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Abstract. The present paper peruses MEMS based piezoresistive pressure sensor and its fabrication techniques. Simulation of the pressure sensor is done by using COMSOL Multiphysics software for P-type silicon piezoresistor. The deflection of N-type silicon diaphragm depends upon the Young's modulus of the material and varies with the amount of force applied to the diaphragm. The simulation result emphasizes that an appropriate selection of the piezoresistive material and the amount of force applied on the diaphragm impacts the sensor sensitivity levels upon low power consumption.

Keywords: MEMS, piezoresistivity, pressure sensor, diaphragm deflection.

1 Introduction

MEMS technology has become very important for microelectronics. This technology has originated from integrated circuit technologies; but it is evolving differently. The systems made from this technology are called Micro Electro Mechanical Systems (MEMS). These devices have the ability to sense, control and actuate on the micro scale and generate effects on the macro scale.[1] These systems are made of small components with size 1-100 micrometers; and device size is 0.02-1 millimetre. MEMS are not just about the miniaturisation of mechanical components or making things out of silicon. In fact, the term 'MEMS' is actually misleading as many micro machined devices are not mechanical in a strict sense. MEMS is a manufacturing technology; a paradigm for designing and creating complex integrated devices and systems using batch fabrication techniques similar to the technologies used in IC manufacturing extended into micro meter scales.[1] The MEMS market include applications in automotives, IT peripherals, telecommunication devices, consumer electronics & life style products, medical and life science applications, biomedical instruments, household appliances, industrial process control, aerospace, defence and homeland security.[1]

The MEMS concept has grown to encompass many other types of small things like thermal, magnetic, fluidic, and optical devices and systems with or without moving parts.

Common Features of MEMS technology are:

- It involves electronic and non-electronic elements.
- It can perform functions that include chemical/biochemical reactions and experiments.

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- Some MEMS involve large arrays of micro-fabricated elements such as un-cooled infrared imaging devices and both reflective and non reflective projection displays.

MEMS devices are made similarly to ICs, therefore standard IC technologies like Photolithography, oxidation, wet/dry etching and decomposition of standard materials can be used for MEMS.

Piezoresistive pressure sensor are some of the first MEMS devices to be commercialized compared to capacitive pressure sensor, as they are simple to integrate with electronics, their response is more linear and are shielded from RF noise.

MEMS have several distinct advantages as a manufacturing technology:

- The multifaceted nature of this technology and its micromachining techniques, as well as its diversity of applications, has resulted in an unparalleled range of devices across previously unrelated fields such as biology and microelectronics.
- MEMS, with its batch fabrication techniques, enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost.
- MEMS provide the basis for the manufacture of products that cannot be made by other methods.

These factors make MEMS as pervasive technology as integrated circuit microchips.

In this paper the sensitivity of a square shaped pressure sensor is analysed. The pressure applied on diaphragm is causing a deflection in shape, thus changing the resistance in the sensor which can be read as change in current flow. Thus amount of current flow can be related to the magnitude of the applied pressure.

2 MEMS Fabrication Techniques

Most MEMS device use some form of lithography based micro fabrication borrowed from microelectronics industry enhanced with specialized techniques called micro machining [2].

2.1 Lithography

It is the process by which a pattern is transferred into a photosensitive material by selective exposure to a radiation source such as light.

A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If a photosensitive material is selectively exposed to radiation the pattern of the radiation on the material is transferred to the material exposed. [3]

Photolithography is typically used with metal or other thin film deposition, wet and dry etching.

There are two types of photoresist: Positive and Negative Photoresist.

- For positive resists, the resist is exposed with UV light wherever the underlying material is to be removed. In these resists, exposure to the UV light changes the chemical structure of the resist so that it becomes more soluble in the developer.
- Negative resists behave in just the opposite manner. Exposure to the UV light causes the negative resist to become polymerized, and more difficult to dissolve.

2.2 Etching

Etching is the process of using strong acid (liquid or gaseous state) to cut into unprotected parts of metal surface to create a design in metal. There are two categories of etching process:

- **Wet Etching:** Wet chemical etching basically consists in selective removal of material by dipping a substrate into a solution that dissolves it. The chemical nature of this etching process provides a good selectivity, which means the etching rate of the target material is considerably higher than the mask material if selected carefully.[4]

- **Dry Etching:** Dry etching refers to the removal of material, typically a masked pattern of semiconductor material, by exposing the material to a bombardment of ions usually a plasma of reactive gases such as fluorocarbons, oxygen, chlorine, boron tri-chloride; sometimes with addition of nitrogen, argon, helium and other gases that dislodge portions of the material from the exposed surface.[5]

Table 1. Comparison between wet etching and dry etching

Wet Etching	Dry Etching
Highly selective	Easy to start and stop
No damage to substrate	Less sensitive to small changes in temp
Cheaper	More repeatable
	May have anisotropies
	Fewer particle in environment

- **Deep-Reactive Ion Etching:** Deep RIE is a highly anisotropic process for realizing, steep sided holes or trenches in silicon wafer with high aspect ratios. The Bosh Process was successful in producing a high aspect ratio (>100) with high etching selectivity to oxide and photo resist. The bosh process alternates between two modes: a standard, nearly isotropic plasma process and a deposition process of chemically inert passivation layer, it prevents etching of side wall of the trench.

3 Materials and Method

Nowadays, the finite element method (FEM) is widely used for thermal effect reduction, stress analysis and reliability enhancement of piezoresistive sensor. In this paper a structural model of sensor is built using this method using COMSOL Multiphysics v4.2 software to study structural stress and demonstrate sensor sensitivity. The FEM simulation of MEMS piezoresistive pressure sensor conducted in present study is significant advance towards device design optimization in MEMS prototyping.

COMSOL Multiphysics is a finite element analysis, solver and Simulation software / FEA Software package for various physics and engineering applications, especially coupled phenomena, or multi physics. The software also offers an extensive interface to MATLAB and its toolboxes for a large variety of programming, pre-processing and post-processing possibilities. COMSOL Multiphysics allows for entering coupled systems of partial differential equations (PDEs).

In the model N-type and P-type materials are used for the study of sensor. N-type silicon is used for sensor diaphragm whereas P-type Silicon has been taken as the piezoresistor material.

Table 2. Material Properties

Material Property	Diaphragm
Material	Silicon
Density	2330 [Kg/m^3]
Young Modulus	129 GPa
Poisson's Ratio	0.22 to 0.28
Dielectric	11.9
Thermal conduction	148 W/(m x k)
Electrical Resistivity	4.59 (ohm x cm)

4 Pressure Sensors

Pressure measurement is a key part of many systems, both commercial and industrial. Silicon has proved to be a good material from which small pressure sensors can be built. Pressure sensors constitute the largest market segment of mechanical MEMS device. MEMS based pressure sensor is based on piezoresistive effect [6]. Piezoresistivity is the change of resistance of material when submitted to stress. The effect was first discovered by Smith and it was proposed that the change in conductivity under stress in bulk n-type material and designed an experiment to measure the longitudinal as well as transverse piezoresistance coefficients. Kanda did a piezoresistance coefficient study about impurity concentration, orientations, and temperature [7]. Pfann designed several semiconductor stress gauge to determine shear piezoresistance effects. Lund studied temperature dependence of piezoresistance coefficient by four point bending experiment [8]. Pressure is measured by monitoring its effect on a specifically designed mechanical structure, referred to as sensing element. The application of pressure to sensing element causes a change in shape and resulting deflection (strain) in material can be used to determine magnitude of pressure.

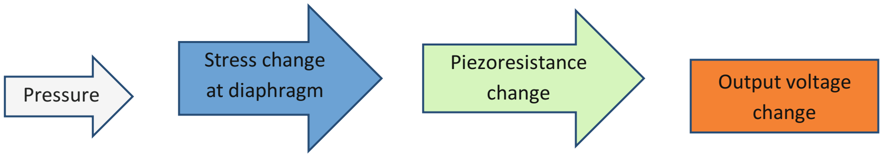

Fig. 1. Principle of piezoresistive pressure sensor

5 Concept and Sensor Design

The sensor design includes two basic elements: the thin elastic diaphragm and piezoresistive material. The diaphragm is made fixed around edges, with trace wire on the surface. The wire is made up of p-type piezoresistive material. When pressure is applied on the back of diaphragm, it deforms changing resistance of wire and thus pressure causing the deformation can be measured.

5.1 Mathematical Analysis

The analysis is done for square shape diaphragm deflection.

The Load-deflection relationships for square diaphragm with length L and thickness H are given below [9]:

$$\frac{P\,a^4}{EH^4} = \frac{4.2}{1-v^2}\left[\frac{w}{H}\right] + \frac{1.5}{1-v^2}\left[\frac{w}{H}\right]^3 \tag{1}$$

'P' is measured in Pascal (Pa); 'w' is center deflection of diaphragm, 'a' is half the side length, 'E' is Young's Modulus and 'v' is Poisson's Ratio. To keep deflection in range above formula is reduced to:

$$\frac{Pa^4}{EH^4} = \frac{4.2}{1-v^2}\left[\frac{w}{H}\right] \tag{2}$$

Maximum deflection at center of diaphragm is given by:

$$w_{max} = \frac{Pa^4}{4.2EH^4} \tag{3}$$

Maximum stress at center of each edge is given by:

$$\sigma_{max} = 0.308\left[\frac{L}{H}\right]^2 \tag{4}$$

$$\varepsilon = \frac{\sigma}{E} \tag{5}$$

Thus, the following relation can be established:

$$P = \frac{\sigma}{0.308}\left[\frac{H}{L}\right]^2 \tag{6}$$

$$w_{max} = \frac{1}{20.6976}(1 - v^2)[\frac{L^2}{H}]\varepsilon \tag{7}$$

It is clear from above relations that maximum deflection is directly proportional to square of length of diaphragm and inversely proportional to thickness of the diaphragm.

5.2 Simulation

In this design, a square membrane with side 1mm and thickness 20 µm is considered. Edges are 0.1mm wide to represent the remainder of the wafer. These edges are made to be fixed while the centre area of the membrane is left free for movement on application of pressure. Near to one edge of membrane an X-shaped piezoresistor is placed.

The piezoresistor is considered to be of a consistent p-type dopant density of 1.32×1019 cm–3 and a thickness of 400 nm. The diaphragm is made up of n-type silicon.

The edges of the die are aligned with the {110} orientation of the silicon with respect to the global X and Y axes. The piezoresistor is oriented to be at 45º to the die edge, and so lies in the {100} direction or orientation of the crystal.

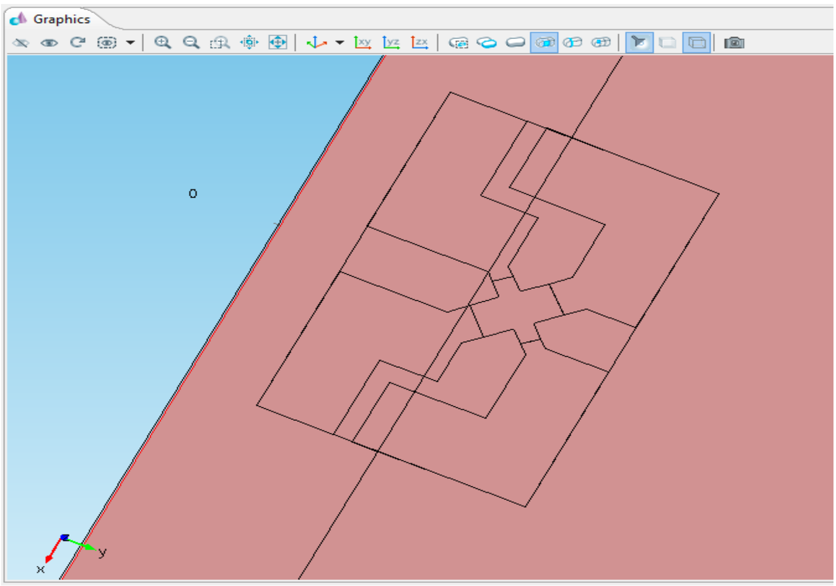

Fig. 2. Piezoresistor geometry 2D view

The piezoresistor is assumed to have a uniform p-type dopant density of 1.32×1019 cm−3 and a thickness of 400 nm. The interconnections are assumed to have the same thickness but a dopant density of 1.45×1020 cm−3. Only a part of the interconnections is included in the geometry, since their conductivity is sufficiently high that they do not contribute to the voltage output of the device.

6 Result and Discussion

Displacement of diaphragm as a result of 100 kPa pressure difference applied to membrane at its center is 1.2 µm. The result is in good agreement with theoretical and mathematical result. The RED colour shows the maximum displacement at the center of the diaphragm, similarly the displacement along the edges are zero as they are fixed, this is shown by BLUE colour.

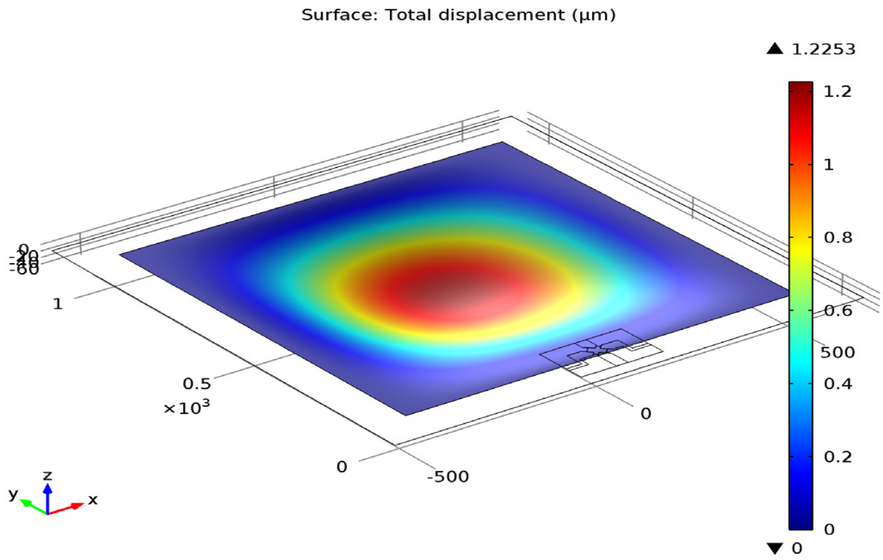

Fig. 3. Diaphragm displacement as result of 100kPa applied pressure

The stress along the edges shows a maximum magnitude of 38 MPa at centre of each of two edges along which plot is made. The stress is in negative direction along the edge having piezoresistor and the side geometrically opposite to it; while it is in positive direction along the remaining two edges.

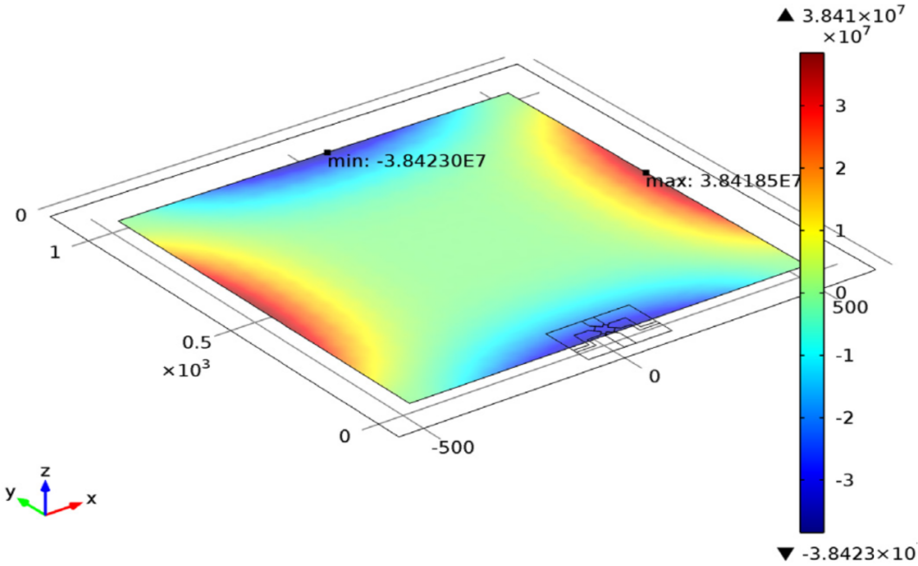

Fig. 4. Shear stress in the local co-ordinate system

Stress has its max value close to the piezoresistor with value of approximately -35Mpa.

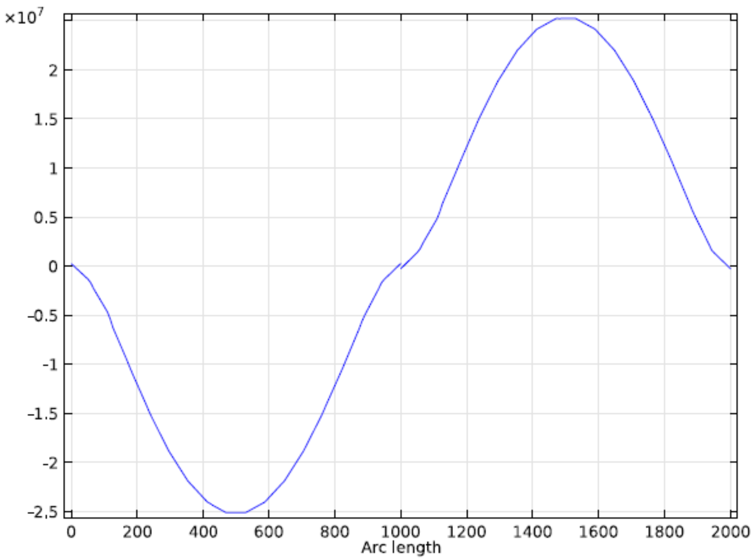

Fig. 5. Plot of local shear stress along two edges of diaphragm

The above graph shows the negative and positive magnitude of stress along the edges of the diaphragm. Here, the X-axis represents the arc length while the Y-axis depicts the stress experienced by the edges of the diaphragm.

With an applied bias of 3v a typical operating current of 5.9 mA is obtained. The model produces output voltage of 54 mV, similar to actual device output of 60mV.

References

1. van Heeren, H., Salomon, P.: Technology Watch, Electronics Enabled Products Knowledge Transfer Network, Wolfson School of Mechanical and Manufacturing Engineering, pp. 1,6,14,15. Loughborough University, Loughborough (2007)
2. Senturia, S.D.: Microsystems Design, pp. 29, 30. Kluwer Academic Publishers, New York (2002)
3. Senturia, S.D.: Microsystems Design, p. 50. Kluwer Academic Publishers, New York (2002)
4. Senturia, S.D.: Microsystems Design, p. 57. Kluwer Academic Publishers, New York (2002)
5. Senturia, S.D.: Microsystems Design, p. 58. Kluwer Academic Publishers, New York (2002)
6. Smith, C.: Piezoresistive effect in germanium and silicon. Physics Review 94, 42–49 (1954)
7. Kanda, Y.: A Graphical Representation of the Piezoresistance Coefficient in Silicon. IEEE Transactions on Electron Devices ED-29(1), 64–70 (1982)
8. Lund, E., Finstad, T.: Measurement of the Temperature Dependency of the Piezoresistance Coefficients in P-Type Silicon. In: Advances in Electronic Packaging-ASME, EEP, vol. 26(1), pp. 215–218 (1999)
9. Senturia, S.D.: Microsystems Design, p. 86. Kluwer Academic Publishers, New York (2002)