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Multi objective design optimization of graphene piezoresistive MEMS pressure sensor using design of experiment

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Abstract. This paper investigates the effect of diaphragm thickness, dimensions of piezoresistors, doping profile and temperature compatibility on sensitivity and non-linearity of graphene MEMS pressure sensor. Taguchi method is used for maximizing the sensitivity and minimizing the nonlinearity of the designed pressure sensor. L27 orthogonal array is utilized for five input factors with three levels. Output voltage is obtained from simulation in COMSOL for different combinations of the input parameters as per L27 orthogonal array. It was found that diaphragm thickness and length of the sensing element shows maximum contribution in increasing the sensitivity of the pressure sensor. Similarly, interaction of diaphragm thickness with piezoresistors thickness and doping concentration shows a major contribution in reducing the non-linearity of the pressure sensor. Other factors such as operating temperature affects both sensitivity and nonlinearity of the pressure sensor with a very low contributing percentage of 0.40% and 2.16%, respectively. Pareto Analysis of variance (ANOVA) was employed to validate the predicated results of the designed pressure sensor. The result indicated that the optimum design shows a sensitivity of 4.10 mV/psi with very low non linearity of 0.1%.

Keywords: Optimization / piezoresistive / pressure sensor / taguchi / pareto analysis / sensitivity / graphene

1 Introduction

In the recent years, demand of Micro Electro Mechanical System (MEMS) pressure sensor of high sensitivity and linearity in the Biomedical Field has been gradually increased [1]. MEMS pressure sensor converts exerted pressure into electrical signals through various transduction mechanism such as piezoresistive, piezoelectric, capacitive, optical and resonant sensing mechanism [2]. Among these mechanisms, piezoresistive is most widely used, due to high dynamic range, low complexity, miniature size, high reliability and low cost [3]. In piezoresistive pressure sensor, applied pressure acts on its diaphragm to generate output displacement of diaphragm. Due to diaphragm displacement, stress is induced in diaphragm. Maximum stress is induced at the fixed part of the diaphragm while minimum stress is induced at the center. Sensing element (piezoresistor) are placed at maximum and minimum stress areas which is responsible to convert the applied pressure into electrical output voltage [4]. So, various design parameters related with diaphragm and sensing element are the key factors which affect the performance characteristics of pressure sensor [5].

Sensitivity and non-linearity are the key performance characteristics of a pressure sensor. Effect of Thickness of diaphragm is a critical parameter which affects sensitivity and linearity of pressure sensor. Singh et al observed the effect of variable diaphragm thickness and positioning of piezoresistors to investigate the performance of the pressure sensor to overcome the effect of over and under etching in bulk micromachining during fabrication [6]. Ali et al. reported the effect of varying diaphragm of pressure sensor for monitoring glaucoma disease [7]. Tang et al. reported effect of different thickness of square and circular silicon diaphragm on diaphragm displacement and induced stress [8]. Niu et al. also studied effect of silicon diaphragm thickness on linearity and sensitivity through FEA. They reported that at applied pressure of 150 MPa, sensitivity of the sensor was 1.1126 mV/MPa with 0.3% linearity [9]. Dimensions and doping concentration of piezoresistors also affects sensitivity and linearity of pressure sensors. Sosa et al. studied effect of length and width of boron doped silicon piezoresistors on sensing area which affects sensitivity of the sensor [10]. Zhang et al. studied the effect of length and doping concentration of silicon nanowire piezoresistors on sensitivity and SNR. They reported that long and thin piezoresistors results in better SNR and sensitivity [11]. Lou et al. optimized geometry of silicon nanowires piezoresistors for 0–20 psi pressure for

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sensitivity [12]. Meti et al. discussed the effect of length of piezosistors on the output voltage of the sensor by using piezoresistive transduction mechanism. They reported that considering the meander shaped resistor with 50 μm length give the sensitivity of 2.36 mV/KPa [13]. Lin et al simulate a pressure sensor to investigate the sensitivity and linearity of the pressure sensor. Effect of diaphragm shapes, piezoresistor dimensions such as including length, orientation, and dopant concentration are also analyzed to obtain a sensitivity of 0.24 mV/V/(lbf/in^2) with maximum of 0.1% full-scale span linearity error is noticed [14]. Sensing material also plays an important role in improving performance characteristic of the sensor. For this pressure sensor, graphene is taken as a sensing material that enhances the sensitivity profile of the pressure sensor as compared to other materials [15]. Due to high thermal conductivity in graphene, the electron mobility is more at higher temperature which increases the sensitivity of the pressure sensor even when operated at higher temperature also. This makes graphene pressure sensor to be utilized at wider operating range as compared to other sensing materials [16]. Optimizing operating temperature is also required as it affects sensitivity of pressure sensor. Doping is the best strategy for enhancing the conductivity, mobility, sensitivity of the 2D material [17]. Graphene doping is carried out to increase the conductivity of the material which in turn increases the sensitivity and reduces the non-linearity in the performance characteristic of the pressure sensor [18]. Although exploration of new doping species and doping concentration plays an important role in maintain the balance between sensitivity and non-linearity.

From the above literature, it can be concluded that there are certain factors which affects sensitivity and linearity of pressure sensor significantly. In most of the studies, one or two design parameters were considered to study their effect on output characteristics of pressure sensor. To study the cumulative effect of design parameters on output characteristics of pressure sensor, it is necessary to consider more design parameters. DOE is an effective approach to study cumulative effect of design parameters on output characteristics with limited experiments [19]. So, in this paper investigation of cumulative effect of each factor on the performance of the graphene pressure sensor has been carried out using Taguchi approach. COMSOL Multiphysics 5.3a version is used to simulate different model of piezoresistive pressure sensor with different combination of input design factors. Different combinations of input factors were employed with their interactions that can able to evaluate the high output value in terms of high sensitivity and low non linearity. This research uses a systematic approach of investigation of in a limited simulated experiments and prediction model is develop to optimize the input factors for graphene pressure sensor.

2 Principle of piezoresistive pressure sensor

Pressure sensor operates on different transduction principle such as piezoresistive, capacitive, opto-mechanical and piezoelectric. Zhao et al. [9] designed a pressure sensor based on nano polysilicon thin film. They utilize the piezoresistive transduction principle for the measurement of applied pressure. Chun et al. [10] propose a stretchable graphene sensor for strain measurement. This sensor works on variation in resistivity of the sensor. The relative change in resistance detected is ~0.005. Vladimír Kutiš et al. [11] model a pressure sensor to investigate the effect of the position of electrodes using the piezoelectric principle Eswaran P [12] et al. discuss different types of pressure sensors based on the capacitive transduction principle. Meetu Nag et al. [13] design a piezoresistive pressure sensor for measurement of tyre pressure. Myong Chol Kang et al. [14] proposed a capacitive pressure sensor to enhance the sensitivity and operating range respectively. Kha et al. [15] discuss potential application of MEMS grapheme pressure sensor with different transduction principle.

Capacitive pressure sensor shows better performance in terms of sensitivity. However, the fabrication complexity and issues related to nonlinear performance, reduces the choice of making capacitive pressures sensor [16]. Similarly optics has the issues related to proper alignment of the internal lens used for focusing the light [15]. Piezoresistive pressure sensor are more preferred due to simple internal circuitry and less issues related to fabrication process that overall reduces the cost of making of piezoresistive pressure sensor of high sensitivity [17]. However small decrement in linearity is noticed while working on increasing the sensitivity of the piezoresistive pressure sensor. In this piezoresistive phenomenon is utilized for obtaining the output voltage from the pressure sensor. Figure 1 shows the pictorial representation of the operating principle of the pressure sensor. On the application of pressure, the diaphragm deforms at center due to which a suitable change in resistance occurs in piezoresistors. Change in resistance is the cause of generated output voltage, which is measured with the help of bridge configuration [18].

Here R1, R2, R3 and R4 are piezoresistors. The size and shape is taken in accordance to analyse the linear elasticity of the resistor using Finite Element Method [20]. For piezoresistors, the change in resistance is expressed in longitudinal and transverse direction as shown in equation (1).

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t, \tag{1}$$

σ_l and σ_t are the stress generated in longitudinal and transverse directions respectively.

π_l and π_t are the piezoresistive coefficient of the material. For this pressure sensor graphene piezoresistive coefficient are considered which are given by equations (2) and (3)

$$\pi_l = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \tag{2}$$

$$\pi_t = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}). \tag{3}$$

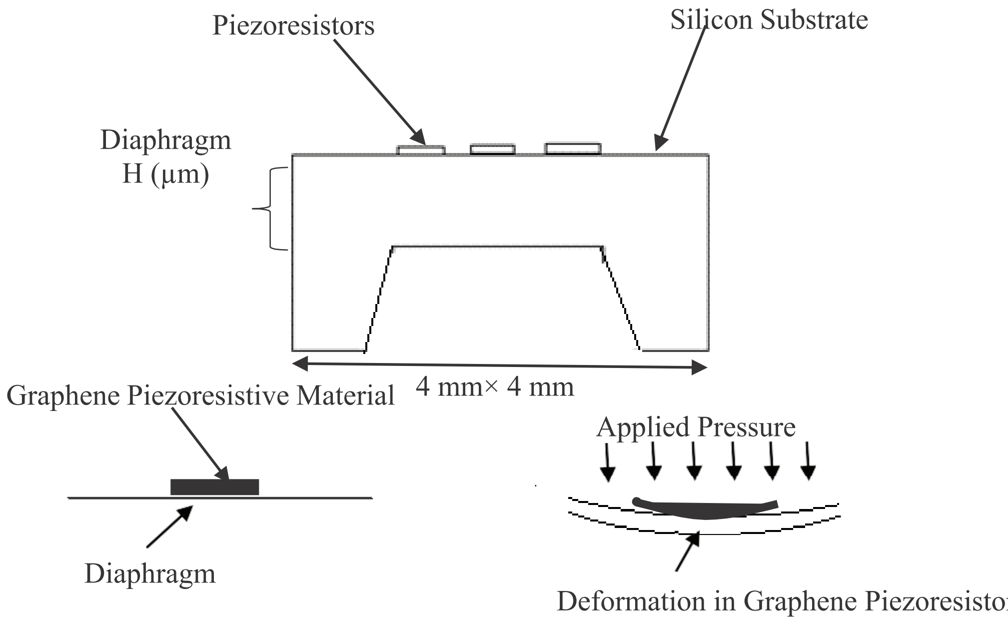


Fig. 1. Cross-sectional View of the graphene pressure sensor & Diaphragm deformation on applied pressure [19].

The resistors are connected in Wheatstone bridge configuration and thus, the output voltage is calculated as shown in equation (4).

$$V_{out} = \left(\frac{R2}{R1 + R2} - \frac{R4}{R3 + R4}\right)V_{in} \ . \tag{4}$$

3 Design approach

Graphene pressure sensor has a wide operating range with temperature compatibility. The dimensions of the pressure sensor defines the type of application for which graphene pressures sensor has been utilised. Considering the medical field the operating range was ranged between 0 and 100 psi. The dimensions of the sensor are defined in Table 1.

Application of pressure is from top, so that it can be distributed uniformly. The combination of two resistors are mend for measuring compressive stress and the other two resistor are mend for measuring tensile stress.

Material plays an important role in operating characteristic of the sensor. For this pressure sensor, graphene is taken as a sensing material that enhances the sensitivity profile of the pressure sensor as compared other materials [18]. Following properties are utilized for simulating the graphene pressure sensor in COMSOL Multiphysics environment as shown in Table 2.

Factors that affect the sensitivity and linearity are diaphragm thickness, dimensions of the piezoresistors (length and thickness), doping profile and operating temperature. Each factor are assigned three different levels in which a noticeable variation is measured that are responsible for enhancing the sensitivity of the pressure sensor with negligible non linearity. Design of experiment was used to employ orthogonal array by Minitab for five input factor with their interactions so that it can be possible to analyze the effect of each input factor on the other factor.

Table 1. Specifications of the pressure sensor

Sensor specifications	Value
Size of the device	4 mm × 4 mm
Diaphragm Thickness	H µm
Diaphragm Length	2 mm × 2 mm
Shape of Diaphragm	Square diaphragm
Dimensions of the piezo-resistors	L × 10 × T (Length × Width × Thickness) µm
Input Voltage	3.3V
Applied Pressure Range	0-100 psi
Substrate Material	Silicon Wafer
Sensing Material	Graphene
Material for Contact Pads	Gold and Tin

Figure 2 shows a sequential process flow of Taguchi approach for obtaining the optimum combination of all the input factors so that it is able to reduce the non-linearity while maintaining the high sensitivity of the graphene pressure sensor. As shown the below, the flow chart is divided in four different phases.

Phase I defines the selection procedure of the input factors along with their interactions that was responsible for increasing the sensitivity and reducing the non-linearity.

Table 2. Material properties required during simulation of pressure model.

Material	Properties	Value	Unit
Graphene	Young's modulus	1.0	T Pa
	Poisson's ratio	0.17	Unit less
	Electrical conductivity	10^2	S/m
	Thermal conductivity	5000	$W\ m^{-1}\ K^{-1}$
	Density	2000	$k\ g\ m^{-3}$
	Relative permittivity	2.14	Unit less
Silicon	Young's modulus	170×10^9	Pa
	Poisson's ratio	0.28	Unit less
	Heat capacity at constant pressure	700	$J\ Kg^{-1}.K^{-1}$
	Thermal conductivity	130	$W\ m^{-1}\ K^{-1}$
	Density	2329	$k\ g\ m^{-3}$
	Coefficient of thermal expansion	2.6×10^{-6}	K^{-1}
Gold	Relative permittivity	1	Unit less
	Electrical conductivity (σ)	4.5×10^6	S/m

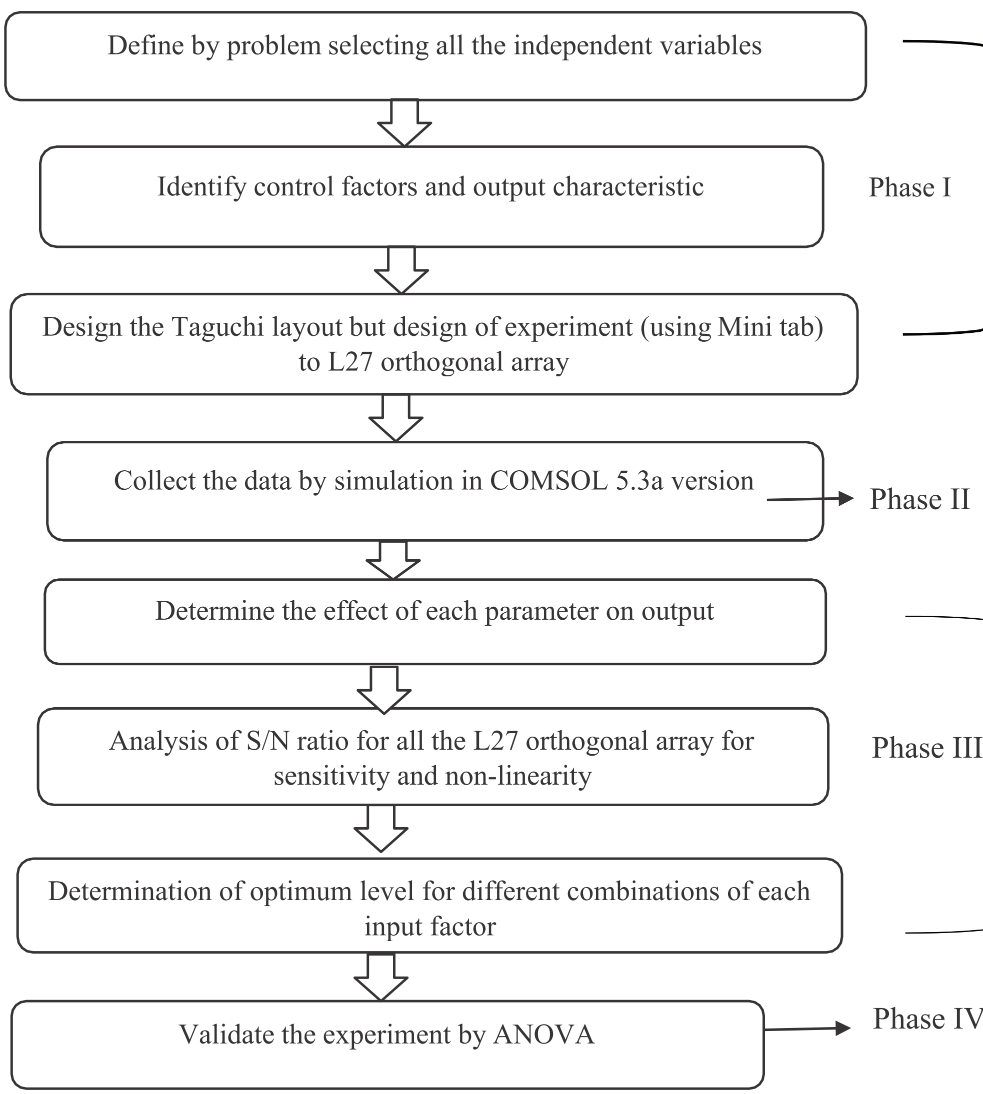


Fig. 2. Flowchart of process sequence of Taguchi method.

In Phase II, simulations were conducted for 27 different combinations of input factors for obtaining the sensitivity and non-linearity of the pressure sensor.

Phase III defines the statical calculation done by Minitab by obtaining S/N ratio for each L27 Orthogonal Array. Phase IV is the validation phase that validate the result generated by Taguchi by using Analysis of variance method called as Pareto ANOVA.

Non linearity was calculated by using equation (5). In this equation input pressure is the calibrated pressure.

$$NL_{\text{input}} = \frac{V_{0\left(P_{\text{input}}\right)} - \left(\frac{V_{0(P_{\max.})}}{P_{\max.}} \times P_{\text{input}}\right)}{V_{0(P_{\max.})}} \times 100\%. \quad (5)$$

4 Selection of input factor

4.1 Diaphragm thickness

Piezoresistive pressure sensor consists of substrate material as silicon and sensing material as graphene. Bulk micromachining is done to fabricate a diaphragm which is a thin membrane that converts applied pressure into output deflection. Many researches are working to optimize the dimensions of the thin diaphragm [21]. Presently the thickness of the diaphragm commonly varies from 20 μm to 70 μm [22]. Variation in diaphragm thickness with combination of length of diaphragm plays an important role in achieving maximum deflection of the diaphragm. However, lesser the thickness of diaphragm more the non-linearity introduced in the pressure sensor. Extensive research has been carried out to investigate the appropriate value of thickness of diaphragm in order to reduce the non-linearity and increase the sensitivity of the pressure sensor. Reduction in non-linearity in based on characteristic properties of the material such as stress status of the material, temperature effect on crystal lattice, defects during crystal growth all these lead to non-linearity [23].

Analytical modelling is done to show-case a dependency of deflection of diaphragm on the application of applied pressure. Maximum diaphragm deflection at the centre for square diaphragm is given by equation (6)

$$D_{\text{centre}} = 0.01512(1 - P^2)\frac{PL^4}{Et^3} \quad (6)$$

where D_{centre} is the deflection at the centre of the diaphragm is, υ is the Poisson ratio, P is the applied pressure, L length of the diaphragm and t is the thickness of the diaphragm.

Certain assumptions are taken in lieu of geometry of the pressure sensor. Thickness taken is very less as compared to twice of length and width is also very less as compared to length of the diaphragm (almost < 2 length). According to Hooks law, the stress component in X and Y direction is given by equation (7).

$$\sigma_x = \frac{E_z}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y), \quad \sigma_y = \frac{E_z}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x). \quad (7)$$

Here, σ_x is the stress generated in x direction, σ_y is the stress generated in y direction, E is the young modulus of elasticity and $^{\nu}$ is the Poisson ratio. From the above equation it is clear that generated stress is a factor of material property and Poisson ratio. Sensitivity and linearity of the pressure sensor is affected by aforesaid factor. The simulated result shows that the obtained internal stress is capable to improve the non-linearity and make the pressure sensor linear, but simultaneously reduces the sensitivity of the sensor. Sensitivity is inversely proportional to thickness of the diaphragm. As per the literature review thinner diaphragm has improved sensitivity but simultaneously increases the non linearity. Sensitivity depends upon length and thickness of the diaphragm as well as piezoresistive coefficient of silicon (π_{44}) as shown in equation (8).

$$\text{Sensitivity} = 0.1539_{\pi_{44}}(1-\vartheta)\left(\frac{\text{Length}}{\text{Thickness}}\right)^2. \quad (8)$$

The ratio of length and thickness needs to be optimized to obtain a value that can satisfy both the requirement of the sensor in terms of sensitivity and non-linearity. Non linearity is the factor of structural non-linearity, piezoresistive non-linearity and bridge non-linearity. Structural non linearity has a maximum weightage in defining the non-linearity for the pressure sensor as it defines the relation between the output voltage and diaphragm of the pressure sensor.

So, to obtain large deflection with reduced non linearity various combinations of the diaphragm thickness and length is studied and it was noticed that square shape diaphragm with 2 mm × 2 mm diaphragm size yields better results. However variation in thickness shows a remarkable variation in the output deflection. In this paper, three different levels are considered for diaphragm thickness. For a particular set of range variation are almost very less, so considering a noticeable change in deflection, three levels such as 20 μm, 40 μm and 60 μm is taken for optimization of best combination of diaphragm thickness to reduce the non- linearity and enhancing the sensitivity of the pressure sensor. Minimum the thickness of diaphragm more the deflection [24]. However, the effect of thickness is also analysed with interaction with other input factors.

4.2 Dimensions of piezoresistors

Nonlinearity is an important factor in assessing the electrical performance of a MEMS pressure sensor [25]. Non linearity is due to the dependency on the piezoresistive coefficient on the stress profile which is measured in x and y direction. Piezoresistive coefficient is defined in context of sensing material. Length, width and thickness are the three designing parameter of the piezoresistors that affects the performance of the pressure sensor. Length of the piezoresistor is taken more as compared to width. The selection of the width is taken by considering the fabrication limitation to fabricate minimum feature thickness of the pressure sensor. The width of the piezoresistor is taken as fixed value of 20 μm. Thickness

Table 3. defines the different value of factors creating three levels such as Level 1, Level 2 and Level 3.

Design factors	Level		
	1	2	3
(A) Diaphragm Thickness	20 μm	40 μm	60 μm
(B) Length	390 μm	400 μm	410 μm
(C) Thickness	0.09 μm	0.1 μm	0.2 μm
(D) Doping Concentration	$_{10}12$ cm^{-3}	$_{10}14$ cm^{-3}	$_{10}16$ cm^{-3}
(E) Temperature	20 °C	40 °C	60 °C

of the piezoresistor depends upon the material of the sensing element. For this pressure sensor, Graphene is taken as the material for sensing element. Monolayer graphene has thickness is 0.34 nm, as the thickness increases it comes under the category of few layer graphene. During simulation, considering the piezoresistors as mono layer graphene shows non applicability. However during fabrication also transferring monolayer graphene on silicon substrate material is a typical task. So considering the practical approach, three levels of thickness is taken as 0.09 μm, 0.1 μm and 0.2 μm.

Length of the piezoresistors is also taken in accordance to the device dimensions and diaphragm length. Considering 4 mm × 4 mm device dimensions with 2 mm diaphragm length four piezoresistor have to be placed. Two for measuring compressive stress and two for measuring tensile stress. Change in resistance depends on length of the resistor. For fabricating piezoresistor of 1–2 KΩ, the dimensions of the length of piezoresistor can be varied from 390 μm to 410 μm. Three different levels are selected in this range to acquire the required sheet resistivity as sheet resistivity is also have an effect on sensitivity of the pressure sensor. 390 μm, 400 μm and 410 μm are taken as three levels to analyze the effect of length on the performance of the pressure sensor.

4.3 Temperature

Thermal properties of graphene such as thermal conductivity has make graphene as a key material for fabrication of pressure sensor operated in wide range. Compared to other materials such as metals, carbon nanotubes, graphene has higher thermal conductivity which is proved by many researchers for different thermal applications [26]. Using piezoresistive phenomena, the resistance of the piezoresistior varies with temperature alteration that effects the operating temperature range and sensitivity of the pressure sensor [27]. In addition, the piezoresistive coefficient is also a function of doping level, as well as temperature of the sensing material. So it is required to analyze the effect the temperature on the pressure sensor that defines the accuracy level of the measured output value. Many researchers defines the operating temperature of the pressure sensor. Taking graphene as a sensing element improves the operating temperature range. In this paper, by running the parametric sweep for different temperature ranges from −10 °C to 60 °C [18]. It was notices that major variations is seen at room temperature and above value. Taking this into consideration three different levels of analyzing the effect of temperature on pressure sensor is analyzed at 20 °C, 40 °C and 60 °C, which covers the range of low temperature to high temperature.

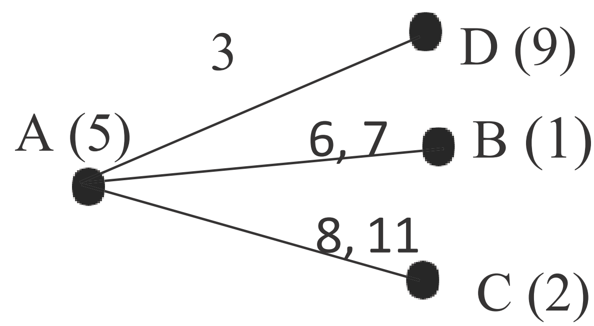


Fig. 3. Linear graph for L_{27} orthogonal array for interaction.

4.4 Doping profile

Doping is the best strategy for enhancing the conductivity, mobility, sensitivity of the 2D material. Graphene doping is done to increase the conductivity of the material so that it is possible to increase the sensitivity and reduces the non-linearity in the performance characteristic of the pressure sensor. Although exploration of new doping species and doping profile plays an important role in maintain the balance between sensitivity and non-linearity. Chemical doping on graphene is a good strategy in tuning the electrical properties, however deposition of residue of doping degrades the performance. To analysis the effect of doping level is a necessary task to ensure the optimum value of doping that will enhance the performance of the pressure sensor as well as reduced the non-linearity of the sensor [28]. However, further increase in doping concentration may lead to decrement in piezoresistive factor which increases the error in the measured output with reduction in mobility of the electron and effectively reduces the sensitivity of the pressure sensor. To analyses the effect of doping concentration on sensitivity and non-linearity, three different concentration of dopant were used such as 10^{12}, 10^{14}, 10^{16} cm^{-3} to represent low medium and high doping profile. These values were selected to analyze the effect of each level on performance of the pressure sensor in terms of sensitivity and non-linearity.

Table 4. Input Factor and interactions combinations using Taguchi L_{27} (313) standard orthogonal array for pressure sensor.

Experiment number	Factors and interactions												
	1 **B**	2 **C**	3 **A*D**	4 **E**	5 **A**	6 **A*B**	7 **A*B**	8 **A*C**	9 **D**	10 **E**	11 **A*C**	12 **e**	13 **A*D**
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

5 Design of experiment

Taguchi is one of the method for analyzing the quality characteristic of the different input parameters [29]. This method utilizes orthogonal arrays that provides a set of limited experiments at different input parameters and responses are measured as per these experiments. In this study, thickness of diaphragm, effect of length of the piezoresistor and temperature are analyzed for maximum sensitivity and minimum nonlinearity of the pressure sensor. Analysis of variance is also carried out for analyzing the effect of each dimensions of the piezoresistors as well as for analyzing the working range of pressure sensor for maximum sensitivity. Three different levels are maintained with different factor that affect the sensitivity of the pressure sensor. Each input factor has a dependency on the output variable. Two different cases is analyzed in this paper, considering sensitivity as "larger the better" and non-linearity as "smaller the better".

$$SN_{Larger\,the\,better} = -10\,log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right] \tag{9}$$

$$SN_{Smaller\,the\,better} = -10\,log\left[\frac{1}{n}\sum_{i=1}^{n}y^2\right] \tag{10}$$

where "*y*" denotes the n observation of the output variables. Five input designing factor were considered as shown in Table 3.

From the above literature review it is noticed that the diaphragm displacement greatly vary the change in resistance of piezoresistors. Therefore, it important to analyze the interactions between diaphragm thicknesses with the other input factors. Temperature also affects the performance of the pressure sensor. Taking graphene as a

Table 5. Simulated and calculated results for sensitivity and non-linearity for L_{27} orthogonal array input factor combinations.

Experiment number	Factor					Designation	Simulated parameter		Calculated SN ratio	
	A	**B**	**C**	**D**	**E**		**Sensitivity (mV/Psi)**	**Nonlinearity (%)**	**Sensitivity**	**Nonlinearity**
1	1	1	1	1	1	$^{A}1^{B}1^{C}1^{D}1^{E}1$	3.785365	0.0265	11.56216	31.52219
2	2	1	1	2	1	$^{A}2^{B}1^{C}1^{D}2^{E}1$	3.726129	0.1632	11.42516	15.74307
3	3	1	1	3	1	$^{A}3^{B}1^{C}1^{D}3^{E}1$	3.643132	0.3556	11.2295	8.980163
4	1	1	2	2	2	$^{A}1^{B}1^{C}2^{D}2^{E}2$	3.794807	0.1132	11.58379	18.9217
5	2	1	2	3	2	$^{A}2^{B}1^{C}2^{D}3^{E}2$	3.753133	0.2076	11.48788	13.65574
6	3	1	2	1	2	$^{A}3^{B}1^{C}2^{D}1^{E}2$	3.61064	0.3925	11.15168	8.122977
7	1	1	3	3	3	$^{A}1^{B}1^{C}3^{D}3^{E}3$	3.803895	0.0483	11.60457	26.32225
8	2	1	3	1	3	$^{A}2^{B}1^{C}3^{D}1^{E}3$	3.713871	0.3447	11.39654	9.251522
9	3	1	3	2	3	$^{A}3^{B}1^{C}3^{D}2^{E}3$	3.604436	0.4843	11.13675	6.296996
10	1	2	1	2	3	$^{A}1^{B}2^{C}1^{D}2^{E}3$	3.795636	0.2735	11.58569	11.26093
11	2	2	1	3	3	$^{A}2^{B}2^{C}1^{D}3^{E}3$	3.790309	0.1947	11.57349	14.21462
12	3	2	1	1	3	$^{A}3^{B}2^{C}1^{D}1^{E}3$	3.626758	0.1539	11.19037	16.25313
13	1	2	2	3	1	$^{A}1^{B}2^{C}2^{D}3^{E}1$	3.793712	0.2450	11.58129	12.21573
14	2	2	2	1	1	$^{A}2^{B}2^{C}2^{D}1^{E}1$	3.742877	0.0846	11.46411	21.44815
15	3	2	2	2	1	$^{A}3^{B}2^{C}2^{D}2^{E}1$	3.623542	0.2015	11.18267	13.91261
16	1	2	3	1	2	$^{A}1^{B}2^{C}3^{D}1^{E}2$	3.80756	0.4500	11.61294	6.93575
17	2	2	3	2	2	$^{A}2^{B}2^{C}3^{D}2^{E}2$	3.736101	0.0156	11.44837	36.11229
18	3	2	3	3	2	$^{A}3^{B}2^{C}3^{D}3^{E}2$	3.657604	0.2894	11.26393	10.76908
19	1	3	1	3	2	$^{A}1^{B}3^{C}1^{D}3^{E}2$	3.848615	1.0577	11.70609	0.4871
20	2	3	1	1	2	$^{A}2^{B}3^{C}1^{D}1^{E}2$	3.755002	0.2641	11.4922	11.56395
21	3	3	1	2	2	$^{A}3^{B}3^{C}1^{D}2^{E}2$	3.637109	0.0007	11.21513	62.73685
22	1	3	2	1	3	$^{A}1^{B}3^{C}2^{D}1^{E}3$	3.79663	0.2882	11.58797	10.80547
23	2	3	2	2	3	$^{A}2^{B}3^{C}2^{D}2^{E}3$	3.757509	0.3012	11.498	10.42208
24	3	3	2	3	3	$^{A}3^{B}3^{C}2^{D}3^{E}3$	3.684269	0.0428	11.32703	27.37884
25	1	3	3	2	1	$^{A}1^{B}3^{C}3^{D}2^{E}1$	3.790646	0.1996	11.57426	13.99516
26	2	3	3	3	1	$^{A}2^{B}3^{C}3^{D}3^{E}1$	3.792181	0.2224	11.57778	13.05866
27	3	3	3	1	1	$^{A}3^{B}3^{C}3^{D}1^{E}1$	3.630561	0.0976	11.19947	20.20686

sensing material the operating temperature range of the pressure sensor increases as graphene pressure sensor provides better performance in higher temperature as compared to other sensing material. However, on higher temperature it slightly affects the sensitivity of the pressure sensor. The concept of interactions is defined by linear graph for L_{27} orthogonal array as shown.

From the liner graph in Figure 3, it is shown that interactions of diaphragm thickness (A) with the Doping Profile (D) is associated in 3rd column. Similarly with length of the piezoresistor is associated in 6th and 7th column, similarly thickness is associated in 8th and 11th column. Temperature has its individual effect on the performance of the pressure sensor which is also analyzed and shown in 4th column. Table 4 shows all the 27 possible combinations. Each combination is simulated in COMSOL Multiphysics 5.3 a version by using MEMS module. Combination of fine tetrahedral mesh was used to simulate the design. Tetrahedral elements are best to model complex geometry which provide better simulation results with improved functionality for meshing with tetrahedral elements in COMSOL Multiphysics. Output voltage is measured in terms of Voltage. Sensitivity and linearity is calculated for this pressure sensor.

5.1 Taguchi approach

Sensitivity and linearity both are contradictory parameter that affects the performance of the pressure sensor. For achieving highest sensitivity, non-linearity will increases that affects the overall performance of the pressure sensor.

By applying Taguchi method in this paper, optimized value of all the input factor are revealed, by which there is a good combination of sensitivity and non-linearity is stuck to obtain best performance of the pressure sensor, as by any way it is not, at all possible to say that non linearity is completely removed or if it is possible to achieve 100% sensitivity. On practical ground sensitivity is scarified to reduce the non-linearity in the pressure sensor. In this a detailed analyses has been done to evaluate the optimized

Table 6. Response table *f* mean SN ratio for sensitivity and non linearity.

Input factors & interactions	Mean SN ratio for sensitivity				Mean SN ratio for non-linearity			
	Level 1	Level 2	Level 3	Max-Min	Level 1	Level 2	Level 3	Max-Min
(A)	11.59986	11.48484	11.21073	0.389136	14.61023	16.16334	19.40639	4.796159
(B)	11.39756	11.43365	11.46421	0.066657	15.42407	15.90248	18.96166	3.537598
(C)	11.4422	11.42938	11.42385	0.018352	19.08753	15.20926	15.88318	3.878277
(D)	11.40638	11.40554	11.48351	0.077971	15.12333	21.04463	14.012	7.032635
(E)	11.42405	11.44711	11.42426	0.023059	16.78696	18.70347	14.68954	4.013934
A × D (3)	11.43945	11.43605	11.41993	0.019523	17.62988	14.40997	18.24835	3.838378
A × D (13)	11.43742	11.42278	11.43523	0.014638	19.23765	16.10125	14.84106	4.396598
A × B (6)	11.4395	11.42568	11.43025	0.013818	16.97174	19.9317	13.38477	6.546929
A × B (7)	11.44201	11.42387	11.42954	0.01814	28.76264	11.5443	9.873026	18.88961
A × C(8)	11.43756	11.42712	11.43075	0.010439	16.78968	13.41528	20.08325	6.667977
A × C (11)	11.43379	11.43822	11.42341	0.014808	14.00768	15.35436	20.92617	6.918489

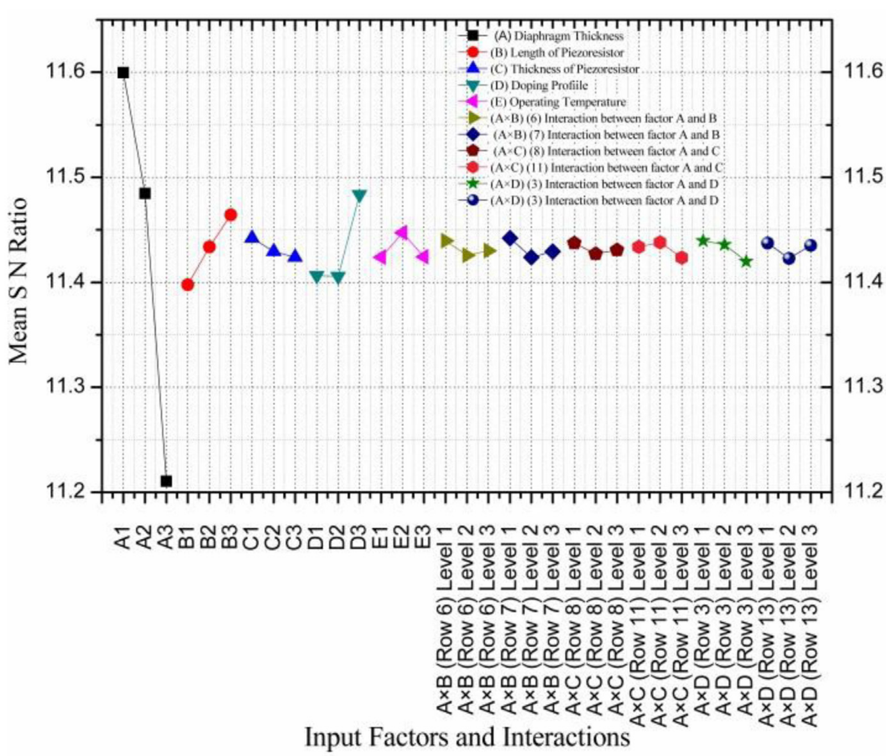


Fig. 4. The larger-the-better SN ratio graph for sensitivity.

parameter of all the input factors for enhancing the sensitivity and reducing the non-linearity of the pressure sensor. Simulated results and obtained Signal to Noise ratio for sensitivity and non-linearity is listed in Table 5.

Table 6 shows the response table by showing all the input factors and their interactions response on the output of the pressure sensor in terms of mean S/N ratio for sensitivity and nonlinearity. It is clear that highest value of max-min shows the highest involvement in increasing the sensitivity of the pressure sensor as well as reducing the non-linearity of the pressure sensor. The steep gradient of each factor shows the significant factor.

From Figure 4, it is analyzed that Diaphragm thickness and length of the piezoresistor were more significant in increasing the sensitivity of the pressure sensor. Other factors such as thickness of the piezoresistor, doping profile and temperature also show its presence in enhancing the sensitivity of the graphene pressure sensor. Taking graphene as a sensing element improves the temperature compatibility of the graphene pressure sensor.

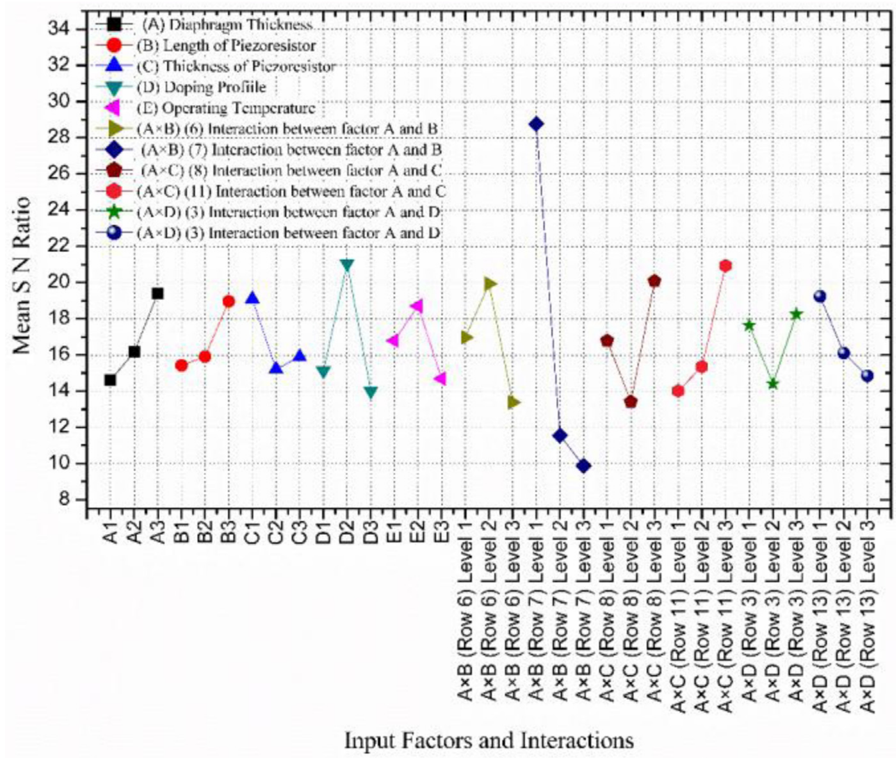


Fig. 5. The smaller-the-better SN ratio graph for non-linearity.

Table 7. Pareto ANOVA analysis of factors and interactions for sensitivity.

Analysis of Factors and Interactions at each levels											
	A	B	C	D	E	A*D 3	A*D 13	A*B 6	A*B 7	A*C 8	A*C 11
Sum at Factor level											
Level 1	104.3988	102.578	102.9798	102.6574	102.8165	102.955	102.9367	102.9555	102.9781	102.938	102.9041
Level 2	103.3635	102.9029	102.8644	102.6498	103.024	102.9244	102.805	102.8311	102.8149	102.8441	102.944
Level 3	100.8965	103.1779	102.8146	103.3516	102.8183	102.7793	102.9171	102.8722	102.8658	102.8768	102.8107
Sum of Squares of Differences	19.42338	0.541079	0.043072	0.9743	0.085383	0.052863	0.030298	0.024087	0.041861	0.013646	0.028068
Contribution Ratio (%)	91.36958	2.545291	0.202615	4.583208	0.401649	0.248675	0.142527	0.113307	0.196919	0.064194	0.132034
Cumulative Contribution	91.36958	93.91487	94.11749	98.7007	99.10234	99.35102	99.49355	99.60685	99.80377	99.86797	100
Pareto ANOVA											

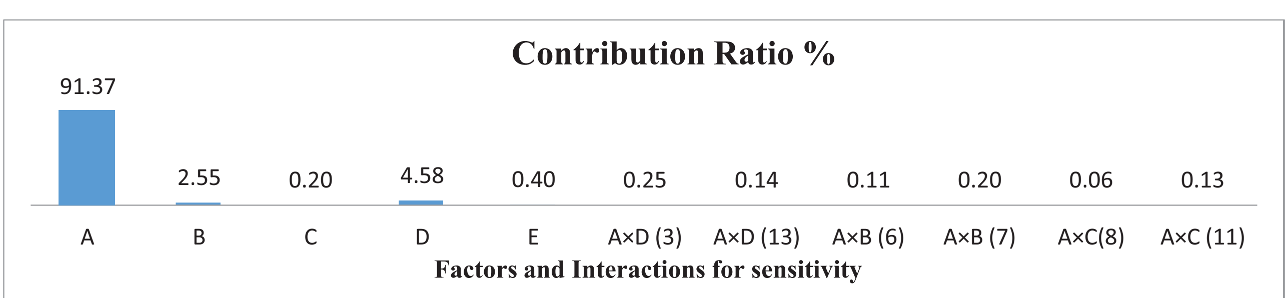
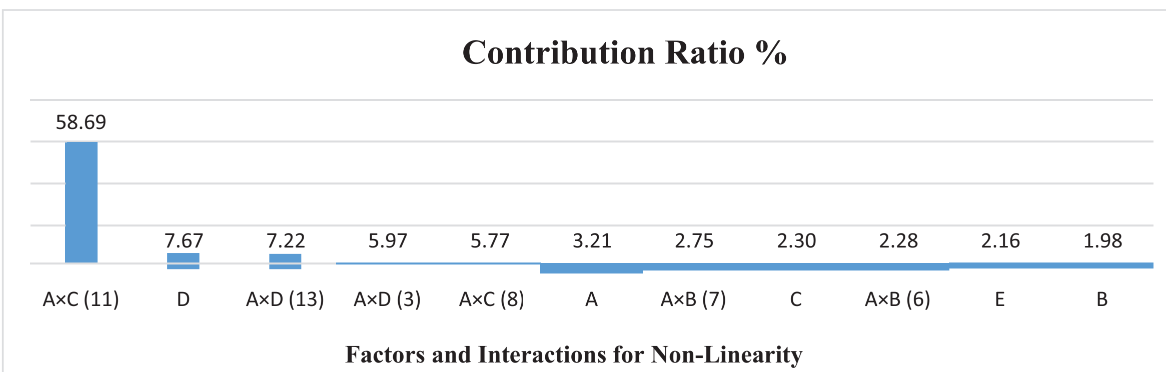
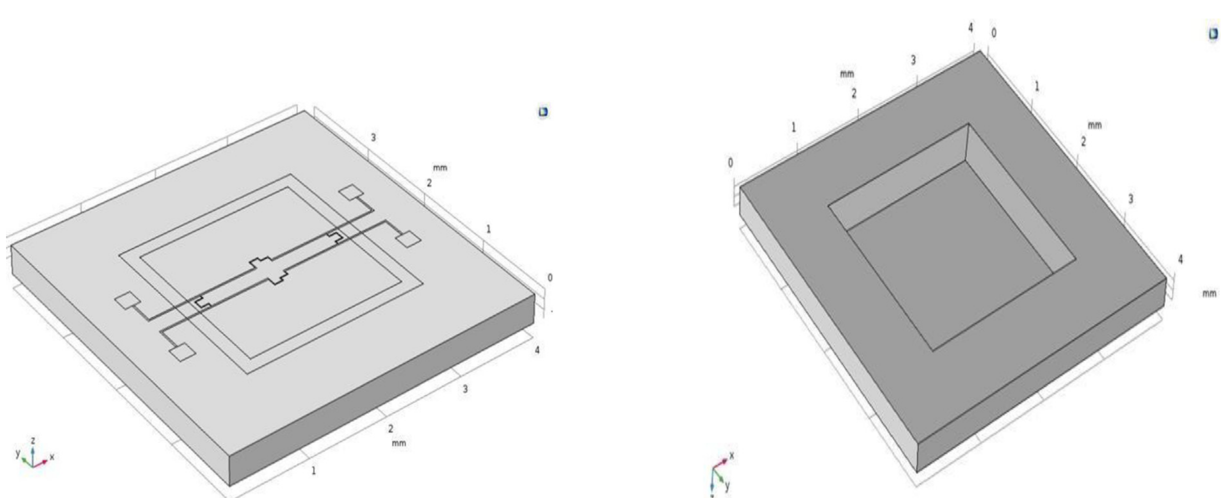


Table 8. Pareto analysis for factors and interaction for non linearity.

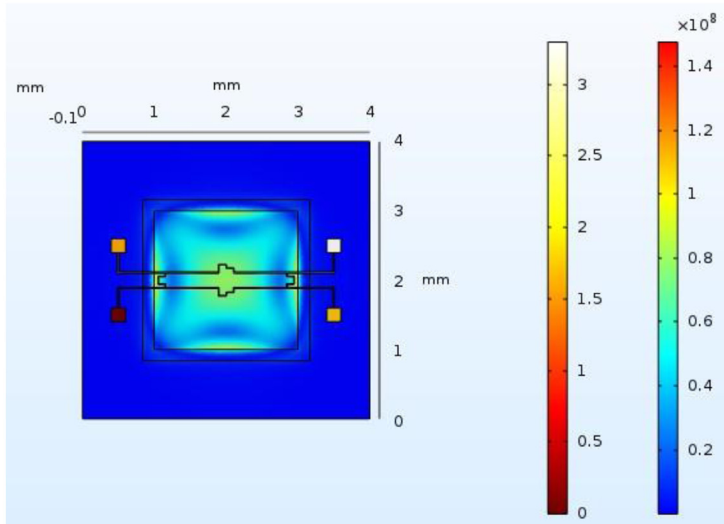
Analysis of Factors and Interactions at each levels											
	A	B	C	D	E	A*D 3	A*D 13	A*B 6	A*B 7	A*C 8	A*C 11
Sum at Factor level											
Level 1	131.4921	138.8166	171.7878	136.11	151.0826	158.6689	173.1389	152.7456	258.8638	151.1071	131.4921
Level 2	145.4701	143.1223	136.8833	189.4017	168.3312	129.6898	144.9113	179.3853	103.8987	120.7375	145.4701
Level 3	174.6575	170.655	142.9486	126.108	132.2058	164.2352	133.5695	120.4629	88.85723	180.7493	174.6575
Sum of Squares of Differences	2910.546	1790.271	2086.812	6946.14	1958.893	2064.159	2491.169	5223.69	53142.64	5402.387	6538.652
Contribution Ratio (%)	3.214107	1.97699	2.30446	7.670601	2.163199	2.279445	2.75099	5.768504	58.68525	5.96584	7.220613
Cumulative Contribution	3.214107	5.191097	7.495557	15.16616	17.32936	19.6088	22.35979	28.1283	86.81355	92.77939	100
Pareto ANOVA											



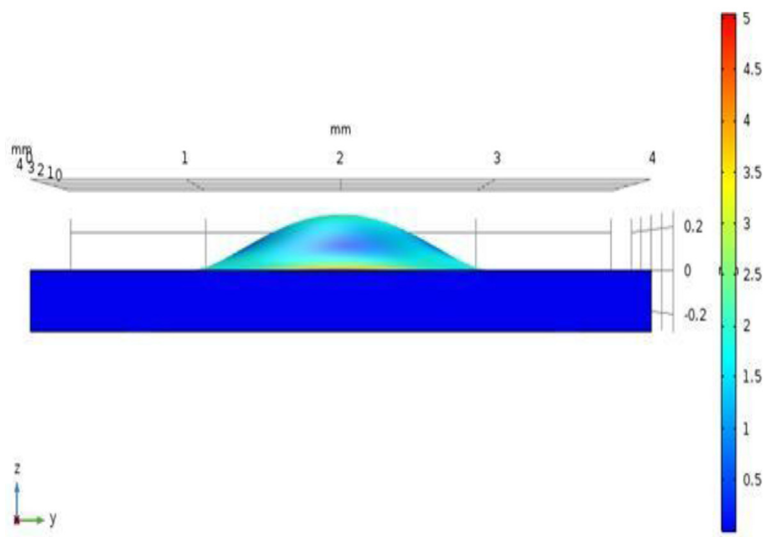


(a) (b)

Fig. 6. Optimized model of graphene pressure sensor (a) Top view, (b) Bottom view.



(a)



(b)

Fig. 7. (a) Simulated model in COMSOL multiphysics, showing the stress variation on the application of applied pressure. (b) Shows the displacement of diaphragm on applied pressure.

Meanwhile, as shown in Figure 5, the doping concentration (D), the interaction between diaphragm thickness and doping concentration (A × D), and the interaction between diaphragm and length of piezoresistors (A × B) were more significant in affecting the linearity performances of the graphene pressure sensor.

From the whole taguchi method it is analyzed that certain parameters directly affects the sensitivity and linearity of the graphene pressure. Table 7 shows the summarized report of optimum combination of all the factors for enhancing the sensitivity and reducing the non-linearity of the graphene pressure sensor such as in Table 9.

5.2 Pareto ANOVA validation approach

Pareto ANOVA is a validation tool that helps to validate the results obtained from Taguchi method regarding the significant factors in enhancing the sensitivity and reducing the non-linearity of the graphene pressure sensor. It deals with Pareto distribution that uses a powerful tool of statics for power law probability distribution by using 80/20 approach for each factor. Mathematically, assuming sensitivity "S" as a random variable with a Pareto distribution Type I, then the probability that sensitivity should be greater that some specific quantity "x", i.e. the survival function for high sensitivity of graphene pressure sensor is given by equation (11) where x_m is the minimum possible required value of sensitivity and α is the positive parameter.

$$\overline{F}(x) = \text{Probablity}(S > x) = \begin{cases} \left(\dfrac{x_m}{x}\right)^{\alpha} & x \geq x_m \\ 1 & x < x_m \end{cases}. \quad (11)$$

Tables 7 and 8 show Pareto ANOVA analysis for sensitivity and non-linearity, respectively. The Pareto

Table 9.

Factors ➡	Diaphragm thickness	Length of piezoresistor	Thickness of piezoresistor	Doping profile	Operating temperature
Optimised value	20 μm	410 μm	0.09 μm	$_{10}16$ cm^{-3}	40–60 °C

Table 10. Comparative study of optimized Graphene pressure sensor with the existing graphene pressure sensor.

Parameters	Optimized model	Chuang Lia [30]	Manjunath [31]	Shou-En zhu [28]
Sensitivity	4.10mV/psi	30.9mV/V/psi	2.29Ω/Bar	0.586 mV/psi
Non linearity	0.1%	0.25%	0.65%	Very low

diagram clearly demonstrates that the findings related to significance obtained from taguchi were similar to the results obtained from Pareto ANOVA in terms of contribution ratio. It is noticed that to increase the sensitivity of the graphene pressure sensor, diaphragm thickness, doping profile and length of piezoresisitor has the major contribution of 91.37%, 4.58% and 2.55%, respectively.

Similarly for reducing the non-linearity, interaction of diaphragm thickness and thickness of piezoresisitor plays a major role by showing 58.69% contribution. This factor can be easily managed by limiting the thickness of the graphene membrane as it highly affects the performance of the graphene pressure sensor in the terms of sensitivity also. Other factor such as doping profile shows contribution of 7.69% in reducing the non-linearity of graphene pressure sensor. Temperature also plays an important role in enhancing the sensitivity for a larger operating temperature range. Graphene, due to good thermal conductivity makes it possible to utilize the graphene pressure sensor at higher temperature also. In this paper it is noticed that temperature shows its significance in both increasing the sensitivity and reducing the non-linearity of the pressure sensor by showing a contribution of 0.40% for sensitivity and 2.16% for reducing the non-linearity. Thickness of graphene membrane for piezoresistor should be maintained properly for the fact that the change in resistance is a function of stress in piezoresistor. On application of applied force, generated stress is inversely proportional to thickness of piezoresistor. On reducing the thickness of piezoresistor, stress increases and that surely increases the change in resistance. From the analysis, by taguchi method minimum thickness of piezoresistor increases the sensitivity of the graphene pressure and its interaction with diaphragm thickness reduces the non-linearity in the output performance of the graphene pressure sensor.

6 Optimized model and result discussion

The optimum design for the graphene pressure sensor was finalized to attain the high sensitivity and negligible non linearity as shown in Figure 6. Thin diaphragm thickness (level 1–20 μm), more length of piezoresistors (level 3–410 μm), thin piezoresistors (level 1–0.09 μm), high doping profile (level 3–10^{16} cm^{-3}) and moderate temperature (level 2–40 °C) should be used to achieve high sensitivity and with very less non linearity.

Figure 7 shows the simulation of optimized geometry of the pressure sensors. Table 10 shows the comparative study with the existing graphene pressure sensor with the optimized model by taguchi approach for increasing sensitivity of the pressure sensor in lieu of maintaining very less non linearity. The optimized model can be considered to be an improved version of the existing graphene pressure sensor with highest sensitivity and good linearity performances. During simulation, the factors affecting the measurement uncertainty are sensitivity, linearity, repeatability, temperature effect. This uncertainty is reduced by selecting the optimized design for the piezoresistive pressure sensor. Selection of material greatly improves the uncertaninty causes by temperature drift. Polysilicon is used as a material for piezoresistor for the fact that polysilicon shows good sensitivity at room temperature.

But comparing graphene pressure sensor with this optimum design, it shows better results as compared to polysilicon pressure sensor at room temperature. On increasing the operating temperature of polysilicon pressure sensor, non- linearity increases and sensitivity starts reducing with a factor of 0.20.

7 Conclusion

In this paper, multi objective of enhancing the sensitivity designing parameters of pressure sensor are discussed in detail to know the significance of each parameters on the sensitivity of pressure sensor. Effect of diaphragm thickness, dimensions of piezoresistors, doping profile and temperature was analyzed in accordance to improve the sensitivity. It was found that other factors such as operating temperature affects both sensitivity and nonlinearity of the pressure sensor with a very low contributing percentage of 0.40% and 2.16%, respectively. Pareto Analysis of variance (ANOVA) was employed to validate the predicated results of the designed pressure sensor. The result indicated that the optimum design shows a sensitivity of 4.10 mV/psi with very low non linearity of 0.1%. Many researchers are working to finalize a working model of graphene pressure sensor that shows an improvement in the sensing technology with lesser time and cost. Comsol Multiphysics provides the platform for simulating the optimum geometry for obtaining the better results as compared to the existing graphene pressure sensor showing the sensitivity of 4.10 mv/psi with an analysis of effect of each factor on the output.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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