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STUDY OF THE IMPACT OF THERMAL DRIFT ON RELIABILITY OF PRESSURE SENSORS

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Abstract

Piezoresistive pressure sensors, using a Wheatstone bridge with the piezoresistors, are typically supplied with a voltage ranging from 3 to 10 V involve thermal drift caused by Joule heating. In this paper, an accurate numerical model for optimization and predicting the thermal drift in piezoresistive pressure sensors due to the electric heater in its piezoresistors is adopted. In this case, by using the solution of *2D* heat transfer equation considering Joule heating in Cartesian coordinates for the transient regime, we determine how the temperature affects the sensor when the supply voltage is applied. For this, the elevation of temperature due to the Joule heating has been calculated for various values of supply voltage and for several operating times of the sensor; by varying different geometrical parameters. Otherwise, the variation of the coefficient π_{44} in *p-Si* and pressure sensitivity as a function of the applied potential, as well as, for various times, for different dimensions of the device, have been also established. It is observed that the electrical heating leads to an important temperature rise in the piezoresistor. Consequently, it causes drift in the pressure sensitivity of the sensor upon application of a voltage. Finally, this work allows us to evaluate the reliability of sensors. Also, it permits to predict their behaviour against temperature due to the application of a voltage of a bridge and to minimize this effect by optimizing the geometrical parameters of the sensor and by reducing the supply voltage.

Keywords: Sensitivity, Temperature effect, Joule heating, Finite difference method, Pressure sensors.

1. Introduction

Piezoresistive pressure sensors based on Silicon have the advantages of excellent linearity of electrical response, high sensitivity, good technological compatibility,

Nomenclatures

A_{pzr}	Cross sectional area, m^2
a	Length of membrane, m
C	Specific heat of silicon, J/kg °C
C_{th}	The thermal capacitance, J/°C
d	Thickness of membrane, m
h	Heat transfer coefficient, W/m^2 °C
K	Thermal conductivity, W/m °C
L_{pzr}	Length of piezoresistor, m
R	Resistance, Ω
R_{th}	Thermal resistance , °C /W
S	Sensor sensitivity, V/V/Pa
T	Temperature, °C
t	Time, s
V_0	Voltage, V

Greek Symbols

ρ	Mass density, kg/m^3
ρ_e	Electrical resistivity, Ω·m
α	Thermal diffusivity, m^2/s
π_{44}	Piezoresistive coefficient, Pa^{-1}
τ	Thermal constant, s

Abbreviations

CMOS	Complementary metal oxide semiconductor
FDM	Finite Difference Method
MEMS	Microelectromechanical systems
SPICE	Simulation program with integrated circuit emphasis

small size, low power, mass production and some other advantages [1-4]. Nevertheless, they often suffer from the temperature drift.

The study of the thermal behaviour of these sensors is necessary so as to determine the parameters that cause the output characteristics drift. The knowledge of the phenomena causing its thermal drift, presents a particular interest. The Joule heating in piezoresistive microcantilever sensors was indicated by Ansari and Cho [5]. Their approach bases on the analytical and numerical techniques to characterize the Joule heating in such microcantilevers. They developed a theoretical model for predicting the temperature produced by the Joule heating. The same authors have introduced a simple and accurate conduction–convection model to predict the temperature distribution in p-doped piezoresistive microcantilevers because of self-heating [6].

The thermomechanical modeling of a piezoresistive pressure sensor has been studied previously [7]. Recently, Beddiaf et al. [8], the thermal effects of capacitive pressure sensor due to the temperature taking into consideration the geometric shape, the materials’ properties and also the heat transfer mechanisms, using Finite Element Analysis (*FEA*) established in COMSOL are investigated. An analytical model to study the self heating in the piezoresistive pressure sensors with circular shape of membrane has been developed by Pramanik et al. [9]. Their analysis focuses on the development of the *SPICE* compatible thermal model of Silicon *MEMS* piezoresistive pressure sensor for *CMOS-MEMS* Integration. However, the sensitivity of the piezoresistor to the stresses of the square-shaped membrane sensors is greater than in circular form with the thicknesses of the upper membrane about 2 µm. On the other hand, when the temperatures rise from room temperature to 100 °C, the sensitivity of both sensors may be reduced by about 15%. Moreover, at the same temperature and characteristic length, square-shape diaphragms are more sensitive than circular ones [10]. For these considerations and some applications such as aviation that requires great pressure sensitivity and the capacity to the resistance to overload, the sensors are generally made using square or rectangular membranes [11].

Piezoresistive pressure sensors, using a Wheatstone bridge with the piezoresistors, are typically used with a supply voltage ranging from 3 to 10 V involve thermal drift caused by Joule heating. The present work aims to study the effects in these sensors with a square-shaped membrane. The study involves the solution of heat transfer equation considering the conduction in Cartesian coordinates for the transient regime using Finite Difference Method. Further, the paper seeks to explore the geometric influence parameters on these characteristics to optimize the sensors performance. The increase in temperature due to the Joule heating has been computed for various geometrical parameters of the sensor as well as for several operating time. The evolution of the piezoresistvie coefficient π_{44} in *p-Si* and pressure sensitivity have been calculated for several values of supply voltage and for various times, by varying some geometrical parameters of sensor.

2. Theory

In a pressure sensor, as shown in Fig. 1, the resistors are placed in the medium of the edges of the membrane such that two are parallel at edges and the other two are perpendicular. These piezoresistors are joined in a bridge configuration and attached to the bond pads for circuit interconnection. These pairs exhibit resistance changes opposite to each other.

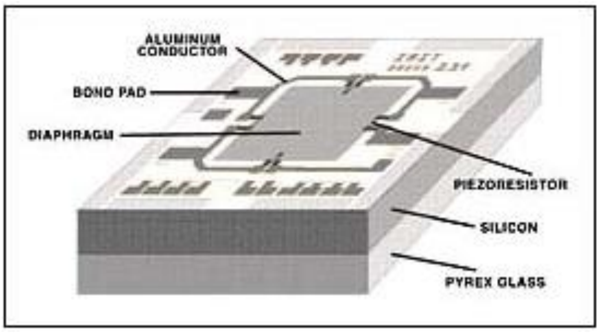

Fig. 1. Image showing piezoresistive pressure sensor.

In this work, it is considered that the Joule heating as the only energy conversion, neglecting the other heat transfer modes such as the convection and radiation. The variation of temperature due to Joule heating, considering the heat transfer by conduction in the piezoresistive pressure sensors, is shown in Fig. 2.

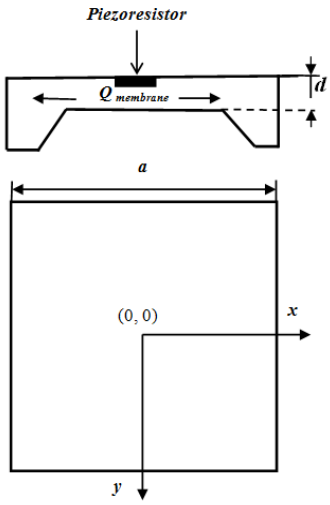

Fig. 2. Piezoresistive pressure sensor structure with heat transfer path.

The heat conduction equation predicting the Joule heating on the piezoresistive pressure sensor considering its two-dimensional form in Cartesian coordinates for transient regime and including thermal energy generation is given by [5, 12]

$$\Delta T(x,y,t)+\frac{q}{k}=\frac{1}{\alpha}.\frac{\partial T(x,y,t)}{\partial t} \tag{1}$$

where q is heat flux, k is thermal conductivity, $\alpha = k/\rho C$ is thermal diffusivity and t is the time. The rate of energy generation by Joule heating is expressed by:

$$q=\frac{V_0^2}{Rda^2} \tag{2}$$

where V_0 is applied electrical potential, d is the thickness of membrane, a is the length of the square-shaped diaphragm and R is the resistance of the diffused piezoresistor, given by the following expression [5]

$$R=\rho_e\frac{L_{pzr}}{A_{pzr}} \tag{3}$$

where L_{pzr} is the length of the piezoresistor, A_{pzr} the cross-sectional area and ρ_e is the electrical resistivity. The initial condition in the all structure is:

$$T(x,y,t)\big|_{t=0}=T_0 \tag{4}$$

The applicable boundary conditions include the adiabatic heat condition and maintain the heat continuity at the edges which are:

$$\begin{cases}\left.\dfrac{\partial T}{\partial x}\right|_{x=0}=0\\ \left.\dfrac{\partial T}{\partial y}\right|_{y=0}=0\end{cases} \tag{5}$$

3. Finite Difference Model Validation

As before noted, this study is devoted to the thermal behavior of the sensors. So, the proposed computational method is based on the Finite Difference Model (*FDM*). The *2D* heat conduction equation in transient regime is discretized using the *FDM* and the obtained system of linear equations is solved by the Thomas algorithm using the Matlab calculation software.

In order to validate the numerical model, the *2D* solution of the heat conduction equation for the transient regime by *FDM* is compared with the analytical model for the resolution of the heat conduction equation assumed one-dimensional and steady state case [5]. The results of the change in temperature as function of voltage for *t*=100 min (case where the temperature is independent of time) is compared with those of the analytical model [5]. According to the Fig. 3, it can be noticed that the results are in good agreement. The comparison of the obtained results allows us to validate the *FDM* model.

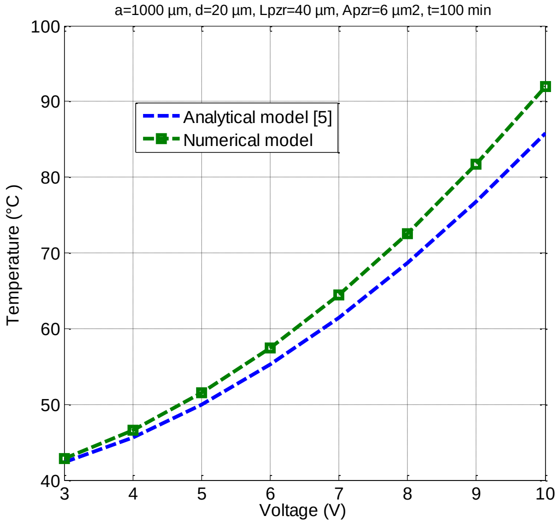

Fig. 3. Temperature rise versus voltage.

As previously mentioned, the thermal drifts provoked by Joule heating in piezoresistive pressure sensors affect greatly the performance of such sensors. This research paper is focused in the study of this thermal drifts in this sensors type. As known, the geometric influence parameters on the rise of temperature have an enormous impact. It is necessary to study the geometric influence parameters on these characteristics to optimize the sensors performance. For simulation, the material properties of Silicon used in this work are [5, 6]: Mass density, ρ =2320 kg/m^3, Heat transfer coefficient, h =2.219 W/m^2 °C, Thermal conductivity, K= 150 W/m °C and Specific heat, C =712 J/Kg °C.

4. Results and Discussions

Since the thermal drifts generated in the pressure sensors by Joule heating influence its optimum response, it is necessary to minimize and optimize these drifts by optimizing his geometric parameters.

4.1. Applied voltage effect on temperature rise's

To see the effect of applied voltage on the temperature generation in the piezoresistive pressure sensors, the thickness of the diaphragm and the length of the membrane are varied. Based on the results shown in Fig. 4, the temperature variation is represented according to the applied voltage for different values of the thickness *d*. The $T(V_0)$ goes on decreasing as the Silicon membrane thickness is increased. Therefore, according to earlier studies [7, 8, 11], this leads to weakening the pressure sensitivity of the sensors.

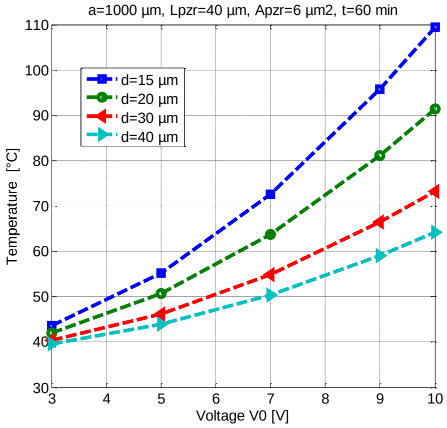

Fig. 4. Effect of bias voltage on the rise of temperatures for several membrane thicknesses *d*.

To highlight the effect of the length of the diaphragm, we plot in Fig. 5, the temperature variation vs. the applied voltage for several values of the diaphragm *a*. It is observed that the temperature rise generated by the Joule heating in piezoresistive pressure sensors is a decreasing function of the side length of *a*. So, to reduce this effect, it is required to have a large side length. This solution is easy to establish and does not affect the pressure sensitivity. However, it leads to the enlargement of the size of the sensors, which is a disadvantage.

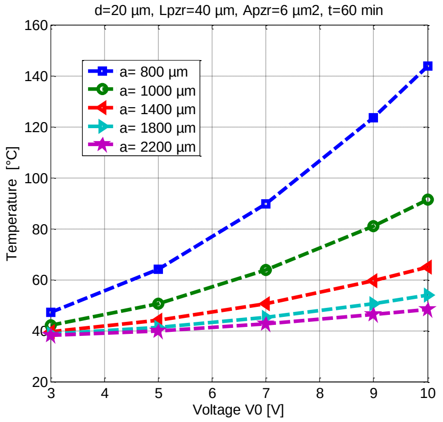

Fig. 5. Effect of bias voltage on the rise of temperatures for several side lengths *a*.

4.2. Variation of temperature as a function of time

In order to acknowledge the evolution of the temperature created by joule heating for a period of 3 hours, the temperature rise is analyzed by varying several geometrical parameters. It has been found in Fig. 6 that the temperature takes a steady state value and the temperature rise goes on decreasing as the length of the diaphragm is increased. This suggests that the time constant of the structure goes on increasing, suggesting that, longer of the side length of the diaphragm, larger will be the time taken by the temperature to achieve its steady state value. Also, it is observed in Fig. 7 that greater the thickness of the Silicon diaphragm, lesser is the Joule heating. Nevertheless, to increase the pressure sensitivity, thickness of the diaphragm must be reduced. According to these Figs. 6 and 7, the two parameters have an enormous effect on the Joule heating. So, when these parameters are great, this is leading to lessen the Joule heating. However, these parameters are themselves limited by: the dimensions of the device, the precision and reliability.

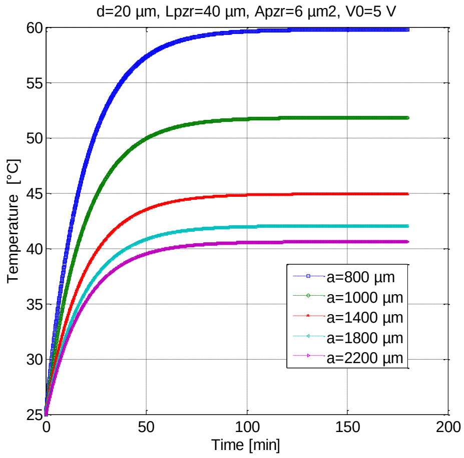

Fig. 6. Temperature rise for different membrane side lengths.

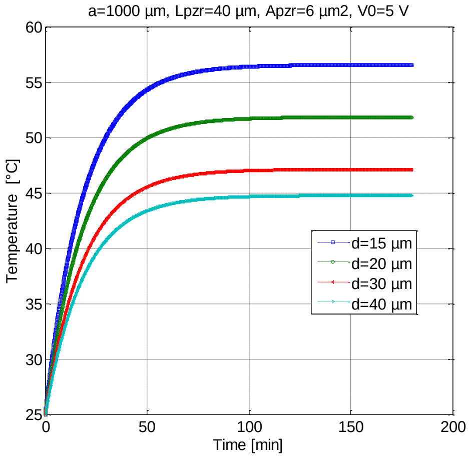

Fig. 7. Temperature rise for several membrane thicknesses *d*.

It is found that the curves of Figs. 6 and 7 are analogous to the circuit constituting the loading of a capacitor connected to a voltage source through a resistor. In this case, a correspondence between the temperature T and the voltage across the capacitance can be made. So, an empirical relationship between the rise in temperature and operating times using Figs. 6 and 7 is obtained

$$T(t) = T_f(1 - e^{-t/\tau}) + T_0 e^{-t/\tau} \tag{6}$$

where T_f is a constant, its values are got from the empirical relationship deduced from Figs. 6 and 7. τ is the time constant of the thermal system which given by

$$\tau = R_{th} C_{th} \tag{7}$$

where R_{th} and C_{th} respectively represent the thermal resistance and the thermal capacity.

The thermal resistance R_{th} (°C /W) is defined as the temperature rise at steady state given by

$$R_{th} = \frac{T_f - T_0}{Q} \tag{8}$$

where C_{th}, the thermal capacitance, is expressed by (J/°C), obtained from the time constant and the thermal resistance.

4.3. Piezoresistive coefficient π_{44}

4.3.1. Effect of applied voltage in π_{44}

The knowledge of π_{44} representing the piezoresistive effect when the stress is applied, is used to quantify the changes in electrical grandeur, induced by the applied stresses.

The basic conclusion of Kanda's work is that the piezoresistive coefficient obeys to the following relation [13]

$$\pi_{44}(N,T) = \pi_{44}(N_0, 300K) P(N,T) \tag{9}$$

By coupling the temperature variation as a function of applied voltage from the used model Eq. (6) with Kanda's Eq. (9), we obtain the variation in piezoresistive coefficient for the p-type Silicon (doping concentration N=3.10^{18} cm^{-3}) as a function of voltage. Note that the p-type piezoresistors have a larger sensitivity. This makes p-type piezoresistors well-suited for full-bridge applications.

Boukaabache [11] demonstrated that the temperature decreases the piezoresistive coefficient π_{44}. It is known from the previous results that the temperature rises by increasing the bias voltage of the Wheatstone bridge. The π_{44} accordingly decreases with increasing voltage, as shown in Figs. 8 and 9. It can be easily seen from these Figs. 8 and 9 that the π_{44} is a decreasing function with the applied voltage. It is also observed that this coefficient is proportional to the geometric parameters of the membrane.

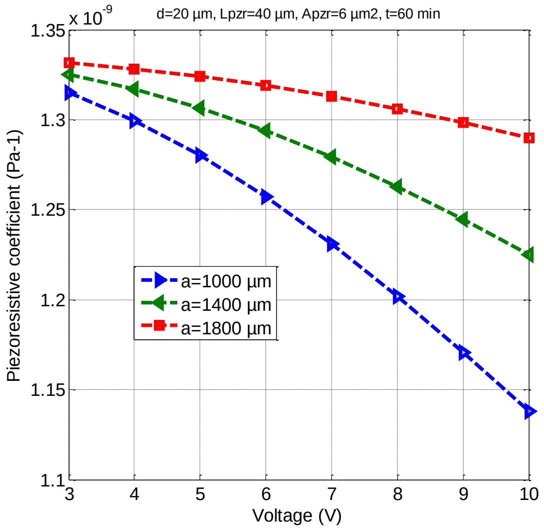

Fig. 8. Variation of π_{44} as a function of applied voltage for different *a*.

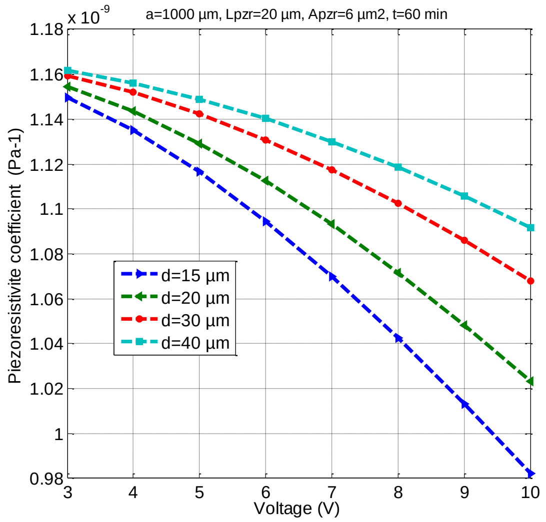

Fig. 9. Variation of π_{44} as a function of applied voltage for different *d*.

4.3.2. Variation of π_{44} as a function of *t*

The strong dependence of this coefficient to the temperature has prompted us to take stock of its variations as function of time to optimize the increase in temperature due to Joule heating during the use of sensor for an prolonged time. Figures 10 and 11 show that the piezoresistive coefficient is a decreasing function of time, this decrease is due to electrical heating in the piezoresistors, which will influence the pressure sensitivity and the sensor response. Therefore, this coefficient is an increasing function of the diaphragm dimensions.

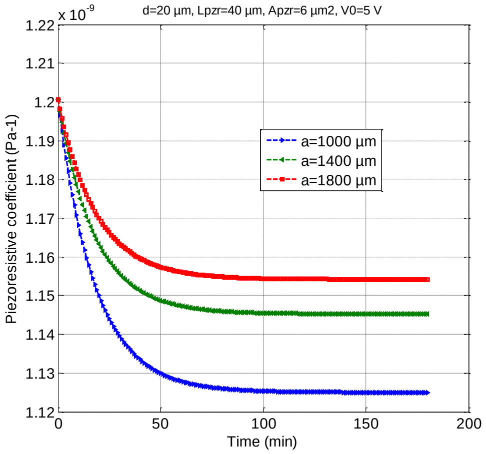

Fig. 10. Variation of π_{44} as a function of time for different *a*.

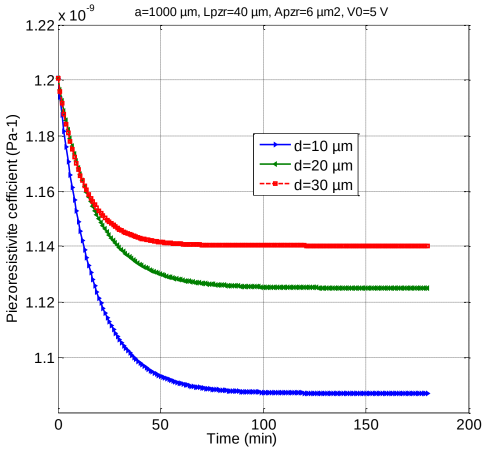

Fig. 11. Variation of π_{44} as a function of time for different *d*.

4.4. Pressure sensitivity

The performance of a piezoresistive pressure sensor in terms of sensitivity is of very important. The sensitivity of these sensors is a key feature to define and to optimize their performance. In the middle of the edge of the square-shaped membrane of length *a* and thickness *d*, the sensitivity of the piezoresistor is defined by [11]

$$S = 0.1479\pi_{44}(a/d)^2 \tag{10}$$

4.4.1. Effect of applied voltage in the pressure sensitivity

The coefficient of the piezoresistivity varies on function of the voltage. Sensitivity is related to π_{44} by the Eq. (10). Thus, it is dependent on the applied voltage. The power source of the Wheatstone bridge is an electrical parameter which can causes the non-idealities of piezoresistive pressure sensors. This parameter causes a rise in temperature. This latter will influence on the measurement accuracy by minimizing the pressure sensitivity of the sensor. We may note that the sensitivity decreases almost linearly with the bias voltage (Figs 12 and 13). Moreover, the variation of the sensitivity as a function of the length of the membrane is in sharp increase. However, it is inversely proportional to the thickness of the membrane.

The geometrical parameters play an important role in optimizing the sensor sensitivity by minimizing the thermal drift generated when the bridge supply by a voltage source.

Therefore, to increase the sensitivity, it is necessary to have a large length of the membrane. This option is easy to implement. However, it gives large size defect, which is a drawback.

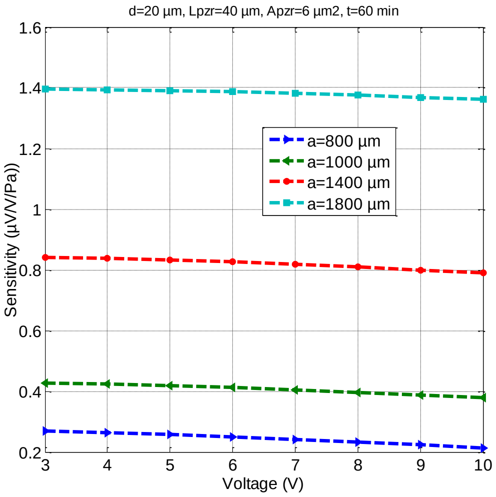

Fig. 12. Variation of sensitivity as a function of applied voltage for different *a*.

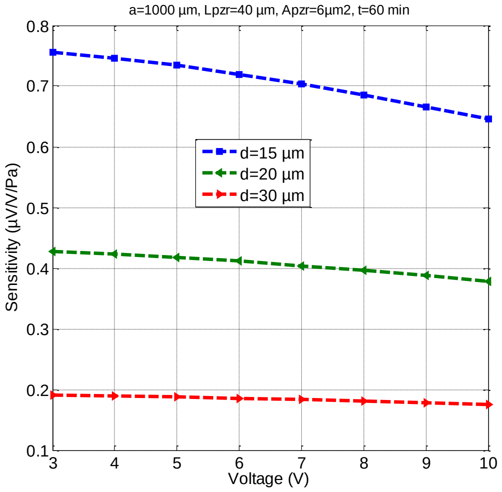

Fig. 13. Variation of sensitivity as a function of applied voltage for different *d*.

4.4.2. Variation of pressure sensitivity as a function of *t*

In order to acknowledge the Joule heating in the response of the sensor, the pressure sensitivity have been calculated for different operating time, by varying some geometrical parameters. It has been found in Figs. 14 and 15 that the sensitivity goes on decreasing function of time and beyond 100 min the pressure sensitivity assumes a steady state value. Also, it is observed that greater the length of the diaphragm, the sensitivity increases.

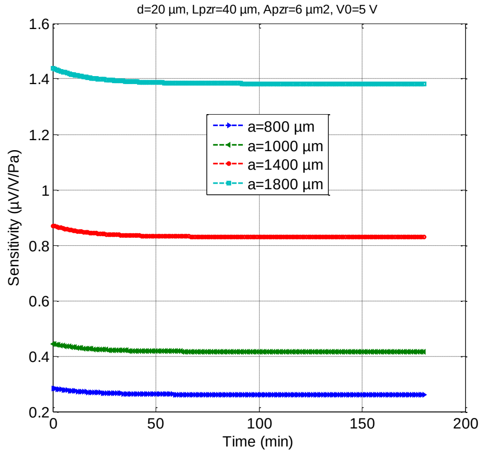

Fig. 14. Variation of sensitivity as a function of time for different *a*.

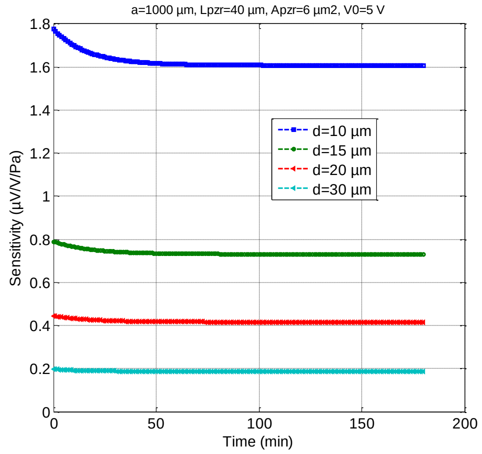

Fig. 15. Variation of sensitivity as a function of time for different *d.*

5. Conclusion

At the end, this work has demonstrated that it is possible to model, with good precision, the impact of Joule heating in a piezoresistive pressure sensor, with a square-shaped membrane, using Finite Difference Method (*FDM*).

- The choice of the square-shaped membrane sensors is justified by its optimal response (high pressure sensitivity).
- The model established gives an opportunity to study the temperature rise caused by Joule heating of sensors characteristics. We attempted to study the geometric influence parameters on these characteristics to optimize the sensor performance.
- Results showed that low bias voltage should be applied for reducing Joule heating. They also show that the temperature change is proportional to the applied voltage.
- The Joule heating goes on decreasing as the membrane thickness is increased. But, this affects greater the pressure sensitivity of the device.
- In addition, the temperature rise created by Joule heating in sensors is a decreasing function of the side length of the membrane. So, to minimize this effect, it is necessary to have a large side length. This option is easy to implement and does not affect the sensitivity to pressure. However, it gives large size defects, which is a drawback.
- To highlight the effect of the operating time of the device, some geometrical parameters have been used. The results showed that Joule heating is reduced substantially for a short operating time.
- Therefore, to know the influence of supply voltage in the piezoresistive coefficient and pressure sensitivity for several operating times of the sensor, a few geometrical parameters have been varied. The obtained results showed that the two parameters goes on decreasing function with increasing a supply voltage.
- The obtained results allow us to optimize the pressure sensitivity of sensors by optimization the geometrical parameters.
- Finally, these sensors types can be used for a biomedical application. It will be inserted in the soles of a shoe allows us the measure of a diabetic foot pressure. This applied pressure is transformed into a voltage by a display system which consists of a piezoresistive pressure sensor that indicates its reply through a display circuit (*LED*).

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