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Design and Simulation of MEMS Pressure Sensor Using COMSOL Multiphysics Tool and Analysis of its Compatibility with Digital Interfacing Unit for Pressure Measurement

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***Abstract*—**

This paper summarizes variation of characteristic which arises from the longitudinal change of stress that induced in the sensor circuit main part or the p-type Si piezoresitive element with respect to induced stress. This sensing or conversion of stress to analog voltage resulted from the piezeoresistive effect occurred within the sensor when stress applied. The location of the sensor on the membrane surface has chosen near to the fixed edge of the plate where maximum stress exits. The p- Si piezoresistive sensor has included in readout circuit configuration as one of the two elements in the sensor circuit and the other one of them placed in a stress-free region that is on the fixed edge with the same orientation. This circuit configuration is chosen to generate readable analog sensor output voltage which is simple and convenient to make both analytical and computer-aided analysis. Since the two sensing elements used in the sensor circuit are identical, in absence of pressure the output voltage is found to be nearly half of the biasing voltage. And also we observed that the sensor output voltage linearly varies with the applied pressure at the center of the diaphragm. Finally, the change in output voltage per one 100kPa pressure is calculated in the longitudinal orientation. We have determined that this resolution is matched with 8-bit analog to digital converter's output resolution if suitable signal conditioning circuit is employed for pressure measurement purpose.

***Keywords*— MEMS, Peizoresistor, Diaphragm, Readout circuit, Longitudinal stress**

I. INTRODUCTION

The current high demand of micro-structured electronic sensors relies on the high quality of design and simulation followed by advanced fabrication to make them compatible with CMOS circuitry. MEMS (Micro-Electro-Mechanical System) sensors are one of them. They are produced and available in the market in different form. Capacitive, piezoelectric and piezoresitive are a few to mention.

In this paper, we present the design and simulation of p-type Si piezoresisitve based MEMS pressure sensor readout circuit proposed to be used for pressure measurement. The output voltage of this sensor circuit studied to investigate its compatibility with 8 bit resolution digital interfacing unit like analog to digital converter.

A piezoresistive effect means a change in electrical resistance which a homogeneous body undergoes when subjected to mechanical stress. [1]

A typical micro-electromechanical systems (MEMS) pressure sensor studied in [2] consists of a thin, deformable membrane and piezoresistive sensing element which is used to measure the amount applied pressure when heat energy is applied and courses to buckle. This structure is used in the design process is used in this paper but on an element is added in the stress-free region for reference purpose.

The general application of the theory of piezoresistive pressure sensor built on 100 Si wafer has been discussed in detail on [3] including how the relative resistivity change with the applied pressure that induced stress in the piezoresistor integrated within the diaphragm.

In the past time, not only the application of piezoresistor as sensor has studied, its effect in MOSFET device simulated and analysed in [4] based on experimentally determined piezoresistive coefficients. Hence it demonstrates piezoresistivity effect can tune the operation of an active electronic device.

Only piezoresitive can't be useful for sensor design and also for simulation. A circuit called the readout circuit is require to observe sensor effect as it used in [5]. Bridge circuit in half and quarter configuration can be used for readout circuit design purpose.

In this work, we studied the circuit containing two identical piezoresitors diffused in 100um by a 100um squared diaphragm with one of the element located in the stress-free region and the other one is in the region where it subjected to the induced stress by applied pressure on the deformable region of the diaphragm.

II. Theoretical study of Pizo-Resistive Pressure Sensor

A Si piezoresistor is defined as a layer of rectangular made from a silicon material. Assume that the length (*L*), width (*y*) and thickness (*z*) are parallel to *x*, *y* and *z* axis respectively. The thickness, *z*, of the layer is much smaller than its width, *y*, and its width is smaller than its length, *L* (i.e., *L>>y>>x).*

If the piezoresitor subjected to no stress, resistance between its terminals is

$$R_0 = \rho_0 \frac{L}{yz} \tag{1}$$

And the relative resistance change is

$$\frac{\Delta R_0}{R_0} = \frac{\Delta L}{L} - \frac{\Delta y}{y} - \frac{\Delta z}{z} + \frac{\Delta \rho_0}{\rho_0} \tag{2}$$

For most semiconductors, the stress-induced resistivity change is several orders of magnitude larger than the geometrical change-induced resistance change, so the resistivity change by stress is the determinant factor of the piezoresistivity.[6]

When the piezoresitor subjected to stress, the resistance is expressed in (1) will be modified to

$$R = \frac{L}{yz} \rho' \tag{3}$$

Where ρ' is effective resistivity of the material and it is expressed as second rank tensor. The fractional change in resistance change with respect to R_0 is

$$\frac{\Delta R}{R_0} = \frac{\rho' - \rho_0}{\rho_0} \tag{4}$$

$$\frac{\rho' - \rho}{\rho} = \pi_l T_l + \pi_t T_t + \pi_s T_s \tag{5}$$

Where in (5) π_l is referred to as the longitudinal piezoresistive coefficient, π_t the transversal piezoresistive coefficient and π_s, the shearing piezoresistive coefficient. Similarly, T_l, T_t and T_s are longitudinal, transfers and shearing components of the stress.[7]

Both transfer and longitudinal piezo-resistive coefficient are given by the equations

$$\pi_l = \pi_{11} + 2(\pi_{12} + \pi_{44} - \pi_{11})(l_1^2 m_1^2 + l_1^2 n_1^2 + m_1^2 n_1^2) \text{ and}$$
$$\pi_t = \pi_{12} + 2(\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 l_2^2 + m_1^2 m_2^2 + n_1^2 n_2^2) \tag{6}$$

Where π_{11}, π_{12} and π_{44} are piezoresitive coefficient and l_i, m_i and n_i are direction cosine relative to principal axes. The numerical values of the piezoresistive coefficient are summarized as follows [8]

	π_{11}	π_{12}	π_{44}
n-type	-102.2	53.4	-13.6
p-type	6.6	-1.1	138.1

Now in more general way of expression, we can represent (5) as

$$\frac{\Delta R}{R_0} = \pi_l T_l + \pi_t T_t + \pi_s T_s \qquad (7)$$

The change of piezoresistance is also proportional to its carrier mobility change [9] with as a result of pressure change at the center of the diaphragm which can be expressed as using a similar formula, as:

$$\frac{\Delta R}{R_0} = \frac{\Delta \mu}{\mu_0} = \pi_l T_l + \pi_t T_t + \pi_s T_s \qquad (8)$$

The maximum stress on square diaphragm is observed at the centre of its edge. For transfer component or parallel to edge and longitudinal or perpendicular to the edge is expresses as

$$T_t = 1.02P\frac{a^2}{h^2} \text{ and } T_l = \nu T_t \qquad (9)$$

Where P, a, h and ν are pressure, width, thickness and Poisson ratio of the plate

To validate the above relation (9) with finite element based COMSOL Multiphysics simulation tool, we introduced the following circuit as a sensor circuit or readout circuit instead of half or quarter bridge circuit unlike other type used previously.

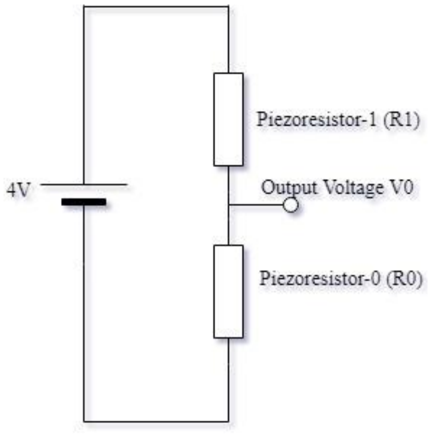

Fig I Circuit for sensor readout

The reason to choose this circuits is related to its simplicity to perform both numerical and analytical computation and to check whether they agree with each other or not. The other reason is to reduce the computational effort of finite element solver of COMSOL Multiphysics simulation tools to get a good result at relatively a short period of time.

From electronic circuit analysis point of view, in the above figure, there are two piezoresistor R1 and R0 connected and they looks simple series combination of resistors. And we choose this technique, because it is impossible to study only single piezoresistor behaviour without including it in circuit as one element.

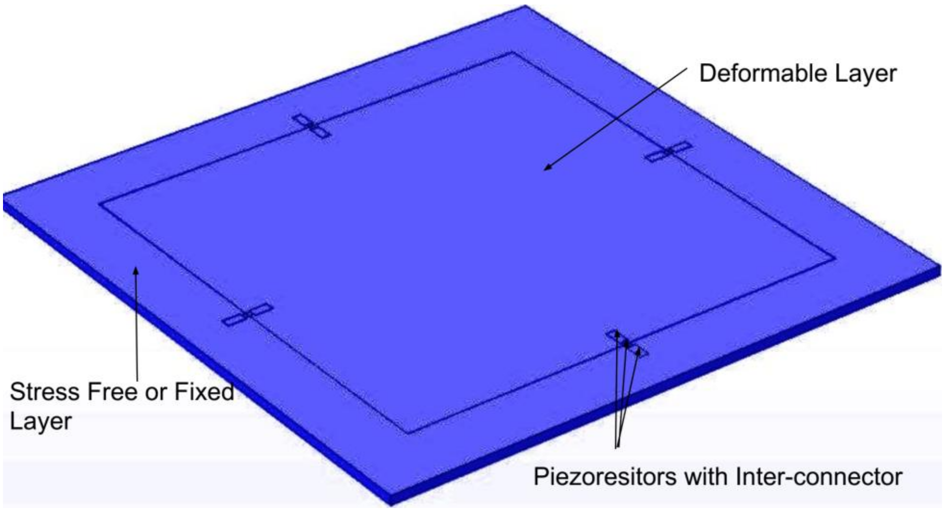

Fig II 3 dimensional view of sensor stricture

The first resistor R0 is located in the stress-free region and the second one in the maximum stress surface region on the deformable plate or silicon diaphragm. By varying the stress across R1 and calculating the output voltage V0, it is possible to study how the mobility of charge carriers' and resistivity affected because of the stress. By following conversional circuit analysis, the output (V_0) and fraction output voltage changes ($\frac{\Delta V}{V}$) are:

$$\frac{\Delta V}{V_0} = \frac{R_1}{R_0} \tag{10}$$

In the last expression based on the variation of the applied pressure, we can drive the further relationship between R_1 and R_0. During the absence of pressure, R_1 and R_0 are equal when the pressure is changed by a certain amount R_1 become R_0 plus a certain change in the magnitude of R_o.

In accordance with the previous done practical observation piezoresistivity effect is occurs predominantly by resistive change rather than geometric parameters change. Therefore, we can conclude that

$$\frac{\Delta V}{V_0} = \frac{\rho_1}{\rho_0} = \frac{\mu_0}{\mu_1} = \frac{R_1}{R_0} \tag{11}$$

After some mathematical arrangement, we can drive the following relationship $\rho_1 = \left(\frac{\rho_0}{V}\right)\Delta V$ help as to calculate the resistivity of stressed Si piezoresistor using known quantities resistivity of unstressed Si at room temperature (ρ_0), biasing voltage (V) and measurable difference between output and biasing voltage (ΔV).

III. Result and discussion

As it is already studied earlier, when the combination of two piezoresitors is exposed to stress induced by applying the pressure at the centre of a diaphragm where the circuits have buried near to the fixed edge, it exhibits a change in carrier mobility. This due to the pizoresistive nature which is the main cause of resistivity change and in turn to change the sensor circuit output voltage.

The design is chosen in such a way that the stress affects the active section of the piezoresitor which is located from the upper surface up to 400nm down in the diaphragm. This is similar to the operation principle of the piezoresistive shell with oriented in a longitudinal direction or perpendicular to one of the fixed edges of the diaphragm. The resistors are diffused in all four sides of the diaphragm to maintain the symmetry of deformation and purpose of clear study. But pressure and output voltage study have done for one of the four resistors to save time and computational resources.

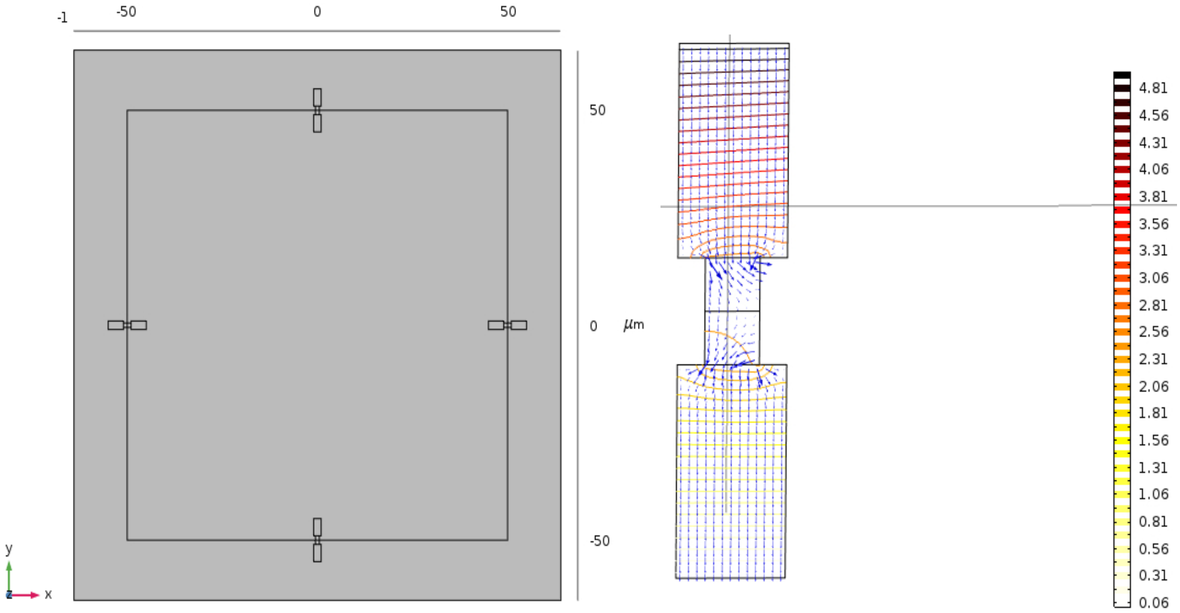

Fig.II The circuit structure and carrier mobility visualization

The dimension of the piezoresistor formed on the diaphragm is 4um by 8um. In the second diagram carrier movement indicated by the blue arrow and potential distribution across the circuit has simulated and studied. The upper piezoresistor is located in the stressed region and the lower one is in fixer or stress-free region. This configuration have done by defining the difference between the larger square that encloses the smaller one and the smaller square itself as a fixed constraint in the physics model. 5V voltage is applied at the top edge of the upper piezoresitor, ground terminal is assigned at the bottom edge of the lower piezoresitor and the output voltage is taken from the right side of the two connectors that link the two pizoresistors.

The deformation corresponds to 1000kPa pressure applied on the surface of the plate is given in the following plot. The maximum stress induced in the sensor is observed exactly in the middle of the fixed edge and agree theoretically calculated value using (9). This shows that in finite element software, the physics model setup has been correctly done.

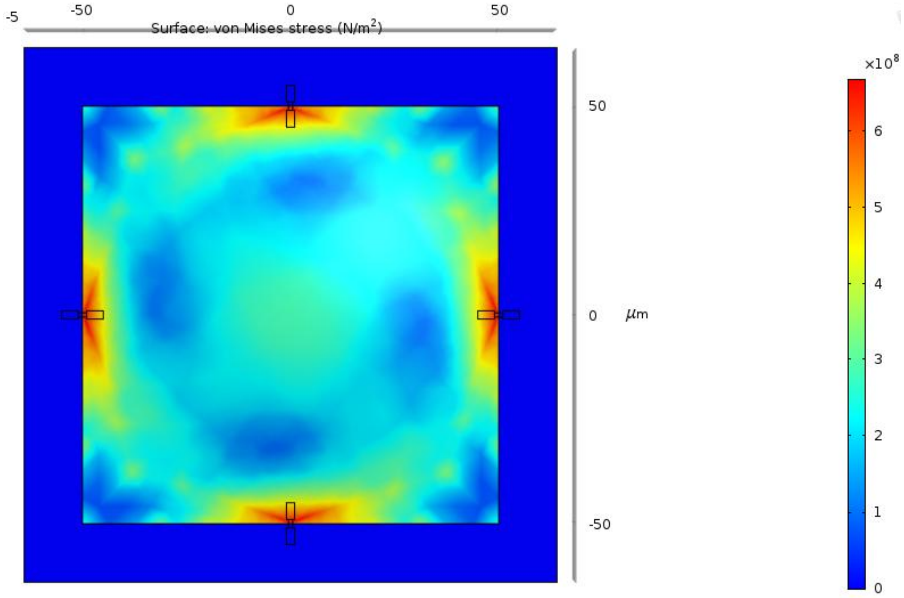

Fig.IV Stress distribution induced by 1000kPa pressure

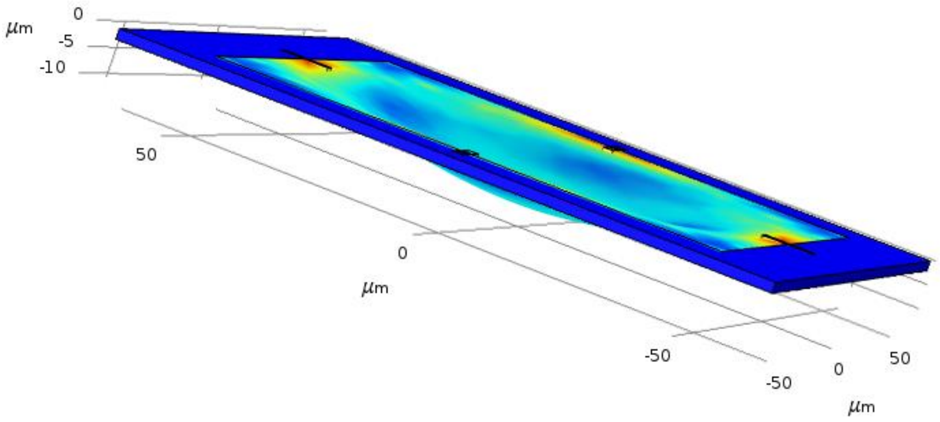

Fig. V Plate deformation due to 1000kPa pressure

As studied the response of the piezoresistor combination output, the output varies from 2500mV to 2548mV. 2500mV which is half of the applied voltage observed when 0kPa or under no pressure condition. In this case, both piezoresistor possesses almost the same electrical behaviour and hence the output obtained in equal to half of the total applied voltage as it expected and linearly rise to 2548mV to which the maximum pressure 1000kPa used. The overall characteristics of the piezoresistive voltage divider circuit are demonstrated below.

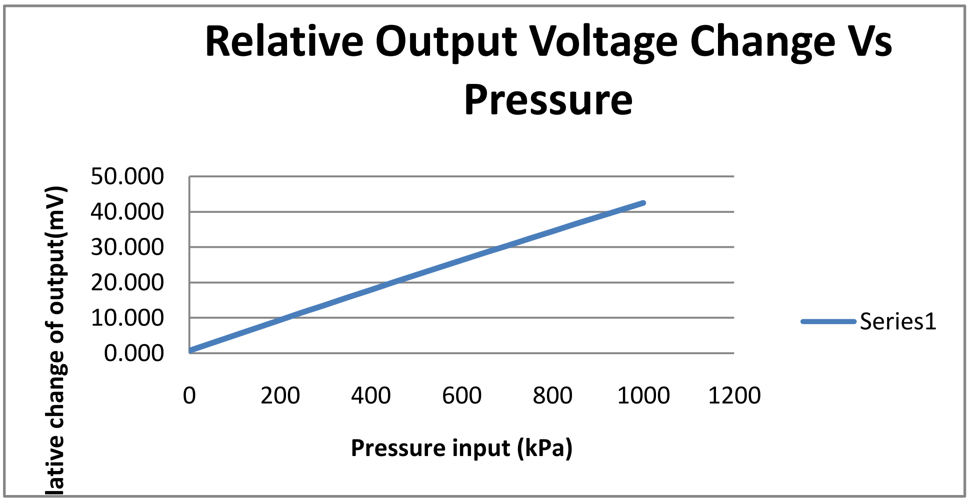

Fig VI Characteristics of the Sensor

In the above diagram relative change of the output is the difference between the actual output voltage and the theoretical reference voltage which is 2.5V or (2500mv). The output rises linearly with applied pressure at the average step value of nearly 2.1mv per 50kPa. This tells as the sensitivity of the sensor circuit is 2.1mV per 50kPa or 4.2mv per 100kPa. On the others, hand the minimum input analog voltage to be converted to a digital signal using 8bit ADC with 5V reference voltage is about 19.5 mV which nearly five times that of 4.2mV. Therefore by using an appropriate matching circuit like instrumental amplifier effect pressure measurement is possible with this sensor readout circuit if it restricted to operate under normal condition.

IV. CONCLUSIONS

The studies of the electrical characteristic drift of p-type Si piezoresistor which is integrated with deformable plate were done with the help of simulation and analytical methods. The simulation output of the designed readout circuit has compared with some analytically evaluated aspects that is the maximum stress value and output voltage under no stress condition. The other objective of the study or compatibility with other interfacing units for further task or pressure measurement has also done with a satisfactory result. In future, we will also use it as an essential input for a compact design suitable to define its PSPICE model solely used for CMOS design and process.

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