Sensors & Transducers, Vol. 211, Issue 4, April 2017, pp. 8-15

Sensors & Transducers
Published by IFSA Publishing, S. L., 2017
http://www.sensorsportal.com

Optimum Combination and Effect Analysis of Piezoresistor Dimensions in Micro Piezoresistive Pressure Sensor Using Design of Experiments and ANOVA: a Taguchi Approach

Kirankumar B. Balavalad and B. G. Sheeparamatti
Department of Electronics and Communication Engineering, Basaveshwar Engineering College,
Bagalkot-587103, Karnataka, India (Affiliated to VTU, Belagavi, Karnataka, India)
E-mail: kiranb4004@gmail.com, sheepar@yahoo.com

Received: 8 March 2017 /Accepted: 10 April 2017 /Published: 30 April 2017

Abstract: Piezoresistive (PZR) pressure sensors have gained importance because of their robust construction, high sensitivity and good linearity. The conventional PZR pressure sensor consists of 4 piezoresistors placed on diaphragm and are connected in the form of Wheatstone bridge. These sensors convert stress applied on them into change in resistance, which is quantified into voltage using Wheatstone bridge mechanism. It is observed form the literature that, the dimensions of piezoresistors are very crucial in the performance of the piezoresistive pressure sensor. This paper presents, a novel mechanism of finding best combinations and effect of individual piezoresistors dimensions viz., Length, Width and Thickness, using DoE and ANOVA (Analysis of Variance) method, following Taguchi experimentation approach. The paper presents a unique method to find optimum combination of piezoresistors dimensions and also clearly illustrates the effect the dimensions on the output of the sensor. The optimum combinations and the output response of sensor is predicted using DoE and the validation simulation is done. The result of the validation simulation is compared with the predicted value of sensor response i.e., V. Predicted value of V is 1.074 V and the validation simulation gave the response for V as 1.19 V. This actually validates that the model (DoE and ANOVA) is adequate in describing V in terms of the variables defined.

Keywords: MEMS, Pressure sensors, Piezoresistive pressure sensors, DoE, ANOVA.

1. Introduction

MEMS technology combines silicon based MEMS are one of the promising process technologies which are responsible for the fabrication of tiny-integrated devices [1]. Micro sensors are the miniaturized devices that sense the environmental factors like pressure, temperature and light in general. Micro-pressure sensors sense and detect the change in pressure. There are pressure sensors which work on different transduction mechanisms like capacitive, piezoelectric, resonant and piezoresistive. Compared to all other pressure sensors, piezoresistive pressure sensor (PZRPS) achieves high sensitivity and better linearity [2]. MEMS pressure sensors have a wide horizon of applications including automobiles, industries, defense and domestic. Automotive sector remains the biggest area for MEMS pressure sensors [3-5]. Primitive pressure sensors were developed using strain gauge mechanism but now there has been a rapid development both in fabrication capabilities and packaging, after finding piezoresistivity in silicon and germanium [6-7]. Typically PZRPS are designed, analyzed and validated using Wheatstone bridge configuration. The piezoresistors are placed or diffused using boron diffusion on selected regions of maximum stress onto silicon diaphragm. Then these resistors are connected in the form of Wheatstone bridge [8]. Paper [9] presented, several types of semiconductor stress gauges to measure the longitudinal, transverse, shear stress and torque, and employed a Wheatstone bridge type gauge in mechanical signal sensing. Kanda's [10] model is referred for proper designing of the model in order to improve the performance of the sensor. The work in [11] presents the simulation and sensitivity analysis of four different models such as, piezoresistive pressure sensor by Lynn Fuller, Silicon pressure transducer by M. Bao, Pressure sensor die by Tai-Ran Hsu and Motorola Xducer Piezoresistor. [12] describes about the better techniques to enhance the performance of the sensor, designing sensor with optimized geometry of the diaphragm. Also shape and location of the piezoresistors are considered for better sensitivity.

Authors in [13] have analyzed relationship between the different dimensions of a square and circular diaphragm with Piezoresistors for a pressure range of 0 to 1MPa. Results show that the square diaphragm has the highest induced stress for a given pressure. The paper suggests that the square diaphragm is preferred for high pressure generating high stress. Paper [14] presents the design and simulation of MEMS Piezoresistive pressure sensor for the pressure sensing range of 0 to 1.1 bar. Authors present different configuration of piezoresistor placement using meander shape with different number of turns to enhance sensitivity. Diaphragm is an important part of the sensor and scholars have worked on optimization of the diaphragm to improve the performance of the sensor. Paper [15] presents, optimization of a piezoresistive MEMS pressure sensor to find an optimal diaphragm shape by Finite Element Method using ABAQUS®. Three different shapes of diaphragms are considered in this study, they are circular, square and rectangular diaphragms. There are works in literature, worked on finding the optimum combination of piezoresistors dimensions to obtain better output voltage and sensitivity. Taguchi method has been utilized for optimization in literature, paper [16] presents the use of Taguchi and Two-Level Factorial approach to optimize the size of diaphragm thickness, slot width, and slot length for capacitive sensor.

Paper [17], has used Taguchi method to understand the effect of parameters in analyzing the silicon piezoresistive pressure sensor. There are works on studying the effect of piezoresistor dimensions, paper [8] presents design of silicon based piezoresistive micro pressure sensor. Finite Element Analysis is used find the effect of design parameters like the side length and the thickness of the diaphragm in determining the sensitivity of the sensor. The paper makes an effort to determine the optimum length and positioning of piezoresistors. Our previous work [18] describes the design and simulation of micro piezoresistive pressure sensor for pressure range of 0 to 1 MPa. The works considers placement of piezoresistors at maximum stress area and piezoresistor dimensions were varied to find the better combination. All the works mentioned, considers the placement of resistors at maximum stress area. But there are very little works which explains the individual resistor dimensions viz., length, width and thickness effect on the output of the sensor. In this work DoE and ANOVA (Analysis of Means) using Taguchi method are in used to find the best combination of piezoresistors dimensions and to analyze the effect of individual piezoresistor dimensions on the output of the sensor. This paper is the first of its kind in find the optimized dimensions and illustrate the individual piezoresistor effect on sensor performance using DoE and ANOVA.

Organization of the paper: Section 2 illustrates the design of the piezoresistive pressure sensor, in Section 3 describes the use of DoE to find the optimum combinations of piezoresistors for high sensor response (output voltage). Section 4 describes the use of ANOVA to analyze the effect of piezoresistor dimensions on the sensor performance. Section 5 proposes conclusion.

2. Design of Piezoresistive Pressure Sensor

Piezoresistive pressure sensor is designed with placing four piezoresistors on a square diaphragm. The diaphragm dimension is 400 μm×400 μm and 10 μm thickness (Fig. 1) [18].

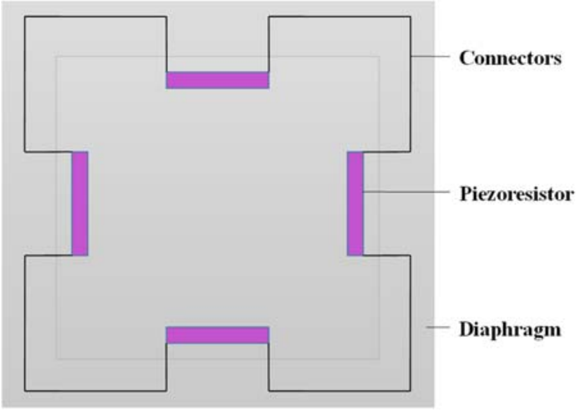

Fig. 1. Piezoresistor pressure sensor schematic view.

P-type silicon piezoresistors are used as they exhibit good gauge factor compared to n-type. Diaphragm is considered as n-type silicon. Cr and Al is used as connectors. Cr is usually considered to have a bonding between the semiconductor and the metal contact. The properties of the materials used for simulation are mentioned in Table 1. Resistors and connectors are configured in the form of Wheatstone bridge with applied input voltage of 5 V. Initially the bridge is balanced with a small offset voltage. Pressure in applied to the back side of the diaphragm, as shown in Fig. 2.

Table 1. Material properties of the model.

Material Property	P-type Silicon (Piezoresistors)	N-type Silicon (Diaphragm)
Young's Modulus	129 GPa	170 GPa
Poisson's ratio	0.22	0.28
Density	2330 [kgm^{-3}]	2330 [kgm^{-3}]

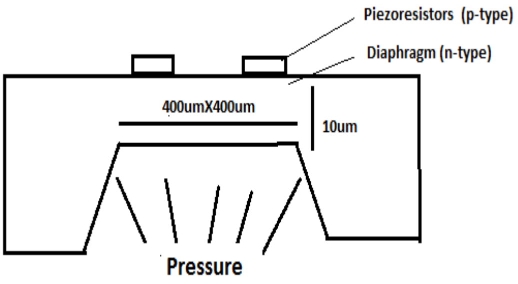

Fig. 2. Piezoresistive Pressure Sensor.

Pressure is varied from 0 to 1 MPa following the design aspects mentioned in our previous work [18] i.e., diaphragm thickness 10 um is considered, keeping fabrication aspects in mind. For diaphragm dimensions, the concept of thin plate theory has been included, according to which the length of the diaphragm must be at least 10 um×20 = 200 um [19]. Small deflection theory of bending of thin plates says that, the maximum deflection must be within 1/5th of the thickness of the diaphragm. So the diaphragm with 10 µm thickness should have deflection around 2 µm. The diaphragm dimensions were finally fixed by carrying out simulation of maximum deflection v/s diaphragm dimensions. Simulation results show that the maximum diaphragm dimension should be 400 um×400 um and the results are mentioned in Table 2.

Table 2. Diaphragm dimension and displacement.

Diaphragm Thickness (um)	Diaphragm Size (um^2)	Max. Displacement (um)
10	400×400	2.6254
10	500×500	6.3379
10	600×600	13.024

The designed models are simulated using COMSOL Multiphysics. The designed models are simulated for the pressure range of 0 to 1 MPa. The potential distribution plot is shown in Fig. 3 for input voltage of 5 V.

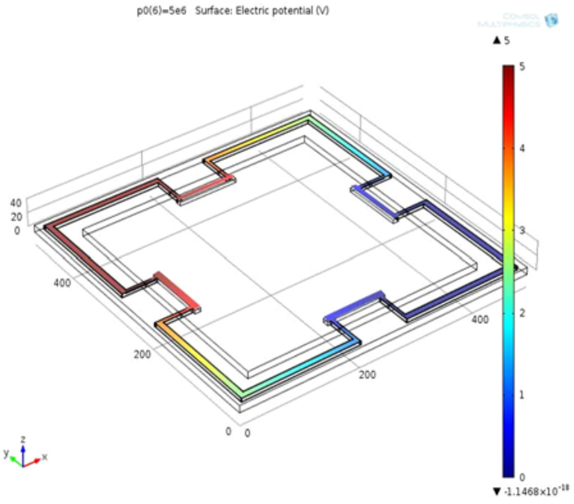

Fig. 3. Electric potential of the PZR pressure sensor.

3. DoE: A Taguchi Approach to Find Optimum Combination of Piezoresistor Dimensions

Basically the paper follows Design of Experiments using Taguchi methods. Taguchi method is also known as robust design method. This method considers first the number of parameters influencing the quality characteristics/responses of the devices [20]. Typically, a process optimization will have several control factors which directly decide the desired value of the output. The optimization process then involves determining the best control factor levels so that the output is at the desired level [21]. In this case the design set up and performance parameters are described in Fig. 4.

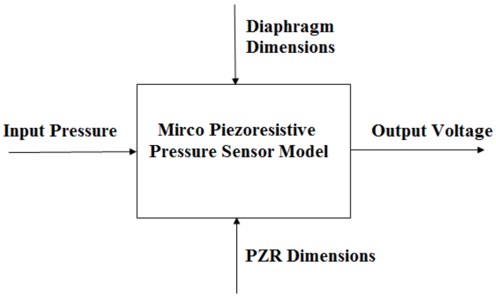

Fig. 4. Signal Factor diagram for DoE.

Pressure is input to the sensor, the performance of the sensor in normal operating conditions mainly depend upon, diaphragm dimensions and piezoresistor dimensions. In this work the focus in on finding the effect of individual resistor dimensions on the performance of the sensor, keeping all other conditions ideal. Although temperature is one of the noise factors which affect the performance of the sensor, it is not considered here as the focus is on PZR dimensions optimization. DoE was performed with varying dimensions of piezoresistors with predefined combinations following L9 orthogonal array. Although DoE gives insight about the effect and optimum piezoresistor combinations, there is one more method called ANOVA (Analysis of Means), which gives a better insight of effect analysis of individual dimension effect analysis. In this work both DoE and ANOVA are used to serve the cause.

The factors affecting the sensor performance are piezoresistor dimensions viz., 1. Length (A). 2. Width (B). 3. Thickness (C).

The above mentioned factors are taken here for effect analysis and to find the optimum combinations. Each of these factors (A, B, C) are assigned with the three distinct levels. The level assignment is based on the literature studies and the papers (works on piezoresistor pressure sensors) that we have published. The literature reveals that the lower bound on the piezoresistor length is 50 µm, for width it is 5 µm and for thickness it is 4 µm (and below). The upper bound happens to be 100µm for length, 15 µm for width and 6µm for thickness. Table 3, presents the factors and their levels assigned.

Table 3. Factors and their levels.

Factors	Level 1	Level 2	Level 3
Length (A)	50 µm	75 µm	100 µm
Width (B)	5 µm	10 µm	15 µm
Thickness (C)	4 µm	5 µm	6 µm

For the levels assigned, the simulation was conducted as per the L9 orthogonal array, which is a standard array. In this array 1, 2, 3 represent the levels of respective factors. In the array, for any pair of columns, all combinations of factor levels occur and they occur equal number of times, hence the array is orthogonal. The last column of the Table 3, represents the responses, i.e., output voltage of the sensor. Simulation was conducted for six repeated times and an average value is taken for say experiment i, where i =1, 2, 3, … 9 different experiments/simulation combinations. The factors, their combination and the simulation results are tabulated in Table 4.

Table 4. Experiment as per L9 orthogonal array.

Expt. No	**Column Number and Factor Assigned**			**Output Voltage 'V' (mV) at 1MPa of input pressure**
	1. Length (A)	**2. Width (B)**	**3. Thickness (C)**	
1	1	1	1	V_1=348.02
2	1	2	2	V_2=203.73
3	1	3	3	V_3=183.69
4	2	1	2	V_4=769.93
5	2	2	3	V_5=424.22
6	2	3	1	V_6=351.35
7	3	1	3	V_7=1169
8	3	2	1	V_8=715.37
9	3	3	2	V_9=483.67

From the response data in the Table 3, the overall mean is computed, as

$$m = \frac{1}{9}\sum_{i=1}^{9} V_i = \frac{1}{9}[V_1 + V_2 + \cdots + V_9]$$
$$=516.54 \text{ mV}$$

3.1. Effect of Factors at Different Levels

This section presents the effect of the Length, Width and Thickness factors at different levels. All the mean values and effect values are in mV.

3.1.1. Effect of Length (A) at Different Levels

The effect of Length (A) at level 3 is given by the result of experiment number 7, 8, 9.

$$m_{A3} = \frac{1}{3}[V_7 + V_8 + V_9] = 789.34$$

The effect of Length (A) at level 2 is given by the result of experiment number 4, 5, 6.

$$m_{A2} = \frac{1}{3}[V_4 + V_5 + V_6] = 515.16$$

The effect of Length (A) at level 1 is given by the result of experiment number 4, 5, 6.

$$m_{A1} = \frac{1}{3}[V_1 + V_2 + V_3] = 245.14$$

The effect of length (A) at level A3 is given by, (m_{A3}-m) = 272.8.

The effect of length (A) at level A2 is given by, (m_{A2}-m) = -1.38.

The effect of length (A) at level A1 is given by, (m_{A1}-m) = -271.40.

3.1.2. Effect of Width (B) at Different Levels

The effect of Width (B) at level 3 is given by the result of experiment number 3, 6, 9.

$$m_{B3} = \frac{1}{3}[V_3 + V_6 + V_9] = 339.57$$

The effect of Width (B) at level 2 is given by the result of experiment number 2, 5, 8.

$$m_{B2} = \frac{1}{3}[V_2 + V_5 + V_8] = 447.77$$

The effect of Width (B) at level 1 is given by the result of experiment number 1, 4, 7.

$$m_{B1} = \frac{1}{3}[V_1 + V_4 + V_7] = 762.31$$

The effect of Width (B) at level B3 is given by, (m_{B3}-m) = -176.97.

The effect of Width (B) at level B2 is given by, (m_{B2}-m) = -68.77.

The effect of Width (B) at level B1 is given by, (m_{B1}-m) = 245.77.

3.1.3. Effect of Thickness (C) at Different Levels

The effect of Thickness (C) at level 3 is given by the result of experiment number 3, 5, 7.

$$m_{C3} = \frac{1}{3}[V_3 + V_5 + V_7] = 592.30$$

The effect of Thickness (C) at level 2 is given by the result of experiment number 2, 4, 9.

$$m_{C2} = \frac{1}{3}[V_2 + V_4 + V_9] = 485.77$$

The effect of Thickness (C) at level 1 is given by the result of experiment number 1, 6, 8.

$$m_{C1} = \frac{1}{3}[V_1 + V_6 + V_8] = 471.58$$

The effect of Thickness (C) at level C3 is given by, (m_{C3}-m) = 75.76.

The effect of Thickness (C) at level C2 is given by, (m_{C2}-m) = -30.77.

The effect of Thickness (C) at level C1 is given by, (m_{C1}-m) = -44.96.

All the above calculations are theoretical. The same was implemented using Minitab 17 software the results show exact similarities to the theoretical. The individual analysis of means for Length, width and thickness are plotted in Figs. 5, 6, 7. All the factors effects can be plotted in the form of means plots as shown in Fig. 8.

Above figure shows the analysis of means for length factor of piezoresistor. This mean is around the overall mean. Where α is the maximum acceptable level of risk for rejecting a true null hypothesis. It is expressed as a probability ranging between 0 and 1. A is frequently referred to as the level of significance, it should be set before beginning the analysis. The most commonly used a-level is 0.05. At this level, the chance of finding an effect that does not really exist is only 5 %. Fig. 7, describes the means plot for piezoresistor thickness factor. All level factor effects can be observed that they are near to overall mean.

The combined plot of analysis of means for all three factors is shown in Fig. 8.

The interaction plot of the 3 factors is plotted in Fig. 9. The plot considers the interaction of all factors, keeping one factor constant and varying other two. This plot gives better insight on optimum levels and combinations desired.

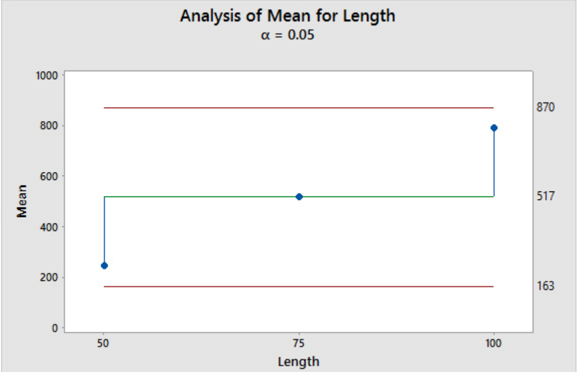

Fig. 5. Analysis of Mean for Length.

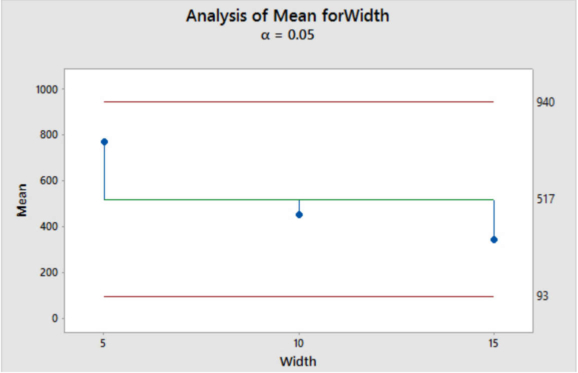

Fig. 6. Analysis of Mean for Width.

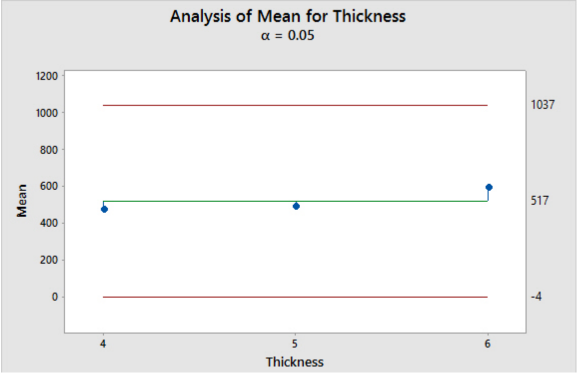

Fig. 7. Analysis of Mean for Thickness.

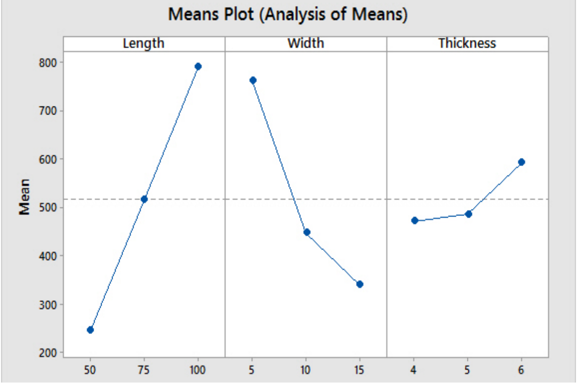

Fig. 8. Analysis of Means for the factors.

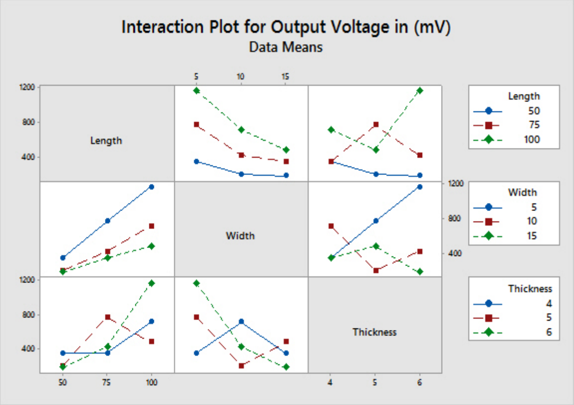

Fig. 9. Interaction plot for 3 factors.

Based on the theoretical calculation, observations and plots using Minitab 17, now we can find the optimum combinations of factors. The optimum combinations are indicated where the contribution of the level to deviate away from the mean. Table 5, presents the optimum levels indicated with * mark.

Table 5. Optimum Combinations.

Factors	Levels		
	1	2	3
A Length	245.14	515.16	789.34*
B Width	762.31*	447.77	339.57
C Thickness	471.58	485.77	592.30*

The means plot describes thickness has got least effect, so it can be neglected while considering the combinations. But considering all factor effects the optimum combinations to have enhancement in output voltage the combinations need to be preferred are $A_3B_1C_3$ or $A_3B_1C_2$. Minitab 17 was trained for optimum combinations, and the following plot shows the required combinations with levels, which are in accordance with the calculated optimum combinations. The optimum combinations with levels are plotted in Fig. 10.

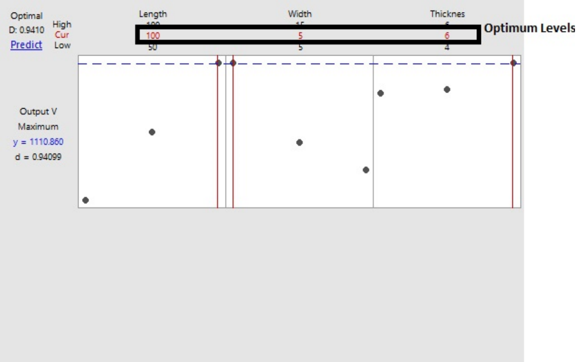

Fig. 10. Optimization Plot.

The objective of the Taguchi methods is to predict optimum condition/combinations. The optimum predicted conditions as mentioned in the Table 5 $A_3B_1C_3$. Using the additive model, the value of V under optimum combinations as,

$$V = m + (m_{A3} - m) + (m_{B1} - m) + (m_{C3} - m) = 1.074\text{V}$$

A verification simulation is conducted after determining the optimum conditions and predicting the response with these combinations. The result of the verification simulation is compared with the predicted value of V. Predicted value of V is 1.074 V and the verification simulation gave the response for V as 1.19 V. So this actually concludes that this model is adequate in describing V in terms of the variables defined.

4. ANOVA: Analysis of Means Approach to Find the Effect of Piezoresistor Dimension of Sensor Response

The effect of different factors of piezoresistor and an optimized levels and combinations were defined using means plot in the previous section. But the better insight of relative effect of different factors can be obtained by decomposition of variance, known as Analysis of Variance (ANOVA). ANOVA also provides the variance for the factor effects and variance of the prediction error. It involves three decompositions viz., grand sum of squares, sum of squares due to mean and total sum of squares.

Where **Total sum of squares = (Grand sum of squares – sum of squares due to mean)**

The model of experimentation is same as defined in Section 3 following Fig. 4. All factor and their levels defined in above section i.e., in DoE are followed in this section too. Same responses i.e., the output voltage for input pressure of 1 MPa is considered for ANOVA.

ANOVA:

1. Grand Sum of Squares (GSS) is given by
   GSS = $\sum_{i=1}^{9} V_i^2$ =3204819.33 (mV)^2
2. Sum of Squares due to Mean (GSM) is given by
   GSM = (number of experiments)Xm^2
   = 9(516.54)^2=2401322.14 (mV)^2
3. The Total Sum of Squares (TSS) is given by
   TSS = $\sum_{i=1}^{9} (V_i - m)^2$ =803373.24 (mV)^2
4. TSS=GSS-GSM=3204819.33-2401322.14≈
   803497.19 (mV)^2
5. Sum of Squares due to individual factors
   1) Sum of squares due to Factor A. Length
      =[3(m_{A1}-m)^2+3(m_{A2}-m)^2+3(m_{A3}-m)^2]
      =444239.11 (mV)^2

2) Sum of Squares due to Factor B. Width
$=[3(m_{B1}-m)^2+3(m_{B2}-m)^2+3(m_{B3}-m)^2]$
$=289351.74\ (mV)^2$

3) Sum of Squares due to Factor C. Thickness
$=[3(m_{C1}-m)^2+3(m_{C2}-m)^2+3(m_{C3}-m)^2]$
$=26123.30\ (mV)^2$

Based on the above findings, ANOVA table is prepared, and is shown in Table 6.

Table 6. ANOVA table.

Factors	DoF	Sum of Squares	Mean Squares	F Ratio
A. Length	2	444239.11	222119.55	1.211
B. Width	2	289351.74	144675.87	0.78
C. Thickness	2	26123.30	13061.65	0.007
Error	0	0	----	
Total	6	759714.15	----	
(Error)	4	733590.85	183397.71	

The above table is prepared by neglecting the effect of factor C-Thickness, as it has minimum effect.

DoF - Degree of Freedom. F ratio is calculated by F=Mean square value/error.

From ANOVA Table 6, factor A is responsible for (444239.11/759714.15)=58.47 % percent of variation of V (output voltage). Simillarly All factor effects are tabulated in Table 7.

Table 7. Effect of individual factors on the putput of sensor.

Factors	Percentage effect of factors for variation in output voltage in '%'
Length of piezoresistor	58.47
Width of piezoresistor	38.08
Thickness of piezoresistor	3.43

5. Conclusions

The paper presents a very unique and novel technique of finding the individual effect of piezoresistor dimensions on the output of the sensor and the optimum combinations of levels required to enhance the output voltage. Design of Experiment and ANOVA methods are used to achieve the purpose. The results and observations suggest the best combination of levels to optimize the response of the sensor is $A_3B_1C_3$ i.e., 100 µm×5 µm×6 µm. The predicted response after optimization (using DoE) was 1.074 V and the validation simulation using the optimum combinations shows the response value of 1.19 V. And ANOVA method describes that the effect of Length of the piezoresistor has highest effect on the output variations of the sensor. Length has 58.74 % effect next is width with 38.08 % effect and least is the effect of thickness 3.43 %. Therefore to enhance the output response of the sensor, length of piezoresistor has to be carefully addressed.

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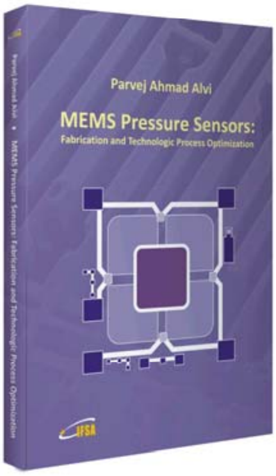
Parvej Ahmad Alvi

MEMS Pressure Sensors:

Fabrication and Technologic Process Optimization



So far, no book has described the step by step fabrication process sequence along with flow chart for fabrication of micro pressure sensors, and therefore, the book has been written taking into account various aspects of fabrication and designing of the pressure sensors as well as fabrication process optimization. A complete experimental detail before and after each step of fabrication of the sensor has also been discussed. This leads to the uniqueness of the book.

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