Journal of Applied Sciences

ISSN 1812-5654

ANSInet
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Journal of Applied Sciences 11 (8): 1426-1430, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1426.1430

Piezoresistive Pressure Sensor Design, Simulation and Modification using Coventor Ware Software

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Abstract: In this study, the properties of a modified MEMS Piezoresistive (PZR) Pressure Sensor device is investigated. The wheatstone bridge circuit configuration is used to arrange the implanted piezoresistors to measure small resistance change. In the methodology of the study CoventorWare simulation software is used to design and simulate the existing pressure sensor. Modification to improve the pressure sensor's output was then made to the design. The modification made involved the incorporation of additional resistors in parallel with the existing resistors forming the Wheatstone bridge making them eight implanted resistors in all instead of four. Results showed that the modified sensor gives a lower output voltage when the x and y edge offsets are varied with a maximum output voltage of 96 mV compare to the typical sensor maximum output voltage of 185 mV. It also has a wider dynamic range from 0 to 9.5 MPa for pressure measurement as compared to the typical sensor, which has a range from 0 to 4.0 MPa.

Key words: MEMS pressure sensors, piezoresistors, coventor ware simulation software, finite element method

INTRODUCTION

Pressure sensors are the key part of many commercial and industrial systems. Today, pressure sensors constitute the largest market segment of MEMS devices. There are three main types of pressure sensors: the metal strain gauge, piezoresistive (PZR) and capacitive type (Bao, 2005). The piezoresistive strain gauge uses the piezoresistive effect of bonded or formed strain gages to detect strain due to applied pressure. This is the most commonly employed sensing technology for general-purpose pressure measurement. Capacitive pressure sensor uses a diaphragm and pressure cavity to create variable capacitor to detect strain due to applied pressure. Generally, these technologies are applied to low pressures (Absolute, Differential and Gauge) (Elwenspoek and Wiegerink, 2001).

The change in resistance of a strained germanium or silicon filament is larger than that of a metal strain gauge. This effect is called Piezoresistive effect. The sensitivity of Piezoresistive devices is characterized by the gauge factor K given by Thomsen and Ritcher (2005):

$$K = \left(\frac{dR}{R}\right) \Big/ \varepsilon_L \qquad (1)$$

where, dR is the change in resistance due to deformation, R is the initial resistance and ε_L is the strain.

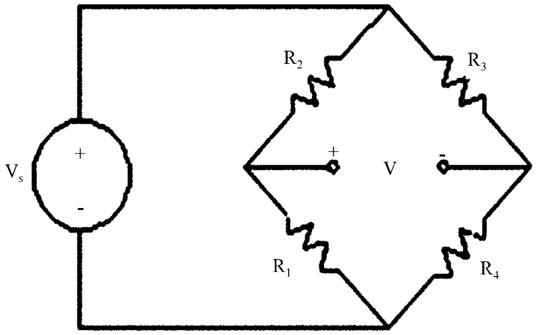

Fig. 1: Wheatstone bridge

The Wheatstone bridge is an electrical circuit for precise comparison of resistances (Chou *et al*., 2009). Figure 1 shows a typical Wheatstone bridge circuit. This Configuration will be implanted on the membrane of the pressure sensor.

The output voltage of the bridge is given by:

$$V_0 = \left[\frac{R_2R_4 - R_1R_3}{(R_3R_4)(R_1R_2)}\right] \times V_S \qquad (2)$$

Normally all resistors are chosen equal to each other, resulting in zero output voltage. For sensor application at least one of the resistors has to be dependent on

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Corresponding Author: John Ojur Dennis, Department of Fundamental and Applied Sciences, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak, Malaysia the measurement. When $R_1 = R_2 = R_3 = R$ and $R_4 = R + \Delta R$, the output voltage can be expressed (http://www.coventor.com):

$$V_0 = \left(\frac{\Delta R / R}{4 + 2\left(\Delta R / R\right)} \right) \times V_S \qquad (3)$$

Equation (3) is used for the diaphragm membrane stress analysis and Eq. 4:

$$\left(\frac{L}{H}\right)^2 < \frac{\sigma_{safe1}}{0.294P} \qquad (4)$$

represents the limitation of L/H ratio with respect to the pressure range for the sensor, where the membrane side length, (L) and the thickness, (H), must be chosen carefully to satisfy for all pressure (P) without breaking the membrane. The ratio will determine the range of pressure of interest.

MATERIALS AND METHODS

CoventorWare simulation software is used in this research to design, simulate and modify the pressure sensor. It consists of three main components: Architect, Designer and Analyzer (http://www.coventor.com). The Architect is used to design the schematic of the Wheatstone bridge that is implanted on the silicon membrane. Designer is used to build the 3D design of the diaphragm. Analyzer is used to analyze the membrane deflection with given pressure. The design steps involved include selecting the substrate layer and wet etch of the backside of the substrate to create a membrane. The diaphragm is 1600 × 1600 μm, the membrane layer 1053 × 1053 μm and the thickness of the membrane is 10 μm. The next process is mesh creation for the device that is essential to allow Analyzer to do the pressure FEM analysis on the model. The analysis is done using CoventorWare mechanical FEM solver MemMech. The analysis simulates the diaphragm deformation under a series of different pressures. The result is used in Architect schematic. The PZR sensor model creation in Architect includes the schematic design of the piezoresistors that follows the Wheatstone bridge arrangement. This model is called the typical sensor in this project. Figure 2 shows the schematic of the PZR sensor circuit in Architect. The op-amp is used to amplify the voltage output of the circuit.

Modifications to the schematic are done in Architect by depositing four additional piezoresistors in parallel with the existing ones making a total of eight. The new schematic of modified sensor is shown in Fig. 3.

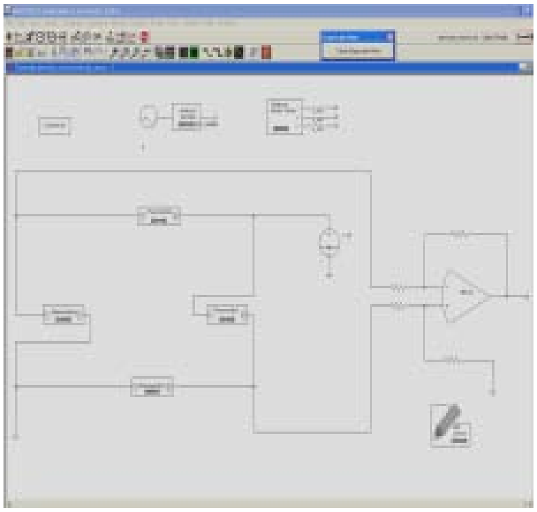

Fig. 2: Pressure sensor schematic in Architect

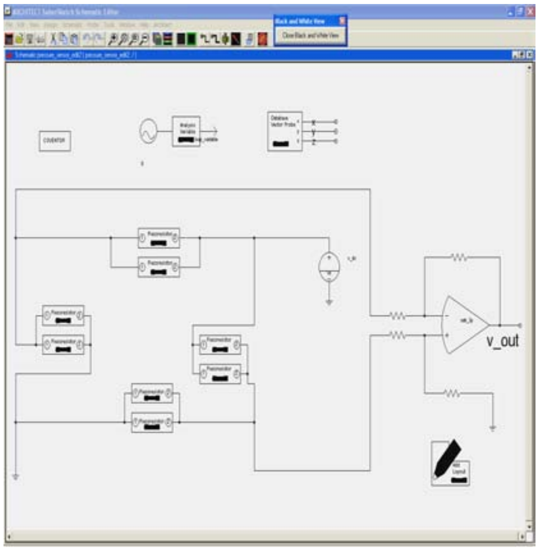

Fig. 3: Modified sensor schematic in Architect

The parameters that are taken into consideration are the y and x edge offset of the piezoresistors placement on the membrane and the effect of variation in the thickness of the piezoresistors.

RESULTS AND DISCUSSION

Figure 4 shows 3-D model creation of the diaphragm with mapped bricks mesh generated in Designer part of the software. There are only two steps involved; the

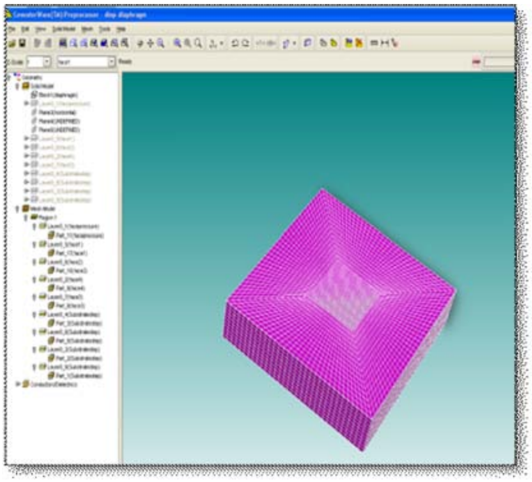

Fig. 4: 3-D diaphragm model with mapped mesh

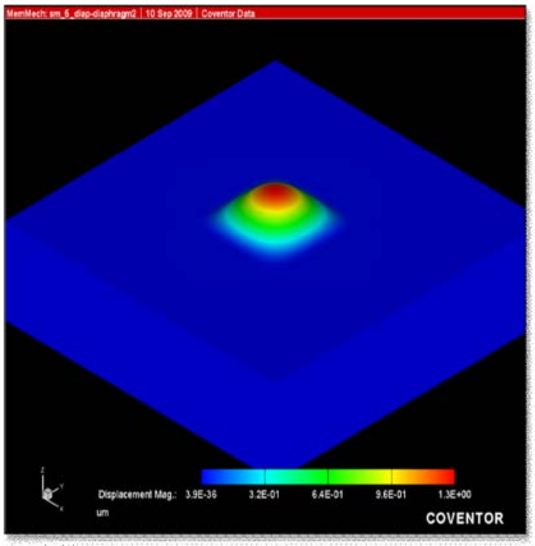

Fig. 5: Membrane displacement with respect to maximum pressure applied

substrate step and the anisotropic backside wet etch. The substrate layer material uses Silicon_100. The wet etch properties are 390 μm depth and -35.3 degree angle. The membrane is designed with width of 500 μm and thickness of 10 μm. This is the typical dimension of membranes for MEMS pressure sensors. The range of initial pressure applied is between 0 to 0.2 MPa. The Highest displacement of the membrane for an applied pressure of 0.2 MPa is at the center of the membrane. The resulting membrane displacement with a maximum displacement of about 1.3 μm is shown in the Fig. 5.

For membrane stress analysis, two different thicknesses of 5 μm and 10 μm for the membrane are used.

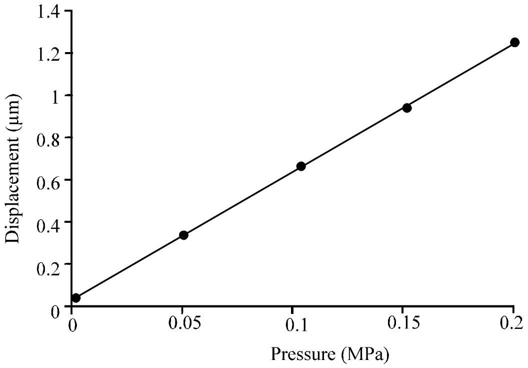

Fig. 6: Displacement vs. pressure for membrane thickness of 10 μm

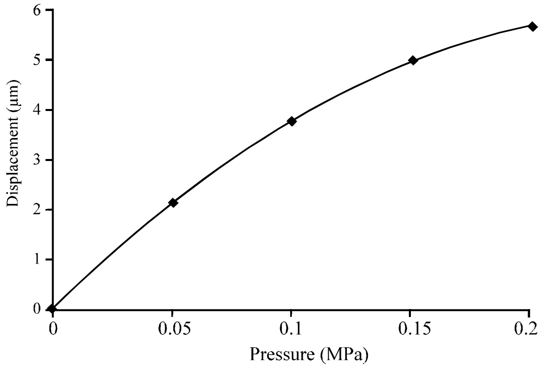

Fig. 7: Displacement vs. pressure for membrane thickness of 5 μm

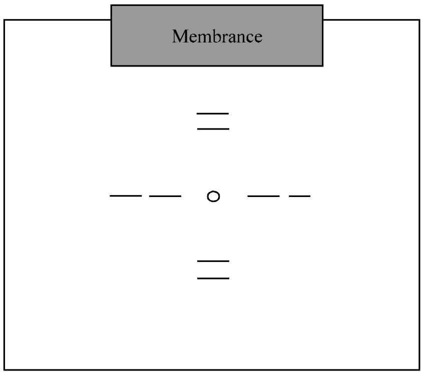

Fig. 8: Piezoresistors placement within the diaphragm membrane

Figure 6 shows the linear dependence of displacement on the applied membrane pressure for the 10 μm thick membrane and Fig. 7 shows the results for a diaphragm with a membrane thickness of 5 μm. The dependence of displacement on pressure is not linear in this case. The displacement of the 5 μm thickness membrane is higher

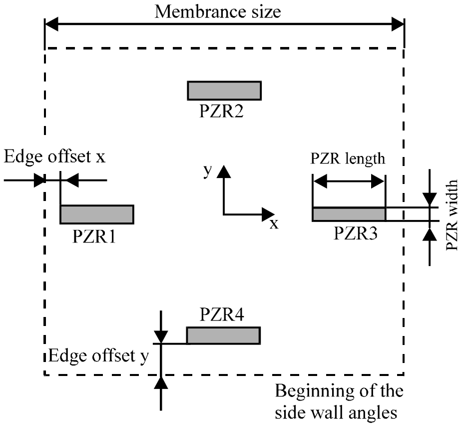

Fig. 9: Edge offset of piesoresistors in the x and y directions on the membrane

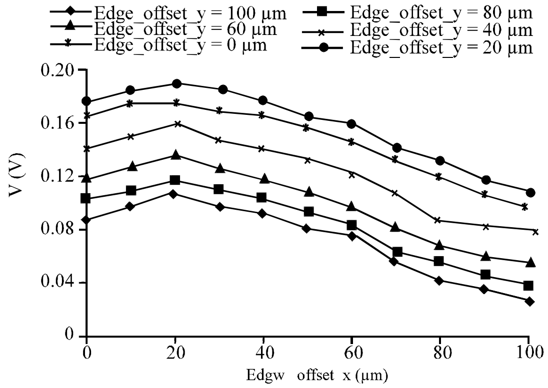

Fig. 10: Output voltage vs. x and y edge offset for typical sensor device

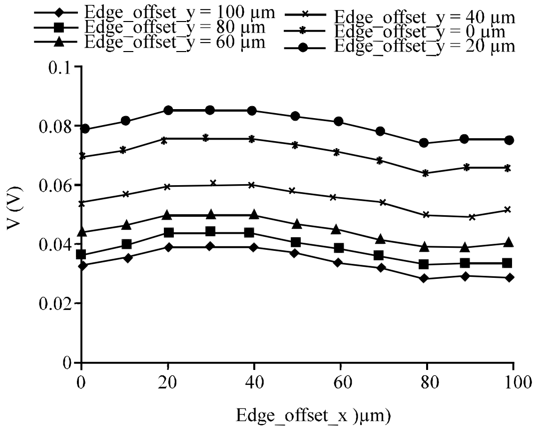

Fig. 11: Output voltage vs. x and y edge offset for the modified sensor device

than that of the 10 µm membrane for the range of pressure from 0.0 to 0.2 MPa. The 5 µm membrane has displacement range from 0.0 to 5.6 µm while the 10 µm membrane has displacement range from 0.0 to 1.3 µm.

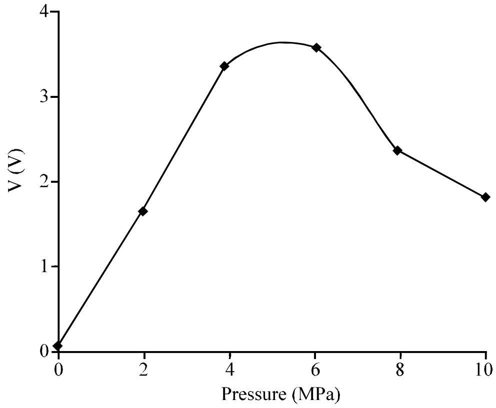

Fig. 12: Output voltage vs. pressure for typical sensor

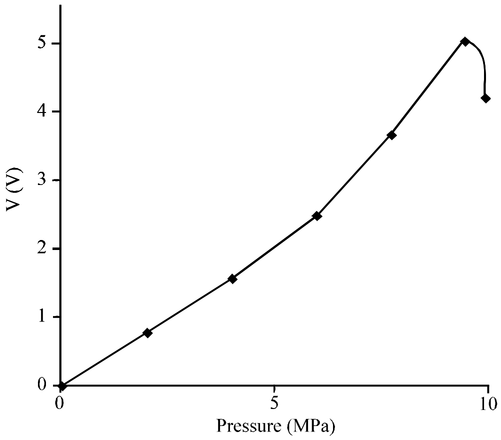

Fig. 13: Output voltage vs. pressure for modified sensor

Figure 8 shows the placement of all eight piezoresistors for the modified membrane. Blue rectangle line is the diaphragm's membrane area and the pink lines are the eight piezoresistors. The small circle in the middle of the membrane shows the origin of the coordinate system.

Figure 9 shows the *x* and *y* edge offset of the piezoresistors. The Vary analysis in Architect varies the *x* and *y* edge offset range from 100 µm to 0 by 20 µm and the output voltage determined. Piezoresistors 1 and 3 are pushed towards the center of the diaphragm and 2 and 4 to the edge of the membrane.

Figure 10 shows the output voltage for the typical sensor. The highest voltage output is when the y edge is 20 µm with a maximum output voltage of 185 mV at the *x* edge offset of 20 µm. The lowest line in the graph is the value of the output voltage when y edge is 100 µm.

Figure 11 shows a similar graph of output voltage versus *x* and *y* edge offset for the modified sensor. The maximum output voltage is when *x* edge offset is between

Table 1: Output voltage comparison between typical and modified pressure sensor

Pressure (MPa)	V_0 typical (V)	V_0 modified (V)
0	0.0	0.0
2	1.6	0.8
4	3.6	1.6
6	3.7	2.5
8	2.4	3.7
10	1.7	4.5

40 and 20 μm and the *y* edge offset is 20 μm. The highest output voltage is 96 mV.

Figure 12 shows output voltage for typical sensor when a pressure in the range of 0 to 10 Mpa is applied. The maximum voltage is 3.65 V at pressure of 5.0 MPa.

Figure 13 shows output voltage for modified pressure sensor when a pressure in the range of 0 to 10 Mpa is applied. The maximum voltage is 5.0 V at pressure of 9.5 Mpa.

Table 1 shows a comparison of the output voltage for the typical and modified sensor when a pressure from 0 to a maximum of 10 MPa is applied.

As observed from Fig. 6 and 7, as the thickness of the pressure sensor membrane is increased its displacement decreases. The lower membrane displacement indicates lower sensitivity to the pressure. On the other hand, a higher membrane thickness results in a linear relationship between the pressure and the displacement which is a desirable characteristic. A comparison between the output voltages as a function of *x* and *y* edge offset for the typical and modified sensor devices shows a lower overall edge offset for the modified device. However, the linear dynamic range and the maximum output voltage as a function of the applied pressure are higher for the modified sensor as compared to the typical indicating a higher sensitivity even though the properties of the piezoresistors used in both sensors are the same.

CONCLUSION

PZR pressure sensors have been designed. The modification of an existing PZR pressure sensor was successfully designed and simulated using CoventorWare simulation software. The modified sensors results in a lower output voltage when the *x* and *y* edge offsets are varied with a maximum output voltage of 96 mV compare to the typical sensor maximum output voltage of 185 mV. It also has a wider dynamic range in the linear region for pressures from 0 to 10 Mpa.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Universiti Teknologi PETRONAS for providing the facilities for carrying out the research work.

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