Design, Simulation and Fabrication of MEMS-based Piezoresistive Accelerometer

A.K. Upadhyay[a,b], Ajay. D Thakur[b], S. Santosh Kumar[a], M. Santosh[a], S. Shekhar[a], N. Singhal[a], R. Mukhiya[a] and S.C. Bose[a]
[a]CSIR-Central Electronics Engineering Research Institute, Pilani-333031, India
[b]Indian Institute of Technology, Patna-801103, India

***Abstract*-This paper presents the design, FEM-based simulations and fabrication of a single degree of freedom MEMS-based piezoresistive accelerometer. Design and FEM-based simulations have been performed using COMSOL® Multiphysics. For the fabrication of the piezoresistive accelerometer, bulk micromachining techniques have been used. Associated readout circuit performs the operations like sensor offset compensation, amplification and temperature compensation. The interface circuit consists of a high CMRR variable gain amplifier, offset compensation and second amplifier for further amplification. Fabricated accelerometer has been tested using LDV and shaker.**

I. INTRODUCTION

MEMS based inertial sensors, including accelerometer and gyroscope, have become very popular in the market due to their robust performance, small size and lower power consumption [1]. Most commonly, Fabrication of an accelerometer can be performed using surface micromachining and bulk micromachining techniques [2]. Typical popular applications of accelerometer include: (a) triggering unit for airbag deployment in automobiles, (b) heart monitoring and physical body movement tracking systems, (c) inertial sensors in aviation sector, (d) military application such as inertial navigation, (e) inertial sensing in gaming and mobile computing devices, etc. The device fabricated in this work has potential application for low range of acceleration (low-g) measurement, suitable for micro air vehicle (MAV) application.

In this work, research has been focused on the design of a single-axis MEMS-based piezoresistive accelerometer, which is realized by deep reactive ion etching (DRIE) and complementary metal oxide semiconductor (CMOS) compatible wet bulk micromachining technique.

Surface micromachined devices can be fabricated monolithically on a single chip along with their signal conditioning circuit, making them cheaper than bulk micromachined counterparts. However, due to inherent technological limitations (e.g., small proof-mass), surface micromachined devices have low sensitivity and in addition suffer from stiction issues (undesirable adhesion of surfaces). In bulk micromachining, there is no technological limitation of the physical device dimensions and large proof-mass can be fabricated, which increases the sensitivity of the device [1].

Bulk micromachined accelerometer consists of proof-mass and cantilever beams, where proof-mass is suspended by cantilever beams at one end and cantilever beams are anchored at the other end. There are number of approaches used to make accelerometer like as piezoelectric, piezoresistive, tunnelling, capacitive, optical, thermal and electromagnetic. In this work, research is focused on piezoresistive transduction mechanism. Piezoresistive approach is best compatible in term of MEMS fabrication processes. Piezoresistive sensors are easy to fabricate and they require simple read out circuit. In addition, they provide low power consumption, less non-linearity, low drift and high reliability [4]. However, their temperature dependency is high and sensitivity is low compared to capacitive based sensors [5].

II. DESIGN AND SIMULATION

A fixed and guided type suspension has been chosen for the design of the accelerometer which is also compatible for fabrication of the device like cantilever and proof-mass release with bulk micromachining [3, 4].

Simulations of MEMS-based accelerometer are carried out using FEM-based simulation tool COMSOL® Multiphysics. Structural mechanics module of COMSOL® is used for simulation of the mechanical analysis and piezoresistive analysis of the accelerometer. Three-dimensional (3D) solid structure is created in COMSOL® Multiphysics and it is shown in Figure 1. Free tetrahedral meshing elements are used for the entire geometry of structure for simulations, because of its irregular shape. Frame ends of the cantilever beams have fixed constraint in all directions, as boundary conditions for mechanical simulations. Acceleration of 1 g (1 g = 9.8 m/s^2) in out-of-plane direction is applied as body load on the proof-mass.

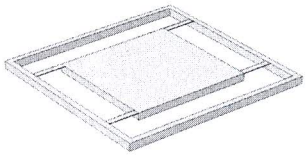


Fig.1: Fixed and guided type structure for accelerometer

The dimensions of the proposed accelerometer are given in Table 1, including cantilever beam and proof-mass. For FEM simulations, the thickness of cantilever beam of 20±1 μm is considered. COMSOL® Multiphysics simulations results presented in the subsequent section correspond to 1g acceleration in out-of-plane direction with a thickness of cantilever beam 20 μm. Simulation results have also been verified with analytical results.

Table 1.1: Dimension of piezoresistive accelerometer

Structure	Geometrical dimension
Cantilever bea	1000 μm × 200 μm × 20 μm
Proof-mass	3800 μm × 3800 μm × 380 μm
Frame(anchor	6200 μm × 200 μm × 380 μm

Modal analysis and frequency response:

Modal analysis of the proposed accelerometer structure has been done in solid mechanics under structural mechanics module of COMSOL® Multiphysics with the Eigen frequency study. The Eigen modes, mode shapes (deformed shapes) are special shapes of vibrated structure when excited correspond to Eigen frequency or resonant frequency. The structure vibrates in a complex combination of all the mode shapes. By understanding the Eigen modes, all the possible types of vibration can be evaluated. Modal analysis refers to evaluating and predicting the Eigen modes and Eigen frequency of a structure.

The frequency response of MEMS-based accelerometer has been carried out in solid mechanics under structural mechanics module of COMSOL® Multiphysics with the frequency domain study.

The mode shapes and frequency response for first three fundamental modes of the designed proposed structure of accelerometer predicted using FEM-based simulations which are shown in Figure 2(a–b), 3(a-b) and 4(a-b).

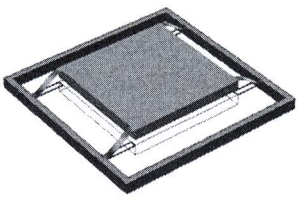


Fig. 2(a): Mode shape 1 along Z-axis (Out of plane)

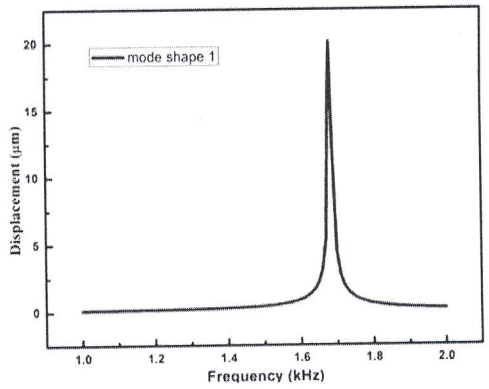


Fig.2 (b): Simulated frequency response of the accelerometer (out of plane).

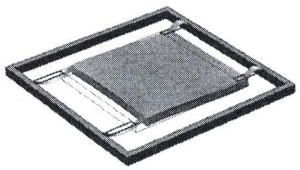


Fig. 3(a): Mode shape 2 across X-axis

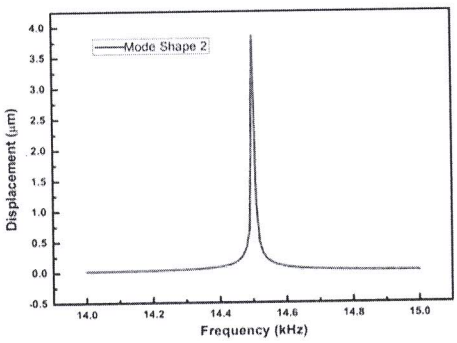


Fig. 3(b): Simulated frequency response of the accelerometer (across X-axis).

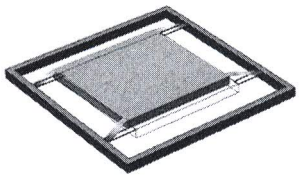


Fig. 4(a): Mode shape 3 across Y-axis

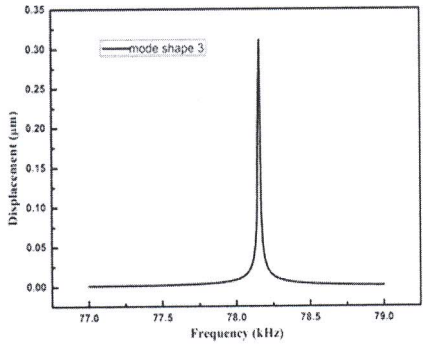


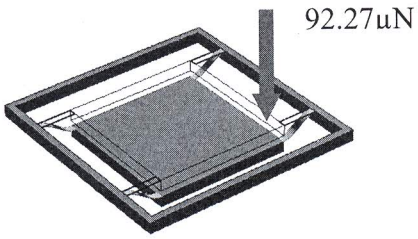
Fig. 4(b): Simulated frequency response of the accelerometer (across Y-axis).

The first mode shape is along the out-of-plane direction and Eigen frequency or resonant frequency is 1.68 kHz, which is very less than that of the other modes of vibration. There is a second mode across X-axis and third mode across Y-axis with Eigen frequency or resonant frequency of 14.502 kHz and 78.156 kHz, respectively.

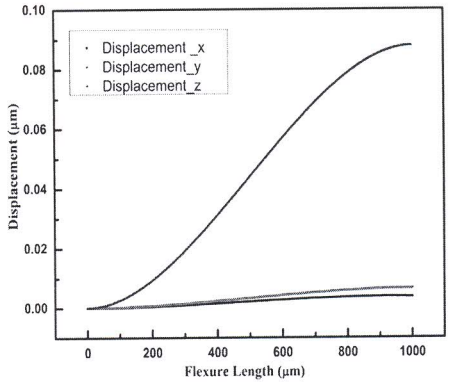
The higher value of Eigen frequency of second and third modes signify that the cross-axis sensitivities and lower value of Eigen frequency signify that the prime-axis sensitivity for the proposed designed structure of accelerometer and make it out-of-plane single DoF.

Displacement analysis:

The stationary study is used to simulate deflection, stress and strain in solid mechanics structure. When external acceleration is applied to the proposed structure of accelerometer, the proof-mass deflects in opposite direction of applied acceleration due to inertial force. FEM-based simulation result for displacement of the proof-mass under applied 1g acceleration in out-of-plane direction is shown in Figure 5(a) and graph for displacement of the proof-mass in along and across the axes directions are shown in Figure 5(b). The cantilever beam deformation is in *s*-shape with a maximum deflection of 0.084 μm at the mass end. There is deflection in out-of-plane direction (without any rotation) and this is much more compared to other two directions, which is desired.



(a)



(b)

Fig.5: (a) 1g force applied on the proof-mass and (b) Displacement of the accelerometer along the beam length.

FEM-based simulation results of the structure of the accelerometer and analytically calculated results are summarized in Table 2. It is seen that the analytically calculated value is comparable with the simulated results.

Table 2: Comparison of analytically calculated and FEM-based simulation results

Parameters	Analytical calculated	FEM simulated
Proof-mass displacement in Z-axis direction	0.085μm	0.084 μm
Ist mode resona requency	1.71 kHz	1.68 kHz

Stress Analysis:

Stress analysis of the proposed structure of accelerometer has been done in solid mechanics under structural mechanics module of COMSOL® Multiphysics with stationary study. There are different stresses induced in cantilever beam due to applied acceleration on the proof-mass.

The surface tractions and stresses are acting on the plane of the cantilever beam and these are typically decomposed into three orthogonal components. One component is normal to the surface and it is known as direct stress.

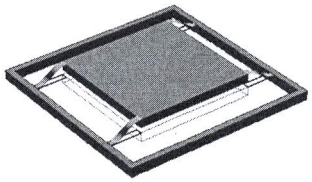


Fig.6: Illustration of stress analysis of the proposed accelerometer structure in COMSOL® Multiphysics and stress

variation at the both proof-mass and frame end in mode shape z-axis (out of plane).

The other two components are tangential to the surface and it is known as shear stress. There is direct stress tends to change the volume of the material which depends on Young's modulus and Poisson's ratio. There is shear stress tends to deform the material without changing the volume of material.

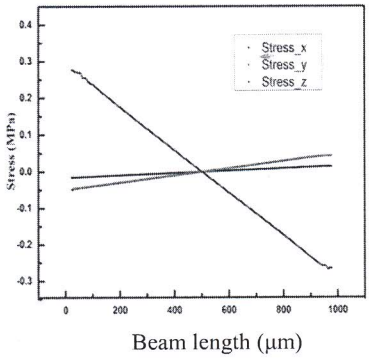


Fig.7: Illustration of graph for variation of the stress along with beam length. It is clear that there is tensile stress at one end and compressive stress at another end of the beam.

FEM-based simulation results of stresses induced in cantilever beam of the proposed accelerometer structure for 1g acceleration applied on proof-mass in out-of-plane direction are shown in Figure 6. Where stresses (σ) σ_{xx}, σ_{yy} and σ_{zz} are the principal stresses or direct stresses along the three axes and shear stresses across the different plane are identical (like as $\sigma_{xy} = \sigma_{yx}$, $\sigma_{yz} = \sigma_{zy}$, and $\sigma_{xz} = \sigma_{zx}$) as a result of static equilibrium. The longitudinal stress (σ_{xx}) is maximum, and the transverse stresses are minimum (σ_{yy} and σ_{zz}) which is desired in this work. Stress, σ_{xx} is tensile (0.28 MPa) near the frame end of the cantilever beam and compressive near the proof-mass end of the cantilever beam, which is shown in Figure 7.

Piezoresistor positioning:

In the design of accelerometer structure, cantilever beams are realized in the <110> direction and eight n-type phosphorous diffused poly-silicon piezoresistors are realized on the surface of the (100) SOI wafer.

Eight two terminal phosphorous diffused poly-silicon piezoresistors are placed in such a way where stress is maximum (tensile or compressive) at the both end of the four cantilever beams. There is sensing of the amount of stress by poly-silicon piezoresistor utilizing the piezoresistive properties of poly-silicon.

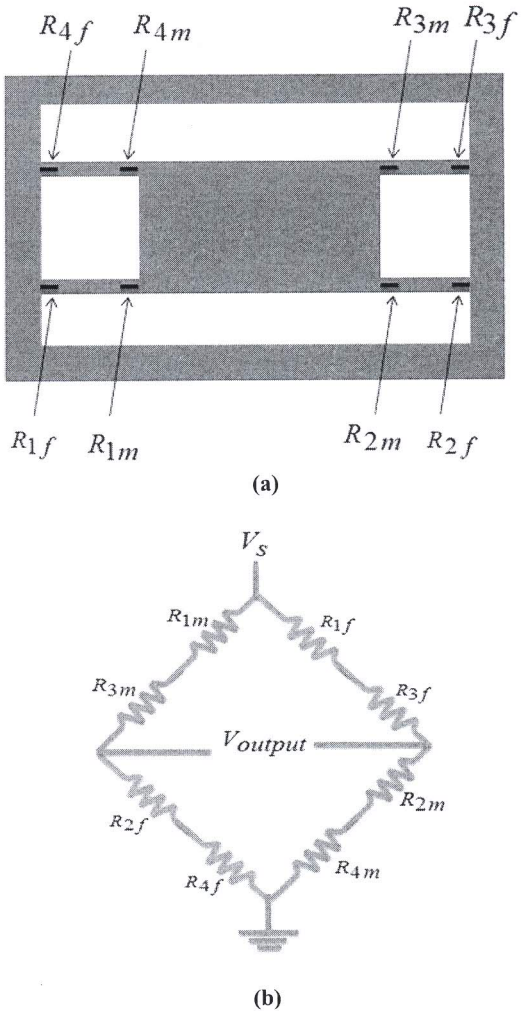


Fig.8: (a) Poly-Si piezoresistors doped in proposed accelerometer structure and (b) Wheatstone bridge connection of piezoresistors for high sensitivity and low cross axis sensitivity.

The sensitivity of an accelerometer is defined as the ratio of output voltage over input acceleration. In a Wheatstone bridge circuit, the fractional change in resistance is directly converted to a voltage signal. If Δa_z is the differential acceleration change on the proof-mass, the sensitivity (S_{zz}) is given by equation (1). The cross-axis sensitivities for lateral and transverse accelerations are very less compared to the prime axis sensitivity.

$$S_{zz} = \frac{\Delta V_{out}}{\Delta a_z} = \frac{\Delta R}{R}\frac{1}{\Delta a_z}V_s \qquad (1)$$

III. ACCELEROMETER FABRICATION

Fabrication of MEMS-based piezoresistive accelerometer has been carried out using SOI wafer. Specifications of the SOI wafer are chosen as per our device design specifications and fabrication processes. The specifications of SOI wafer, which are used for the

fabrication of the piezoresistive accelerometer are shown in following Table 1.3.

Table 1.3: Specifications of SOI wafer for piezoresistive accelerometer

Wafer	Specification
Grade	Prime-CZ
Thickness	380±5 μm
Type and Doped	P-Boron
Diameter	3 inch
Orientation	<100>
Resistivity	10-20 ohm-cm;
Active layer	20±1 μm; N-type; 4-6 ohm-cm
Buried Oxide	1 μm

Accelerometer has been fabricated using a combination of wet and dry bulk micromachining process. SOI wafers are used for the device fabrication, cantilever beams were released by DRIE technique and proof-mass by CMOS compatible 25% wt. TMAH wet micromachining. Photographs of the fabricated devices are shown in Figure 9.

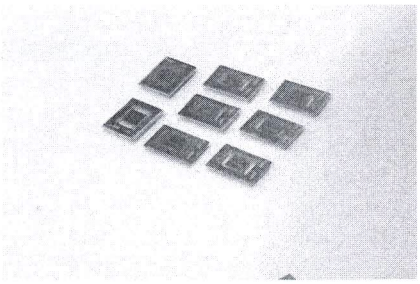


Fig.9: Fabricated accelerometer sensors

These chips are mounted on the PCB or header as per chosen electronic design circuitry. The fabricated device is mounted on the printed circuit board (PCB) by epoxy and hardener. In the piezoresistive accelerometer, non-conducting epoxy is used and it is baked at 130 °C for 25 min.

IV. TESTING AND CHARACTERIZATION

Fabricated devices were characterized using LDV for frequency and phase response, which are shown in Figure 11 [3]. Tested results show that the device has first mode resonance frequency of around 1.7 kHz, which is similar to the simulated results. After packaging, the device was integrated with readout electronics for further characterization using shaker. The circuit performs the operations like sensor output offset compensation, amplification and temperature compensation. The interface circuit consists of a high CMRR variable gain amplifier, offset compensation and second amplifier for further amplification. The fabricated circuit (ASIC) controlled by an external microcontroller (ADuC-841). The control algorithm is also implemented on microcontroller. Accelerometer module with sensor is illustrated in Figure 12. Acceleration response of the module is depicted in Figure 13. The sensor module has sensitivity of 500 mV/g for a 3.3 V DC bias.

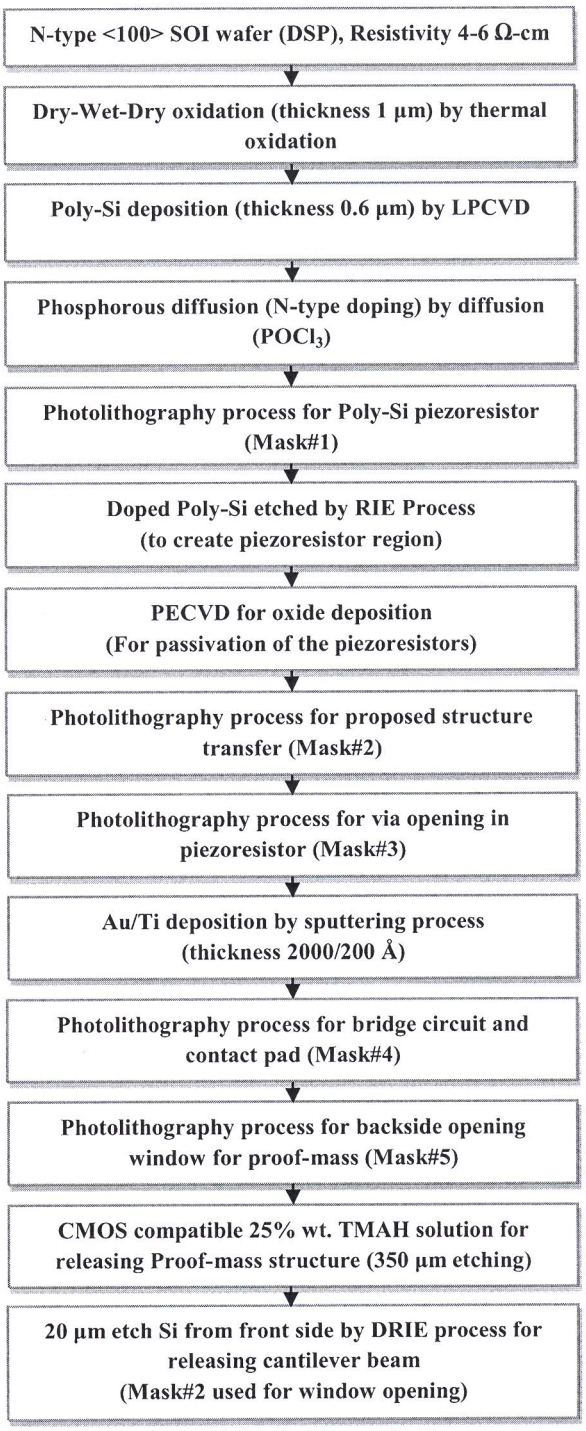


Fig. 10: Complete fabrication process flow

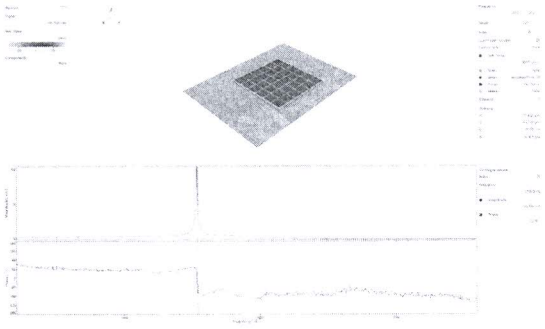


Fig.11: Ist mode frequency response of the accelerometer evaluated using LDV.

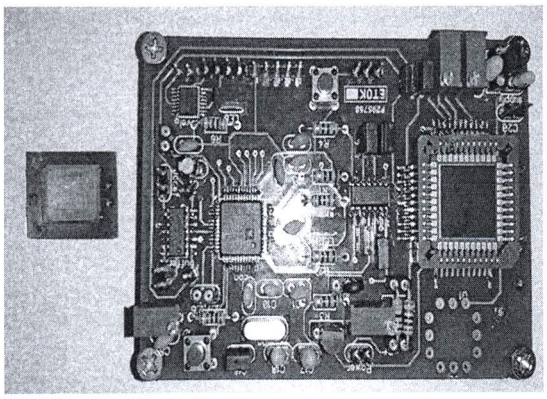


Fig.12: Accelerometer module with depicted accelerometer sensors.

V. CONCLUSIONS

A single degree-of-freedom piezoresistive accelerometer was designed and fabricated. The designed device was fabricated using bulk micromachined MEMS microfabrication process. Phosphorous diffused polysilicon piezoresistors are realized on the surface of the cantilever beam. This low-g piezoresistor accelerometer has a specific application in micro air vehicle (MAV). Making a multi-axis accelerometer based on piezoresistivity may be taken up in future.

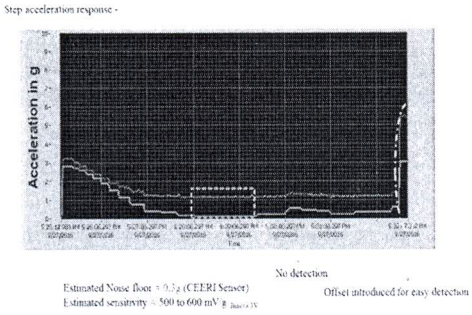


Fig. 13: Acceleration response of the accelerometer tested using shaker.

ACKNOWLEDGEMENTS

Authors would like to acknowledge generous support of the Director, CSIR-CEERI, Pilani. Authors would also like to thank all the technical members of Smart Sensors Area at CSIR-CEERI, Pilani. Authors would like to acknowledge the financial support from CSIR, New Delhi.

REFERENCES

[1]. N. Yazdi, F. Ayazi and K. Najafi, IEEE 86, 8 (1998).

[2]. J. W. Judy, Smart Materials and Structures 10, 1115 (2001).

[3]. A. Sharma et al., Microsystem Technologies 21, 2221 (2015).

[4]. R. Mukhiya, R. Gopal, B. D. Pant, V. K. Khanna, T. K. Bhattacharyya, Microsystem Technologies 21, 2241 (2015).

[5]. A. Alvin Barlian *et al.* IEEE 97, 3(2009).