DESIGN OF A MEMS PIEZOELECTRIC ACCELEROMETER

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Abstract

The piezoelectric micro accelerometers have wide applications in the field of auto mobiles, inertial navigation and bio medical instrumentation. The main aim of our research is to develop a piezoelectric accelerometer that can measure body movements in assessing the neurological disorders like parkinsons disease. The most important specifications for medical applications are amplitude range +/-5g. resolution 10^{-3}g, bandwidth d.c.-50 Hz, off axis sensitivity < 5%, low drift and power consumption < 1mW. The accelerometer design employs a proof mass suspended by four beams. When the device is accelerated the mass moves relative to the anchor, the beams deflect causing the piezoelectric layers to deform and hence a charge is induced .The amount of charge generated depends upon the piezoelectric properties of PZT material, and many dimensional design considerations. This design is proved to get very high sensitivity, good frequency response. FEM simulations are performed by the CoventorWare® to investigate the device behavior. Displacement of the structure due to the applied acceleration of 1g has been simulated. Charge sensitivity is found to be $3.201X10^{-6}$ Col/g at the resonant frequency of 58Hz has been evaluated.

Key Words: Coventorware, Piezoelectric Accelerometers, Charge Sensitivity, Off axis sensitivity,Silicon On Insulator(SOI).

1.Introduction

Micro electro mechanical systems which permits the integration of micro machined mechanical structures with integrated circuits, has been the growing area of research in last two decades. MEMS have a wide range of applications including automotive ,industrial, biomedical and information processing. Silicon micro machining , taking the advantages of well established processes and materials in microelectronics ,is commonly used to fabricate mechanical micro structures. There are many functional materials that can be fit with MEMS. PZT is the one of those materials that is attractive because of their high sensitivity in sensor applications. Its high electromechanical coupling and piezoelectric constant, which are an order of magnitude larger than ZnO and AlN. Accelerometers have been used in many fields including for activation of automotive safety systems, for machine and vibration monitoring and in biomedical applications for activity monitoring. In 1982 ,Chen et al. fabricated a Silicon bulk micro machined piezoelectric accelerometer with cantilever beam structure using a ZnO film and obtained a sensitivity of 47µV/g. In 1984 Chen and Muller redesigned the same accelerometer with a huge Si mass which was 20 times their previous design and were able to obtain the sensitivity of 5mV/g with a resonant frequency of 8.4KHZ. In 1996 Nemirovsky et al. designed a PZT thin film piezoelectric accelerometer[1] with a sensitivity of 320mV/g. In 1997 De Voe and Pisano designed a ZnO accelerometer [2]which gives a low sensitivity of 0.95fC/g. In 1999 Reus developed a ZnO accelerometer[3] with single proof mass and two suspension beams with a sensitivity of 0.1pC/g and a resonant frequency of 4.5khz. In 1999 Beeby developed a bulk micro machined accelerometer[4] with a very high sensitivity of 16pC/g. In the same year 1999 Eichner designed a bulk micro machined PZT accelerometer[5] with a single proof mass and 2 suspension beams and the sensitivity of 0.1mV/g was obtained with 13kHZ resonant frequency. In 2003 Li-Peng Wang fabricated a bulk micro machined piezoelectric accelerometer with annular diaphragm structure and obtained a sensitivity of 0.77pC/g with resonant frequency of 3.7kHZ. In 2007 Hui Yang designed the bulk micromachined piezoelectric accelerometer with 12 different structures . All the above accelerometer designs make use of bulk micromachining or surface micro machining with piezoelectric sensing. Every design has its own advantages and disadvantages. However we have designed an accelerometer that is useful for biomedical applications where our main goal is to get the good sensitivity with given specifications.In order to measure physical activity accelerometers must be able to measure +/- 5g at the waist level and frequencies between 0 to 30 Hz.

2.Design

Piezoelectric material provides its own internal biasing requirement, either due to absence of a center of symmetry in the case of single-crystal materials such as aluminum nitride (AIN) or zinc oxide (ZnO)
or due to a permanent polarization present in ferroelectric materials such lead–zirconate–titanate (PZT). A typical piezoelectric accelerometer consists of a layer of piezoelectric material sandwiched between a mounting plate and a seismic mass. When a force or a pressure is applied to the opposite faces of the piezoelectric material, an electric charge is produced. This charge can be amplified to give an output voltage that is proportional to the applied force or acceleration.

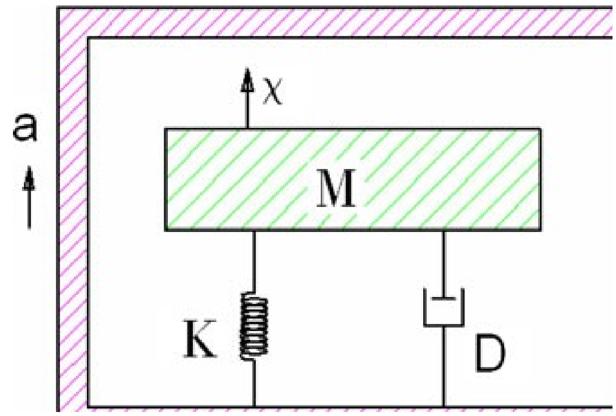

Figure1. Basic Accelerometer Model

The basic equation (1) of the system is

$$M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + kx = -F = -Ma$$

The most important characteristics of an accelerometer are the sensitivity and the operating frequency range. The sensitivity is defined as the ratio between the electrical output (charge or voltage) and the mechanical input (force or acceleration);the band where the sensitivity remains practically unchanged defines the operating frequency range which is upper limited by the first resonance frequency of the device. In the classical accelerometers, which are one-directional, the increase of the sensitivity is obtained by increasing the seismic mass. Nevertheless, the added mass produces a lowering of the resonance frequency and, therefore, a narrowing of the operating frequency range. Mechanical accelerometers consist of a spring-mass system, with a seismic mass carried by elastic tether beams.

Band width	dc-50HZ
Amplitude range	+/- 5g
Off axis sensitivity	<5%
Power consumption	< 1mw

Table1.Specifications of Accelerometer

Acceleration along the sensitive axis leads to a deflection of the seismic mass, with elastic forces from the tether beams balancing the external forces.The design shown in figure 3 employs a proof mass with four crab leg beams.Crab leg beam consists of a added thigh section L_a to the beam L_b . The added thigh section, length 'La' minimizes the peak stresses in the flexure. The deflection of the thigh also reduces the extensional stresses. the stiffness 'K'of the crab-leg flexure unlike the fixed-fixed flexure, can be varied by varying the values of lengths and widths of thigh and shin segments. The crab-leg flexure has linear characteristics closely matching the linear deflection model[10] for small deflections as shown in Figure.2

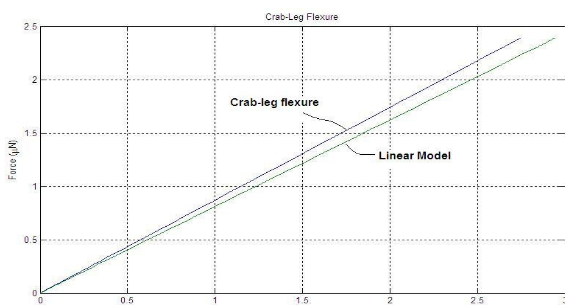

Figure2.Deflection of the crab leg flexure

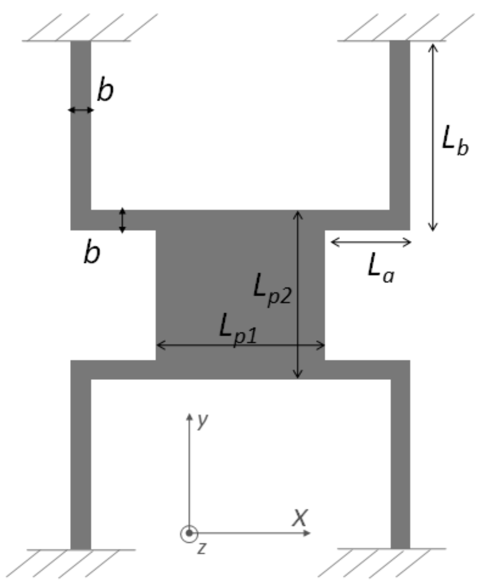

Figure3. Structure of Accelerometer

With *m* and *k* the seismic mass and the spring constant of the spring-mass system, the resonance frequency of the spring . The spring constant estimated as

$$k = \frac{\propto E_{max} b \sum \frac{E_i}{E_n} \frac{t_i^3}{12} + t_i \frac{E_i}{E_n} (h_i - h_n)^2}{l^3}$$

where α is a constant value correlated to the springs, *Emax* is the maximum Young's modulus of the stack materials, *l* is the equivalent length of the spring, given by a contribution of *La* and *Lb*, as shown in Fig.3*b* is the width of the beam ,*hn* is the neutral axis position assumed in the homogeneous domain. *Ei, ti*, *hi* represent the Young's modulus, thickness and the neutral axis position for the *i* th element . This design enables us to measure the body tremors(table.4) in the frequency range of (2-30)Hz with a very high sensitivity. In our design we have chosen mass and stiffness constants of the beams as the important parameters as these two parameters decide the resonant frequency of the device and there by the operating frequency range(figure4). The beam stiffness depends on the length of the beam, thickness of the beam(figure5).

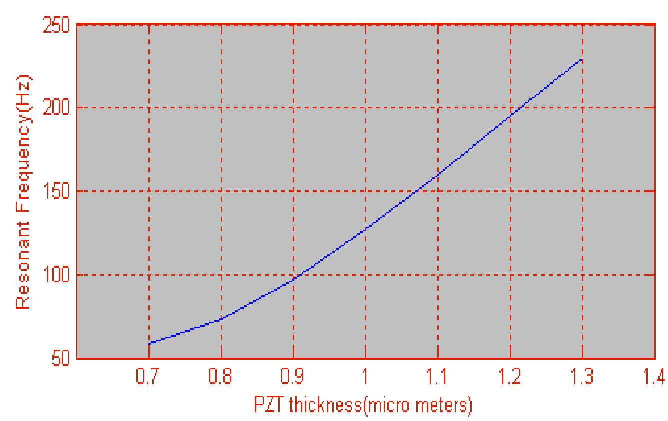

Figure 4. Effect of PZT thickness on Resonant frequency

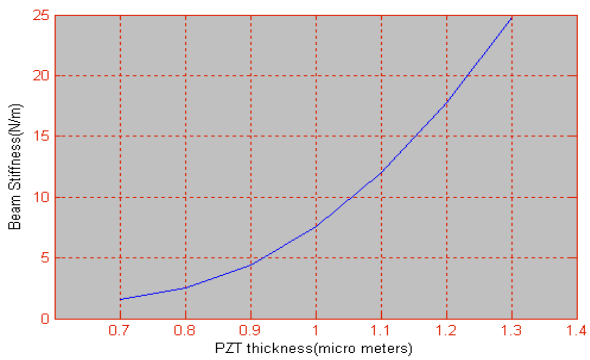

Figure 5. Effect of PZT thickness on beam stiffness

3.Piezoelectric Sensing

The charge induced on the beam is due to piezoelectric effect of PZT film deposited on the beam.The induced electric polarization due to stress is given by [5]-[6]

$D= € E_{FIELD} + d\,\sigma$

Where € and d are the permittivity and piezoelectric coefficient of PZT.
For piezoelectric sensing usually electric field is not applied so

$D= d\,\sigma$

The normal stress according to piezoelectric relations given by M.S Weinberg [6]

$$\sigma = E_p.\frac{1}{R}.Z_p = E_p.\frac{M}{\sum E_i(I_i + A_i h_i^2)}.z_p$$

Where E_p is the youngs modulus of PZT,I_i is the moment of inertia of each layerin the beam,A_i is the cross section area of each layer,Z_i is the distance between center of each layer and neutral plane of the beam.

According to M.S.Weinberg[6] the charge produced on the electrode is

$$Q = \int D.w.dl = \int d_{31} E_p.\frac{M}{\sum E_i(I_i + A_i h_i^2)}.z_p.w.dl$$

Therefore charge sensitivity is nothing but the charge produced by unit acceleration.

4.Fabrication

In the past, manufacturing methods employed to make inertial MEMS devices could be roughly divided into either surface or bulk micromachining . Newer methods involving the use of silicon on insulator (SOI) substrates are becoming increasingly popular. The use of SOI substrates combines the manufacturing advantages of surface and bulk micromachining. The other advantages of using SOI technology are feasibility of fabrication of very high aspect ratio structures by using deep reactive ion etching (DRIE), effective electrical isolation between two silicon layers by an oxide layer resulting in superior electrical performance, SOI substrates facilitate the combining of CMOS electronics and MEMS devices on the same wafer, Process complexity and costs are reduced when the SiO2 layer is used as an etch stop. Thus, SOI technology is the best choice for making devices like high performance accelerometers and gyroscopes etc.

SOI substrate is formed with 450 µm Si 2 µm SiO_2 and 15 µm Crystal Si. Thermal grown oxide of 0.1 µm thickness is stacked on the SOI wafer. Reactive Ion Etching is done to form the mass and beams from the front side. PZT material of 0.7 µm is deposited on the front side by sol-gel deposition. Aluminum of 0.6 µm is deposited on the front side using PECVD technique. PZT and Aluminium are removed from front side by applying masks. 450 µm Si is removed from backside to form the beams. FEM simulations are performed by the CoventorWare® to investigate the device behavior. An example of simulation results is shown in Fig.5 Displacement of the structure due to the applied acceleration of 1g has been simulated. Charge sensitivity is found to be $3.201X10^{-6}$ Col/g at the resonant frequency of 58Hz has been evaluated.

Table.2. Material properties of layers

Material	Young's modulus (GPa)	Density (X10 $^{-15}$ kg/ μm^3)
Aluminium	77GPa	2.3
Si_iO_2	70 GPa	2.2
PZT	148 GPa	7.85
Silicon	160 GPa	2.5

Table.3. Designed accelerometer parameters

Proof mass length(μm)	3000
Beam length,L_a(μm)	600
Beam length,L_b(μm)	2200
Beam width(μm)	200
Beam Thickness (μm)	16.8
PZT thickness(μm)	0.7
Aluminium thickness(μm)	0.6
Thickness of proof mass(μm)	450

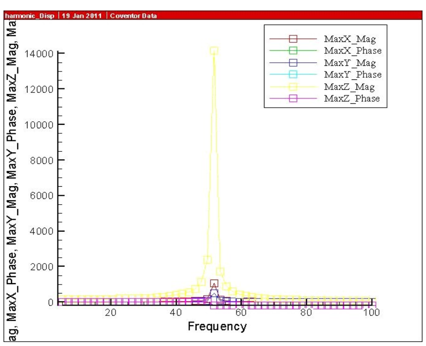

Figure 6.Frequency Response of Accelerometer

Table.4.Frequency ranges of tremors

Tremor type	Frequency (HZ)
Normal hand tremor	9-25
Essential tremor	4-12
Parkinsons disease	3-8
Cerebral lesions	1.5-4

5.Conclusion

A high sensitivity MEMS Piezoelectric accelerometer is designed and analyzed in CoventorWare® to investigate the device behavior . This design proved to get high sensitivity because of its structure, device dimensions ,and the PZT material properties. We can further increase the sensitivity by increasing proof mass dimensions but there is a trade off between proof mass and resonant frequency. The advantages of SOI technology and structure of accelerometer are exploited to achieve the high performace accelerometer useful for medical applications.

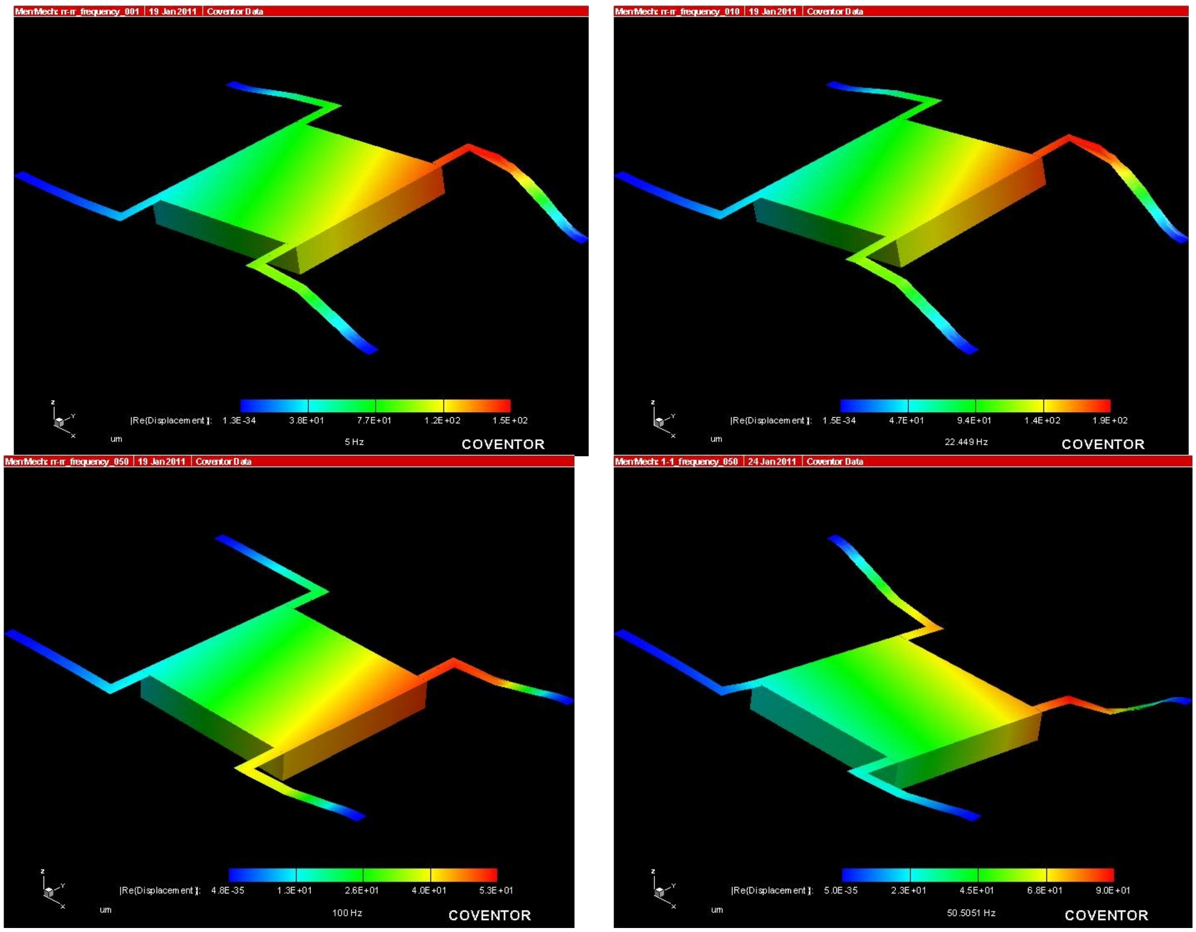

Figure 7. Examples of results obtained by thesimulation of the device behavior in Coventorware Environment at 5Hz,22Hz,50Hz,100 Hz

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