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Design Issues of Piezoresistive MEMS Accelerometer for an Application Specific Medical Diagnostic System

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ABSTRACT
This paper reports the design and simulation of finite element method (FEM)-based micro-electro-mechanical-systems (MEMS) piezoresistive accelerometer used in a strapdown medical diagnostic system. A square proofmass with four flexures is used in this design. Here, p-doped single-crystal silicon are used as eight piezoresistors implanted on the flexures for sensing the maximum stress; and they are connected in the form of a wheatstone bridge with each arm containing two piezoresistors. Basically, here two different geometric configuration but of same material have been designed and simulated using FEM-based tool for dynamic range ($\pm$)2g. To assure better performance characteristics, different analysis for both the configurations are done. Configuration 1 is found to have better performance with respect to load withstanding capability, eigen value analysis, better response characteristic, and low cross-axis sensitivity. Furthermore, the measurement scheme adopted is the wheatstone bridge, which gives better performance as offset is almost nullified.

KEYWORDS
Cross-axis sensitivity; Eigen value; MEMS piezoresistive accelerometer

1. Introduction

Micromachined MEMS accelerometers find its application from a simple vibration monitoring system to a complex inertial navigation system. Demand for low-cost, high-resolution, and high-sensitivity micromachined accelerometers have been increasing to cater to the need in various fields. The performance factors of MEMS accelerometers depend on several aspects of geometric design, device sensing mechanism, scaling limitations, associated electronic circuits, and fabrication aspects. There are different transduction mechanisms like capacitive, piezoelectric, and piezoresistive [1]. Stress-based measurement generally use piezoresistive and piezoelectric whereas displacement-based measurements usually use capacitive. Among the many technological alternatives available, the advantages of piezoresistive types are that they have a DC response, they have simple read-out circuits and are capable of high sensitivity and reliability. They utilize simple principle of transduction and microfabrication as compared to other types. This paper focuses on the modelling and simulation of two different types of piezoresisitive accelerometer configurations. A relative comparison of both the structures are done and the simulated results of eigen mode analysis, time-dependent analysis, and sensitivity analysis are given. This comparison would help in optimizing the design structure and solve various issues related to stress, doping concentration of the piezoresistors, reduction in cross-axis sensitivity, etc. Hence, with enhanced sensitivity and performance of the MEMS accelerometer, it can be made suitable to be used in a strapdown diagnostic system for the diagnosis of various neurodegenerative disorders. Neurodegenerative essentially means progressive loss of structure or function of neurons [2]. The main symptoms are tremor of body parts, rigidity, bradykinesia, postural instability, etc. None of the pathologies that cause tremor are fully understood, and epidemiological and neurophysiological studies are hampered by the lack of diagnostic methods other than purely clinical. Certain literature reveal the loss of dopamine to be one of the main causes of tremor. Different types of neurodegenerative diseases where tremor occurs are Parkinson, essential tremor, epilepsy, stroke, etc. There are different pathological tremor like rest tremor (3–6 Hz), kinetic tremor (4–12 Hz), and postural tremor (2–7 Hz) [2]. Tremor is a roughly sinusoidal oscillatory movement. The non-stationery features of tremor demands sensitive, reliable, low-cost and stable sensor mandatory. Among the different MEMS sensors available, accelerometer possess desirable features suitable for emerging applications in biomedical applications. MEMS accelerometers respond to frequency and intensity, measure tilt and body motion, and miniaturization has made batch fabrication and low-cost possible. As tremor carries social and psychological burden, hence an attempt has been made to design and simulate an optimized MEMS accelerometer having a bandwidth ranging from 0.1 to 25 Hz with a maximum acceleration amplitude of 2 g. Hence, a relative comparison of two different configuration of piezoresistive MEMS accelerometer has been done in order to develop a final optimized structure for housing it in the strap-down tremor diagnostic system.

2. Theoretical background on piezoresistive effect

The piezoresistive effect is a change in the electrical resistivity of a semiconductor or metal when mechanical strain is applied. The resistance value of a resistor is determined both by the bulk resistivity and the dimension as given by $R = \rho l/A$, where R is the resistivity, ρ is the bulk resistivity, and l and A stands for length and area, respectively. The resistivity changes are seen to be more dominant in comparison to dimensional changes in semiconductor materials and this have led to its usage in applications involving stress sensitivity. The piezoresistivity coefficients of a doped single-crystal silicon piezoresistor are influenced by its relative orientation to crystallographic directions. For a rectangular coordinate system, there exist a symmetric resistivity matrix relating the electric field components E_i and current density component i_i as given by [3]

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_6 & \rho_5 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{bmatrix} \times \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix}.$$

Thus , matrix $E = \rho_{\text{anisotropic}} \times$ current density. Here, $\rho_{\text{anisotropic}}$ is the resistivity of the semiconducting materials. Also, applied stress on such anisotropically affected materials may be expressed as a matrix with six independent stress components corresponding to its cause and effect direction as given by

$$\sigma = \begin{bmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{bmatrix}.$$

The relative change in resistivity can be expressed as the product of piezoresistive coefficient matrix and the stress matrix. The piezoresistive coefficients of single-crystal silicon are not constants but are influenced by the doping concentration, type of dopant, and temperature of the substrate. Different piezoresistive coefficients get affected differently by temperature and doping concentration. The piezoresistive coefficient for the piezoresistors along the (110) direction is given by 1/2 $[\pi_{11}+\pi_{12}+\pi_{44}]$ [3]. For single-crystal silicon, different piezoresistivity components exist for different doping concentrations [4].

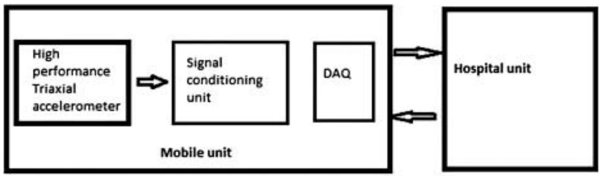

Figure 1: Block diagram of the proposed pathological tremor diagnostic system.

3. Proposed pathological tremor diagnostic system

The proposed tremor diagnostic system consists of the high-performance triaxial MEMS accelerometer, signal conditioning unit and data acquisition unit all housed inside the mobile unit, and the hospital unit consisting of the presentation analysis and storage unit. The block diagram of the pathological tremor diagnostic system is shown in Figure 1.

4. Design configuration of MEMS accelerometer and working

The MEMS accelerometer design chosen is a simple mass spring device. Here, two configurations are designed and simulated using COMSOL 4.3. Design configuration 1 consist of a proofmass, four flexures on either side of the proofmass aligned with its edge and frame on single-crystal silicon. Here, p-type single-crystal silicon (110) piezoresistors are implanted at two different locations, one near the proofmass and the other near the frame. Piezoresistors are positioned keeping in mind that it senses the maximum stress and gives the maximum deflection in the desired direction. Design configuration 2 is chosen to be of same geometric size but the flexures are placed in position non-aligned with the proofmass edge. Both the accelerometer design configuration structures with all its parts have been simulated and the 3D view is shown in Figures 2 and 3 below.

The MEMS accelerometers have piezoresistors implanted on their beams. Whenever there is proofmass displacement, the suspension beams deflect and this causes strain on the piezoresistors. This results in change in resistivity as explained in Section 2 and thus, the signal transduction occurs which can be picked up by any electronic circuit. Each suspension beam contains two piezoresistors therefore out of total eight piezoresistors four suffer from tension when the other four suffer from compression. It is seen that compressive stress increases the resistance value and due to tensile stress the resistance value increases. The piezoresistors are connected in the form of a wheatstone bridge as this type of

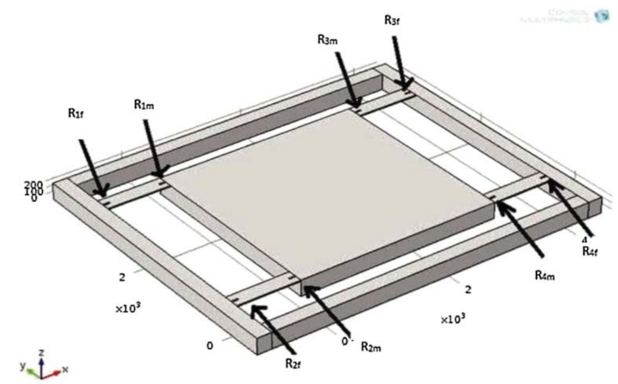

Figure 2: Accelerometer structure1 simulated using COMSOL 4.3.

connectivity gives us a reduced cross-axis sensitivity [5]. The change in the output voltage of the wheatstone bridge is proportional to the applied acceleration.

Eigen value analysis is very important as it is the basis of many dynamic response analysis. Here modal analysis has been done for an overall understanding of the natural frequencies and the modal shapes. Here, the first six eigen frequencies are simulated for both the structures of design configurations 1 and 2 as shown in Figures 4–9. The eigen frequency value are found to be higher in case of configuration 1 as compared to configuration 2 as shown in Table 1. This shows that structure 1 has safer zone and better performance even if the frequency range of operation of the device is increased to several orders. Also, higher the natural frequency the more the linear is the output-to-input characteristic and higher the frequency it can measure. Here, the eigen modes 1, 3, and 5 for both configurations 1 and 2 are plotted.

5. Time-dependent analysis

The MEMS accelerometer has been simulated for various displacement 2 g. Sinusoidal input is given and point

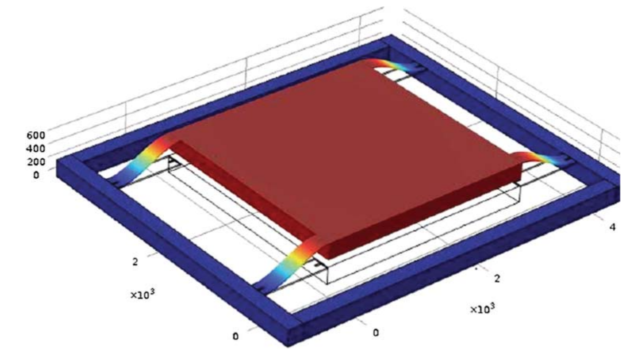

Figure 4: Sensor deflection at eigen mode 1 for configuration 1.

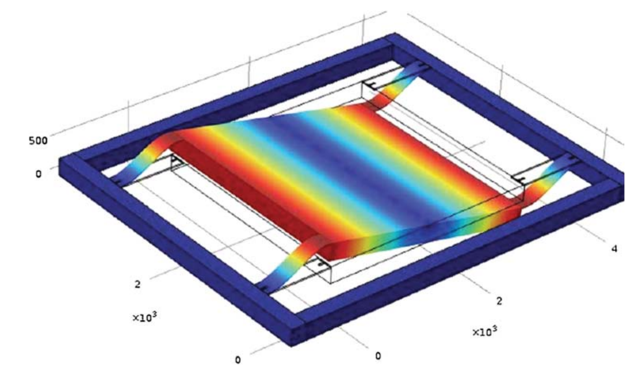

Figure 5: Sensor deflection at eigen mode 3 for configuration 1.

evaluation at centre of the mass as well as various other points of the structure has been observed for both configurations 1 and 2. The structures are taken and point evaluation of displacement, velocity, and acceleration for both have been simulated. Also stress analysis have been done for both the structure. The simulated results of the displacement characteristic and the von Mises stress for both the structures are shown in Figures 10–13. It has been observed that the total displacement is higher in configuration 1 than in configuration 2. Also, the von Mises stress show that configuration 1 can withstand better loading condition though both are of the same material.

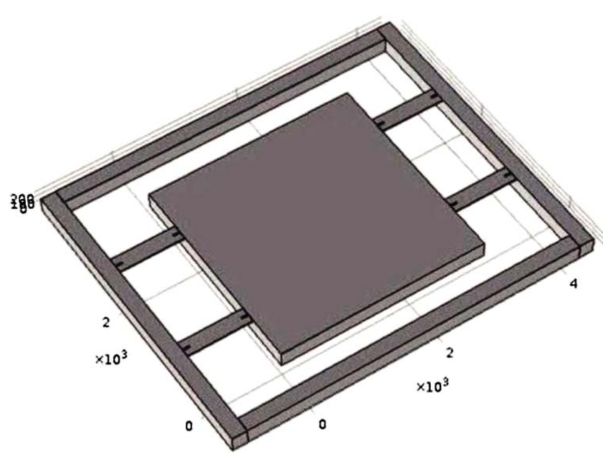

Figure 3: Accelerometer structure 2 simulated using COMSOL 4.3.

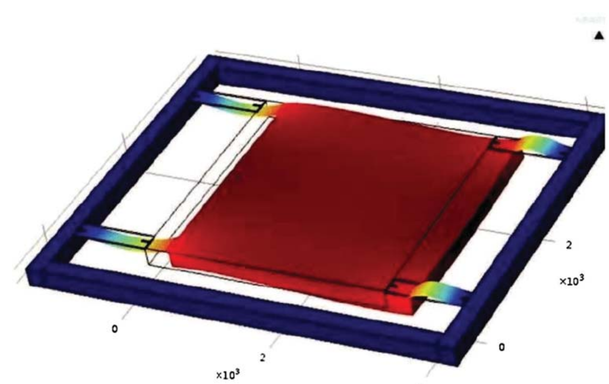

Figure 6: Sensor deflection at eigen mode 5 for configuration 1.

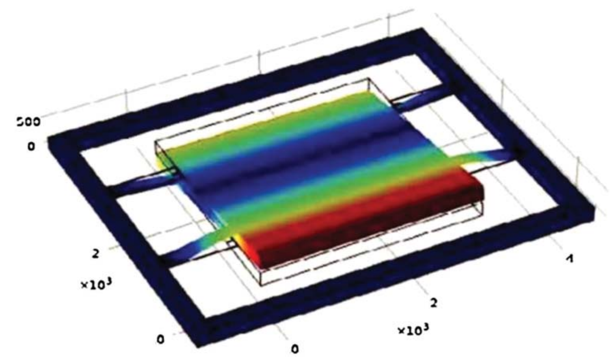

Figure 7: Sensor deflection at eigen mode 1 for configuration 2.

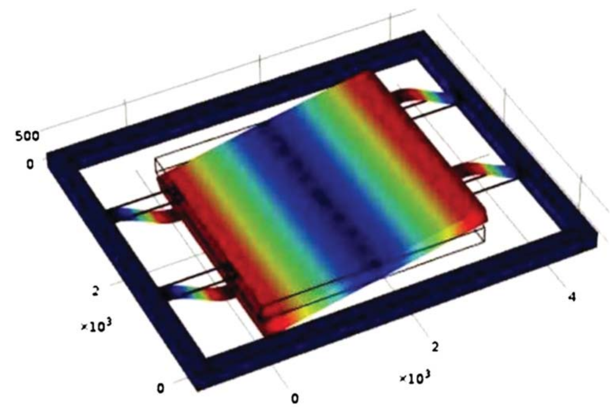

Figure 8: Sensor deflection at eigen mode 3 for configuration 2.

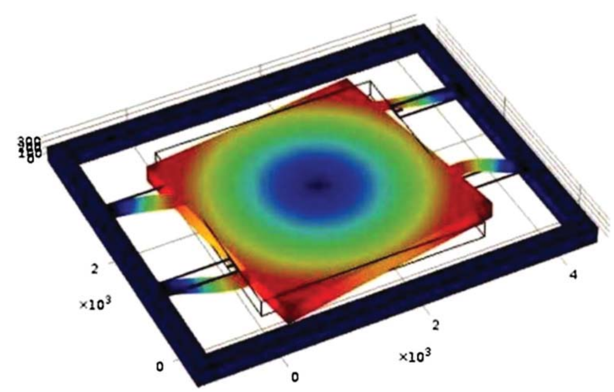

Figure 9: Sensor deflection at eigen mode 5 for configuration 2.

6. Sensitivity analysis

Sensitivity is determined by the relative change in output per unit voltage per applied differential acceleration. For maximum sensitivity, the accelerometer must have maximum prime axis sensitivity and small cross-axis

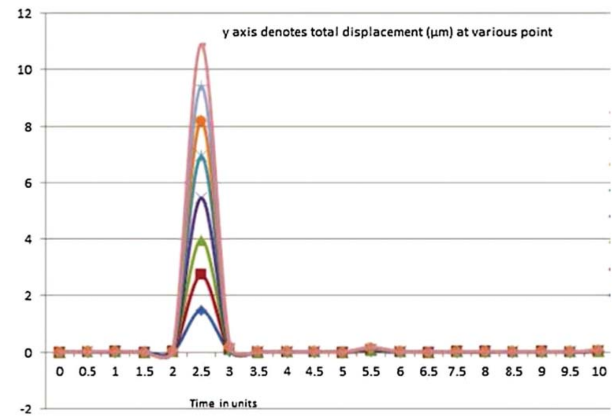

Figure 10: Total displacement in configuration 1.

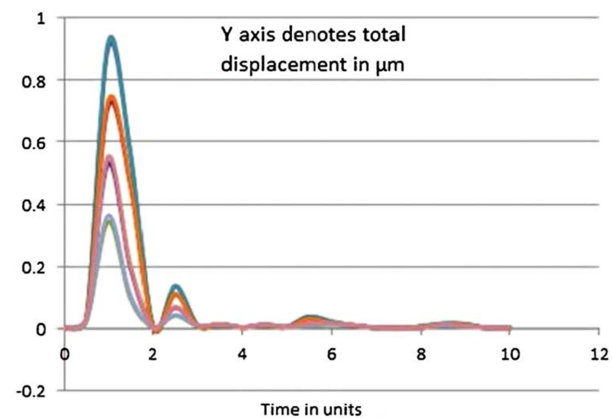

Figure 11: Total displacement in configuration 2.

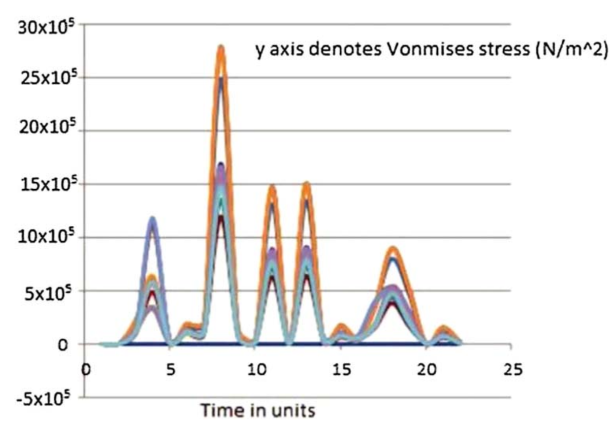

Figure 12: von Mises stress observed in configuration 1.

sensitivity [5]. The cross-axis sensitivity shows how much perpendicular acceleration or inclination is coupled to the signal. Some of the factors which affect the

Table 1: Eigen frequencies for six different modes for configurations 1 and 2

Modes	1	2	3	4	5	6
Config1, eigen freq(Hz)	2412.68	3922.97	5446.59	25,636.50	1.119e5	1.23e5
Config2, eigen freq(Hz)	2374.64	2427.18	5467.72	26,228.96	83,805.51	1.15e5

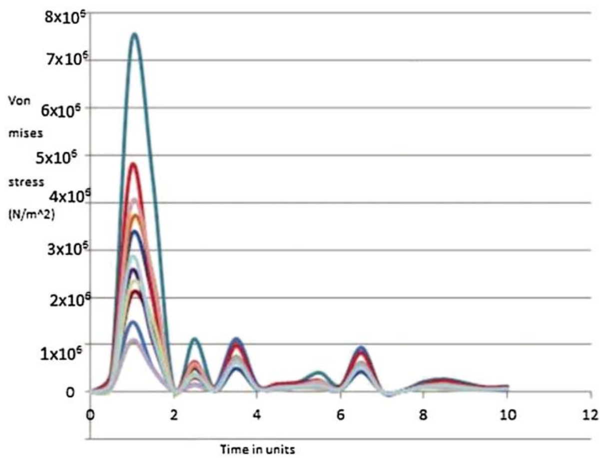

Figure 13: von Mises stress observed in configuration 2.

sensitivity of an accelerometer include the geometric configuration of the device mainly the positioning of the piezoresistors along with its length, cross-sectional area, and the doping concentration. Also, the measurement scheme associated for the signal pick-up must be able to nullify the offset and hence enhance the overall performance of the device. In this case p-type-doped piezoresistors is taken and the flexure thickness is minimum so as to get the largest resistance change, hence the largest sensitivity. The measurement scheme chosen here is the wheatstone bridge circuit. To achieve low cross-axis sensitivity along a particular direction, stiffness should be high along that direction. Stiffness depends upon a number of flexures, geometric structure, and position of flexures [6]. In this case, the stiffness is high along the x-axis, and as the proofmass is parallel to the x-axis, the cross-axis sensitivity is low. Also, by placing the flexures in-line with the proof mass edges, the y-cross-axis sensitivity can be improved. In configuration 2, it is seen that the distance between the flexure is less compared to configuration 1. When the distance between the flexures is increased, the stiffness along the y-axis is found to improve which in turn reduces the cross-axis sensitivity. Thus, configuration1 has better performance in case of cross-axis sensitivity, giving maximum output voltage for the z-axis acceleration.

7. Conclusion

The piezoresistive MEMS accelerometer of configurations 1 and 2 have been modelled and simulated for the triaxial sensing of tremor used for medical diagnostic system. A relative study of both the structures have been done and the results relating to eigen values, time-dependent analysis, stress analysis, and sensitivity-based studies have been done and simulated. Also, study has been done to get low off-axis sensitivity and wheatstone bridge measurement scheme to enhance the performance of the device has been chosen. The stress distribution is not same everywhere and maximum stress occurs at the edges which gives an idea where to place the piezoresistors for maximum sensitivity. Thus, the study and simulation results show that configuration 1 where the flexures are aligned with the proof mass edge is a better design structure in terms of performance as compared to configuration 2. Also, a similar type of structure as in [5] has a sensitivity of 6.5 mili volts/g as compared to the given configuration 1 here which has a calculated sensitivity of 10.5 mv/V/g. The idea is to fabricate the three individual single accelerometer and finally by complex packaging technique giving a triaxial accelerometer.

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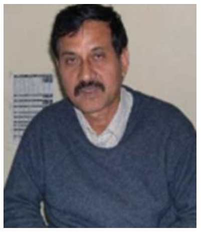

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