Design Optimization of Capacitive MEMS Accelerometer for Improved Sensitivity

Keya Sanyal
ECE Department
MCKV Institute of Engineering
Kolkata, India

Kalyan Biswas
ECE Department
MCKV Institute of Engineering
Kolkata, India

ABSTRACT
In this paper design of a two-axis capacitive accelerometer is described. Variation of capacitance of the device with applied acceleration as well as sensitivity of the device is analyzed. The performance analysis of the device is done using ANSYS Multyphysics software. From the analysis results, a capacitive mems accelerometer with enhanced sensitivity has been proposed. The sensitivity of the accelerometer has efficiently been enhanced with the increase of beam length and reduction beam width.

General Terms
MEMS capacitive comb type accelerometer; capacitance sensitivity analysis, Modeling and simulations.

Keywords
MEMS, Sensors, Capacitive, Accelerometer, Sensitivity.

1. INTRODUCTION
MEMS accelerometers have achieved great commercial success in recent decades because of their small size, low weight, low cost and low energy consumption. During last decades, MEMS (Micro-Electro Mechanical Systems) technology has been grown rapidly and was successfully fabricate in achieving miniaturized mechanical structures and their integration with microelectronic components. Acceleration sensors have been amongst the first implemented MEMS products [1-3]. Among many MEMS applications, capacitive detection is known to offer several benefits compared to other sensing methods, especially due their ease of implementation. Capacitive methods do not require integration of a special material, which makes them compatible with almost any fabrication process. They also provide good DC response and noise performance, high sensitivity, low drift, and low temperature sensitivity. The MEMS device design, modeling and optimization for better performance has become an interesting and important research issue [4-7]. Recently, various efforts on MEMS device design optimization have been made and published [8-11]. Characterization of the accelerometers in terms of sensitivity and usable range is also studied by many researchers in recent times [12-13].

The dependence of the device sensitivity on the design parameters (such as beam width, beam length) is analyzed. ANSYS FEM simulation [14] is used to derive the device sensitivity for various design options. An optimized design guidelines of the MEMS comb accelerometer device is suggested from this analysis.

2. BASIC PRINCIPLE
The MEMS accelerometers usually consist of a proof mass suspended using an elastic element (spring). When the device is accelerated, an inertial force is applied to the proof mass, resulting in its deflection in the direction opposite to the applied acceleration. The acceleration can be extracted from the measurement of the capacitance between suspension element and electrode stress in the suspension elements. A schematic structure of the capacitive accelerometer is shown in Fig. 1. All upper capacitors are wired parallel for an overall capacitance C_1 and likewise all lower ones for overall Capacitance C_2, Otherwise capacitance difference would be negligible to detect. The MEMS Accelerometer is composed of movable proof mass with plates that is attached through a mechanical suspension system to a reference frame, movable plates and fixed plates represents capacitors. When an acceleration is applied on the device, the proof mass deflects and the gap between fixed fingers and moveable fingers varies which leads to a change in capacitance. The deflection of proof mass is measured using capacitance difference.

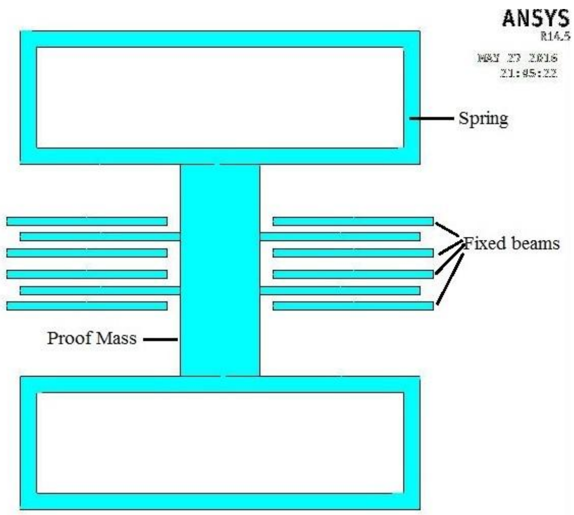

Fig 1. Schematic Diagram of capacitive Accelerometer

3. MODELLING AND ANALYSIS
3.1 Mathematical Model
As described in Fig.1, the beam width and beam length of the structure is denoted as W_b and L_b respectively for each section of the folded-beam. The width and length of central proof mass are considered as W_m and L_m respectively. The device thickness (thickness of the poly-silicon layer) is h and there is total N_f sensing finger groups. For each movable finger, the finger width and length are W_f and L_f separately. When there is no acceleration, the capacitance gap between each movable finger and its left/right fixed fingers is *d*.

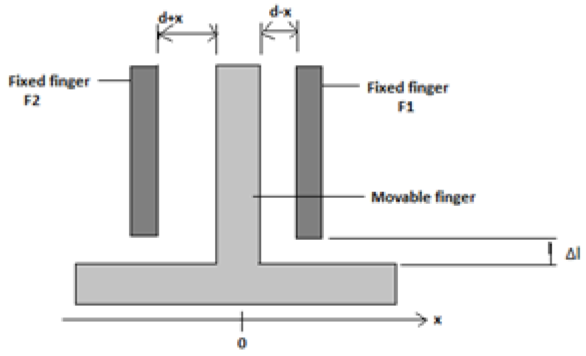

Fig 2. Differential Capacitance of MEMS Accelerometer

Assume that the length not covered with mobile finger is null ($\Delta L_f = 0$) as shown in Fig. 2. The static sensing capacitance of the MEMS comb accelerometer when there is no acceleration (a = 0) is:

$$C_0 = \frac{\varepsilon_0 N_f L_f h}{d} \quad (1)$$

When there is acceleration (a≠0) along horizontal direction, the movable mass experiences an inertial force toward right by x (Fig. 2). The value of capacitances C1 and C2 are changed to:

$$C_1 = \frac{\varepsilon_0 N_f L_f h}{d}\left(1-\frac{X}{d}\right) \approx \frac{\varepsilon_0 N_f L_f h}{d}\left(1-\frac{X}{d}\right) \quad (2)$$

$$C_2 = \frac{\varepsilon_0 N_f L_f h}{d-X}\left(1+\frac{X}{d}\right) \approx \frac{\varepsilon_0 N_f L_f h}{d}\left(1+\frac{X}{d}\right) \quad (3)$$

The differential capacitance change

$$\Delta C = C_1 - C_2 = \frac{2.\varepsilon_0.N_f.L_f.h}{d}\left(\frac{X}{d}\right) \quad (4)$$

Considering the total sensing mass of the accelerometer as *m*, the inertial force $F_{Inertial}$ experienced by the sensing mass for acceleration *a* along sensitive direction is:

$$F_{Inertial} = -ma \quad (5)$$

Taking total spring constant of the beams as *K*, the displacement *X* of the movable mass can be calculated as:

$$X = \frac{F_{inertial}}{K} = \frac{ma}{K} \quad (6)$$

3.2 Sensitivity analysis

From Eq. (6), the displacement of the device along the sensitive direction can be expressed as [10]:

$$X = \frac{ma}{K} = \frac{\rho.h.a(W_m.L_m + N_f.W_f.L_f)L_b^3}{2.E.W_b^3} \quad (7)$$

And the displacement sensitivity S_d becomes:

$$S_d = \frac{\rho.h(W_m.L_m + N_f.W_f.L_f)L_b^3}{2.E.W_b^3} \quad (8)$$

Considering the displacement of the movable mass and fingers (*X*) is much smaller than the static capacitance gap *d*, and ΔL_f much lower ($\Delta L_f \approx 0$) the capacitance sensitivity S_c can be expressed as [10]

$$S_C = \frac{2.N_f.\varepsilon_0.h.(L_f - \Delta L_f)}{d^2} S_d \quad (9)$$

The different geometrical parameters used in this simulation is given in Table-I. The various displacement of moving mass is achieved by applying various accelerations such as 0g, 10g, 20g, 30g etc. The displacements of proof mass along y-axis is simulated and measured by the FEA software ANSYS.

Table 1. Physical and geometrical parameters of model

Parameters	Design
Capacitance gap (d)	2 μm
Device Thickness (h)	5.2 μm
Mass Width (W_m)	34 μm
Mass Length (L_m)	812 μm
Beam Width (W_b)	6 μm
Beam Length (L_b)	150 μm
Finger Width (W_f)	34 μm
Finger Length (L_f)	120 μm
Number of Fingers (N_f)	136 μm
Young's modulus of poly-si (E)	1.72×1011 pa
The Dielectric constant of air (ε_0)	8.854×10-12 F/m
The Density of poly-si (ρ)	2330 kg/m^2
Gravity Acceleration (g)	9.8 m/s^2
Total mass (m)	2.81×10-10 kg
Spring Constant (K)	1.13×102 N/m

4. RESULTS AND DISCUSSIONS

Displacement, Capacitance and Sensitivity of the device has been calculated and plotted using MATLAB software. Some parameters like beam width and beam length is also varied. The simulated results have been plotted as shown below.

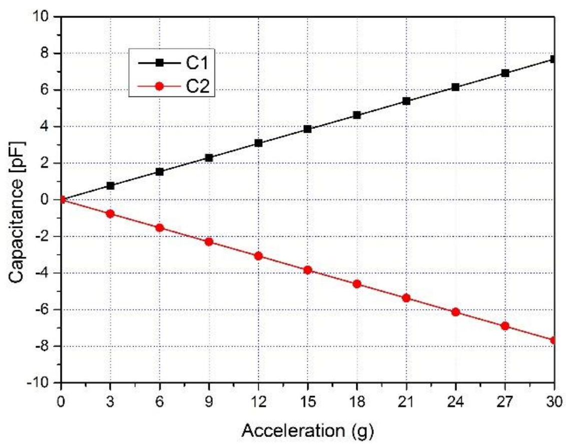

Fig 3. Capacitances vs. Acceleration of proof mass

One capacitance (C_1) increases linearly and another capacitance (C_2) decreases linearly with the increased values of acceleration. The variation of the values of both capacitances as calculated by equation (2) and (3) with respect to applied acceleration is shown in Fig 3.

As a part of simulation, a 2D model is prepared using ANSYS and the displacement of the proof mass is measured from the deformed structure. The calculated result of displacements and simulated results of displacement for applying acceleration is tabulated in the Table-II. It can be seen that the calculated and simulated output voltages matched with nearly 6%.

When acceleration is applied, proof mass is displaced from its original position. Depending the value of displacement the capacitances are also changed. The relation between capacitances and displacement are shown in equation (2) and equation (3). The various displacement of moving mass is achieved by applying various accelerations such as 0g, 10g, 20g, 30g. Displacement of different part of the structure after application of acceleration is shown in Fig. 4. From the figure, it is understood that the maximum displacement happens for the proof mass and the corresponding beams attached to it.

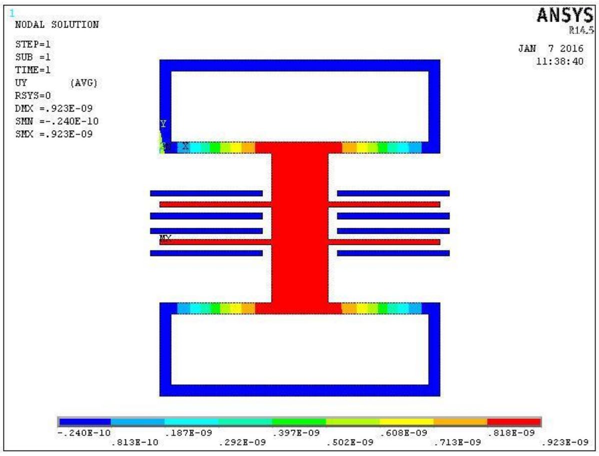

Fig 4. Displacement along y-direction for 10g acceleration.

Table 2. Calculated and simulated Output voltages for different accelerations (input voltage to the sensing capacitor is 15V)

Acc.	Mass	Force	Displacement		
a(g)	m (kg)	F=m*a (Nt)	Calculated (Matlab)	ANSYS	Diff (%)
0		0	0	0	0
10		2.75×10^{-8}	2.43×10^{-10}	2.31×10^{-10}	5.19
20	2.81×10^{-10}	5.51×10^{-8}	4.87×10^{-10}	4.63×10^{-10}	5.18
30		8.26×10^{-8}	7.31×10^{-10}	6.93×10^{-10}	5.48
40		1.10×10^{-7}	9.75×10^{-10}	9.23×10^{-10}	5.63
50		1.38×10^{-7}	1.22×10^{-9}	1.16×10^{-9}	5.17

As the basic principle of the accelerometer device is the displacement of the proof mass with respect to applied acceleration, the displacement of the proof mass is calculated using MATLAB software and the displacement was measured from the simulation using Finite Element method. The calculated and simulated values of displacement is shown in Table-II. Both results matches very well.

The effect beam length and beam width on the displacement as well as capacitance of the proof mass has also been studied. Variation of capacitances with respect to beam length and beam width is plotted in Fig.5 and Fig.6 respectively.

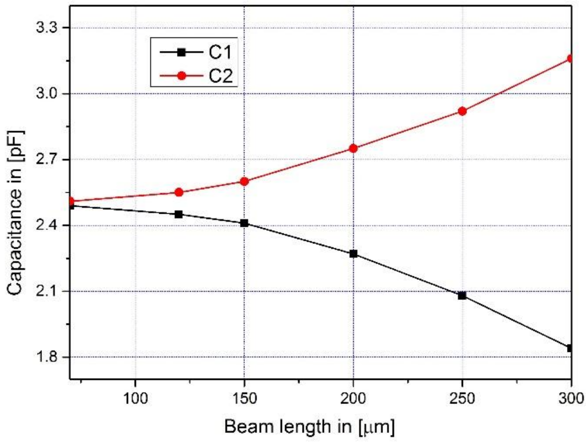

Fig 5. Variation of Capacitances as a function of beam length

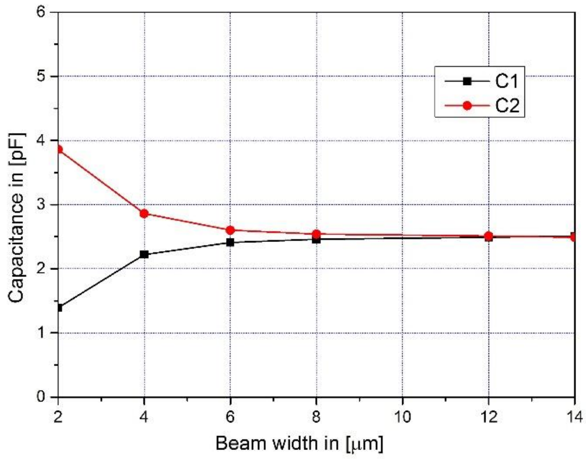

Fig 6. Variation of Capacitances as a function of beam width

From Fig. 5 and Fig. 6, it is observed that the change in capacitance of the device output is increased with increase in beam length and decrease in beam width.

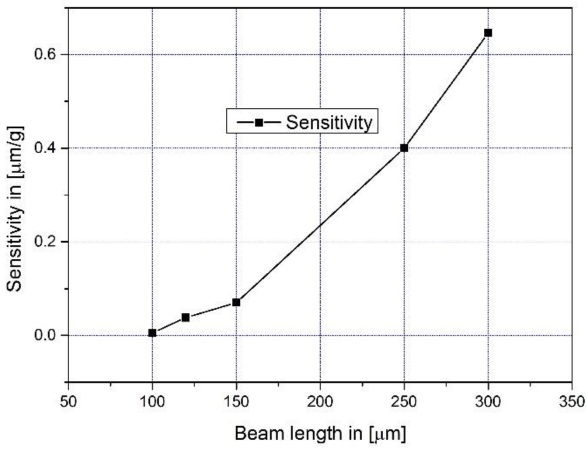

Fig 7. Variation of Sensitivity with the variation of Beam length

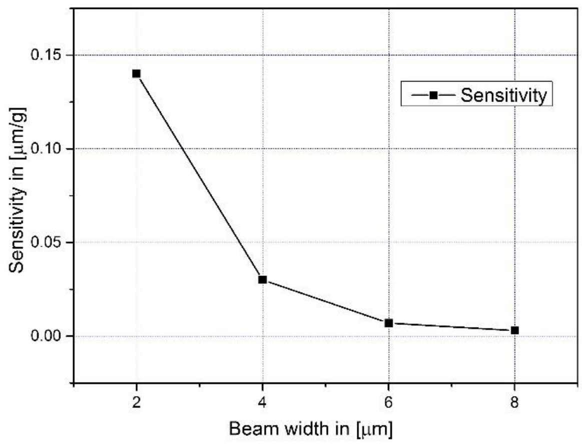

Fig 8. Variation of Sensitivity with the variation of Beam width

To achieve better performance of the device, its sensitivity must be improved. The displacement sensitivity has been calculated using Equation (8).The variation of displacement sensitivity with respect to beam length and beam width has been plotted in Fig.7 and Fig.8 respectively. From Fig. 7 it is observed that sensitivity of the device increase with higher beam length. Fig. 8 shows that the sensitivity increases with thinner beam width. So, to improve the sensitivity of the device, longer beam length and thinner beam width is recommended.

5. CONCLUSIONS

Finite element analysis software ANSYS is used to simulate the proposed MEMS based Capacitive Accelerometer. Variation of Capacitance and sensitivity against the beam length and beam width of the device is also analyzed in detail. It has been noted that sensitivity of the device increases with the increase in beam length and reduction of beam width. These findings gives the guidelines for design of MEMS capacitive accelerometers with improved sensitivity.

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