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# Numerical Investigation Including Mobility Model for the Performances of Piezoresistive Sensors

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In this work, we present an analysis based on the study of mobility, which is a very important electrical parameter of a piezoresistor and which is directly bound to the piezoresistivity effect in the piezoresistive pressure sensor. We determine how temperature affects mobility when an electrical potential is applied. For that end, a theoretical and numerical approach based on mobility in *p*-type Silicon piezoresistor and a finite difference model (FDM) for self-heating has been developed. So, the evolution of mobility has been established versus time for different doping levels and with temperature rise using a numerical model combined with that of mobility. Furthermore, it has been calculated for some geometric parameters of the sensor such as membrane side length and its thickness. Also, it is computed as a function of bias voltage. It was observed that mobility is strongly affected by the temperature rise induced by the applied potential when the sensor is actuated for a prolonged time. As a consequence, there is a drift in the output response of the sensor. Finally, this work makes it possible to predict their temperature behavior due to self-heating and to improve this effect by optimizing the geometric properties of the device and by reducing the voltage source applied to the bridge.

**Keywords:** Sensors, Piezoresistivity, Mobility, Bias voltage.

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## 1. INTRODUCTION

For these exceptional performances, such as linearity, great sensitivity to pressure, and its small size. The piezoresistive pressure sensor is the most widespread among pressure sensors, which makes it the most widely used in many areas [1-6]. Nevertheless, their major drawback is the temperature drifts [7-11], especially those generated by self-heating due to the applied electrical potential. The study of bias voltage effect in these sensor types is important to optimize the output characteristics drift. Accordingly, numerous research papers have been realized in this field in order to reduce this effect [12-15]. Briefly, the influence of supply voltage and the geometric properties of a piezoresistor on temperature distribution, thermal deflections and thermal stress characteristics in piezoresistive microcantilever sensors was proposed by Zahid et al. [12]. In their work, they used analytical and numerical models to characterize the internal heating in such microcantilevers. As a consequence, we have previously adopted a numerical model of self-heating in piezoresistive pressure sensors [13, 14]. We studied the impact of thermal drift on pressure sensitivity of these sensors. The obtained results permit to improve the sensitivity and it too permit to estimate the reliability of sensors. Next, the doping effects on the temperature environment behavior of a Silicon resistor are studied using several models of hole mobility by Boukabache et al. [15]. In this paper, we present a theoretical and numerical investigation founded on a mobility model in *p*-type Silicon piezoresistance with that of *FDM* technique for internal heating, to optimize the effect of bias voltage on the piezoresistivity in pressure sensors. For this we have coupled the finite difference model of electric heater with that of Arora mobility. The evolution of mobility with operating times of sensors has been computed for several doping levels, as well as, for temperature produced by self-heating. Further, the study seeks to explore the parameters influencing mobility to optimize the response of the device.

## 2. THEORY

Many physical, electrical or geometric parameters can cause the non-idealities of piezoresistive pressure sensors. One can cite the temperature generated by self-heating when these devices are powered by a voltage source as a physical and electrical parameter [13, 14]. These parameters have a considerable influence on the accuracy of the measurement by minimizing the pressure sensitivity of the sensor [14-18]. This study emphasizes the influence of these parameters on mobility when a supply voltage is applied and, consequently, on the output characteristics of the sensor. Mobility is a fundamental physical parameter that conditions the operation of electronic components such as sensors [19]. In this research we are interested in the effect of self-heating on the mobility in pressure sensors.

In this case, we neglect the other modes of heat transfer, and we only consider conduction as the only mode of thermal energy transfer as shown in Fig. 1.

Mobility in piezoresistor is greatly affected by temperature; specifically, that induced by internal heating effect, when the bias voltage is applied to the sensor. This effect is governed by the following equation [12]:

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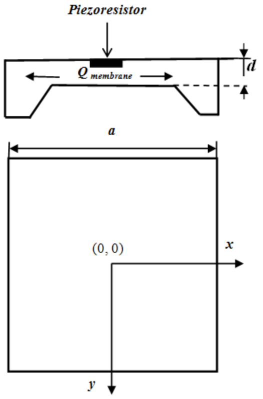

**Fig. 1** – Piezoresistive pressure sensor structure with heat transfer path

$$-k\nabla^2 T(x,y,t) = -\rho c\frac{\partial T}{\partial t} + Q\ , \tag{1}$$

where $k$ is the thermal conductivity, $Q$ is the heat flux, $\rho$ is the mass density, $t$ is the time, and $C$ is the specific heat. Otherwise, the rate of energy production by self-heating is given by the following expression [12, 13]:

$$Q = \frac{A_{pzr}}{L_{pzr}\cdot d\cdot S_m}\frac{V_0^2}{\rho_e}\ , \tag{2}$$

where $V_0$ is the electrical potential, $d$ is the membrane thickness, $S_m$ is the square-shaped diaphragm area, $L_{pzr}$ is the length of the piezoresistance, $A_{pzr}$ is the cross-sectional area, and $\rho_e$ is the electrical resistivity.

In this section, a 2D solution of the heat transfer equation considering the conduction in cartesian coordinates for the transit state is developed by the FDM. The initial condition in all structure is:

$$T(x,y,t=0) = T_0\ . \tag{3}$$

The boundary conditions including the adiabatic heat condition and conserving the heat continuity at the edges are:

$$\frac{\partial T}{\partial x} = \left.\frac{\partial T}{\partial y}\right|_{x=y=0} = 0\ . \tag{4}$$

After discretization of this equation by the latter, we obtained a system of linear equations which is solved by the Thomas method using MATLAB. As part of the reliability studies of these sensors, we focused on the thermal drifting in mobility during their operating time. So, we use the Arora mobility model formula given by [20]:

$$\mu(T) = \mu_{mn}\frac{\mu_{0n}}{1+\left(\dfrac{N_A}{N_{cn}}\right)^{\theta}} \tag{5}$$

where $\mu_{mn}$ is the minimum mobility, $\mu_{0n}$ is the difference between the maximum and minimum values of mobility, $N_{cn}$ the concentration reference, and $\theta$ is an exponential factor. The final mobility expression is:

$$\mu(T) = 88\left(\frac{T}{300}\right)^{-0.57}\left(\frac{1250\left(\dfrac{T}{300}\right)^{-2.33}}{1+\left(\dfrac{N_A}{1.26\times10^{17}\left(\dfrac{T}{300}\right)^{2.4}}\right)^{0.88\left(\frac{T}{300}\right)^{-0.146}}}\right). \tag{6}$$

## 3. RESULTS AND DISCUSSION

As we have pointed out already, in general, piezoresistive sensors have an important shortcoming in form of thermal drifting particularly those due to bias voltage of the device [12, 14]. So, the temperature rise produced by self-heating in a piezoresistor affects strongly the performance of such sensors. This paper aims to put emphasis in the study of the geometrical and physical influence parameters on mobility. This involves the numerical resolution of heat transfer equation in variable regime and in cartesian coordinates. Its solution can be written as follows:

$$T(t) = T_m(1-e^{-t/\tau}) + T_0\ , \tag{7}$$

where $T_m$ and $\tau$ are the constant and the thermal time constant. Noted that, the validation of the results of a numerical model for self-heating can be found in our recent work [14]. Afterwards, the mobility variations with the physical, electrical and geometrical parameters are obtained by coupling the temperature expression (Eq. (7)) with Arora's mobility formula (Eq. (6)).

### 3.1 Effect of Temperature Rise and Operating Time on Mobility

In this section, we will establish the evolution of mobility according to the operating time of the sensor for various concentrations and for temperature created by the internal heating. As we can see in Fig. 2 and Fig. 3, after operation of the device for a period of up to 180 min and under a voltage of 5 V, the mobility is a decreasing function with time and with doping level, as well as with temperature. Mobility is improved for a short operating time on the one hand and for a low doping concentration on the other hand.

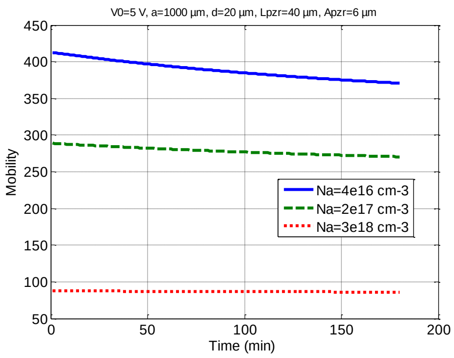

**Fig. 2** – Variation of mobility in operating time for several doping levels

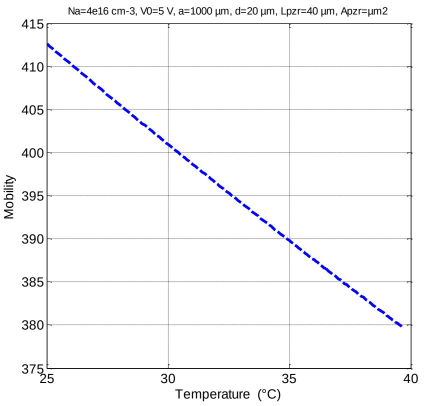

**Fig. 3** – Variation of mobility with temperature provoked by self-heating

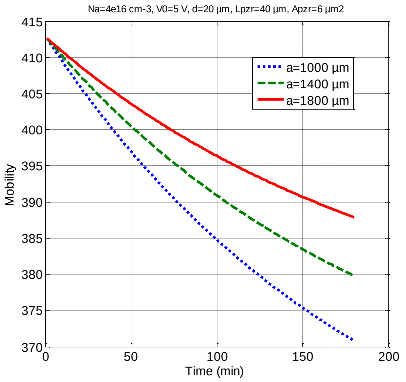

**Fig. 4** – Variation of mobility as function of time for various diaphragm side lengths

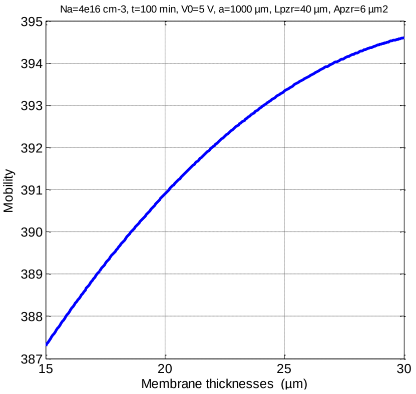

**Fig. 5** – Mobility variation with membrane thicknesses

### 3.2 Effect of Geometric Parameters of the Membrane on Mobility

To highlight the effect of the geometric parameters of the structure such as thickness and side length of the membrane on mobility, we have plotted their evolutions in Fig. 4 and Fig. 5. For a bias voltage of 5 V, there is a decrease in mobility as a function of the operating time of the device as shown in the following figure (Fig. 4). On the contrary, it increases with the width of the membrane and with its thickness. However, these two parameters are themselves constrained by other manufacturing technological factors. These factors include device sizing, manufacturing accuracy, and reproducibility. In addition, the large size of the device leads to a reduction in pressure sensitivity.

### 3.3 Effect of Applied Voltage in Mobility

The knowledge of mobility evolution when the electric tension is applied is used to quantify the output characteristic from the thermal drifting. Knowing that mobility depends on the temperature, it is obvious that the four piezoresistors of the pressure sensor also depend on it. Therefore, it certainly depends on the electrical bias voltage. Combining the numerical model of self-heating with that of Arora we find the mobility versus supply voltage. As we can notice in Fig. 6, the highest mobility corresponds to a low applied potential. As a result, for height values of mobility the applied voltage must be low.

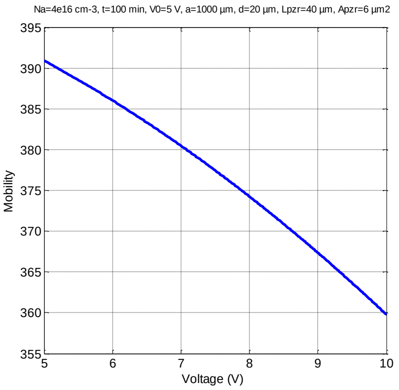

**Fig. 6** – Evolution of mobility with electric potential

## 4. CONCLUSIONS

In the end, this research paper is a contribution to improve the thermal drifts in piezoresistive pressure sensor when the bridge is powered by electrical tension using the numerical model of self-heating with that of Arara mobility. Thus, the effect of temperature rise, operating time and doping levels on mobility was established. So, to ameliorate the mobility against temperature rise caused by an electric heater the sensor should be used in a short time and its piezoresistors must be slightly doped. Then, we have investigated the impact of geometric parameters of membrane on mobility. The results show that, the higher the geometric parameters are, the greater the mobility will be. However, this leads to lessen the pressure sensitivity on one side and gives a large size of sensor in the other side.

Moreover, since mobility decreases with increase in temperature, low bias voltage will be helpful for reducing the electrical heating effect on it.

To summarize, the drifting effects caused by self-heating in output characteristics of sensors can be lessened by applying low supply potential. Thus, when the geometric parameters are great. It can be equally reduced as a high doping level as possible is used. Noted that, these parameters are themselves restricted by the dimensions of the device, the sensitivity and reliability.

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## Чисельне дослідження, що включає модель мобільності для продуктивності п'єзорезистивних датчиків

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У роботі ми представляємо аналіз, заснований на дослідженні рухливості, яка є дуже важливим електричним параметром п'єзорезистора і безпосередньо пов'язана з п'єзорезистивним ефектом в датчику тиску. Було визначено, яким чином температура впливає на рухливість при застосуванні електричного потенціалу. З цією метою розроблено теоретичний і чисельний підхід, заснований на мобільності кремнієвого п'єзорезистора $p$-типу та кінцево-різницевої моделі (FDM) для самонагрівання. Таким чином, еволюцію рухливості встановлено в залежності від часу для різних рівнів легування та підвищення температури за допомогою чисельної моделі в поєднанні з моделлю рухливості. Крім того, рухливість була розрахована як функція напруги зміщення для деяких геометричних параметрів датчика, таких як довжина сторони мембрани та її товщина. Показано, що на рухливість сильно впливає підвищення температури, викликане прикладеним потенціалом, коли датчик приводиться в дію протягом тривалого часу. Як наслідок, виникає дрейф вихідної реакції датчика. Представлена робота дає змогу передбачити їх температурну поведінку через самонагрівання та покращити цей ефект шляхом оптимізації геометричних властивостей пристрою та зменшення амплітуди напруги, що подається на міст.

**Ключові слова:** Сенсори, П'єзорезистивність, Рухливість, Напруга зміщення.