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Analytical Design of Micro Electro Mechanical Systems (MEMS) based Piezoelectric Accelerometer for high g acceleration

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Abstract- This paper describes the analytical analysis of MEMS based accelerometer consisting of proof mass suspended by quasi beams. The mathematical equations have been used to find the geometrical specification to design an accelerometer. The purpose of the work is to optimize the design for high g value of acceleration. An attempt has been made to design a bulk micromachined accelerometer that satisfies certain specifications. The geometry of the accelerometer is to be optimized for 20g acceleration.

Index Terms- Accelerometer, MEMS, micromachined

1. Introduction:

Piezoelectric MicroElectroMechanical Systems (MEMS) based accelerometers are receiving much interest since last few years [1]. Cost effective and small MEMS accelerometers need for more cost efficient and miniaturized accelerometers are much more demanding in the present scenario. A number of different accelerometers are available in the market such as capacitive [2], piezoresistive [3] and piezoelectric [4]. Out of these piezoelectric accelerometers are attracting more attention due to less temperature dependence, better long term stability and higher bandwidth compared to the two principles based accelerometers. Also, piezoelectric devices are self-generating and thus do not needs a stable drive voltage to be applied. Other main advantage of piezoelectric accelerometer is simple structure, fabrication process and read out circuitry [5].Accelerometers now days have been used in different application area. One of the demanding areas of this device is automotive industry.

The accelerometers are being used in release of air bags in modern car systems and other automobiles. In aerospace, these are used to sense microgravity in space laboratories. In medical applications these are used to monitor the vibrations of a patient suffering from Parkinson disease. These are number of such other applications where accelerometers can be used. The aim of this paper to optimize the geometrical parameters for 20 g acceleration and different parameters are mathematically optimized like beam length, width and thickness to get optimum frequency and good sensitivity. A tradeoff is to be made between sensitivity and frequency so as to obtain optimum geometrical specifications.

2. Theory: The parameters which are used in evaluation of accelerometer sensors are sensitivity and operating frequency. A compromise is to make between these two as they are inversely proportional to each other. The measurement of acceleration depends upon the classical Newton's mechanics theory. The accelerometer consists of a proof mass suspended by quasi beams through a spring element as shown in figure-1 where m is proof mass, k is spring constant and β is damping coefficient.

$$m\frac{\partial^2 x}{\partial t^2}+\beta\frac{\partial x}{\partial t}+kx=-ma \quad ---(1)$$

The acceleration causes a force to act on the mass, which is consequently deflected by a distance 'x'. Some form of damping is required in the device; otherwise the system would oscillate at its natural frequency 'ω_n' for any input signal. To derive the motion equation of the system, D'Alembert's principle is applied, where all real forces, acting on the proof mass, are equal to the inertia force on the proof mass [6]. Let *x* be the displacement of the mass *m* relative to the body. When the body has acceleration *a*, the equation of motion for the mass 'm' is given by:

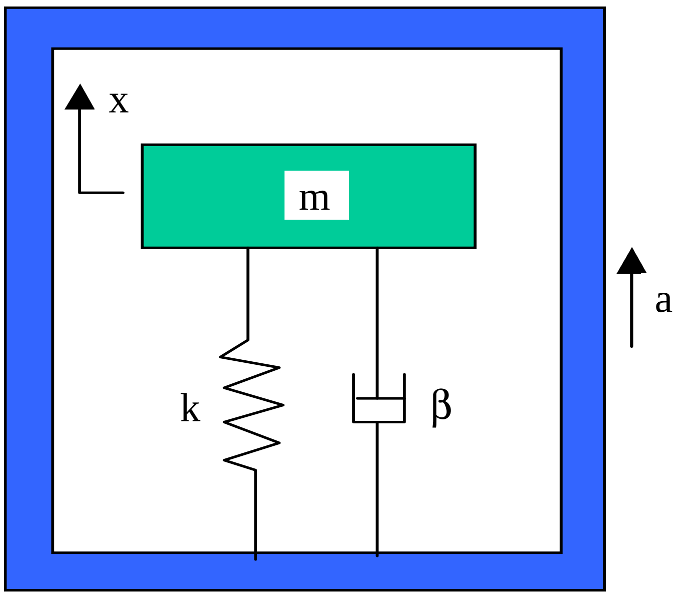

Figure-1 General model of an Accelerometer

where β and *k* are the damping coefficient and spring constant, respectively. Therefore, acceleration can be determined by measuring net stretch or compression ‘x’ of the spring.

3. Analytical Design:

The accelerometer design is to be achieved by using appropriate design equations. The following strategy was kept into mind while designing the accelerometer.

(i) The resonance frequency of the accelerometer for which the device is to be designed. In the present work, the resonance frequency decided for the accelerometer is 1 KHz.

(ii) The parameters which are to be optimized like dimensions of proof mass, Dimensions of silicon beam with which the accelerometer is to be suspended.

(iii) The compromise between resonance frequency and sensitivity is to be maintained as these are inversely proportional to each other.

(iv) Calculations of silicon mass, spring constant, damping coefficient, damping ratio and cutoff frequency need to be done using mathematical equations.

(v) Young’s modulus ‘E’ for silicon is to be selected, in present work E= 190GPa.

(vi) Initial selections for the silicon mass dimensions are made.

3.1 Calculation of various parameters:

The design of device starts for MEMS based Bulk micromachined micro accelerometer. The material selection is an important parameter which is to be kept in mind while designing a device. Silicon SOI wafer <100> orientation having thickness of 525 µm with Young’s Modulus of 190GPa has been chosen as a starting material. The accelerometer will be designed for single axis acceleration detection. The displacement of the silicon mass without external mechanical element is assumed to be zero. The device includes the selection of dimensions of proof mass i.e., length, breadth and thickness of the mass. The dimensions of beams with which mass is suspended. The calculated dimensions must satisfy the specifications for which design is to be optimized. In the present work, accelerometer is to be designed for resonance frequency of 1 KHz and acceleration of 20g which is very high used in space applications. The following parameters are optimized for required specification:

3.1.1 Calculation of Silicon Mass (m):

The proof mass has been calculated by using the calculation of mass for truncated pyramid silicon as we are using bulkmicromachined structure.

$$m = \frac{\rho t(a1^3 - a2^3)}{3(a1 - a2)} - - - - 2)$$

Where ρ= 2300 kg/m^3 is density of silicon, t= thickness of silicon mass and $a1 = a2 - t\sqrt{2}$ Using a1= 3mm and thickness t= 525µm. mass is calculated as 9.58 x 10^{-6} Kg.

3.1.2 Spring Constant (k): Spring constant 'k' depends on the geometry of silicon beam and Young's modulus of material. The proof mass in present design is suspended through four beams, the spring constant is given by

$$k = \frac{Ebh^3}{l^3} \quad ------------ (3)$$

where *l* is length, b is breadth and h is thickness of beam. The dimensions of silicon beam are optimized for the resonance frequency of 1 KHz. The selected parameters are optimized using the various equations [7] and determined the different values using Excel file. The deflection [8] is calculated by:

$$\delta = \frac{l^3 W_b}{12EI} - - - - - - - - (4)$$

Where E is Young's modulus, I is moment of inertia, W_b= force on single silicon beam, which is one fourth of the total force 'F' being applied on the proof mass.

The parametric analysis is performed to fix the beam dimensions to obtain the optimum and acceptable deflection for 20 g acceleration. The effect of beam length on deflection with constant width and varying thickness and constant thickness with varying width of the beam as shown in figure-2 and 3 respectively.

The fundamental resonant frequency is determined by the dimensions of beam. A number of combinations of length, width and thickness of the beam have been used for desired frequency calculation. The variation of frequency has been drawn with varying beam length for constant width and at different thickness. Also the same behavior has been studied for constant thickness at different width as shown in figure- 4 and 5 respectively. The dimensions are finalized and selected according to the frequency and deflection requirement.

The feasible options for the combination of length, width and thickness are shown in table-1.

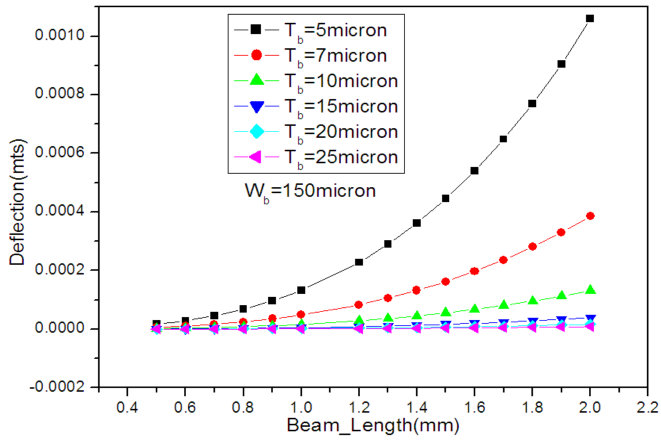

Figure: 2 Deflection versus Beam Length for 20 g input; W_b=150µm and varying thickness

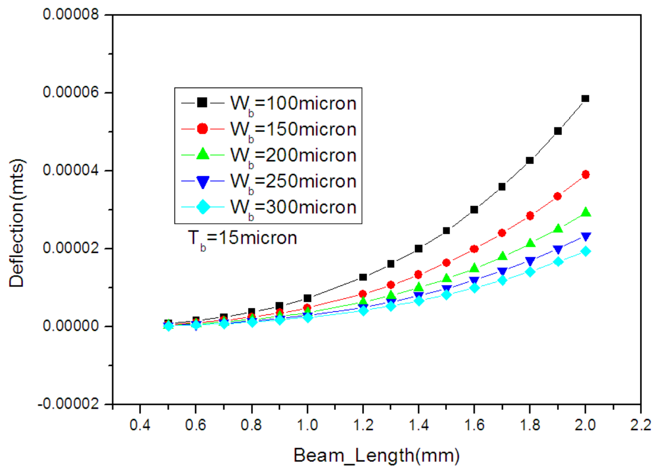

Figure: 3 Deflection versus Beam Length for 20 g input; t_b=15µm and varying width

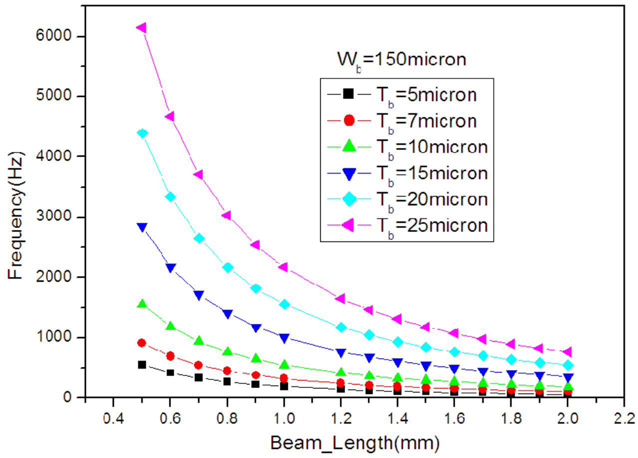

Figure: 4 Natural Frequency versus Beam Length for 20 g input; W_b=150μm and varying thickness

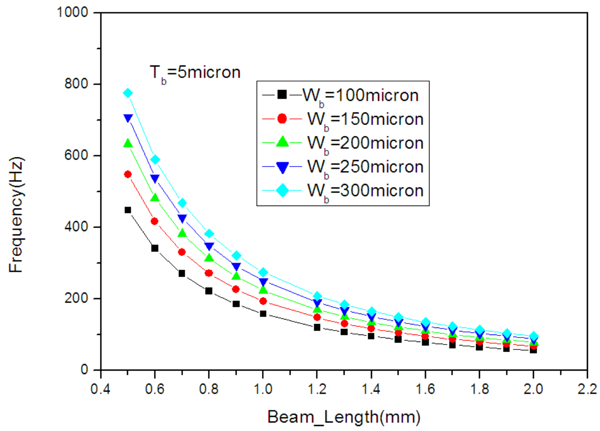

Figure: 5 Natural Frequency versus Beam Length for 20 g input; t_b=15μm and varying width

Table-1: Feasible options after frequency and Deflection analysis

Sr. No	Thickness(μm)	Width(μm)	Length(mm)	Deflection(m)	Frequency (Hz)
1	10	300	0.8	4.22E-6	1085.65
2	15	300	1.2	4.22E-6	1085.65
3	20	300	1.6	4.22E-6	1085.65
4	25	300	2	4.22E-6	1085.65
5	**15**	**150**	**1**	**4.89E-6**	**1009.13**
6	20	150	1.3	4.53E-6	1048.19
7	25	150	1.6	4.32E-6	1072.85
8	20	250	1.5	4.17E-6	1091.80
9	25	250	1.9	4.34E-6	1070.32

Out of all these combinations Sr.no-5 is used for software modeling because only this combination meets the requirement of desired resonance frequency. Although the deflection in this case is little bit higher than others but may be acceptable because all other parameters are in acceptable range as mentioned by previous researchers [6-8].

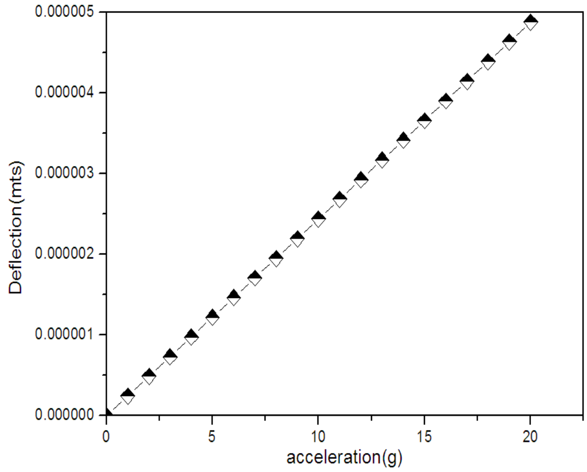

Figure-6: Movable mass versus acceleration

The damping coefficient 'β' is found to be 0.12, damping ratio 'ζ' 0.99 and minimum acceleration a_{min} is 0.00205g. The variation of deflection of the proof mass with applied acceleration has been calculated and the behavior is found to be linear; however it is found that the deflection in the diaphragm increases as the applied acceleration increases as shown in figure-6. After all the mathematical calculations for mass, spring constant , damping coefficient and resonance frequency, it has been found the length, width and thickness of 1mm, 150 µm and 15 µm respectively of the silicon beam is suitable for the present design.

4. CONCLUSION:

Geometrical dimensions for a MEMS micro accelerometer for high g applications have been analytically optimized and the effect of beam length on various important design parameters has been studied.

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