

Design and analysis of hairpin piezoresistive pressure sensor with improved linearity using square and circular diaphragms

Mohsen Hayati¹ ✉, Morteza Fathipour², Hamid Sherafat Vaziri¹

¹Electrical Engineering Department, Faculty of Engineering, Razi University, Kermanshah 67149, Iran

²MEMS&NEMS LAB, Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

✉ E-mail: Mohsen_hayati@yahoo.com

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A novel structure for piezoresistive pressure sensors is proposed. The structure comprises two piezo-resistors, one mounted on a flat diaphragm and the other mounted outside of the diaphragm so that a hairpin-shaped structure is formed. As a result, one of the piezo-resistors will be affected by the input pressure and the other one will not. Also an inverting Operational Amplifier (OP-AMP) amplifier is utilised. The proposed pressure sensor can be designed using both square diaphragm or circular diaphragm and it has the advantage of higher linearity for input pressure range of 1 MPa in comparison with conventional structures. The value of nonlinearity (NL) is decreased from 0.5515% full-scale (FS), for the conventional sensor, to 0.1138% FS (for the proposed sensor with square diaphragm) and 0.0761% FS (for the proposed sensor with circular diaphragm), which shows an improvement in reducing NL about 80% in square diaphragm and about 86% when circular diaphragm is employed. The proposed structure is analysed and simulated using COMSOL multiphysics software.

1. Introduction: Pressure sensors are one of the most important building blocks in process control systems because of their wide application in sensing mechanical parameters such as pressure, flow etc. Therefore, for decades, different structures have been studied and proposed in order to design a pressure sensor with desirable performance such as: high sensitivity, high linearity and also low-cost and easy fabrication process [1]. Piezoresistive pressure sensors are the most common structures of microelectromechanical systems (MEMS) pressure sensors since they were developed for the first time in 1962 [2]. The key idea is to convert stress into an electrical signal by the use of Wheatstone bridge mounted on a thin square diaphragm, which deflects when the pressure is applied. This technique can also be used in other MEMS sensors such as accelerometers [3]. The advantages of piezoresistive pressure sensors are: small size, easy and low-cost fabrication process, which normally uses bulk micromachining techniques, high sensitivity and also a DC output. By changing the dimensions of diaphragm, various operating range can be reached. Increasing the linearity of the sensor is one of the most important challenges in designing piezoresistive pressure sensors. The ideas behind most of the studies are changing the shape of diaphragms or the geometry and location of piezo-resistors so that the best possible sensitivity and linearity are achieved.

In [4], a piezoresistive pressure sensor using a beam-diaphragm structure is proposed. The idea was to separate the areas of positive and negative stresses. As a result, the maximum nonlinearity (NL) of 0.25% full-scale (FS) was achieved but the proposed structure has the problem of fabrication complexity. Bossed diaphragm structures are another technique in order to increase the sensitivity of the sensor [5]. Size of the sensor can be decreased in this method and the NL will be slightly increased but the fabrication process is still complex in comparison with conventional structures. In [6], a piezoresistive pressure sensor using a beam-membrane structure through etching the cross-beam on a flat diaphragm is proposed. In this Letter, a satisfactory value of 0.19% FS for linearity is achieved. However, the structure suffers from a low sensitivity. Changing the value of impurity concentration is another technique that can change the piezo-resistance effect and also can affect the NL in MEMS piezoresistive pressure sensors [7, 8]. In [9], a piezo-resistive pressure sensor using a round shape diaphragm is proposed. However, in this case, the NL was not improved because

of locating the piezo-resistors in areas with different stress patterns. A conventional piezoresistive pressure sensor using flat diaphragm is reported in [10]. In this Letter, the effect of changing the size of diaphragm on the value of NL is studied and the results show that as the size of diaphragm increases, the value of NL will be increased too. Structured diaphragm with a centre boss and four peninsulas (CBP structure) are used to design and piezoresistive pressure sensors with high sensitivity and high linearity [11, 12]. The proposed Letters have satisfactory values of 0.15% FS and 0.36% FS for linearity, however, these values are for low-pressure ranges (below 5 kPa) and they will definitely increase for higher-input pressure. Indeed, the structures have also the problem of fabrication complexity.

In this Letter, a novel structure for piezoresistive pressure sensor is proposed and simulated. The structure does not utilise Wheatstone bridge circuit, and instead an inverting OP-AMP amplifier is employed. As a result, it is shown that the performance of the proposed novel structure is highly improved in comparison with the conventional structure.

2. Conventional structure: A piezoresistive pressure sensor employs two main parts; a diaphragm in order to convert the input stress into deflection and piezo-resistors to convert the deflection into an electrical signal. Fig. 1 shows the von Mises stress distribution in a square diaphragm.

As it is shown in Fig. 1, the high-stress regions are located at the edges of the diaphragm and so piezo-resistors will be located in these areas. Fig. 2 shows the layout of conventional piezoresistive pressure sensor and its circuit structure is presented in Fig. 3. When pressure is applied, the values of R1 and R4 will decrease and the values of R2 and R3 will increase and so the output voltage will be

$$V_{DD} \left(\frac{R + \Delta R}{2R} - \frac{R - \Delta R}{2R} \right) = V_{DD} \left(\frac{\Delta R}{R} \right) \quad (1)$$

The value of resistance change can be described as a function of input stress as follows:

$$\frac{\Delta R}{R} = \sigma_L \pi_L + \sigma_t \pi_t \quad (2)$$

where π_L and π_t are longitudinal and transverse piezoresistive coefficients and σ_L and σ_t are longitudinal and transverse stresses with respect to the current flow.

When pressure is applied on top surface of the sensor, R1 and R4 experience longitudinal and transverse stresses as follows:

$$\sigma_t = P \frac{a^2}{h^2} \text{ and } \sigma_L = -\nu P \frac{a^2}{h^2} \quad (3)$$

where P is the applied pressure, h is the diaphragm thickness, a is half of the diaphragm side length and ν is Poisson's ratio. So R1 and R4 experience a decrease in resistance given by

$$\frac{\Delta R}{R} = -\pi_t P \frac{a^2}{h^2} (1 - \nu) \quad (4)$$

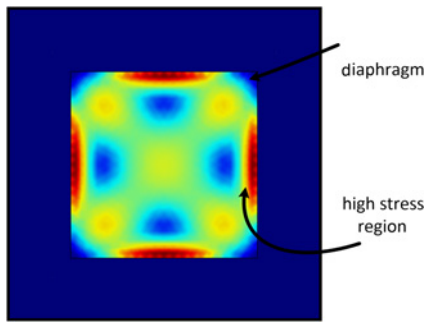


Fig. 1 Distribution of von Mises stress in a square diaphragm

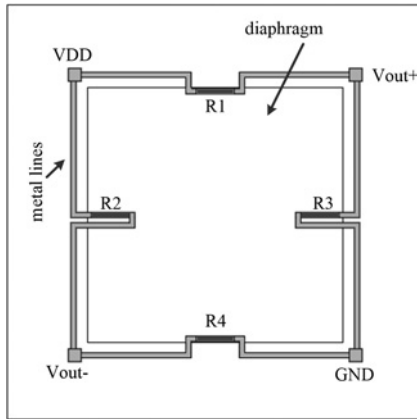


Fig. 2 Layout of conventional piezoresistive pressure sensor

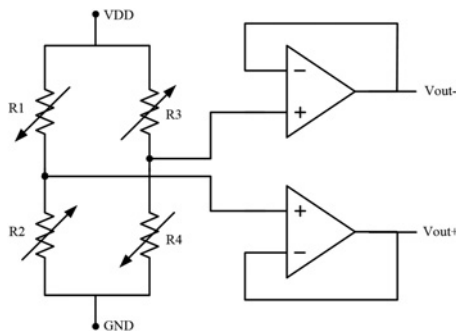


Fig. 3 Circuit structure of piezoresistive pressure sensor

In a same method, R2 and R3 experience longitudinal and transverse stresses as follows:

$$\sigma_L = P \frac{a^2}{h^2} \text{ and } \sigma_t = -\nu P \frac{a^2}{h^2} \quad (5)$$

As a result, they experience an increase in resistance given by

$$\frac{\Delta R}{R} = \pi_L P \frac{a^2}{h^2} (1 - \nu) \quad (6)$$

In single crystal silicon $\langle 100 \rangle$, π_t and π_L have the same value and so the value of sensor output will be

$$V_{out} = V_{DD} \pi_L P \frac{a^2}{h^2} (1 - \nu) \quad (7)$$

In (7), it is assumed that ΔR in all the four piezo-resistors have the same magnitudes. However, in practise, the magnitudes of ΔR in R1 and R4 are different with the magnitudes of ΔR in R2 and R3 because R1 and R4 are both located in the high-stress region while the average longitudinal stresses on R2 and R3 will highly decrease along their length. This can result in NL in the sensor output.

As a case study, a conventional piezoresistive pressure sensor is simulated using a $1000 \mu\text{m} \times 1000 \mu\text{m}$ single crystal silicon diaphragm in order to operate in pressure range of 0–10 bars which is widely used in industrial applications such as measuring the pressure of oil tanks in petrochemical industries. A thin layer of silicon dioxide (SiO_2) is employed to create electrical insulation between diaphragm and the piezo-resistors. Other important parameters of the proposed conventional sensor are mentioned in Table 1.

Fig. 4 shows the output voltage of the proposed conventional sensor for the input pressure 0–10 bar and $V_{DD} = 3 \text{ V}$ using COMSOL simulation software version 5.0.

The simulation procedure is done using 'MEMS module' (piezo-resistivity, domain currents). The areas outside of the diaphragm are assumed as fixed boundaries. Continuity condition is chosen between different types of periodicities between different layers and boundaries of the designed structure.

Table 1 Important parameters of the proposed conventional sensor

diaphragm material	single crystal silicon
diaphragm geometry	$20 \mu\text{m} \times 1000 \mu\text{m} \times 1000 \mu\text{m}$
piezo-resistors material	polycrystalline (lightly doped)
piezo-resistors width and length	$20 \mu\text{m} \times 150 \mu\text{m}$
piezo-resistors thickness	$0.4 \mu\text{m}$
metal lines material	aluminium
SiO_2 thickness	$0.2 \mu\text{m}$

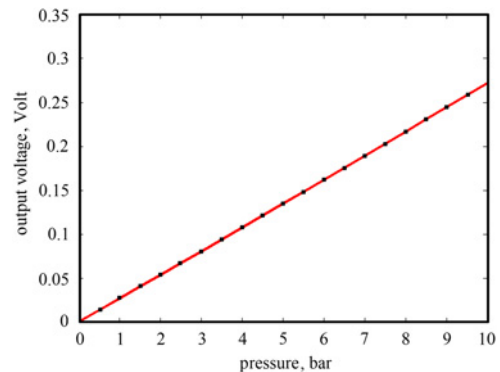


Fig. 4 Output response of the proposed conventional pressure sensor

NL in definition is a deviation of the response curve from the best fit straight line and it is one of the most important parameters to judge about the performance of a pressure sensor. Equation (8) is used to calculate the NL for pressure sensors [13]

$$NL_i(\%FS) = \frac{Vo(p_i) - ((Vo(p_m))/p_m)p_i}{Vo(p_m)} \times 100 \tag{8}$$

where NL_i is the NL for specified input pressures of P_i and P_m is the endpoint input pressure. The NL of the proposed conventional pressure sensor is presented in Fig. 5.

Normally, the maximum value of NL is used to judge about the performance of the sensor and as it is shown in Fig. 5, the maximum magnitude of NL for designed conventional pressure sensor is 0.5515% FS.

3. Hairpin structure: Layout of the proposed hairpin piezoresistive pressure sensor is shown in Fig. 6 and also its circuit structure is presented in Fig. 7. As can be seen in Fig. 6, the proposed structure utilises one piezo-resistor inside the diaphragm and also another piezo-resistor outside of the diaphragm. Despite of conventional structures, the proposed piezoresistive pressure sensor does not employ Wheatstone bridge, and instead an OP-AMP-based inverting amplifier is utilised.

Using electrical relations it can be obtained that

$$\frac{V_{DD}}{R} = \frac{-V_{out}}{R - \Delta R} \tag{9}$$

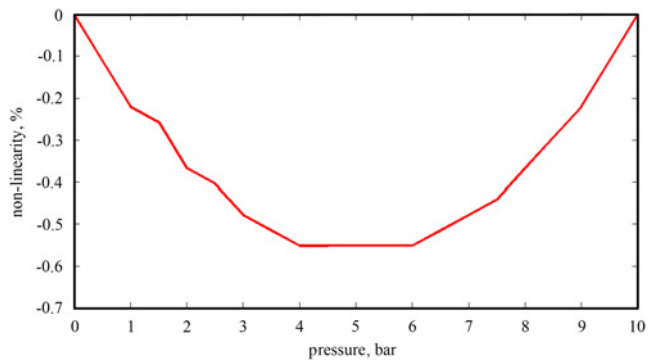


Fig. 5 NL of the proposed conventional pressure sensor

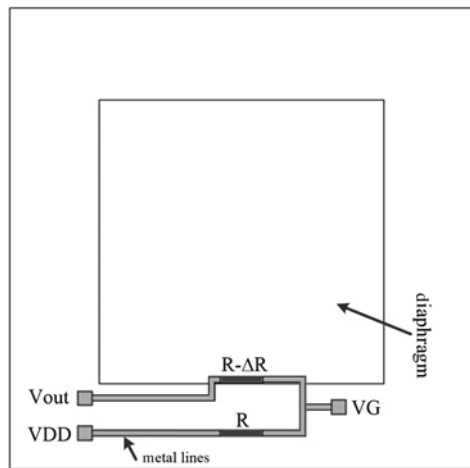


Fig. 6 Layout of the proposed hairpin pressure sensor

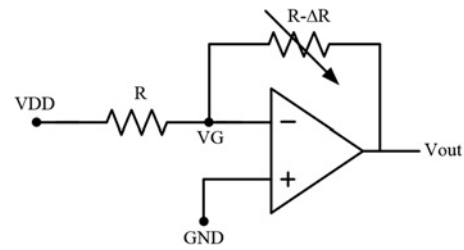


Fig. 7 Circuit structure of the proposed pressure sensor

Moreover so

$$V_{out} = V_{DD} \frac{-(R - \Delta R)}{R} = -V_{DD} + V_{DD} \left(\frac{\Delta R}{R} \right) \tag{10}$$

As can be seen in (10), the output voltage of the proposed sensor contains a constant part of $(-V_{DD})$. This part can be easily neglected in the processing unit, which is normally employed after the sensor or using the circuit shown in Fig. 8, which eliminates the constant part and gives the output voltage which is proportional to input strain (input pressure).

Using (10) and the electrical relations for the circuit shown in Fig. 6, it can be obtained that

$$\frac{V_{DD}}{R} + \frac{V_{out}}{\alpha R} = \frac{V_{DD} - V_{DD}(\Delta R/R)}{R} = V_{DD} \left(\frac{1}{R} - \frac{\Delta R}{R^2} \right) \tag{11}$$

Moreover so

$$V_{out} = -V_{DD} \left(\frac{\Delta R}{R} \right) \tag{12}$$

The minus sign of the output voltage can be neglected in the processing unit or using an inverting amplifier. However, this minus sign can also be used as it will be discussed in the next section.

Fig. 9 shows a comparison between the simulation output responses of the novel piezoresistive pressure sensor and the conventional structure using the same parameters value as shown in Table 1.

As it is expected, the novel pressure sensor has almost the same sensitivity in comparison with the conventional structure.

4. NL in the novel structure: Overall NL in piezoresistive pressure sensor contains three important factors: structural NL, piezoresistive NL and bridge NL [14].

Structural NL refers to diaphragm structure and has three major factors: geometrical NL, material NL and contact NL. Geometrical NL refers to thickness of the diaphragm and it occurs when there is a large displacement under a certain input pressure. Obviously, as the thickness of a diaphragm becomes more, the

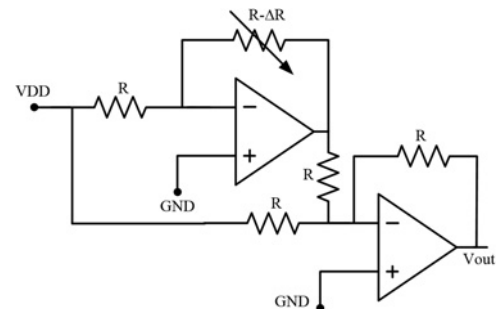


Fig. 8 Suggested circuit structure for the proposed sensor

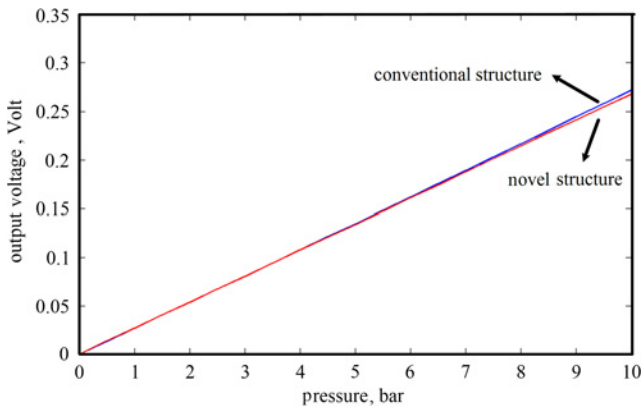


Fig. 9 Comparison between the output responses of the novel piezoresistive pressure sensor and the conventional structure

amount of displacement will be less and so geometrical NL can be neglected for thick diaphragms. However, the sensitivity will be decreased by increasing the diaphragm thickness. Material NL refers to bending and residual stresses in the diaphragm, which is dependent on the diaphragm material and its stress-strain relation. Contact NL refers to change in boundary conditions, and for thin diaphragms it can be neglected.

As it is mentioned in (2), π_L and π_t are longitudinal and transverse piezoresistive coefficients. It is assumed that the values of these coefficients are constants for different applied stresses. While in practise, their value will change lightly for high stresses which cause piezoresistive NL. Bridge NL is related to the structure of the Wheatstone bridge. In a conventional piezoresistive pressure sensor, which uses Wheatstone bridge, it is assumed that the magnitude of $\Delta R/R$ is the same in both longitudinal and transverse resistors (however, they have opposite signs). While in practise, there is a difference which can cause NL in the sensor response. Using electrical relations for the conventional piezoresistive pressure sensors, it can be found that

$$V_{out} = V_{DD} \frac{(\Delta R/R)_L - (\Delta R/R)_t}{2 + (\Delta R/R)_L + (\Delta R/R)_t} \quad (13)$$

Assuming

$$\left(\frac{\Delta R}{R}\right)_L = aP \text{ and } \left(\frac{\Delta R}{R}\right)_t = -bP$$

it can be concluded that

$$V_{out} = V_{DD} \frac{(a+b)P}{2 + (a-b)P} \quad (14)$$

Equation (14) shows that when $a \neq b$, there will be an NL in the relationship between the output voltage and the input pressure.

Since the proposed novel structure does not utilise Wheatstone bridge structure, so it does not experience the bridge NL, which can improve its performance. Fig. 10 shows a comparison between the NLs of the proposed novel pressure sensor and the proposed conventional sensor.

As can be seen in Fig. 10, the value of NL is highly decreased from 0.5515% FS to 0.1138% FS, which shows a notable improvement in the performance of piezoresistive pressure sensors. Other advantage of the proposed structure is that it occupies only one side of the diaphragm and so it is possible to employ four pressure sensors simultaneously as it is shown in Fig. 11.

The output voltages of the four sensors can be added using an OP-AMP direct voltage adder which is shown Fig. 12.

Using electrical relations for the circuit shown in Fig. 12, the output will be

$$V_{out} = -(V_{out1} + V_{out2} + V_{out3} + V_{out4}) \quad (15)$$

By putting (12) into (15), the final output of the structure will be

$$V_{out} = 4 V_{DD} \left(\frac{\Delta R}{R}\right) \quad (16)$$

Equation (16) shows that the output of the sensor can be increased up to four times without changing the input DC supply (V_{DD}), which means the sensitivity of the proposed novel piezoresistive

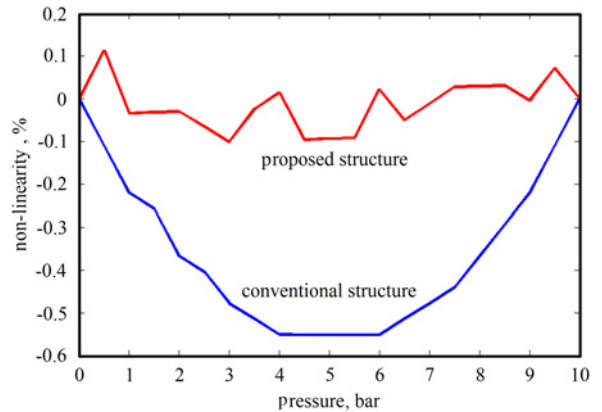


Fig. 10 Comparison between the NLs of the proposed novel pressure sensor and the proposed conventional sensor

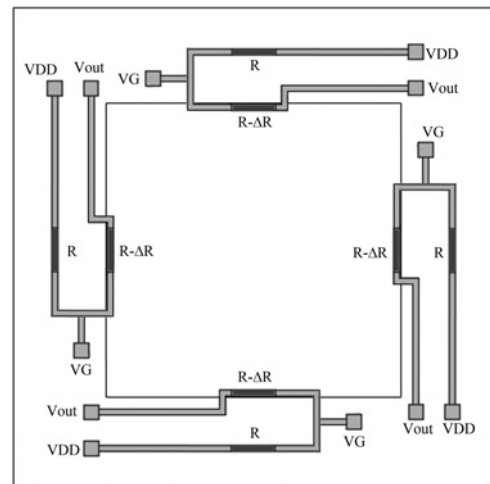


Fig. 11 Structure which contains four hairpin pressure sensors

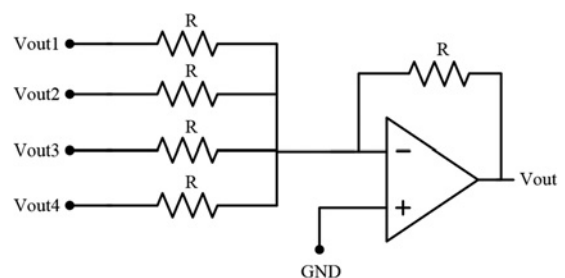


Fig. 12 OP-AMP direct adder circuit

pressure sensor is four times higher than the conventional piezoresistive pressure sensor.

5. Circular diaphragm structure: In the structure of a piezoresistive pressure sensor, it is important to place the piezo-resistors in the high-stress region. When a square diaphragm is utilised, the stress pattern is not uniform in the high-stress region and it has the maximum amount at the middle of edges and then it will slightly decrease. This can also cause NL and so it is necessary to reduce the length of piezo-resistors as much as possible [15]. However, reducing the length of piezo-resistors will increase the fabrication complexity. Since the proposed structure utilises only one piezo-resistor inside the diaphragm, it is also possible to employ circular diaphragm structure. The advantage of using circular diaphragm is that the stress pattern in high-stress region is almost uniform, which can reduce the NL and also there is no need to reduce the length of piezo-resistors. Fig. 13 shows the distribution of stress in a circular diaphragm.

The structure of the proposed piezoresistive pressure sensor with circular diaphragm is shown in Fig. 14.

In the structure shown in Fig. 14, the two piezo-resistors have the same geometry and so the same value of resistance. Important geometrical parameters of the proposed structure with circular diaphragm are mentioned in Table 2.

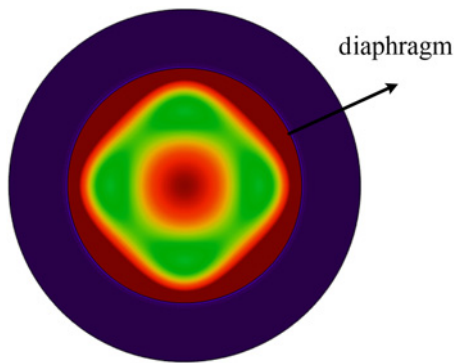


Fig. 13 Distribution of stress in a circular diaphragm

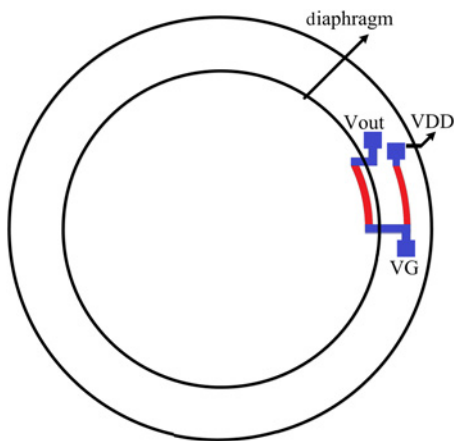


Fig. 14 Structure of proposed hairpin piezoresistive pressure sensor with circular diaphragm

Table 2 Important geometrical parameters of the proposed structure with circular diaphragm

diaphragm radius	565 μm
diaphragm thickness	20 μm
piezo-resistors thickness	0.4 μm
SiO ₂ thickness	0.2 μm

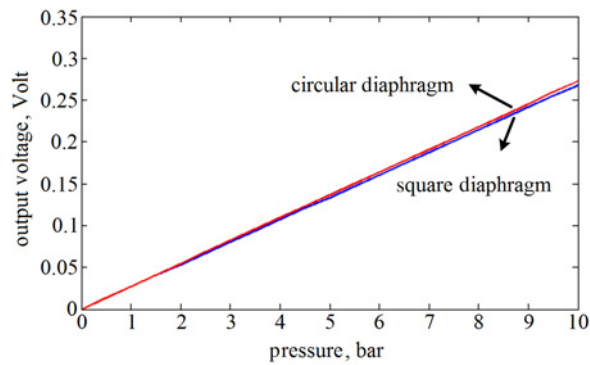


Fig. 15 Comparison between the output voltages of the proposed novel pressure sensors with square and circular diaphragms

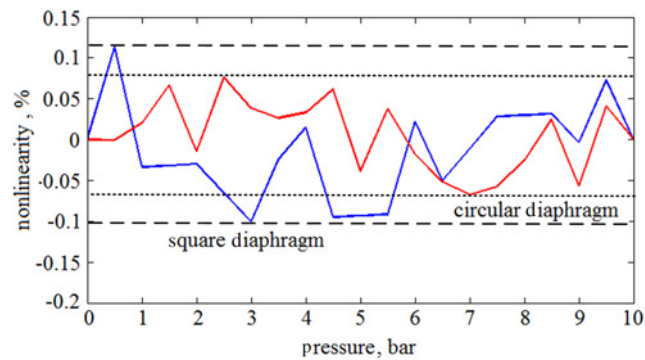


Fig. 16 Comparison between the NLs of the proposed novel pressure sensors with square and circular diaphragms

Fig. 15 shows a comparison between the output voltage of the both proposed novel pressure sensors with square and circular diaphragms. Moreover, a comparison between the NL of the sensors is illustrated in Fig. 16.

In Fig. 16, it is obvious that the value of NL in the proposed sensor with circular diaphragm is about 33% lower than the sensor with square diaphragm (the value of NL is reduced from 0.1138 to 0.0761%).

6. Effect of temperature changing on the sensitivity of hairpin structure: As mentioned, the main idea behind piezoresistive pressure sensors is the change in the value of resistance when the pressure is applied. However, as it is well known, the value of resistance will also change as temperature changes. This can cause an error in the calculation of the input pressure.

Considering the temperature change for the structure shown in Fig. 7, it can be obtained that

$$V_{\text{out}} = -V_{\text{DD}} \frac{R + \Delta R_T - \Delta R}{R + \Delta R_T} \tag{17}$$

where ΔR_T is

$$\Delta R_T = R(\alpha \Delta T) \tag{18}$$

In (18), α is the temperature coefficient of resistivity (TCR) of the piezo-resistors and ΔT is the amount of temperature change.

By putting (18) into (17)

$$V_{\text{out}} = -V_{\text{DD}} + V_{\text{DD}} \frac{\Delta R}{R(1 + \alpha \Delta T)} \tag{19}$$

Moreover, so by neglecting the constant part, the sensitivity of the proposed sensor will be

$$S = \frac{V_{\text{out}}}{V_{\text{DD}}} = \frac{\Delta R}{R(1 + \alpha \Delta T)} \tag{20}$$

Considering $\alpha\Delta T \ll 1$, (20) can be written as

$$S = \frac{V_{\text{out}}}{V_{\text{DD}}} = \frac{\Delta R}{R}(1 - \alpha\Delta T) \quad (21)$$

Using the same method for the conventional structure (1), the sensitivity as a function of temperature change for the conventional piezoresistive pressure sensor is also as the same as (21) and this shows that both the conventional sensor and the proposed hairpin structure have the same TCS.

Equation (21) shows that considering $\alpha = 0.001\text{ }^{\circ}\text{C}^{-1}$ and $\Delta T = 50\text{ }^{\circ}\text{C}$, the value of sensitivity of the sensor will be decreased about 5%.

7 Conclusion: Novel piezoresistive pressure sensor with hairpin structure is analysed and simulated in this Letter. The proposed structure employs two piezo-resistors and an inverting OP-AMP amplifier and it can be implemented in both square and circular diaphragms. It is shown that the proposed structure has a highly improved linearity, because of eliminating the bridge NL. As a case study, a pressure sensor with pressure range of 0–10 bars is designed which is widely used in petrochemical industries for measuring oil tanks pressures. The designed pressure sensor is then simulated using COMSOL multiphysics software. The results show that the value of NL is decreased from 0.5515% for the conventional sensor to 0.1138 and 0.0761% for the proposed sensor with square diaphragm and circular diaphragm, respectively. The proposed piezoresistive pressure sensor with such a desirable performance can be used in modern industrial systems to answer the demands for high-performance measuring devices.

8 References

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