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TECHNICAL PAPER

Sensitivity enhancement and temperature compatibility of graphene piezoresistive MEMS pressure sensor

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Abstract

MEMS pressure sensor has shown a remarkable change in revenue collection during the year 2018. Due to recent growth in smart microsystem technology for automation systems, demand has grown substantially for sensors. High sensitivity, flexibility, miniaturization and bulk production are some of the key factors of a pressure sensor in achieving new heights in the MEMS market. In this paper, Graphene piezo resistive material has been analysed for pressure sensing elements and compared with Polysilicon in terms of sensitivity and sensor performance degradation at different temperature. MEMS pressure sensors using Polysilicon and Graphene piezo resistive materials were simulated on silicon (100) substrate by COMSOL Multiphysics 5.3a version. The simulation result shows that at room temperature polysilicon pressure sensor performs well with pressure sensitivity of 3.81 mV/psi as well as it is found that graphene pressure sensor also shows better results at room temperature showing a pressure sensitivity of 3.98 mV/psi. As on frequently increasing the temperature it is noticed that polysilicon pressure sensitivity degrades with a factor of 0.64 mV/psi. However, graphene pressure sensor shows very less variation in sensitivity at higher temperature. Although it shows a small increment of 0.02 mV/psi in the pressure sensitivity. This analysis opens the path to utilise the graphene pressure sensor at high temperature.

1 Introduction

Silicon is the most widely used semiconductor for the fabrication of solid state electronics. According to the market survey MEMS pressure sensor contribute 17.7% of the total revenue collection (Patra et al. 2018). Average costing of the sensor depends upon the fabrication and packaging type (Singh et al. 2015). Various sensing methods are utilised for sensing application. Piezoresistive sensing is used for dynamic range, high resolution, and high sensitivity. Conventional piezoresistive pressure sensor uses polysilicon as a sensing element which is configure in wheat stone bridge configuration (Malhaire and Barbier 2003). Qu et al. (1998) reported a polysilicon pressure sensor with very less pressure sensitivity of 0.12 mv/psi from their obtained results (Qu et al. 1998). Xiaowei et al. (1998) simulate a polysilicon pressure sensor with having pressure sensitivity of 0.20 mv/psi. Many researcher are constantly working on polysilicon pressure sensor with having an objective of increasing the sensitivity of the pressure sensor. An increment in sensitivity is shown from the past 10 years. Malhaire and Barbier (2003) designed a polysilion on insulator with having a pressure sensitivity of 3.44 mv/psi (Malhaire and Barbier 2003). However, at higher temperature range the sensitivity of the polysilicon pressure sensor gets degraded which makes is difficult to use at a wide working range of temperature. Graphene is a carbon allotropoe which has been utilised to design and develop a pressure sensor which shows better compatibility between the temperature and sensitivity (Zhao et al. 2013).

Many researchers are working on graphene which has good piezoresistive properties along with an advantage of good temperature compatibility. Chen et al. (2011) proposed a graphene strain sensor to characterize its sensitivity on application of mechanical bending strain. Obtained results shows high gauge factor of approximately 150 that was experimentally measured with having electrical resistance of 102 kΩ which satisfy three important keyword

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such as low cost, low contamination and easy processing method (Chen et al. 2011). Zhu et al. (2013) proposed a strain sensor of CVD graphene with SiN as structural element of the sensor showing good linearity at 500 mbar, and high sensitivity of 0.58 mV/psi (Zhu et al. 2013). Bae et al. (2013) proposed a strain sensor used for bio application based on CVD graphene to analyze the piezo-resistive property under tensile strain up to 7.1% showing high sensitivity and good transparency of 75–80% with approximately 10 layers (Bae et al. 2013). Bhatt et al. (2018) proposed a sensor in which cellulose paper was used as a substrate for the realization of flexible strain sensors as Graphene can be easily deposited on paper substrate which is advantageous from the point of view of portability, cost effectiveness, environment friendly and exhibits piezo-resistive effect. The obtained gauge factor is 20.47 and concluded that gauge factor (GF) decreases with increase in number of layers due to distribution of applied stress more evenly among all the layers (Bhatt et al. 2018). Manjunath et al. (2018) proposed a pressure sensor having pressure range of 0–20 Bar with sensitivity of 2.29 Ω/Bar and gauge factor of 112. This pressure sensor utilize reduced graphene oxide as a sensing membrane on stainless steel substrate work in corrective environment with effectless presence of temperature (Manjunath et al. 2018).

Graphene piezoresistive properties plays the major role to enhance the sensitivity of the pressure sensor (Zhao et al. 2013). In this Paper, the behavior of MEMS pressure sensor in terms high sensitivity and temperature compatibility of Polysilicon and Graphene Piezoresitive pressure sensor were compared using COMSOL Multiphysics software 5.3a. The simulation result shows graphene pressure sensor is more sensitive as compared to the polysilicon sensor in lieu of maintaining the temperature compatibility.

2 Mathematical modelling and formulation

The sensing element of the pressure sensor plays a vital role in sensing of the applied pressure and to convert it in the form of change in resistance and further in output voltage. Piezo-resistivity is the property of material which is widely used by sensor. The electrical resistance of the sensing element varies corresponding to response of the mechanical stress. Due to deformation in the sensing element, there is a change in potential distribution which leads to change in carrier mobility and which results in change in resistance of the element (Meti et al. 2016; Sujit et al. 2018). The resistivity depends on the 6 × 6 piezo-resistive coefficient matrix and the sensor tensor. Due to crystalline nature of graphene only 3 non zero independent component (π11, π12, π44) in the piezo-resistive coefficient matrix as shown below

$$\pi = \begin{bmatrix} \pi 11 & \pi 12 & \pi 12 & 0 & 0 & 0 \\ \pi 12 & \pi 11 & \pi 12 & 0 & 0 & 0 \\ \pi 12 & \pi 12 & \pi 11 & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi 44 & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi 44 & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi 44 \end{bmatrix}. \tag{1}$$

The simplified expression for resistance change in a piezo-resistor is given by Eq. (2)

$$\frac{\Delta R}{R} = \pi l \sigma l + \pi t \sigma t, \tag{2}$$

where πt and πl are the transverse and longitudinal piezo-resistive coefficients and σt and σl are the transverse and longitudinal stresses on the surface of the piezo-resistors. Using graphene as a sensing element the piezo-resistive coupling matrix is defined as Eq. (3)

$$\pi = \begin{bmatrix} 66.17e^{-11} & -30.65e^{-11} & -30.65e^{-11} & 0 & 0 & 0 \\ -30.65e^{-11} & 66.17e^{-11} & -30.65e^{-11} & 0 & 0 & 0 \\ -30.65e^{-11} & -30.65e^{-11} & 66.17e^{-11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 90.35e^{-11} & 0 & 0 \\ 0 & 0 & 0 & 0 & 90.35e^{-11} & 0 \\ 0 & 0 & 0 & 0 & 0 & 90.35e^{-11} \end{bmatrix}. \tag{3}$$

3 Design parameter consideration

Pressure sensor is designed on the principle of wheat-stone bridge. Each arms of the wheat-stone bridge consists of piezo resistors whose parameters are optimised in according to material properties, placement of resistor, and shape of resistor (dimensions of piezo resistors) (Tian et al. 2015).

As shown in Fig. 1, four resistance are connected in bridge configuration. The bridge is biased between the points A and C and the output potential difference is calculated at point D and B for the equilibrium condition, which is defined as Eq. (4)

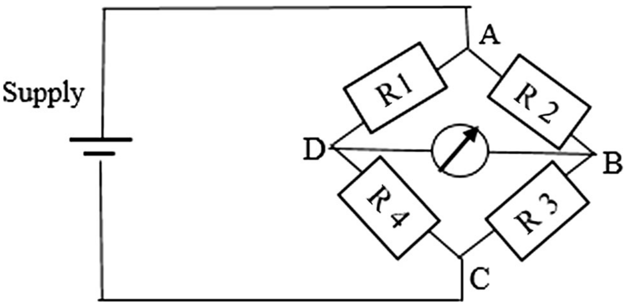

Fig. 1 Wheat stone bridge configuration

$$\frac{R1}{R2} = \frac{R4}{R3}. \tag{4}$$

On the application of the applied pressure, the potential difference is generated at the point D and B that defines the state of unbalancing of the bridge which is defined as

$$\frac{R1}{R2} \neq \frac{R4}{R3}. \tag{5}$$

The potential difference between the points D and B is given by Eq. (6)

$$V_{out} = V_{in}\left[\frac{R1}{R1 + R2} - \frac{R4}{R4 + R3}\right]. \tag{6}$$

In order to maximize the output voltage the ratio of R1, R2, R3 and R4 have to be adjusted. The design process also involves the optimum combination of sensitivity and linearity which is primarily defined by the dimensions of the diaphragm which includes diameter and thickness and also some assumptions such as uniform thickness of diaphragm so that applied pressure can be evenly distributed, infinitely fixed clamping around the membrane periphery, high young modulus of elasticity, negligible stiffening effects. On the application of pressure on the diaphragm, it shows deflection which is directly proportional to the output voltage (mV). The radial and tangential strains at the centre of the diaphragm are identical in ideal stage and can be expressed as

$$\sigma_{Radial} = \sigma_{Tangetial} = \frac{3PR^2(1 - v)}{8t^2Y}, \tag{7}$$

where P—applied pressure, R—radius of the diaphragm, t—thickness of the diaphragm, Y—Young modulus of elasticity, v—Poisson's ratio

The deflection of the diaphragm at the centre must be less than the thickness of the diaphragm for maintaining the linearity of 0.3%. Maintaining these design consideration many researchers get the optimum results of sensitivity. Singh et al. (2015) reported the cost effect e- beam physical vapor deposited based polysilicon piezo-resistive pressure sensor. The dimensions are optimised to get maximum functional devices on one single wafer with higher sensitivity.

The geometry of the pressure sensor is shown in Fig. 2 which clearly defines the top view of the pressure sensor and the bottom view of the diaphragm. The dimension of the pressure sensor for the current study in taken from the aforesaid study (Singh et al. 2015). The device dimension are taken as 4 mm × 4 mm of device size, diaphragm size is 2 mm × 2 mm, diaphragm thickness is 50 µm wafer thickness is 280 µm length of the resistor lines is 400 µm width of resistor lines is 10 µm width of contact lines is 20 µm and contact pad size is 200 µm × 200 µm (Singh et al. 2015). The model of the specified dimension is simulated in COMSOL Multiphysics 5.3 a version. Analytical study of piezo-resistive properties of polysilicon and graphene is studied for a pressure range of 10–100 psi and temperature range of − 10 to 50 °C.

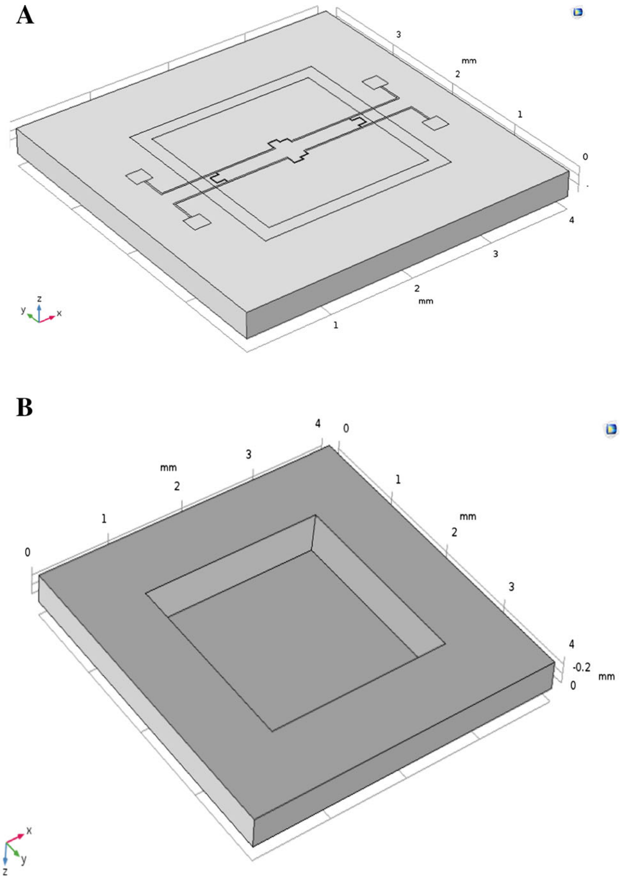

Fig. 2 Geometry of the pressure sensor: A The top layer contains the piezoresistor and metal lines along with contacts. B Bottom Part of the diaphragm of pressure sensor

4 Piezoresitive sensing material considerations

Piezo-resistive sensing materials plays a very important role in the functioning of the pressure sensor. Sensitivity is directly affected by the applied pressure and temperature variation. Here in this paper graphene is introduced as a sensing material for the sensing element due to its unique properties (Lloyd-Hughes and Jeon 2012). The pressure sensitivity and the thermal stresses due to thermal expansion of the diaphragm were taken into consideration (Sarkar et al. 2017).

The values are calculated for a working range of 10–100 psi and temperature range of − 10 to 50 °C. Using COMSOL 5.3a version the properties for ploy silicon is analysed for polysilicon piezo-resistors. It is noticed that the sensitivity of the polysilicon pressure sensor is better at low temperature but on gradual increment in temperature the sensitivity of polysilicon pressure sensor starts reducing due to effect on temperature on polysilicon which shows maximum stress generated of the order of 10^4. To see the effect of temperature on Graphene pressure sensor, same model is simulated with graphene piezo-resistive resistors and it is noticed that due to graphene piezo-resistive properties, the obtained result shows maximum stress generated of the order of 10^8 at the graphene piezo-resistors and that definitely increases the sensitivity of the sensor.

Graphene is also temperature sensitive, but then also it shows better sensitivity as compared to polysilicon in low temperature to high temperature. This property of graphene can be used to make a temperature sensor integrated into the pressure sensor. Hence, this opens up its viability of multi-sensor integration onto a single chip (Shi et al. 2018). Using Polysilicon as a piezo-resistors is also simulated, the obtained result shows the stress variation of the order of 10^4. Simulation Results are shown below.

From the Figs. 3 and 4, it is noticed that using the graphene as a piezo-resistor the simulation results are better as compared to the polysilicon in the terms of pressure sensitivity.

5 Result and discussions

Simulation of the Graphene pressure sensor revels the effect of input parameters on the piezo resistors. Input pressure range of 10–100 psi is considered as the boundary load for finite element analysis. This pressure range covers varied application in multiple fields such as biomedical instruments, process control systems, aerospace applications etc. Analysing the effect of temperature on the performance of the pressure sensor is also carried out for compatibility of the sensor in different working environment. As from the literature review it is revealed that polysilicon shows good results at room temperature but on increasing the temperature above room temperature the performance of the polysilicon starts reducing. Graphene due to its high temperature conductivity shows better temperature compatibility in varied temperature range including room temperature and above. At freezing temperature also graphene proves to be better sensing material as compared to polysilicon. As shown in Fig. 5 at different temperature of − 10 °C, 10 °C, 30 °C, 50 °C, graphene pressure sensor shows better performance in terms of sensitivity and temperature compatibility as compared to polysilicon pressure sensor.

Using polysilicon as a material for piezo resistors at low temperature − 10 °C and pressure range from 10 to 100 psi the sensitivity of the sensor 3.75 mV/psi. But using graphene as a piezoresistive material the sensitivity of the pressure sensor becomes 3.91 mV/psi. On increasing the temperature from freezing point to 10 °C, Graphene pressure sensor shows sensitivity of 3.95 mV/psi and polysilicon pressure sensor shows sensitivity of 3.79 mV/psi. Similarly for 30 °C Graphene pressure sensitivity is 3.98 mV/psi and polysilicon pressure sensitivity is 3.81 mV/psi. Here it is noticed that, at room temperature polysilicon pressure sensor shows better results as

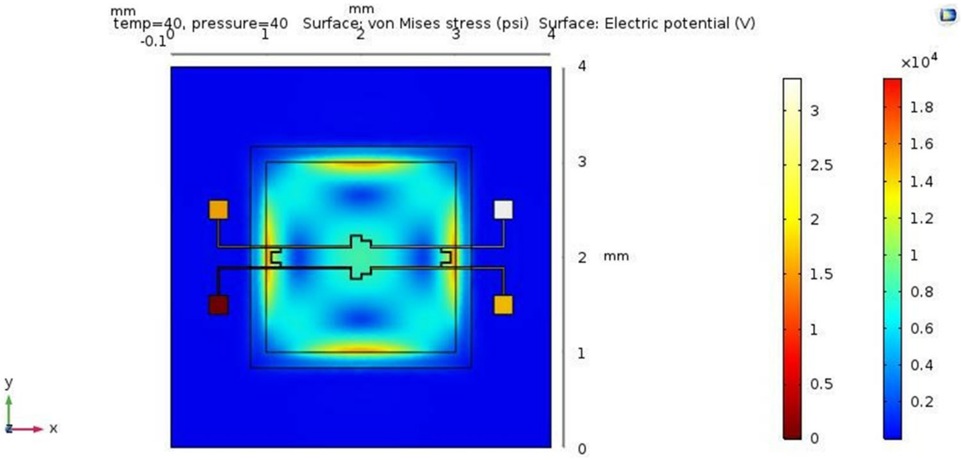

Fig. 3 Simulation result of polysilicon piezo-resistive pressure sensor

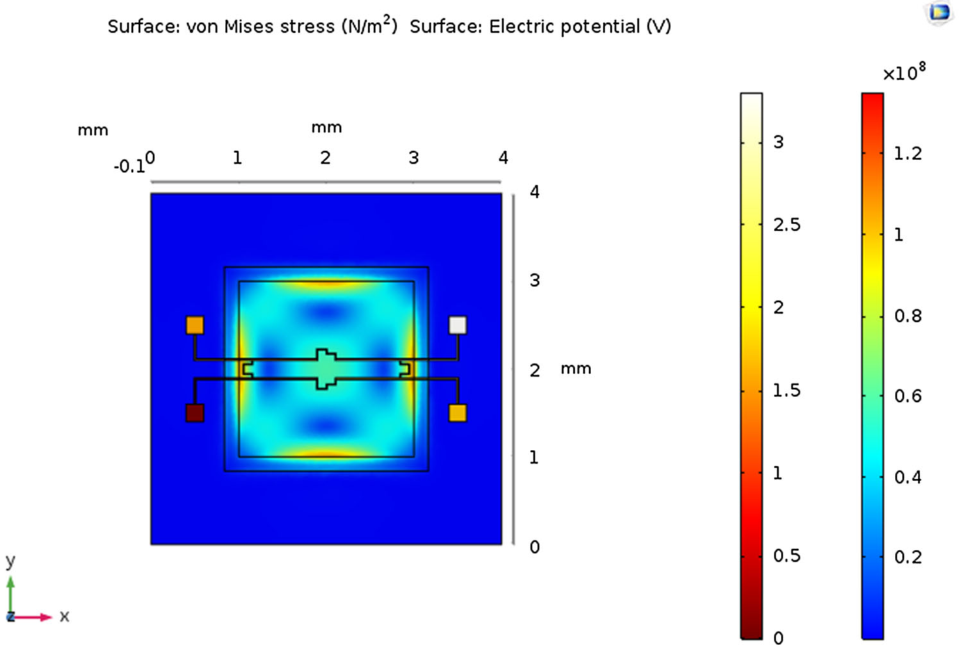

Fig. 4 Simulation result of graphene piezo resistive pressure sensor

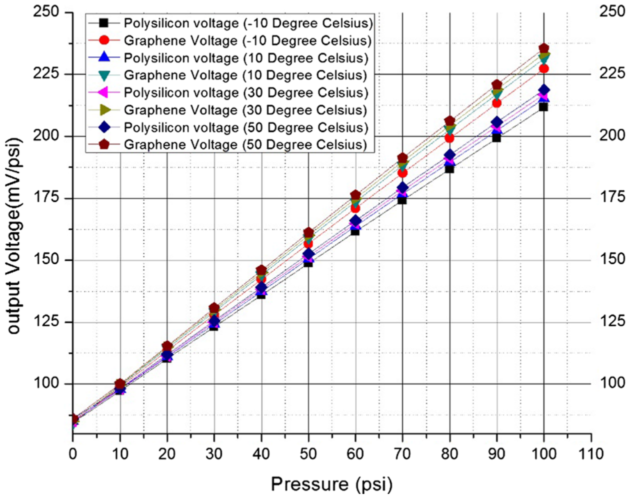

Fig. 5 Comparative analysis of pressure sensitivity of polysilicon pressure sensor and graphene pressure sensor at different temperature range

compared to lower temperature, but not better than graphene pressure sensor. As temperature increases from room temperature, the pressure sensitivity of the polysilicon reduces due to effect of temperature and shows a pressure sensitivity of 3.17 mV/psi. However at higher temperature graphene shows better response with pressure sensitivity of 4.00 mV/psi. Therefore by using graphene as a piezo-resistive material, the overall sensitivity of the pressure is improved. As shown in Fig. 5, graphene pressure sensor shows better result at all temperature ranges as compared to polysilicon pressure sensor.

6 Conclusion

It is noticed that the simulated model of graphene pressure sensor provides an excellent mechanism to compensate for temperature as well as it also increases the sensitivity of the sensor. The sensor is found to have an enhanced pressure sensitivity of 0.83 mV/psi as compared to polysilicon pressure sensor at high temperature. The temperature compatibility totally depends upon the sensing element. From this simulation it is concluded that by using Graphene as a sensing element it is possible to utilize graphene pressure sensor on higher temperature range. Synthesis of graphene also plays an important role in defining the piezo resistive properties of the material. Reduced graphene oxide method enhances the piezo resistive properties in terms of high electrical conductivity, strength, elasticity, large surface area and large output volume. The above mentioned piezo resistive properties enhances the sensitivity of graphene pressure sensor as compared to polysilicon pressure sensor which has fewer piezo resistive properties as compared to graphene.

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