Material and Performance Analysis of MEMS Piezoresistive Pressure Sensor

Tamim Al Mahruz[#1], Rezwan Matin[#2], Fahim Bin Wahid[#3], Tuhin Dev[#4]

 # Department of Electrical and Electronic Engineering, Shahjalal University of Science and Technology, Sylhet, Bangladesh

Abstract — This work focuses on MEMS piezoresistive pressure sensor. The sensor was simulated in COMSOL Multiphysics v4.4. The Motorola MPX100 series sensor was studied. Applied pressure range is varied from 0 to 100 kPa. To gain the optimum output, different combination of material for diaphragm & piezoresistor have been studied and corresponding displacement change, shear stress distribution and output voltage have been shown. Sensitivity of the sensor was also calculated for different combination of materials. Impact of doping concentration on output voltage for both diaphragm & piezoresistor material has also been studied.

Keywords — *MEMS, Piezoresistor, Diaphragm, Output voltage, Displacement, Doping concentration, Shear stress.*

I. INTRODUCTION

Micro-electro mechanical system (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. On the same silicon chip micro-sensors, micro-actuators and microelectronics, all are integrated. Micro-sensors detect changes in the system's environment by mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics process this information and signals the micro-actuators to react and create the changes required [1]. In terms of robustness, low power consumption and accuracy, MEMS sensors have proved its efficiency [2]. MEMS sensors are using in biomedical, optoelectronics, automobile and industrial sectors [3] [4] [5]. For its wide range of application, many research have been done on improving the sensitivity and reliability. The pressure sensing principle can be of different types like piezoelectric, optical, capacitive etc. But piezoresistivity is the most commonly used sensing principle [6]. Semiconductors such as silicon and germanium are piezoresistive materials, but silicon exhibits better piezoresistivity response characteristics [7] [8]. Sensitivity of the sensor can be increased by choosing proper shape of piezoresistors and diaphragm or by changing the dimension of both. Due to symmetry square shaped diaphragm showed better sensitivity than a circular diaphragm [9]. Even by changing the position of the piezoresistors the performance can be improved a lot [10]. Improved sensitivity has been achieved for different crystallographic forms of silicon, by changing materials and by changing doping concentration of piezoresistors [6] [10].

II. PIEZORESISTIVE PRESSURE SENSORS

Piezoresistivity is a property shown by solids, though it is more prominent in certain semiconductors and metals. The piezoresistive effect is defined as the change in electrical resistivity due to applied mechanical strain. Due to applied pressure the inter-atomic spacing in the material changes, which in turn changes the energy band structure of the material and thus the resistivity. If the bandgap of the material due to applied pressure increases then it will be harder for electrons to reach the conduction band, which indicates an increase in resistivity of the material; the opposite is also true. A pressure sensor is a device which produces a proportional output voltage according to the change in pressure stress or strain in the input of a particular system [12]. Furthermore, a system can have more than one pressure sensor with different sensitivities.

The sensing mechanism of a piezoresistive pressure sensor is shown in Fig. 1 below. An input dc voltage is supplied to the sensor at all times and the voltage across the piezoresistive material (or piezoresistor) is always being measured. This is the output voltage. When pressure is applied on the sensor, the diaphragm is stretched. The diaphragm then multiplies and transfers the pressure to the piezoresistor. This changes the resistance of the piezoresistor, and so the voltage across the piezoresistor (i.e. the output voltage) changes.
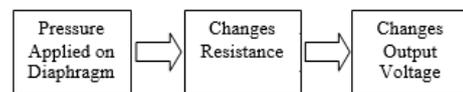
Fig. 1 Sensing Mechanism

When pressure P is applied to the diaphragm then the diaphragm will deform due to the induced stress and there will be a change in resistance ΔR of the piezoresistor and the device will produce an output voltage V_{out}.

$$V_{out} = V_i * \frac{\Delta R}{R} \qquad (1)$$

The sensitivity (S) of the pressure sensor can be expressed as

$$S = \frac{V_{out}}{V_i} * \frac{1}{P} \qquad (2)$$

III. MATERIAL

Silicon is the material of choice in forming both the diaphragm and the piezoresistor of the sensor. Doped silicon, particularly boron-doped silicon, exhibits best piezoresistivity [11]. Silicon shows great degree of piezoresistivity which is essential for fabricating sensors with high coefficient of sensitivity [7] [8]. Also, silicon is the most dominant semiconductor in IC fabrication. This allows for the transistors and the sensor to be built on the same chip, thus allowing smaller devices and reducing manufacturing cost.

IV. DESIGN CRITERIA OF MEMS PIEZORESISTIVE PRESSURE SENSOR

The shape, dimension, position, material and doping concentration of both diaphragm and piezoresistor play significant roles in the sensitivity of the sensor. The length of the piezoresistor dominates over width or thickness in determining sensitivity [14]. In article [13] and [14] it has been reported that by implementing double diaphragm higher sensitivity can be achieved. In article [6] it is reported that by adding new material diaphragm deformation can be made higher and thus sensitivity. By varying dimensions of the piezoresistors (while keeping electrical resistance constant) it has been shown that resistors that sense compressive stress plays a great role in changing sensitivity and thus, to get better sensitivity the size must be kept small for those resistors experiencing compressive stress [10]. Sensitivity also depends on electrical conductivity, hole mobility, ionization factors. Since temperature and doping concentration affect the electrical conductivity, therefore it also affects the sensitivity of the sensor.

V. DESIGN WORK

The relation between displacement and applied pressure for a flat square diaphragm is given by Eq. (3)

$$\frac{Pa^4}{Eh^4} = \frac{42}{(1-v^2)}\left[\frac{y}{h}\right] + \frac{1.58}{(1-v)}\left[\frac{y}{h}\right]^3 \qquad (3)$$

Where, P = applied pressure (Pa), y = centre deflection of the diaphragm, a = half side length, E = young's modulus, h = diaphragm thickness, v = Poisson's ratio of the diaphragm material.

The maximum deflection in the diaphragm can be expressed by

$$w_{max} = -0.013 * \frac{P^4}{E^3} \qquad (4)$$

The maximum stress [16] at the center of each edge of diaphragm is given by

$$\sigma_{max} = 0.308 * \frac{Pa^4}{h^2} \qquad (5)$$

The electric field in the vicinity of surface of diaphragm with applied stress is given by

$$E = \rho * J + \Delta\rho * J \qquad (6)$$

Where ' ρ ' is resistivity, ' J ' is current in piezoresistors, '$\Delta\rho$ ' is induced change in resistivity.
And change in resistivity [17] can be written by

$$\Delta\rho = \Pi * \sigma \qquad (7)$$

Where ' Π ' is piezoresistance tensor, a material property. ' σ ' is shear stress.

The square diaphragm in the model has a thickness of 20 μm and each side of length of 1000 μm. All four sides of the diaphragm are fixed to a membrane. This sensor has only one piezoresistor. The piezoresistor has a thickness of 400 nm. The piezoresistor is placed at the center of a side of the square diaphragm, which is the maximum stress region. The piezoresistor is positioned at a angle of 45° to the edge of the diaphragm. The electrodes (interconnects) have a thickness of 400 nm. These contacts are much wider and are highly doped (p+) which result in their lower resistance than the piezoresistor. The piezoresistor has four contacts, two for applying the bias voltage and the other two are for voltage taps [18]. In this study, an n-silicon diaphragm and a p-silicon piezoresistor is used. The pressure applied on the diaphragm was in the range of 0 to 100 kPa. This pressure induces shear stress on the piezoresistor, which in turn changes its resistance. The diaphragm edge is along a [110] direction in a (100) plane. This means that the piezoresistor axis is along the [100] direction. A bias voltage of 3 V is applied across the piezoresistor axis.

VI. SIMULATION

In this study, simulation has been done in the COMSOL Multiphysics v4.4 environment. It is a finite element analysis (FEA) simulation software package for various physics and engineering applications, especially coupled phenomena, or "multiphysics".
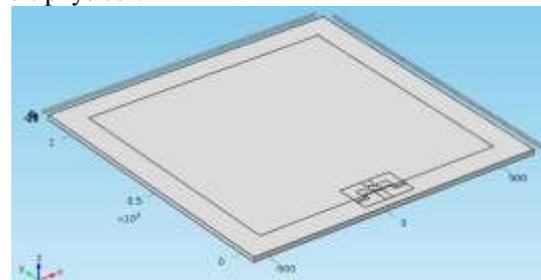
Fig. 2 The Motorola MAP sensor model (3-D view)

The 2-D view of the X-shaped piezoresistor and its circuit diagram[10] is shown in Fig.3.
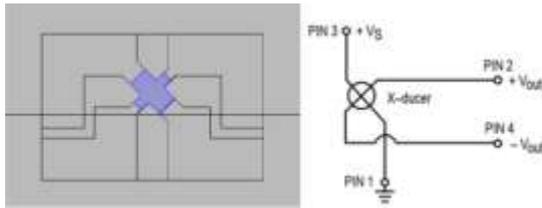
Fig. 3 The piezoresistor (highlighted) and its connections

Three types of study have been done for four different types of combinations of diaphragm and piezoresistor material. The different combinations have been mentioned in Table I.

TABLE I

Combination	Diaphragm	Piezoresistor
1.	N-silicon (single-crystal)	P-silicon (single-crystal)
2.	N-silicon (poly-crystal)	P-silicon (single-crystal)
3.	N-silicon (single-crystal)	P-silicon (poly-crystal)
4.	N-silicon (poly-crystal)	P-silicon (poly-crystal)

For the above four combinations effect of input pressure on diaphragm displacement, the induced sheer stress and output voltage of piezoresistor have been studied. Also, doping concentration of both diaphragm and piezoresistor was varied for the single crystals and relation between output voltage and doping concentration (for interconnects and piezoresistor, both) has been studied.

VII.   RESULTS AND DISCUSSION

A. Material Analysis

All the figures shown below are for the first combination of materials — N-silicon (single-crystal) diaphragm and P-silicon (single-crystal) piezoresistor. Similar plots were observed for the other three combinations & observed values have been reported in corresponding tables.

1) Displacement: Displacement is proportional to the applied pressure. Here the pressure is varied from 0 to 100 kPa & corresponding displacements in μm are shown in TABLE II.
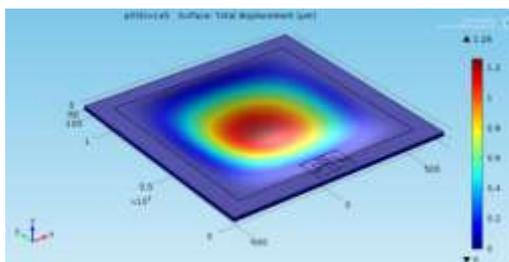
Fig. 4 Displacement Plot

TABLE II

N-silicon (single-crystal) & P-silicon (single-crystal)	N-silicon (poly-crystal) & P-silicon (single-crystal)	N-silicon (single-crystal) & P-silicon (poly-crystal)	N-silicon (poly-crystal) & P-silicon (poly-crystal)
1.26 μm	1.18 μm	1.26 μm	1.18 μm

Difference between first & second two consecutive values come from their crystal alignment. As poly-crystal is a collection of single crystal layer so bending is lower than single crystal. The 1st & 3rd values and the 2nd & 4th values are equal as the diaphragm's material is the same. Thus only the diaphragm material's crystal alignment change can change the displacement.

2) Shear Stress: Due to the diaphragm membrane being fixed to all four edges, the shear stress should be maximum at the midpoint of the edges of the diaphragm when pressure is applied at the center of the diaphragm. As we want maximum stress on the piezoresistor, we placed it at the midpoint of the edge. TABLE III shows the stress on piezoresistor in MPa.
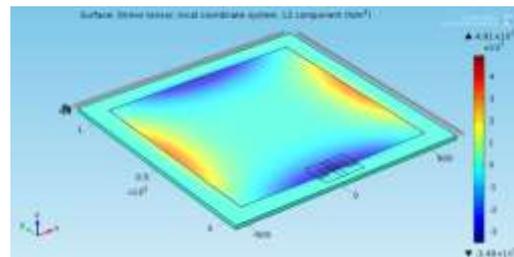
Fig. 5 Shear Stress Plot

TABLE III

N-silicon (single-crystal) & P-silicon (single-crystal)	N-silicon (poly-crystal) & P-silicon (single-crystal)	N-silicon (single-crystal) & P-silicon (poly-crystal)	N-silicon (poly-crystal) & P-silicon (poly-crystal)
34.9 MPa	28.7 MPa	34.9 MPa	28.7 MPa

It can be seen that for single-crystal diaphragm we get more stress at the midpoint of the edge compared to poly-crystal diaphragm. This is desirable since for higher stress, sensitivity is higher. Also, the piezoresistor is placed on the side with lower stress (blue region in the above figure) rather than on one of the other two sides (red regions). This is because the piezoresistors crystal orientation is [100] and the diaphragm edge orientation is [110] [18].

3) Output Voltage vs. Pressure: Voltage is proportional to the applied pressure. A linear graph was achieved as expected.
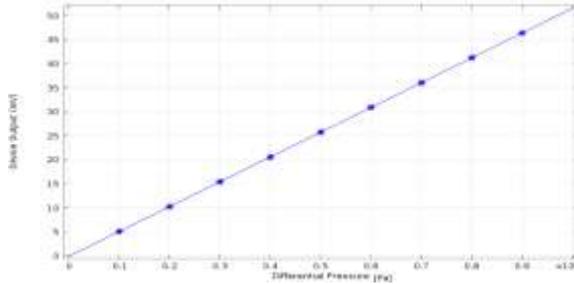
Fig.6 Output Voltage vs. Pressure Plot

TABLE IV shows the output voltage change due to input pressure applied for four types of material combinations. The same range of pressure was applied for all four combinations.

TABLE IV

N-silicon (single-crystal) & P-silicon (single-crystal)	N-silicon (poly-crystal) & P-silicon (single-crystal)	N-silicon (single-crystal) & P-silicon (poly-crystal)	N-silicon (poly-crystal) & P-silicon (poly-crystal)
50 mV	40 mV	30 mV	24 mV

Comparing the second and fourth combination (where both combination have the same diaphragm material) it can be seen that even though the range of pressure was kept same the output voltages were different. The principle reason is that applied pressure changes the resistance, which ultimately changes the output voltage. But here, the poly-silicon grain boundaries of the piezoresistor (in fourth combination) act as defects in the crystal structure & decreases the material's thermal and electrical conductivity. Same can be said for the first and third combination.

B. Doping Concentration

Output voltage increases for interconnects (p-type) doping and decreases for piezoresistor (p-type) doping. Doping is a costly process. Also, high doping may damage the substrate. Furthermore, channelling effect and also the amount of current is needed to be considered. Thus a trade-off has done for doping. As ranges were high, we just took our desired value while doing simulation for doping. Fig.7 and Fig.8 shows the effect of doping (per m^3) on output voltage in mV.

1) Output Voltage vs. Doping Concentration of Interconnects (p-type single-crystal)
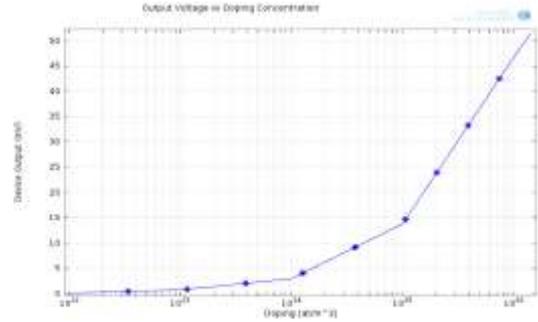
Fig.7 Output Voltage vs. Doping Concentration of Interconnects (p-type single-crystal) Plot

A range of doping concentrations was used for the interconnects since the piezoresistive property of silicon is a strong function of doping concentration within this range. As doping is increased the output increases but the piezoresistive effect of silicon becomes less dominant. Thus a trade-off had to be made. We used a doping concentration of 1.45 x 10^{20} per cm^3.

2) Output Voltage vs. Doping Concentration of Piezoresistor (p-type single-crystal)
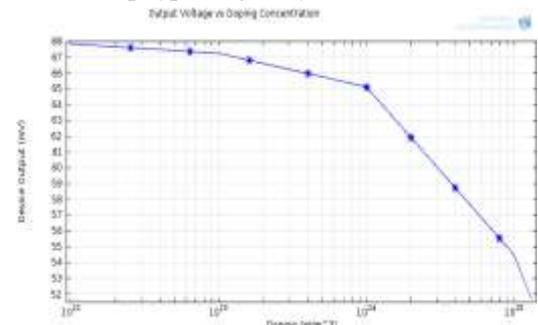
Fig.8 Output Voltage vs. Doping Concentration of Piezoresistor (p-type single-crystal) Plot

The same range of doping concentrations were studied as before but the result observed was opposite. The output seemed to decrease with increasing doping concentration. Here we used a doping concentration of 1.32 x 10^{19} per cm^3.

C. Sensitivity

Sensitivity is defined as the output voltage per kPa pressure applied. TABLE V shows the sensitivities obtained for the four different combinations of materials in mV/kPa.

TABLE V

N-silicon (single-crystal) & P-silicon (single-crystal)	N-silicon (poly-crystal) & P-silicon (single-crystal)	N-silicon (single-crystal) & P-silicon (poly-crystal)	N-silicon (poly-crystal) & P-silicon (poly-crystal)
0.52 mV/kPa	0.4 mV/kPa	0.32 mV/kPa	0.25 mV/kPa

From the table, it is clear that the single-crystal diaphragm and single-crystal piezoresistor combination provides best sensitivity as the others need more pressure to achieve the same level of output voltage.

VIII. CONCLUSION

This thesis was conducted in order to find the combination which produced the most sensitive pressure sensor. It can be easily deduced from the results of the simulation that the n-silicon (single crystal) diaphragm & p-silicon (single crystal) piezoresistor combination is best among all. This combination provides best output & shows highest stress and displacement values, which ultimately leads to the most sensitive sensor among the ones studied. A decent amount of output was improved by moderate doping. The results are good for the pressure chosen. But if the pressure is changed results will be different as poly-silicon can handle much more pressure than single-crystal.

REFERENCES

[1] "An introduction to MEMS (micro-electromechanical systems)," *Prime Faraday Technology Watch*, January 2002.

[2] Tu Xiang-Zheng, Li Yun-Yan, "Silicon diaphragm piezoresistive pressure sensor and fabrication method of the same, " *Grant Publication*, 1993.

[3] Lynch, J., Partidge, A., Law, "Design of piezoresistive MEMS-based accelerometer for integration with wireless sensing unit for structural monitoring," *J.Aersosp. Eng.*,16(3), pp. 108-114, 2003.

[4] Eddy , David S , "Applications of MEMS technology in automotive sensors and actuators," *Proc. IEEE*, vol. 86, Issue 8, 1998.

[5] C Pranamik, H Saha , "Design optimization of a high performance silicon MEMS piezoresistive pressure sensor for biomedical applications," *J. Micromechanics and Microengineering*, 2006.

[6] Naga Jyothi Madduri, Gopinadh Lakkoju, Bhanu Lahari Kasturi, Sravani Sravanam and Talam Satyanarayana, "Design and deformation analysis of MEMS based piezoresistive pressure sensor," *International Journal of Advances in Engineering & Technology*, May, 2014.

[7] Smith, C.S., "Piezoresistance effect in germanium and silicon," *Physics Review*, pp. 42–49, 1954.

[8] Kanda, Y., "Piezoresistance effect of silicon," *Sensors and Actuators A: Physical*, pp. 83–91, 1991.

[9] Y. Kanda and A. Yasukawa, "Optimum design considerations for silicon piezoresistive pressure sensors," *Sensors and Actuators A: Physical*, 1997, 62(1–3): 539–542.

[10] K.J Suja, G.S Kumar, "Dimension and doping concentration based noise and performance optimization of a piezoresistive MEMS pressure sensor," *Springer-Verlag Berlin Heidelberg 2014*.

[11] Tian B, Zhao Y, Jiang Z, "The novel structure design for pressure sensors," *Sens Rev 30(4):305-313*.

[12] Tai-Ran-Hsu, "MEMS and microsystem: design and manufacture," *Tata McGraw-Hill*, New Delhi, 2000.

[13] Suja KJ, Chawdhuary BP, "Design and simulation of pressure sensor for ocean depth measurment," *Appl Mech Matter 313-314:666-670*.

[14] Madhavi KY, Krishna M, Murthy CSE, "Effect of diaphragm geometry and piezoresistor dimension on the sensitivity of piezoresistive micropressure sensor using finite element analysis," *IJESE 1(9)*, 2013.

[15] K. Sakurano, H. Katoh, Y. Chun, and H. Watanabe, "Operation of a work function type SOI temperature sensor up to 250AC," in *IEEE International SOI Conference Proceedings 2007*, Osaka, Japan, pp. 149–150, 2007.

[16] S. Timoshenko, S. Woinowsky-Krieger, "Theory of plates and shells," *McGraw-Hill*, New York, 1959: 16–20.

[17] Chaurasia S, Chaurasia BS, "Analytical models for low pressure square diaphragm piezoresistive MEMS sensor engineering and system (SCES)," *IEEE 2012*, pp1-6, 2012.

[18] Stephen D. Senturia, "A piezoresistive pressure sensor," in *Microsystem Design*, New York: Kluwer, 2002, pp. 481–484.