Multiphysics Simulation of Piezoresistive Pressure Microsensor Using Finite Element Method

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In this study, the electro-mechanical behavior of a specially designed high-sensitive piezoresistor pressure microsensor was simulated using finite element method, through COMSOL multiphysics software. The mechanical deformation of the diaphragm and the distribution of electrical potential in the piezoresistive were evaluated for various pressure values. In order to determine the influence of the temperature sensitivity parameter, different temperature conditions were investigated. According to the obtained results, by increase of the applied pressure, the resistance of the piezoresistor decreased, while, the sensitivity increased. Also, it was observed that at constant pressure, as the temperature increases, the stress on the diaphragm surface decreases, indicating high stress distribution at the sides and the middle of the diaphragm at low temperatures such as -50 °C. Furthermore, the obtained results demonstrated that temperature variations were not very effective on the potential distribution in the piezoresistor. However, the temperature coefficient of sensitivity demonstrated an increasing tendency with increase of the temperature from -50 °C to 50 °C.

Keywords: *Micro-electro-mechanical systems; Pressure sensor; Piezoresistor; Micromachining; Finite element method.*

1. INTRODUCTION

Pressure is one of the most widely used physical quantities in various industrial fields. A wide range of pressure sensors is available with a variety of environmental conditions and variety of features [1-3]. Many pressure sensors can be mounted inside very small containers. The very small dimensions of the pressure sensors allow a network of cells to concentrate on the surface of a finite chip, or to be placed in unavailable cavities [4,5]. The pressure microsensors are divided into different types according to the structure and used mechanism. These include pressure capacitive microsensors, pressure piezoelectric microsensors, and pressure piezoresistive microsensors [6,7].

Piezoresistive microsensors were among the first micro electro-mechanical devices to be commercialized. The advantages of these pressure microsensors are more capacity and more responsiveness. But in contrast to capacitive pressure microcontrollers, they require less power [8]. These devices have enabled the development of metering systems with specific applications that require small dimensions and acceptable sensitivity. Features of pressure piezoresistors include ease of manufacture, relatively low cost, simple measurement mechanism, a wide range of measurements and possibility of integrating with electrical circuits. The process of making micro-electro-mechanical pressure sensors is divided into two categories: bulk micromachining and surface micromachining [4]. The major disadvantage of piezoresistor microsensors is their low sensitivity surface micromachining technique, which is due to the usage of polysilicon as the piezoresistant material. This material is obtained by Low-Pressure Chemical Vapor Deposition (LPCVD) silicon. As a result, the silicon crystal beads are randomly positioned in different directions. Therefore, the Longitudinal Gauge Factor varies between 30 and 45 depending on the impurity level [5]. This is 3 to 4 times lower than that found in silicon single crystals [9]. Conventional piezoresistive microsensors utilize one or two active diaphragm resistors and non-pressure-sensitive reference resistors on the wafer [10,11].

The low longitudinal measurement factor, along with the incomplete bridge structure, reduces the sensitivity of surface sensing microsensors by up to 0.1 sensitivity of conventional sensors derived from volumetric work [12]. This limits the usage of these microprocessors in applications where high sensitivity is required. The main advantages of measuring pressure using piezoresistors are the simplicity of their production process, the excellent linear relationship between the output voltage of the sensor and the measuring pressure. The main disadvantages of these types of sensors should be their temperature sensitivity and leakage current.

Furthermore, due to the low sensitivity of the piezoresistors, the piezoresistor components are not suitable for accurate measurements (very low pressures) [13]. High-temperature sensitivity decreases as the piezoresistor coefficient increases with increasing temperature. The

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resistors have a scale limitation on the pressure sensor, so as the resistance element length decreases, the resistance decreases, which is not desirable.

The resistive element also imposes size limitations on the diaphragm and also results in the effect of mean stress and thus endangers sensitivity [14].

Alcheikh et al. investigated a highly sensitive wide-range resonant pressure sensor. They observed that by increasing pressure, the resonance frequency of the third mode decreases until reaching the veering phenomenon. Also, the effect of various parameters on the performance of the proposed pressure sensor has been investigated [15]. Liu et al. studied a new electrode structure. They could investigate its performance by theoretical analysis and COMSOL software [16]. Tahmasebipour and Modarres simulated a highly sensitive piezoresistive differential pressure microsensor. They reported that the sensitivity of the proposed microsensor was increased about 60 times, as compared whit the base model [17].

Barua et al. showed that micro-pumps have a key dynamic role in the control over drug dispensation. They studied principles and developments of MEMS-based drug delivery systems with micro- pumps [18]. In this study, a piezoresistive pressure microsensor with different designs is investigated. With the special design of this pressure microcontroller, high sensitivity is achieved alongside the small dimensions. The high sensitivity of the proposed microsensor is due to the use of single-crystal silicon in the piezoresistors. Also, its small size is due to the use of a silicon surface micromachining process. Then, the mechanical and electrical behavior of different operating conditions is simulated using the finite element method in COMSOL Software.

2. MODEL DEFINITION AND PROBLEM THEORY

The design of the pressure microcontroller discussed in this study is based on the creation of a hermetically sealed cavity (Figure 1).

Construction of this piezoresistive pressure microsensor begins with a Silicon on Insulator (SOI). The conductor layer of this tablet is used as a raw material for piezoresistors. By adding Boron impurities, 5090 cm^{-3} resistors are made of piezo. The amount of Boron impurities in electrical contact points is 808 cm^{-3}. The insulating layer of silicone tablets is used as a sacrificial layer during the manufacturing process [6]. Pressure diaphragm is made of laminated polysilicon by LPCVD method. The thickness of this layer is 1.2 μm. A 100 nm thick silicon nitride insulation layer is used to separate the piezoresistors from the diaphragm.

In addition to electrical insulation, this layer prevents the penetration of Boron impurities in the piezoresistors into the diaphragm. The influence of impurities is extremely undesirable since the structure of the piezoresistors will be emptied of impurities, its measuring factor will change locally. Additionally, impurity penetration into the diaphragm results in piezoelectricity in its polysilicon structure [19]. Furthermore, presence of the insulating layer leads to the reduction of the current leakage in the microsensor.

In conventional pressure microsensors, the p-n bond structure is used to reduce leakage current. This reduces the operating temperature of conventional pressure sensors to 150 °C. In the pressure microsensor discussed in this study, the piezoresistors are isolated from an insulating membrane with an insulating layer. This increases the operating temperature of the microcontroller to 350 °C [3, 9].

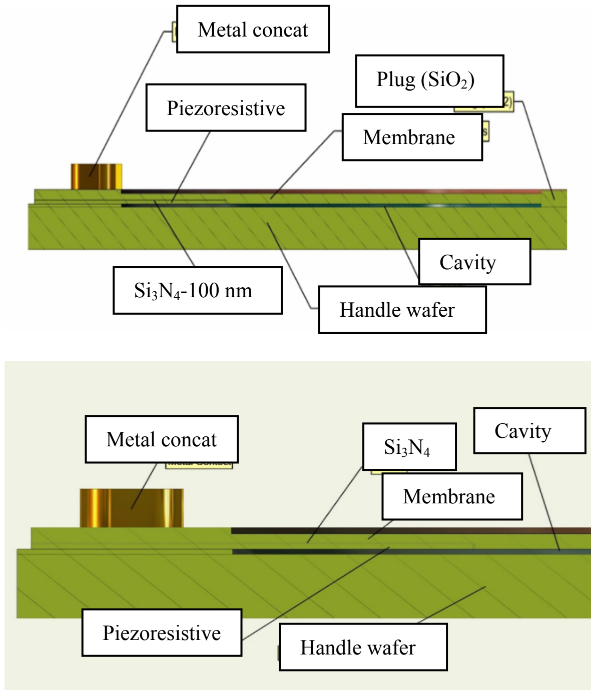

Figure 1. Cross sectional view of the microsensor.

The vacuum chamber pressure of the microsensor is equal to the working pressure of the layered device because it is sealed in this device. As the operating pressure of the device is almost equal to vacuum, the built-in microsensor will be sensitive to atmospheric pressure. After sealing the chamber, the diaphragm will be tightly bound both around and in the center, depending on the subject. Within direct blood pressure measurement applications, non-contact piezoelectric resistance is highly desirable [9]. As shown in Figure 1, in the pressure microsensor discussed, the piezoresistors are protected by a 1.2 μm thick diaphragm layer.

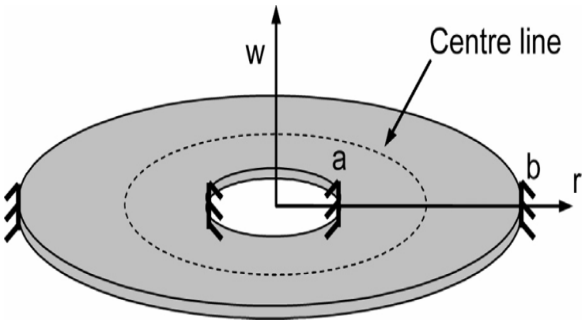

Figure 2. The ring membrane-bound in the center and around [16].

The stress relations governing the ring diaphragm are as follows:

$$\sigma_r = -\frac{192 D w_0}{(a-b)^2 h^2} \qquad (1)$$

$$\sigma_t = -\upsilon \frac{192 D w_0}{(a-b)^2 h^2} \tag{2}$$

$$D = E \frac{h^3}{12(1-\upsilon)^2} \tag{3}$$

In these relations, h denotes the diaphragm thickness, w_0 is the maximal vertical deflection of the membrane, a and b are the inner and outer radius of the diaphragm, respectively. E is Young's modulus, υ is Poisson's coefficient. Equation 1 is related to the Longitudinal and radial stresses on the outer edge of the diaphragm. The change in the conductivity of the piezoresistors located on the outer edge of the diaphragm is dependent on the stress and piezo coefficients:

$$(\frac{\Delta R}{R})_r = \pi_l \sigma_r + \pi_t \sigma_t \tag{4}$$

$$(\frac{\Delta R}{R})_t = \pi_l \sigma_t + \pi_t \sigma_r \tag{5}$$

where, the parameters π_l and π_t are piezo longitudinal and transverse coefficients, respectively. The values of these parameters are calculated by equations (6) and (7) according to the piezo-silicon resistance coefficient π_{44} [19].

$$\pi_l = 0.25 \pi_{44} \tag{6}$$

$$\pi_t = -0.25 \pi_{44} \tag{7}$$

Assuming a uniform distribution of impurities, the value of π_{44} at room temperature is equal to 100×10^{-11} m^2 / N [9].

The sensitivity of the pressure microsensor is calculated by equation (8):

$$S = \left(\frac{\Delta R}{R}\right)_r \frac{1}{\Delta p} \tag{8}$$

where, the parameter Δp is the applied pressure range. The value of this parameter in the present model is 1 atm. Temperature coefficient of sensitivity (TCS) is defined by equation (9):

$$TCS = \frac{\partial S / \partial T}{S} \tag{9}$$

Table 1 shows the geometric dimensions of the microsensor model, and its three-dimensional model is visible in Figure 3. Experimental values of sensor outputs based on the measurements mentioned in reference [9] are given in Table 2.

Table 1. Geometric Dimensions of Pressure Microsensor Model

Parameter	Experimental value
Sensitivity at +20 °C, mV/(V.atm)	24.6
Temperature coefficient of sensitivity (+/−), %/10 °C	−2.0/−3.2
Supply voltage	2.5 V
Working temperature	20 °C
Temperature range	-50 to 60 °C
Pressure range	0 - 100 kPa

Table 2. Experimental values of pressure microsensor

Structure Parameter	Value (μm)
Membrane thickness	1.2
Inner/outer membrane radius	20/80
Gap thickness	0.4
Piezoresistor thickness	0.4
Piezoresistor isolating layer thickness	0.1
Passivation layer thickness	1.2

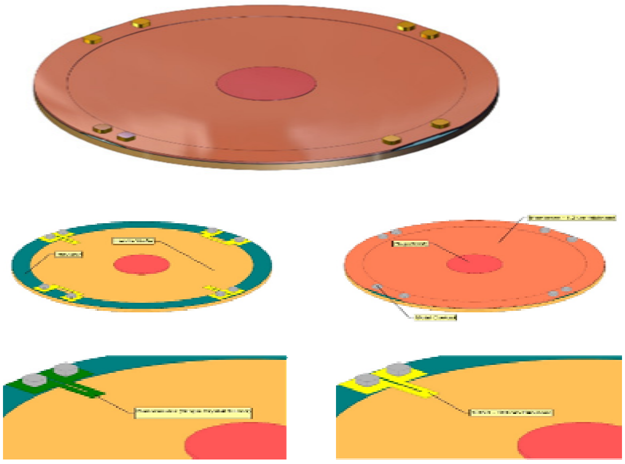

Figure 3. Model of the pressure piezoresistive microsensor.

3. RESULTS AND DISCUSSION

Simulation of pressure piezoresistive microsensor was performed based on the Finite Element Method using COMSOL multiphysics software. The performance of the microsensor was analyzed from three different aspects.

The mechanical behavior of the diaphragm was first evaluated and the stress distribution in the diaphragm was determined. Also, the electrical output of the piezoresistive pressure microsensor was investigated. The sensitivity of the pressure microsensor was determined based on the electrical analysis. In addition to electrical and mechanical analysis, the microsensor behavior at different temperature conditions was investigated. Then, the effect of temperature on the sensitivity parameter was evaluated.

The sensitivity of the piezoresistive pressure microsensor at 100 kPa was 24.03 mV, which is in good agreement with the empirically measured values, as listed in Table 2.

Figure 4 illustrates the von Mises stress at 100 kPa at 20 ^{0}C. It is observed that the von Mises stresses at the diaphragm near the SiO_2 plug as well as at the position of the longitudinal and transverse piezoresistors. The high von Mises stress is due to the low distortion energy (DE) in the area. It should be noted that with the decrease of DE, the fracture phenomenon occurs easily. Figure 5 shows the aperture shape change. As illustrated, the maximum displacement under applied pressure of 100 kPa is equal to 0.16 μm, with the highest deformation observed in the middle regions of the diaphragm.

Figure 6 shows the electrical potential contour and the direction of the electrical charge flow. The strain contours of the microsensor indicate that there is a uniform trend of voltage and current throughout the microsensor and no oscillation is observed in these parameters.

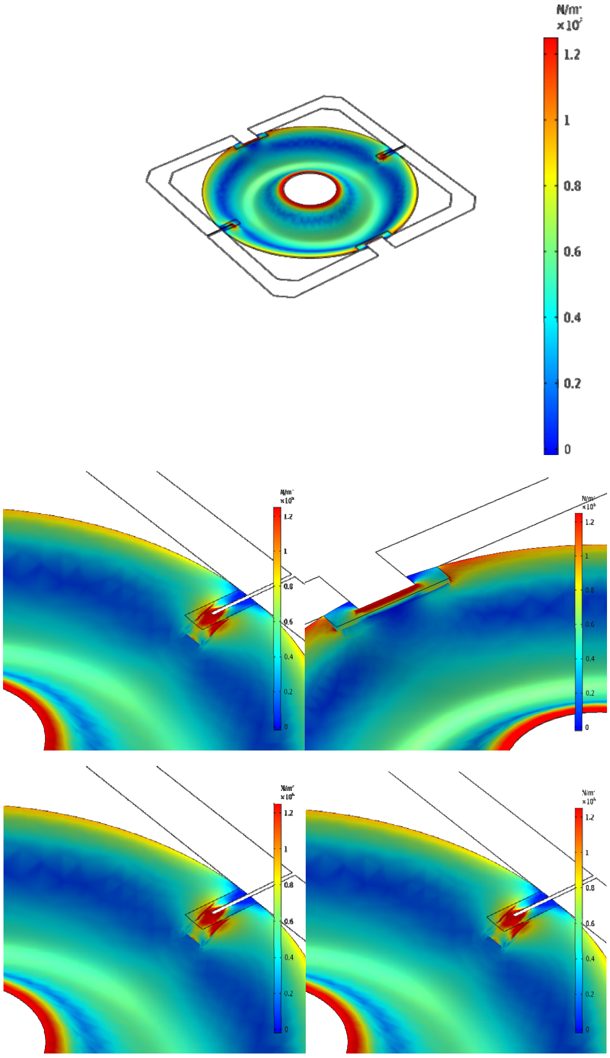

Figure 4. Distribution of stresses in the diaphragm and longitudinal and transverse resistances.

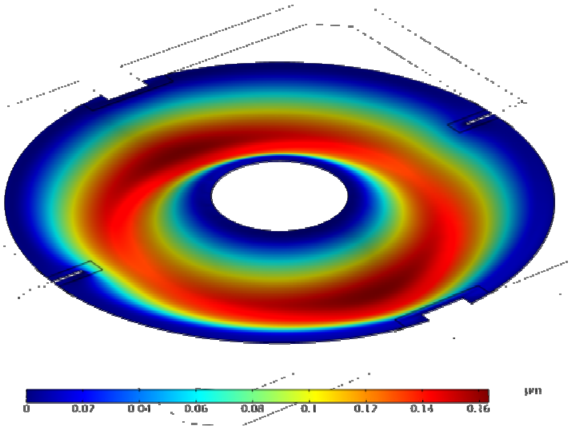

Figure 5. Diaphragm deformation at 100 kPa pressure.

In Figure 7, the influence of temperature on the induced stress is illustrated. Three important temperature points, namely the two endpoints of the operating temperature range (-50 ˚C, 60 ˚C) and standard operating temperature (20 ˚C) were selected for this study. According to Figure 7, it can be seen that at constant pressure, as the temperature increases, the stress on the diaphragm surface decreases and this indicates the high stress distribution at the sides and the middle of the diaphragm at low temperatures such as -50 °C.

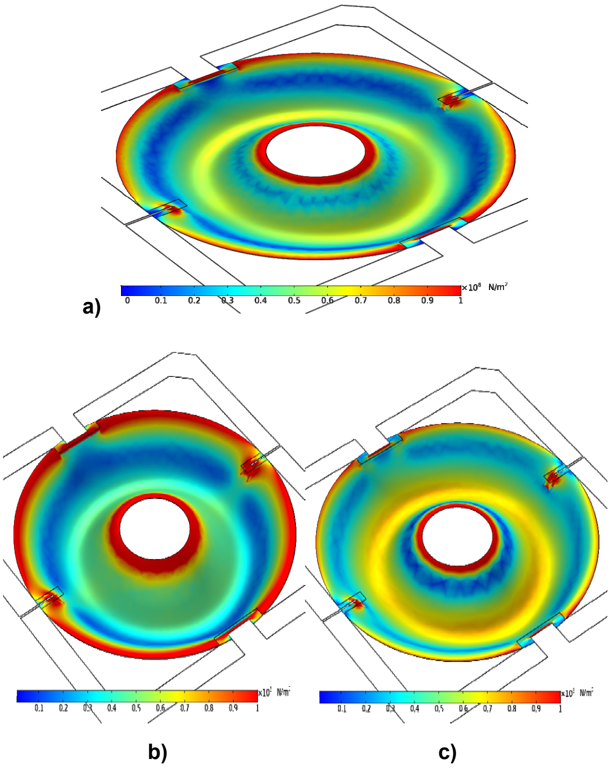

Figure 7. Influence of temperature on the stress distribution in the diaphragm at applied pressure of 100 kPa: (a) standard temperature 20 ˚C, (b) -50 ˚C, and (c) 60 ˚C.

In Figure 8, the influence of temperature on the electrical potential distribution is investigated. The obtained results at different temperatures (at 100 KPa) indicates that temperature variations are not very effective on the potential distribution in the piezoresistor, and at all three temperatures, a similar distribution can be observed.

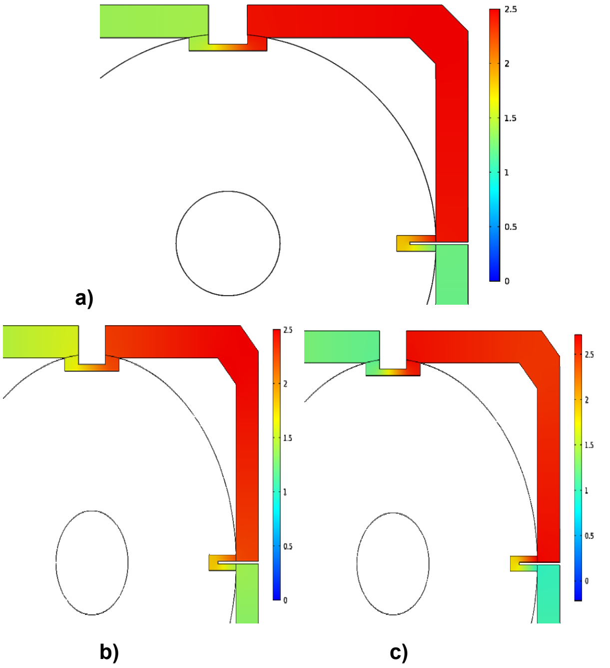

Figure 8. Influence of temperature on the distribution of electrical potentials in piezoresistors at 100 kPa pressure: (a) 20 ˚C, (b) -50 ˚C, and (c) 60 ˚C.

Figure 9 shows the sensitivity variation with applied pressure. The sensitivity of the microsensor at 100 kPa pressure is 24.03 mV/(V.atm), which has 2.3% error with the experimental value. Also, it can be seen that by increasing the pressure from 10 to 100 KPa, the sensitivity of the sensor increases.

Figure 10 shows the thermal coefficient of sensitivity (TCS) in terms of temperature. As the temperature increases from -50 °C to 50 °C, the sensitivity coefficient increases. It is worth noting that in order to derive the temperature dependent data, both the electrical effects of changing the number of current carriers and the mechanical effects of thermal expansion were taken into account.

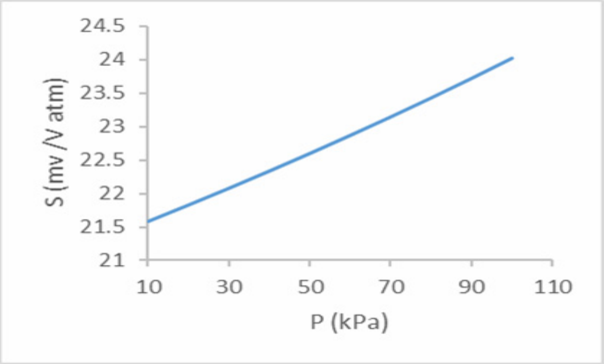

Figure 9. Variation of sensitivity with applied pressure.

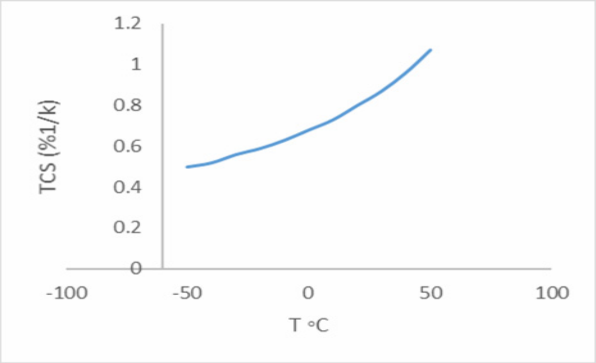

Figure 10. Variation of temperature coefficient of sensitivity (TSC) with temperature.

4. CONCLUSION

In this study, the electro-mechanical behavior of high-sensitive piezoresistor pressure microsensors was simulated by finite element method through COMSOL multiphysics software. Diaphragm deformation at pressure 100 KPa was investigated and the electrical potential distribution in the piezoresistor was evaluated. Also, in order to determine the effect of the temperature sensitivity parameter on the microsensor behavior, different temperature conditions were investigated. Following conclusions were drawn from the present study:

- The maximum displacement of the diaphragm was 0.16 μm (under pressure 100 kPa), with the highest deformation observed in the middle regions of the diaphragm.
- The voltage and current contours revealed that there was a uniform trend of voltage and current throughout the microsensor, and no oscillation was observed in these parameters.
- It was observed that at constant pressure, as the temperature increases, the stress on the diaphragm surface decreases, indicating high stress distribution at the sides and the middle of the diaphragm at low temperatures such as -50 °C.
- The obtained results of the temperature effect on the electric potential distribution demonstrated that temperature variations were not very effective on the potential distribution in the piezoresistor, and at all three temperatures, a similar distribution was observed.
- By increase of the applied pressure (from 10 to 100 KPa), the resistance of the piezoresistor was decreased, while, the sensitivity was increased. The sensitivity of the microsensor at 100 kPa pressure was 24.03 mV/(V.atm), which has 2.3% error with the experimental value.
- Variation of the temperature coefficient of sensitivity (TSC) with temperature indicates that as the temperature increases from -50 °C to 50 °C, the sensitivity coefficient increases.

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МУЛТИФИЗИЧКА СИМУЛАЦИЈА ПОНАШАЊА ПИЕЗООТПОРНОГ МИКРОСЕНЗОРА ПРИТИСКА КОРИШЋЕЊЕМ МЕТОДЕ КОНАЧНИХ ЕЛЕМЕНАТА

Ф. Пашмфоруш

Извршена је симулација електро-механичког понашања специјално пројектованог високо осетљивог пиезоотпорног микросензора притиска применом ФЕМ методе преко COMSOL мултифизичког софтвера. Евалуација механичке деформације дијафрагме и дистрибуције електричног потенцијала код пиезорезистора извршена је за различите вредности притиска. Истражени су различити температурски услови у циљу одређивања утицаја параметра температурне осетљивости. Резултати показују да са порастом притиска отпор пиезорезистора опада док осетљивост расте. При константном притиску са порастом температуре опада напон на површини дијафрагме, што показује да је велика дистрибуција напона на страницама и у средини дијафрагме, при ниској температури -50^0C. Температурне варијације нису имале великог утицаја на дистрибуцију потенцијала код пиезорезистора. Међутим, коефицијент температурне осетљивости има тенденцију пораста са порастом температуре од -50^0Ц до 50^0C.