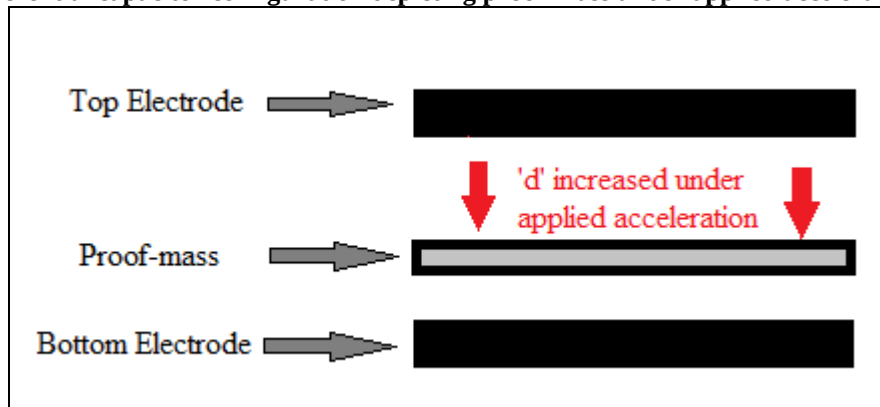
$$C_1 = \frac{\epsilon_r \times \epsilon_o \times a}{d + \Delta} = 16.032608 \text{ fF}$$

And,

$$C_2 = \frac{\epsilon_r \times \epsilon_o \times a}{d - \Delta} = 16.149635 \text{ fF}$$

Where, $\Delta = 0.08 \mu\text{m}$.

Figure 2 Differential capacitor configuration depicting proof-mass under applied acceleration.



And,

$$\Delta C = 0.12 \text{ fF}$$

The sensitivity is thus given as,

$$S = \frac{\Delta C}{\text{Applied Acceleration}}$$

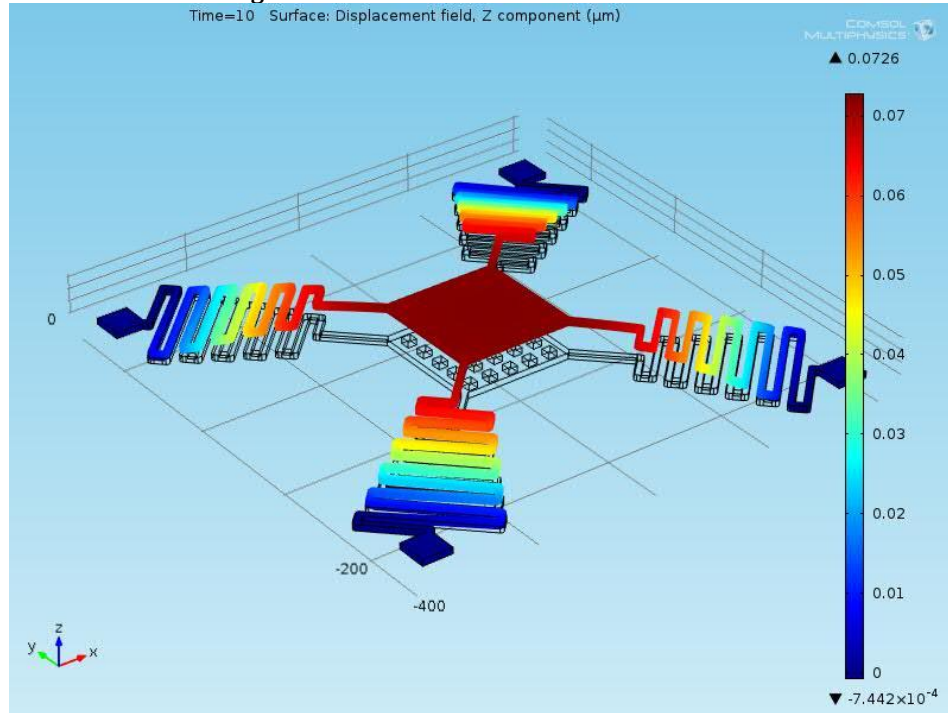
Therefore, at an application of 1 'g',

$$\text{Sensitivity} = 0.12 \text{ fF/g}$$

VI. Conclusion

The paper depicts the various parameters that specified for the design of the accelerometer. The above theoretical analysis of the parameters simplifies the application based queries that we encountered during the first phase of project establishment. The figure 3, shows the simulated design. The device is fit for design of low-G application fields like avionics, military, GPS, seismometry, geophones, “Bio-flips” etc. [3, 4].

Figure 3. COMSOL simulated accelerometer.



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