Study and Implementation of MEMS Piezoresistive Pressure Sensors using COMSOL Multiphysics

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Abstract

Piezoresistive pressure sensors were some of the first MEMS devices to be commercialized.This example considers the design of the MPX100 series pressure sensors originally produced by the semiconductor products division of Motorola Inc. (now Free scale Semiconductor Inc.).Applied pressure range is varied from 0 to 100 kPa. To gain the optimum output, different combination ofmaterial for diaphragm & piezoresistor have been studied and corresponding displacement change, shear stress distribution and output voltage have been shown. 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 processes this information and signals the micro-actuators to react and create the changes required. In terms of robustness, low power consumption and accuracy, MEMS sensors have proved its efficiency. MEMS sensors are using in biomedical, optoelectronics, automobile and industrial sectors. For its wide range of application, many researcheshave 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 Semiconductors such as silicon and germanium arepiezoresistive materials, but silicon exhibits better piezoresistivity response characteristics. Sensitivity of the sensor can be increased by choosing proper shape of piezoresistor and diaphragm or by changing the dimension of both. Due to symmetry square shaped diaphragm showed better sensitivity than a circular diaphragm. Even by changing the position of the piezoresistor the performance can be improved a lot. Improvedsensitivity has been achieved for differentcrystallographic forms of silicon, by changing materials and by changing doping concentration of piezoresistors.

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 band gapof 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. 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, thediaphragm is stretched. The diaphragm then multiplies and transfers the pressure to the piezoresistor.

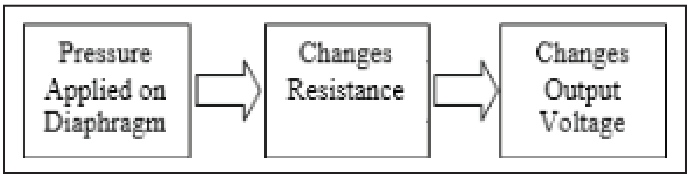

Fig. 1: Sensing Mechanism

This changes the resistance of the piezoresistor, and so the voltage across the piezoresistor (i.e. the output voltage) changes.

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. Silicon shows great degree of piezoresistivity which is essential for fabricating sensors with high coefficient of sensitivity. 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. In article and it has been reported that by implementing double diaphragm higher sensitivity can beachieved. In article 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. 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. Simulation

In this study, simulation has been done in the COMSOL Multiphysics v4.4 environment.

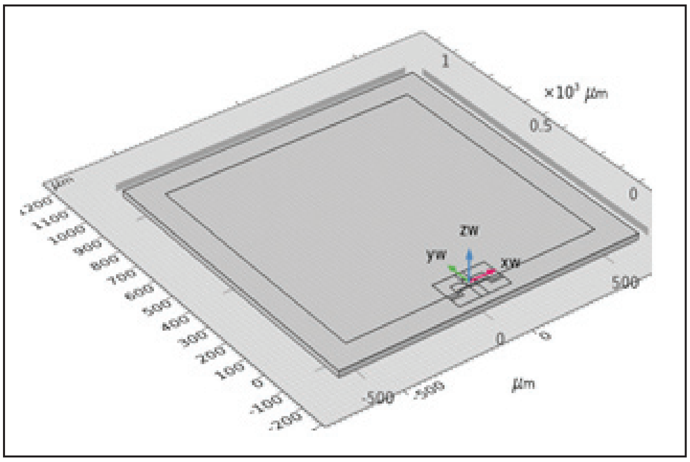

Fig. 2: Model Geometry

It is a Finite Element Analysis (FEA) simulation software package for various physics and engineering applications, especially coupled phenomena, or "Multiphysics".Model geometry as shown in Fig. 2 and detail showing piezoresistor geometry in Fig 3.

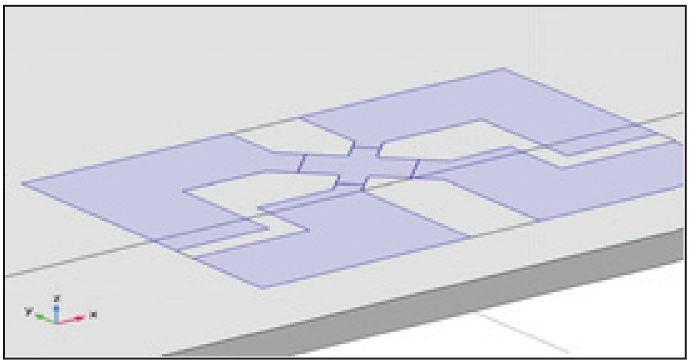

Fig. 3: Detail Showing the Piezoresistor Geometry

VI. Results and Discussion

Displacement: Displacement is proportional tothe applied pressure. Here the pressure is variedfrom 0 to 100 kPa & corresponding displacements inµm as shown in Table 1.

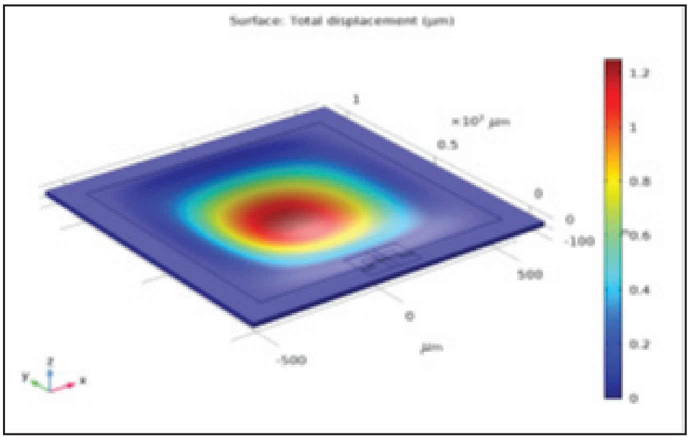

Fig. 4: Displacement of the Diaphragm

Shear Stress: Due to the diaphragm membranebeing fixed to all four edges, the shear stress shouldbe maximum at the midpoint of the edges of thediaphragm when pressure is applied at the center ofthe diaphragm. As we want maximum stress on thepiezoresistor, we placed it at the midpoint of theedge. Table 1 shows the stress on piezoresistor inMPa. It can be seen that for single-crystal diaphragmwe get more stress at the midpoint of the edge.

Table 1: Parameters to Design Piezoresistive Pressure Sensor

Material	Displacement	Stress	O/P voltage	Sensitivity
N-silicon (single-crystal) P-silicon (single-crystal)	1.26 µm	34.9 MPa	50 mV	0.52mV/kPa

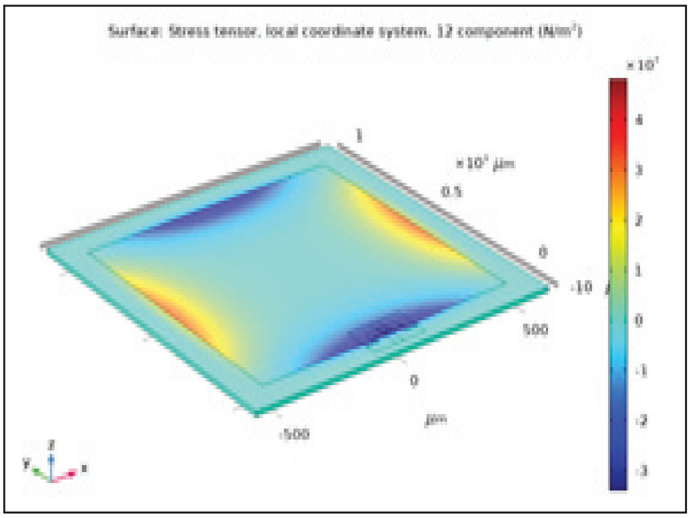

Fig. 5: Shear Stress

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 x10^{20} per cm^3.

A. Sensitivity

Sensitivity is defined as the output voltage per kPa pressure applied. Table 1 shows the sensitivityobtained for the materials in 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.

VII. Conclusion

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. 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.

VIII. Future Work

Piezoresistive pressure sensors were some of the first MEMS devices to be commercialized. Compared to capacitive pressure sensors, they are simpler to integrate with electronics,their response is more linear, and they are inherently shielded from RF noise. They do, however, usually require more power during operation, and the fundamental noise limits of the sensor are higher than their capacitive counterparts. Thus, piezoresistive devices can beused as dominant pressure sensor in the pressure sensor market.

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