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Design and analysis of SU-8 based MEMS Piezoelectric Accelerometer

K. Spruthi, P. Divya Bharathi, A. Daisy Rani
Department of Instrument Technology , Andhra University, Visakhapatnam,
Andhra Pradesh, India, 530003.
kalluri.spruthi@gmail.com

Abstract: This paper describes about the design and simulation of piezoelectric accelerometer using Silicon and SU-8 as substrates with Zinc Oxide as piezoelectric material. Here simulation was done using COMSOL Multiphysics. Both mechanical and piezoelectric analysis were done. In mechanical analysis a resonant frequency of 995.2 Hz was attained using silicon as a substrate and a resonant frequency of 589.9 Hz was attained using SU-8 as a substrate. In piezoelectric analysis at a particular eigen frequency of 995.2 Hz a potential of 1.73 mV was obtained using silicon as a substrate and for SU-8 as substrate a potential of 1.31 mV was obtained at an eigen frequency of 589.9 Hz. The piezoelectric accelerometer yields good sensitivity with SU-8 as substrate compared to silicon as a substrate.

Keywords: Comsol Multiphysics, Piezoelectric Materials, MEMS, Sensitivity, Electric Potential, Resonant Frequency.

Introduction

Micro Electro Mechanical Systems or MEMS is a term coined around 1989 by Prof. R. Howe and others to describe an emerging research field, where mechanical elements, like cantilevers or membranes, had been manufactured at a scale more akin to microelectronics circuit than to lathe machining. There are plenty of applications for MEMS. As a breakthrough technology, MEMS is building synergy between previously unrelated fields such as biology and microelectronics, many new MEMS and Nanotechnology applications will emerge, expanding beyond that which is currently identified or known.

An accelerometer is a device that measures proper acceleration. The proper acceleration measured by an accelerometer is not necessarily the coordinate acceleration (rate of change of velocity). Instead, the accelerometer sees the acceleration associated with the phenomenon of weight experienced by any test mass at rest in the frame of reference of the accelerometer device. Accelerometers have been used in many fields, including for activation of automotive safety systems (airbags, electronic suspension), for machine and vibration monitoring, and in biomedical applications for activity monitoring. Micro machined accelerometers are widely used by the automotive industry, because of their low cost, small size, and broad frequency response. Three sensing mechanisms, piezoresistive, capacitive, and piezoelectric are most commonly utilized for MEMS accelerometers; each one has limitations and advantages. Compared to piezoresistive and capacitive accelerometers, there have been fewer reports of micro machined piezoelectric accelerometers. ZnO and PZT films are the two primary materials reported for use in bulk or surface-micro machined piezoelectric MEMS accelerometers.

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. Chen et al(1982) fabricated a silicon bulk micro machined piezoelectric accelerometer with cantilever beam structure using a ZnO film and obtained a sensitivity of 47μV/g. Chen and Muller(1984) 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. Nemirovsky *et al.*(1996) designed a PZT thin film piezoelectric accelerometer with a sensitivity of 320mV/g. Devoe and Pisano(1997) designed a ZnO accelerometer which gives a low sensitivity of 0.95fC/g. Reus *et al.*(1999) developed a ZnO accelerometer with single proof mass and two suspension beams with a sensitivity of 0.1pC/g and a resonant frequency of 4.5khz. Beeby *et al.*(1999) developed a bulk micro machined accelerometer with a very high sensitivity of 16pC/g. In the same year Eichner *et al.*(1999) designed a bulk micro machined PZT accelerometer with a single proof mass and 2 suspension beams and the sensitivity of 0.1mV/g was obtained with 13kHZ resonant frequency. Li-Peng Wang *et al.*(2002) 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. 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 with 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.

Design and simulation

A typical piezoelectric accelerometer consists of a layer of piezoelectric material sandwiched between a mounting plate and a seismic mass. When a physical force is exerted on the accelerometer, the seismic mass loads the piezoelectric element according to Newton's second law of motion. The force exerted on the piezoelectric material can be observed in the change in the electrostatic force or voltage generated by the piezoelectric material. The basic governing equation of the system is

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

This differs from a piezoresistive effect in that piezoresistive materials experience a change in the resistance of the material rather than a change in charge or voltage. Physical force exerted on the piezoelectric can be classified as one of two types; bending or compression. Stress of the compression type can be understood as a force exerted to one side of the piezoelectric while the opposing side rests against a fixed surface, while bending involves a force being exerted on the piezoelectric from both sides. The design of Piezoelectric accelerometer using COMSOL Multiphysics include two steps.The first step involves the design of accelerometer with appropriate dimensions. Initially a proof mass of dimensions 450×3000×3000 μm is taken. Then the four beams are attached to the proof mass. Each beam is 'L'shaped which is formed using dimensions of 17×200×600 μm and 17×200×2200 μm. Also Piezoeletric layer is deposited over 'L' shaped beam with dimensions 20×200×600μm and 20×200×2200 μm. The design is shown in Figure (1).

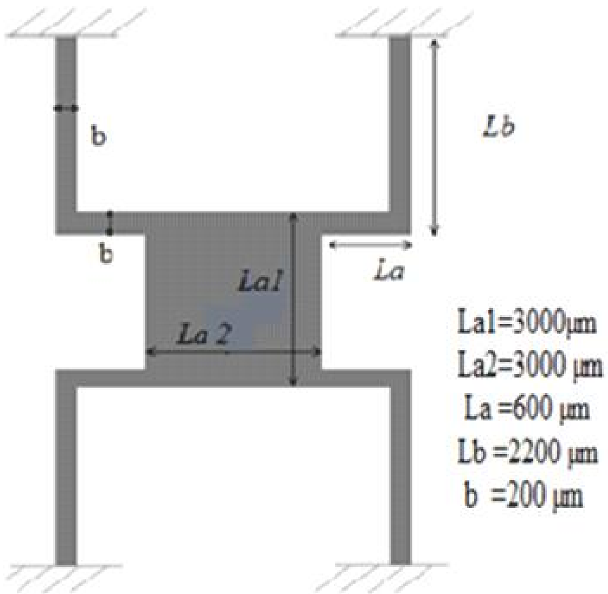

Figure.1: Structure of accelerometer

Appropriate dimensions are necessary in order to attain good sensitivity over a frequency range of 10 to1000 Hz i.e. by changing thickness of beam sensitivity can be improved.The second step of design include assigning of materials to the model. Here we use two different materials as substrate in order to get good result and the properties of materials are shown in table 1. So, we use silicon as substrate which is deposited on proof mass and also on the bottom layer of 'L' shaped beam . And the top layer of beam is assigned with Piezoelectric material Zinc Oxide(ZnO). Similarly another accelerometer with SU-8 as substrate and ZnO as piezoelectric material is also designed.

Generally silicon is used as a substrate because of its availability in abundance nature. But silicon is not an ideal material for many applications as it does not exhibit good wear properties . As it is Crystalline in nature , it is prone to fracturing and chipping . It also has much lower thermal coefficient of expansion which can complicate the fixture . Hence we make an attempt to replace substrate with a polymer because they are available in diverse forms and possess material properties not found in more traditional micro fabrication materials originating from IC industry.

Table 1: Properties of materials that are used as substrates:

PROPERTIES	SILICON	SU-8
Specific heat [J/(g*K)]	0.0026	1.5
Coefficient of thermal expansion [1/K]	2.6e-6	21-102
Density [kg/m^3]	2329	1190
Thermal conductivity[W/(m*K)]	130	0.2
Young's modulus [Pa]	170e9	4.02e9
Poisson's ratio	0.28	0.22
Refractive index	3.48	1.67-1.8

Here SU-8 is used as a substrate. It is a negative, near UV resist and a thermoset polymer. SU-8 is well known to possess excellent thermal and chemical stability. In particular its chemical stability facilitates its application especially for prolonged plasma etching. Its mechanical strength allows it to be a planarization layer in chemical mechanical polishing applications. The versatility of SU-8 as a MEMS material has led to its extensive application in microfluidics and biomedical devices. Here SU-8 is used because it provides high resolution mask and also it is highly transparent that it provides high stability to chemicals and radiation damage. Hence an attempt is made by using SU-8 as substrate over the basic material silicon.

Piezoelectric materials used for the purpose of accelerometers fall into two categories: single crystal and ceramic materials. The first and more widely used are single-crystal materials (usually quartz). Though these materials do offer a long life span in terms of sensitivity, their disadvantage is that they are generally less sensitive than some piezoelectric ceramics. The other category, ceramic materials, have a higher piezoelectric constant (sensitivity) than single-crystal materials, and are less expensive to produce. Ceramics use barium titanate, lead-zirconate-lead-titanate, lead metaniobate, and other materials whose composition is considered proprietary by the company responsible for their development. The disadvantage of piezoelectric ceramics, however, is that their sensitivity degrades with time making the longevity of the device less than that of single-crystal materials. The selection of type of piezoelectric material can be done based on following factors; One on the properties of materials like piezoelectric coefficient , dielectric and elastic properties. The high piezoelectric coefficient is needed to achieve high sensitivity for certain applications. Second is that it should withstand several fabrication process with uniformity and must be patterned easily. Here ZnO is used as piezoelectric material in order to achieve good sensitivity. Zinc oxide (ZnO) is a unique material that exhibits semiconducting, piezoelectric, and pyroelectric multiple properties. Zinc Oxide is an inorganic compound. It occurs naturally as zincite, but most Zinc Oxide is produced synthetically. Zinc Oxide crystallizes in two main forms ,hexagonal wurtzite and cubic zincblende. The wurtzite structure is most stable at ambient conditions and the zincblende form can be stabilised by growing ZnO on substrates with cubic lattice structure. Hexagonal and zincblende polymorphs have no inversion symmetry. This and other lattice symmetry properties results in piezoelectricity of hexagonal and zincblende ZnO and pyroelectricity of hexagonal ZnO. ZnO is a soft material with high heat capacity , high conductivity, low thermal expansion and high melting temperature. Among tetrahedrally bonded semiconductors ZnO has highest piezoelectric tensor or at least one comparable to that of GaN and AlN(Corso et al.1994), this property enables us for the use of Zinc Oxide in piezoelectric applications that require a large electromechanical coupling.

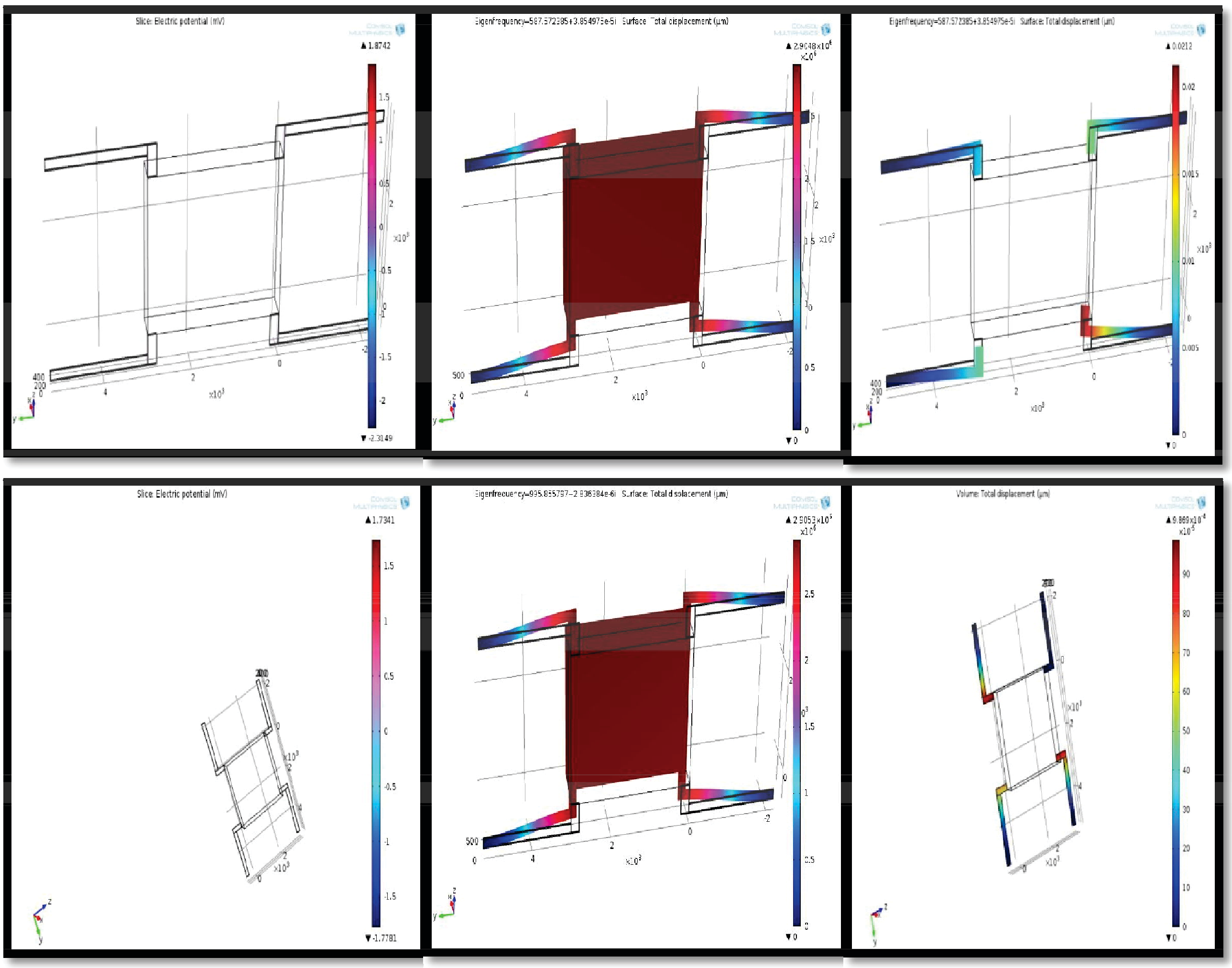

Figure 2: Electric potential, Resonant frequency and Displacement with Silicon and SU-8 as substrates.

Simulation of piezoelectric accelerometer is done using COMSOL Multiphysics. After completion of design, using COMSOL Multiphysics, analysis of model is done in different modes. In order to have good study of results meshing is done for the model because the force applied will be equally distributed and hence the results will be exact. The meshing of different ways are available, usually we prefer normal meshing. The first mode of measurement involves mechanical analysis of the model . The resonant frequency is measured over a frequency range of 10 to 1000 Hz. By simulating good response is obtained at a frequency of 589.9 Hz. This results are observed below from figure 2. The another mode of measurement involves piezoelectric analysis of the model. Here piezoelectric accelerometer rely on the piezoelectric effect of quartz or ceramic crystals to generate an electrical output that is proportional to applied acceleration. The piezoelectric effect produces an opposed accumulation of charged particles on the crystal. This charge is proportional to applied force or stress. A force applied to a quartz crystal lattice structure alters alignment of positive and negative ions, which results in an accumulation of these charged ions on opposed surfaces. The displacement is measured as 1.59×10^{-3} μm with SU-8 as substrate and 9.87×10^{-3} μm with silicon as substrate. At a particular frequency of 589.9Hz the voltage obtained 1.302 mV with SU-8 as substrate and 1.73 mV with silicon as substrate. These results are shown in the below figure (2).

Results and discussion:

A piezoelectric accelerometer with two different substrates along with ZnO as piezoelectric material is designed. The results are shown below in table 2.

Table : 2 Results obtained using COMSOL Multiphysics with different substrates:

Materials that are used as substrate	Resonant Frequency (Hz)	Displacement (μm)	Voltage (mV)
Silicon	995.2	9.87×10^{-4}	1.73
SU-8	589.9	1.59×10^{-3}	1.31

Higher sensitivity is obtained by simulating the model. The variations in deflection is observed at frequency range of 10 Hz to 1000 Hz with Su-8 and silicon as substrates. Here comparison of model with Su-8 and silicon as substrate is done. We know Su-8 is a negative photoresist mask .In contrary to the silicon based process ,su-8 based spin coating process is a low cost and simple procedure and does not need any hazards chemicals and complicated MEMS fabrication. Also an electric potential of 1.31 mV is obtained using Su-8 at a frequency of 589.9 Hz.

Conclusion:

The design and simulation of piezoelectric accelerometer using Silicon and SU-8 as substrates with Zinc Oxide as piezoelectric material is done using COMSOL Multiphysics. From the above results we conclude that the use of a polymer i.e. SU-8 as substrate also yields better results in compared to the ideal substrate material silicon. The sensitivity is good for a piezoelectric accelerometer with SU-8 as substrate. Also highest frequency response is obtained. Further sensitivity can be improved by changing the thickness of beam and proof mass. These conditions enable us for the usage of Polymers as substrate material for various MEMS applications.

References:

Y. Nemirovsky, A. Nemirovsky, P. Muralt, N. Setter (1996): Design of a novel thin film piezoelectric accelerometer, Sensors and Actuators A **56**, 239-249.

D. Eichner,M. Giousouf, Andw. Von Munch (1999): "Measurements On Micromachined Silicon Accelerometers With Piezoelectric Sensor Action," Sens. Actuators, Vol. **A76**, 247–252.

Dal Corso, Andrea; Posternak, Michel; Resta, Raffaele; Baldereschi, Alfonso (1994): "Ab Initio Study Of Piezoelectricity And Spontaneous Polarization In Zno". Physical Review B 50 **(15)**, 10715-10721.

Don L. Devoe, Albert P. Pisano (2001): Surface Micromachined Piezoelectric Accelerometers, *Journal Of Microelectromechanical Systems*, Vol.Lo, No.**2**, 180-186

L.-P. Wang, K. Deng, L. Zou, R. Wolf, R. J. Davis, and S. Trolier- McKinstry, (2002): "Microelectro-mechanical Systems (MEMS) accelerometers with a novel sensing structure using piezoelectric Lead Zirconate Titanate (PZT) thick films," *IEEE Electron Device Lett.*, vol. **23**, 182–184.

P. L. Chen and R. S. Muller (1984) : "Integrated silicon Pi-FET accelerometer with proof mass," Sens. Actuators, vol.**5**, 119–126.

P. L. Chen, R. S. Muller, R. D. Jolly, G. L. Halac, R. D. White, A. P. Andrews, T. C. Lim, and M. E. Motamedi (1982): "Integrated silicon microbeam Pi-FET accelerometer," IEEE Trans. Electron Devices, vol. ED-**29**, 27–33.

Roger De Reus, Jens Ole Gullov, And Patrick R Scheeper, (1999) : "Fabrication And Characterization Of A Piezoelectric Accelerometer," *Journal of Micromechanics and Micraengineering,* **9**, 123-126

S. P. Beeby, N. Ross, And N. M. White, (1999) "Thick Film PZT/Micromachined Silicon Accelerometer," *IEEE Electron. Lett.*, Vol. **35** (23), 2060–2062.