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Temperature Study of Reinforced MEMS Pressure Sensor

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Abstract— Micro Electro Mechanical Systems pressure sensors have been simulated with different parameters for obtaining wider operation range with better sensitivity. The performance has been simulated and analyzed for silicon and SOI (Silicon-on-Insulator) pressure sensors. The performance of silicon and SOI pressure sensor at a given pressure and temperature are compared. The doping concentration of the piezoresistor is varied from 10^{15} cm^{-3} to 10^{20} cm^{-3} and the sensitivity of pressure sensors were compared. A comparative study of temperature sensitivity of silicon and SOI based diaphragms in the temperature from 150K to 500K has also been evaluated in this work.

Index Terms— MEMS, Pressure sensor, piezoresistive, surface concentration, SOI, pressure sensitivity, temperature sensitivity

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1 INTRODUCTION

PRESSURE sensors are key part of many commercial and industrial systems. Pressure sensors can be fabricated either by bulk micromachining, surface micromachining or combination of both. The sensor works on the principle that the change in resistance will occur on the diaphragm due to applied pressure. The aim of this work is to model, compare and analyze the different performance parameters like deflection, voltage output, voltage sensitivity and temperature sensitivity. The fundamental concept of piezoresistive effect is that, an applied stress results in a change in resistivity. Figure 1 shows a schematic cross section of a MEMS pressure sensor using a silicon diaphragm and SOI diaphragm. The simulation of the SOI pressure sensor is performed and compared their performance parameters such as deflection, stress, voltage and sensitivity with conventional silicon pressure sensor. In SOI sensor the piezoresistive elements are on top of silicon formed in the SOI layer [1]. The deflection and sensitivity at different surface concentrations for silicon diaphragm and SOI diaphragm are simulated. Performance of different pressure sensors are also studied over temperature range from 150K to 500K. The SOI piezoresistive pressure sensor is found to maintain an appreciable output and sensitivity for all temperatures under consideration. In this study CoventorWare® is used for simulating various structures.

2 PRESSURE SENSOR DESIGN

The substrate layer material used here is silicon. The area of diaphragm is 500x500 μm^2 and the thickness of the membrane is 12 μm. The deflection is simulated and compared for Si and SOI diaphragm for an applied pressure of 0.9 MPa and at different surface concentration (N) ranging from 10^{15} cm^{-3} to 10^{20} cm^{-3}. When a pressure is applied, the diaphragm deflection results in an induced strain in the piezoresistor. The design parameters of the pressure sensor include membrane size/shape, piezoresistor arrangement, burst pressure and the surface concentration of piezoresistive material [2].

Wheatstone bridge is used to measure the resistance change due to the applied pressure. When a pressure is applied on the diaphragm, the diaphragm deflects and the deflection results in a strain. The strain in term causes the resistance of piezoresistor used in the Wheatstone bridge to change. As a result the bridge is unbalanced which result an output voltage as shown in eqn (1).

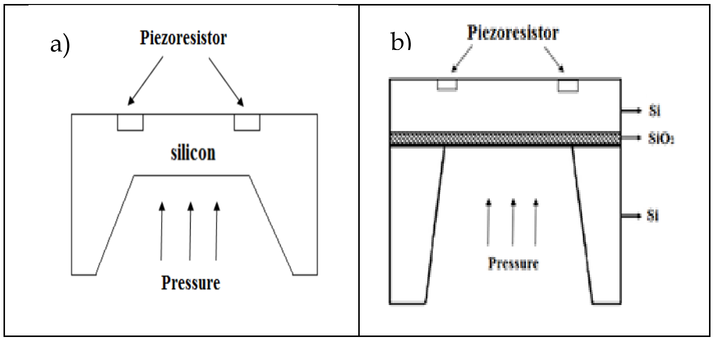

Fig. 1. Schematic cross section of Silicon diaphragm and SOI diaphragm

The circuit representation of Wheatstone bridge is shown in figure 2. The bridge output voltage V_0 is given by eqn (1).

$$V_o = V_{in}\left(\frac{R_1}{R_1 + R_4} - \frac{R_3}{R_2 + R_3}\right) \tag{1}$$

Where V_{in} is the applied voltage to the bridge circuit and R_1, R_2, R_3 and R_4 are the resistances connected in Wheatstone bridge arrangement.

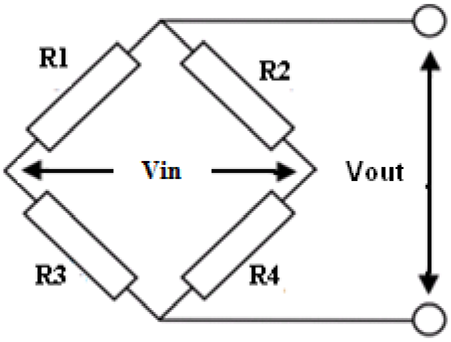

Fig. 2. Basic layout of the Wheatstone bridge

The bridge is balanced when no pressure is applied on the diaphragm. The application of pressure induces stresses in the diaphragm which causes a change in the resistance of piezoresistors. As a result, the Wheatstone bridge will not be in balance anymore and an output voltage can be measured. It is necessary that four resistors are identical in the absence of applied pressure. Thus any mismatch in resistance results in an imbalance of the Wheatstone bridge.

The applied pressure on the diaphragm is limited in such a way that the maximum deflection is limited to 30% of the diaphragm thickness [3]. The maximum deflection of the diaphragm is given by eqn (2).

$$w_{max} = 0.01512(1 - \nu^2)\frac{P_a L^4}{Eh^3} \tag{2}$$

Where, w_{max} is maximum deflection, ν is Poisson's ratio, P_a is applied pressure, L is the length of the diaphragm, E is young's modulus and h is diaphragm thickness. The maximum stress that a silicon diaphragm can withstand is 7 GPa, which is equal to its fracture stress. Under normal operating conditions stress should never exceed the fracture stress of silicon. The minimum thickness of silicon which gives the maximum sensitivity without damaging the diaphragm is given by eqn (3),

$$h_{min} = \left(\frac{0.39P_B}{\sigma_{max}}\right)^{1/2} L \tag{3}$$

Where, h_{min} is minimum thickness of diaphragm, σ_{max} is maximum stress of silicon diaphragm and P_B is the burst Pressure

Burst pressure is the maximum nondestructive pressure that can be applied to the pressure sensor. It is the pressure at which stress in the diaphragm is equal to the fracture stress. In this analysis burst pressure of 10 MPa is considered and which is 10 times the maximum pressure is being measured [4].

$$\sigma_{max} = P\frac{a^2}{h^2} \tag{4}$$

Where, 'a' is half of diaphragm side length.

3 RESULT AND ANALYSIS

3.1 Pressure Sensitivity Analysis

A better sensor design requires two important performance factors, namely high output voltage at a given burst pressure and high sensitivity. It is difficult to design a sensor with both the parameters maximized simultaneously, which translates into performance trade-offs. If a sensor exhibits higher sensitivity, it typically offers low burst pressure. Pressure sensitivity is inversely proportional to burst pressure. Sensitivity of a sensor is expressed as in eqn (5)

$$S = \frac{V_{out}}{V_{in}P} \tag{5}$$

For evaluating the performance of the pressure sensor the variation of doping concentration of piezoresistor is considered first. The p-type doping concentration of the piezoresistor is varied from 10^{15} cm^{-3} to 10 ^{20} cm^{-3} and doped with boron to make it p-type. At an applied pressure of 10 MPa, the output sensitivity of silicon diaphragm and SOI diaphragm are simulated. Output voltage and sensitivity are constant for surface concentration ranges from 10^{15} cm^{-3} to 10^{17} cm^{-3}. As shown in figure 3 single SOI based diaphragm shows better sensitivity when compared to conventional silicon sensor. Sensitivity is a function of doping concentration, after certain doping concentration as shown in figure 3 it is observed that the change in sensitivity rapidly decreases after certain doping concentration, which is about 10^{17} cm^{-3} and till the value it remains fairly constant.

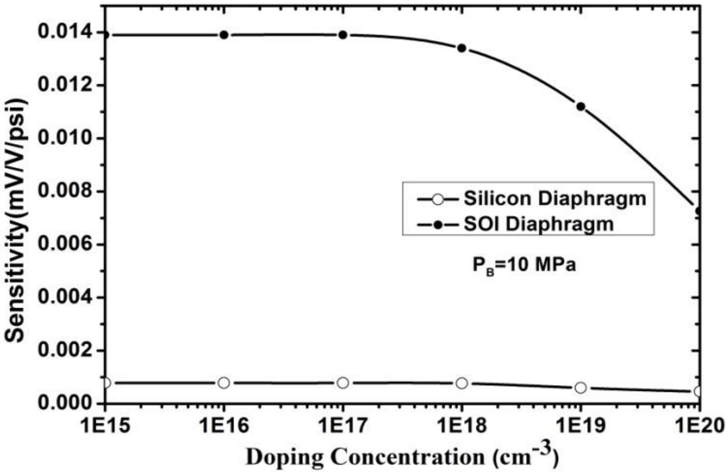

Fig. 3. Sensitivity of different pressure sensors at different surface concentration

In the following simulations, the boron doping concentration of piezoresistor is fixed at 10^{17} cm^{-3}. The deflection (displacement) in silicon and SOI diaphragm are shown in figure 4. SOI diaphragm shows more deflection when compared with silicon diaphragm.

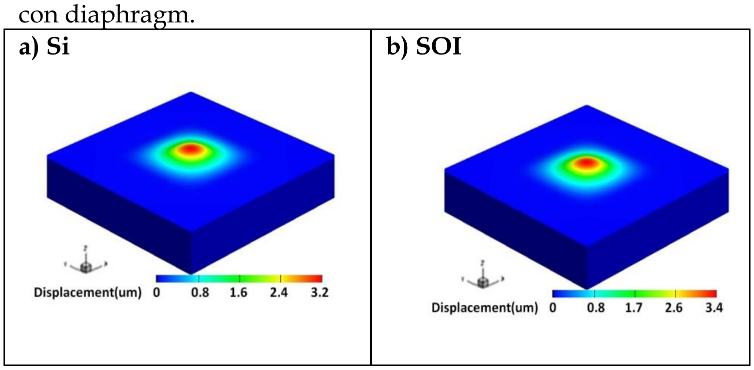

Fig. 4. Deflection of Single Silicon and single SOI pressure sensor

Figure 5 shows the comparison of sensitivity of silicon and SOI pressure sensor at room temperature.

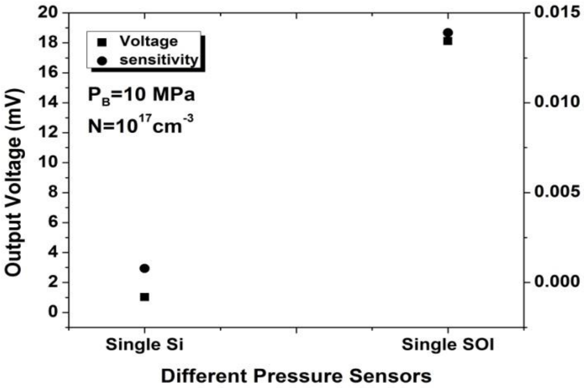

Fig. 5. Output voltage and sensitivity comparison of different structures.

3.2 Deflection Analysis

Deflection of the pressure sensor changes as temperature changes. Due to deflections, strain produced on the diaphragm can be evaluated [5]. The reason for large deflection in SOI diaphragm is that, it is realized by surface micromachining and the vertical and the horizontal edges of the diaphragm are not an integral part of the substrate whereas in the conventional sensor the diaphragm is realized by bulk micromachining and the vertical and horizontal edges of the diaphragm are essentially an integral part of the substrate.

In the steady state, the deflection of the pressure sensor diaphragm is governed by eqn (6) which allows to calculate the membrane deflection w(x, y) as a function of temperature

$$w(x,y) = \frac{2L}{\pi}\sqrt{\alpha\Delta T + \frac{(\alpha\Delta T)^2}{2}} \tag{6}$$

Where L is the length of the diaphragm, ΔT is change in temperature, In P-type material π_{44} is dominate when compared with other piezoresistive coefficients. So π is taken as π_{44} and α is the thermal expansion coefficient.

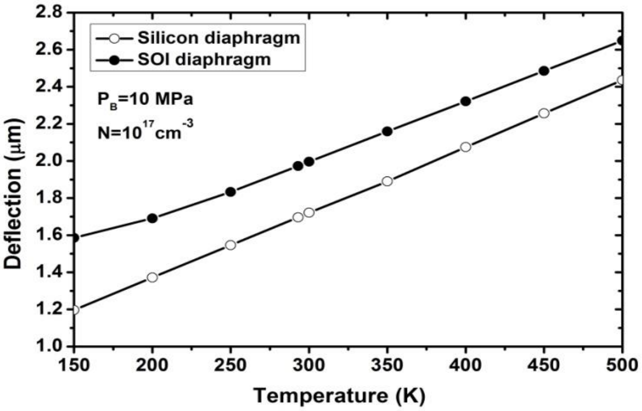

Fig. 6. Deflection of SOI and Silicon pressure sensor with various temperature ranges.

The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure.

Figure 6 shows the deflection in silicon and SOI pressure sensor over a temperature range 150K to 500K. When temperature increases, deflection of SOI also increases linearly. Results proved that SOI pressure sensor deflected more than the silicon pressure sensor.

3.3 Mobility Analysis

The Arora mobility model is used to simulate the doping dependent mobility in Si and takes into account the scattering of the carriers by charged impurity ions which leads to a degradation of the carrier mobility (ionized impurity scattering) [6]. This model presents a single empirical relationship for carrier mobility as a function of temperature and concentration which can be used for temperature from 77K to 500 K.

Arora model gives an empirical relation between temperature and mobility. The hole mobility in a bulk semiconductor (μ_p) is a function of doping concentration N and temperature T is given by the relation in eqn (7).

$$\mu_p = 54.3T_N^{-0.57} + \frac{1.36 \times 10^8 T^{-2.23}}{1 + \left[\left(\frac{N}{2.35 \times 10^{17} T_N^{2.4}}\right)\right] 0.88 T_N^{-0.146}} \tag{7}$$

Where

$$T_N = \frac{T}{300} \tag{8}$$

In general, lattice scattering and ionized impurity scattering are the two scattering mechanisms affecting the hole mobility and here the ionized impurity scattering dominates. So when temperature increases mobility decreases. In this analysis it is assumed that ionization is 100%.

In order to understand the effect of temperature on output voltage the conductivity of the piezoresistor is considered. The conductivity is given by eqn (9)

$$\sigma = \frac{1}{q(p\mu_p + n\mu_n)} \tag{9}$$

As the material is p-type minority carrier concentration can be neglected. Then the conductivity is given by eqn (10).

$$\sigma = \frac{1}{qp\mu_p} \tag{10}$$

The conductivity is a function of carrier concentration and mobility.

Figure 7 shows the change in carrier mobility in the temperature range from 150K to 450K.

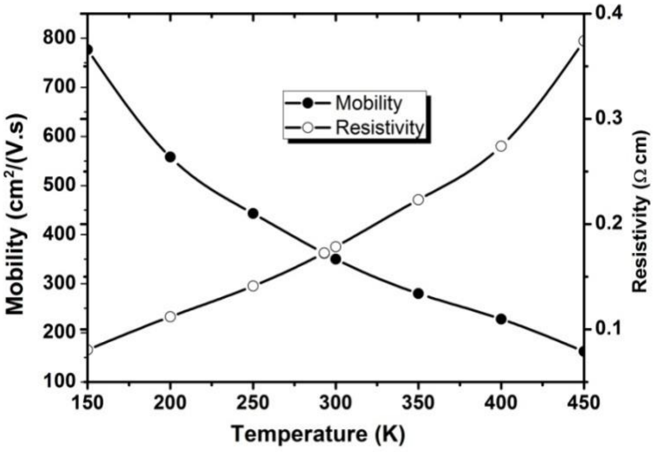

Fig. 7. The mobility and resistivity in boron-doped silicon as a function of various temperature ranges.

As the temperature increases, μ_p decreases. Mobility is the crucial parameter to describe the resistance of a bulk material.

3.4 Sensitivity of Pressure Sensor

The mobility is expected to decrease with decreasing temperature.

$$R = \frac{\rho l}{A} = \frac{1}{q\mu_p N}\frac{l}{A} \qquad (11)$$

By comparing the stresses of the two sensors at its edges, the Si pressure sensor exhibit more stress at its edges than the SOI pressure sensor. The SOI sensors are fabricated using the surface micromachining technique and the diaphragm thickness is too uniform. Moreover the vertical and horizontal edges of the diaphragm are not integral part of the substrate, unlike the Si pressure sensors which is fabricated using bulk micromachining technique, where the vertical and horizontal edges of the diaphragm are essentially integral part of the substrate [7]. The presence of the SiO_2 in the SOI structure increases the flexural rigidity of the structure thereby reducing the stresses at its edges.

The stress in the pressure sensor with silicon diaphragm was found to be more when compared to its SOI counterpart. The sensitivity of SOI pressure sensor is more when compared to the Silicon pressure sensor. **S**tress is inversely proportional to sensitivity, so sensitivity of silicon decreases. Figure 8 shows the sensitivity of different pressure sensor at low temperature, room temperature and high temperature. When temperature approaches to room temperature all the carriers get ionized, so the sensitivity of the material decreases at room temperature.

The resistors in the SOI pressure sensor are dielectrically isolated from the diaphragm with the help of the buried oxide layer. This causes a very less leakage current to occur in the sensor and for which it can be made suitable to large temperature applications. The Si pressure sensor, the pn junction isolation allows more current leakage and this leakage current is probable to increase as the temperature increases [8].

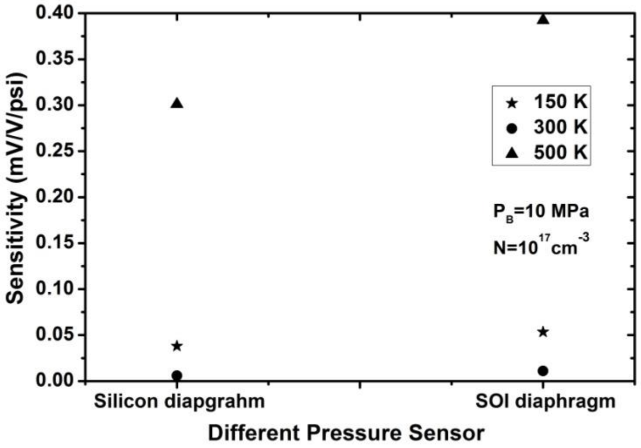

Fig. 7. Sensitivity of different pressure sensors at different temperature ranges.

The resistors in SOI pressure sensor offers higher impedance since the piezoresistor are isolated from the substrate by an insulating layer, in contrast to the bulk Si pressure sensor where leakage current exist and the impedance of the resistors is less. This accounts for higher voltage output in SOI Pressure sensor. The difference is attributed to the composite structure of the SOI diaphragm.

4 CONCLUSION

Optimized the doping concentration of piezoresistor as 10^{17}cm^{-3} and obtained SOI has higher pressure sensitivity. The SOI pressure sensor exhibited greater deflection and experienced less stresses at its edges, than the Silicon pressure sensors. SOI pressure sensor provided higher voltage output and temperature sensitivity at a various range of temperature when compared to conventional silicon pressure sensor. The SOI diaphragm MEMS pressure sensors designed in this study can be used for a wide range of temperatures.

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