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Effect of Piezoresistors Self-heating on output Characteristics of Pressure Transducer based on SOI Structure

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Abstract

Silicon pressure transducers based on SOI-structure have several important advantages, such as high measuring performance, small dimensions and weight, low production cost. Moreover these transducers naturally have extended temperature range that is vital for a number of important applications in such areas as oil and gas industry, high speed vacuum tube transportation, space engineering. The paper investigates the influence of piezoresistors self-heating due to the current flow on the main characteristics of the transducer. Finite element modeling is chosen as a calculation approach due to the structural complexity of SOI-based pressure transducers. The modeling shows that local heating of the transducer structure leads to changes in some key parameters like the piezoresistor resistance and the main strain coefficients. To study the self-heating effect of piezoresistors, the main characteristics of the pressure transducer were calculated depending on the scaling factor. According to the analysis results the critical membrane thickness, where insufficient heat sink appears is 10 µm.

Keywords: mathematical modeling, finite element method, piezoresistor self-heating, high temperature pressure transducer, pressure transducer based on SIO structure.

INTRODUCTION

Pressure transducers based on SOI-structure are of great interest in terms of sensors development for the high temperatures and harsh environments measurements. The need for such measurements is constantly growing within the mechanical engineering, oil and gas industry, space transport evolution [1-3]. Silicon pressure transducers based on SOI structure have several important advantages such as high measuring performance, small dimensions and weight, high manufacturability that result in low production cost. In the near future high temperature pressure transducers based on SOI structure will undoubtedly be demanded in the most advanced fields of human activity.

At the same time pressure transducers based on SOI structure have a significant drawback consisting in the fact that the isolation of the piezoresistor on the substrate using a thick dielectric layer causes the heat sink decrease and the piezoresistor self-heating when the current flows. The thick dielectric layer which usually is SiO_2 has low thermal conductivity, whereby heat generated in the piezoresistor does not have time to dissipate. Local heating of the pressure transducer structure leads to the changes in parameters such as the piezoresistor resistance and the main piezoresistive coefficients. As a result, there is a change in the basic characteristics of pressure transducers, such as zero drift coefficient and coefficient of thermal sensitivity.

In this regard, the task to research and to evaluate the degree of the piezoresistor self-heating and its influence on the characteristics of the transducer becomes relevant. Due to the structural complexity of transducers the optimum way to solve this task is the use of computer simulation tools, such as 3-D simulation ANSYS software [4-7].

THE MODEL OF PRESSURE TRANSDUCER BASED ON SOI STRUCTURE

To calculate the effect of piezoresistors self-heating on the transducer characteristics, the computer models were developed. They differ from each other by the key elements that are the membrane and the piezoresistor. In the models the piezoresistor is located in the volume or on the surface of the membrane. In the first case, the piezoresistor is isolated from the membrane by a p-n junction, which is covered with a dielectric layer to prevent surface leakage. In the second case, the piezoresistor is isolated from the membrane by a dielectric layer to prevent the closure between the piezoresistor and the membrane. Dielectric layers are also used to isolate the membrane and piezoresistors from the metallization layers. Figure 1 shows the structure of two variants of the pressure transducer sensing element in the region of the piezoresistor.

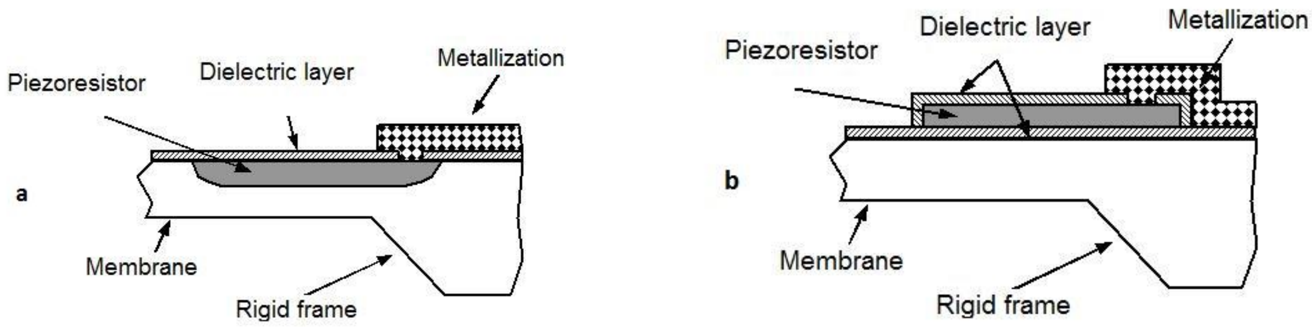

Figure 1: The structure of two variants of pressure transducer sensitive elements in the region of piezoresistors: a) piezoresistor in the volume of membrane b) piezoresistor in on the surface of membrane.

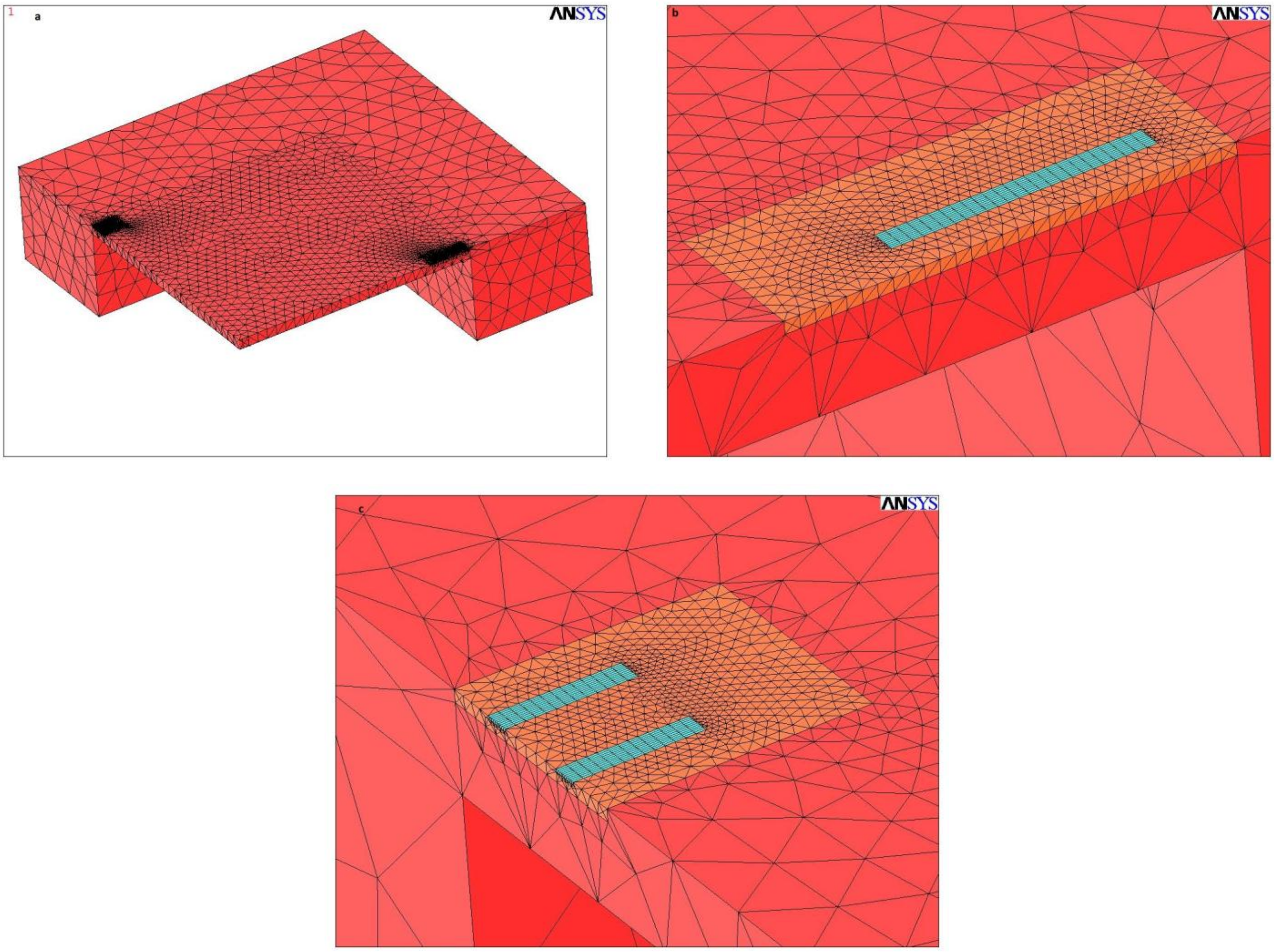

Figure 2: The pressure transducer model after mesh generation: a - general view; b - radial piezoresistor; c - tangential piezoresistor.

Figure 2 shows the model of the piezoresistive pressure transducer with generated finite elements mesh [8]. The model has about 30 thousand elements.

If it is necessary to insulate the surface of a silicon wafer, the silicon dioxide (SiO_2) obtained by thermal oxidation is usually used as the dielectric layer material. SiO_2 obtained by precipitation is used to isolate the structure of the sensitive element already lying on the dielectric layer. The SiO_2 layers obtained by these methods have high values of built-in compressive mechanical stresses which are about 200-300

MPa. Such a dielectric layer on the membrane negatively affects the main characteristics of the sensing element. Moreover this effect is enhanced with an increase of the ratio of the SiO2 layer thickness to the membrane thickness. For example the IPD-9 type transducers with high values of the main characteristics, have a 0.4-0.5 μm SiO_2 insulating layer thickness and a 30 μm membrane [9]. The thickness of the SiO2 layer was chosen empirically, as a trade-off between the required level of leakage current and an acceptable effect on the main characteristics. However, with a membrane thickness of 1 μm, the presence of a 0.4-0.5 μm thick dielectric layer with high mechanical stresses will lead to deformation of the membrane and to the significant change of the main characteristics. Therefore, due to the small thickness of the membrane, the use of dielectric layers of even small thickness is limited [9, 10].

THE CALCULATION OF HEAT GENERATION IN THE SOI STRUCTURE

The heat generation of pressure transducer based on SOI structure occurs as a result of current flow through the piezoresistors. Heat generation results in the temperature increase in the piezoresistors region (so-called piezoresistors self-heating), which leads to the change of the following characteristics:

- resistivity of piezoresistors;

- piezoresistive coefficients.

Since in the pressure transducer piezoresistors are located on the membrane, which thickness is 1-2 orders smaller than the thickness of the rigid frame of the silicon die, the possibility for the piezoresistors to generate the heat sink through the frame is substantially limited. In addition the radial and tangential piezoresistors have a different position with respect to the frame. These factors lead to the temperature gradient appearing on the piezoresistors. This in turn lead to the shift in the radial and tangential piezoresistors resistance and, as a consequence, to the change of the pressure transducer main characteristics.

The paper [9] shows the research of the heat dissipation from piezoresistors in a silicon pressure transducer with a membrane thickness of 10 and 30 μm. Pressure transducers with a planar 1x1 mm membrane and piezoresistors with dimensions of 20x100 μm and resistance of 150-200 Ω were studied. Two variants of the piezoresistors arrangement were considered in this paper: concentrated and distributed. It is shown that the self-heating of the piezoresistors leads to the fact that the dependence of the bridge circuit output signal on the supply voltage becomes nonlinear when a certain threshold voltage is exceeded. The threshold voltage value was 0.2-1.6 V depending on the thickness of the membrane and the arrangement of piezoresistors. The results obtained in [10] allow us to conclude that the effect of piezoresistors self-heating begins to appear in sensitive elements with membranes thickness of 30 μm.

To study the self-heating effect of piezoresistors, the main characteristics of the pressure transducer were calculated depending on the scaling factor. The calculation took into account the heat generation and dissipation of the piezoresistors as well as the silicon resistivity change and the principal piezoresistive coefficient π_{44} variation due to the temperature increase. A full bridge circuit with the 3.6 kOhm resistance of each piezoresistor and a supply voltage of 5 V were considered. With these bridge circuit parameters the total heat generated by the bridge circuit was 6.94 mW. Thus the heat generation of one piezoresistor was 1.74 mW. Table 1 describes the main characteristics of the pressure transducer.

Table 1: The basic pressure transducer characteristics (the calculation).

#	Characteristics	Values
1	Sensitivity (S) at T=20°C, $mV\cdot(V\cdot atm)^{-1}$	24,8
2	Coefficient of nonlinearity (Nl), %	-0,04
3	Zero drift coefficient +/- (ZD+/ZD-), %/10°C	-0,35/0,31
4	Coefficient of temperature sensitivity +/- (CTS+/CTS-), %/10°C	-0,91/1,06

The measured dependence of the silicon resistivity on the temperature for the boron concentration of $5\cdot10^{18}$ cm^{-3} (Figure 3) and the dependence of the main piezoresistive coefficient π44 on the temperature for the boron concentration of $5\cdot10^{18}$ cm^{-3} (Figure 4) were used as the input data for the calculation [11].

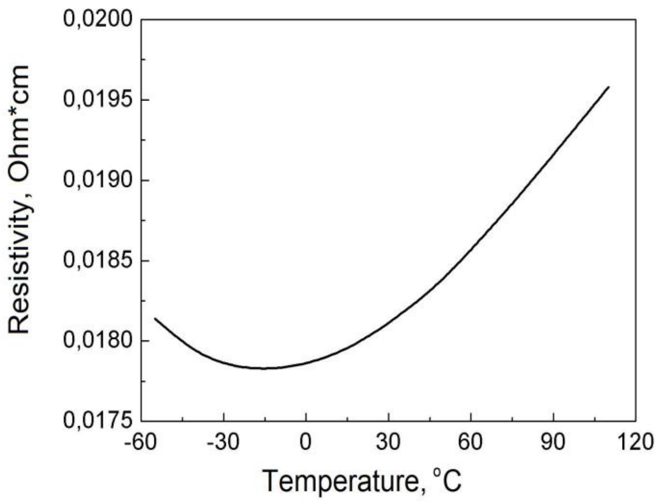

Figure 3: Silicon resistivity depending on the temperature for boron concentration of $5\cdot10^{18} cm^{-3}$.

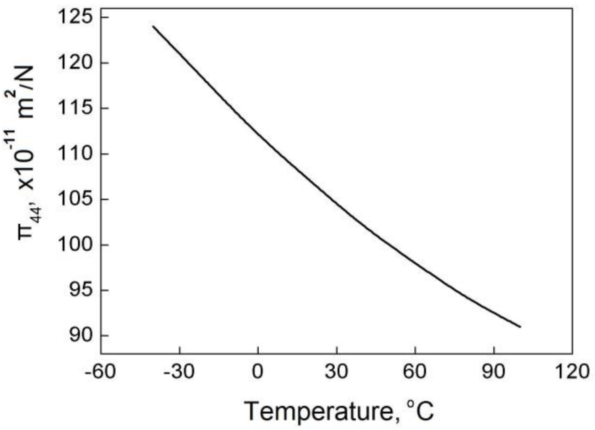

Figure 4: The dependence of π_{44} coefficient on the temperature.

The calculation of the main characteristics dependence was carried out in two stages. First of all, the heat dissipation in the sensing element structure was calculated (thermal analysis), the result of which was the temperature distribution. Further, the calculation results were used as the initial data to obtain the deformation of the sensitive element structure under the temperature and pressure applied (thermal structural analysis). The temperature dependence of the silicon resistivity and π_{44} was taken into account by changing the material parameters (figure 4).

RESEARCH RESULTS

Figures 5 and 6 describe the piezoresistors maximum temperature and the maximum temperature drop depending on the scaling factor for the sensing element variant with the piezoresistors on the membrane surface. The temperature values for the sensing element variant with the piezoresistors placed in the membrane volume differ insignificantly. As can be seen, a 1/40 scaling factor results in the piezoresistors temperature increase to the value of 19.7 °C. Wherein the temperature drop of the piezoresistors is 2.2 °C (Figure 5).

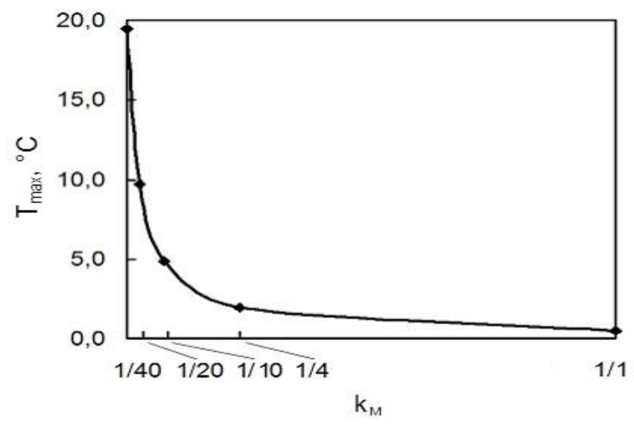

Figure 5: The maximum temperature increase of piezoresistor.

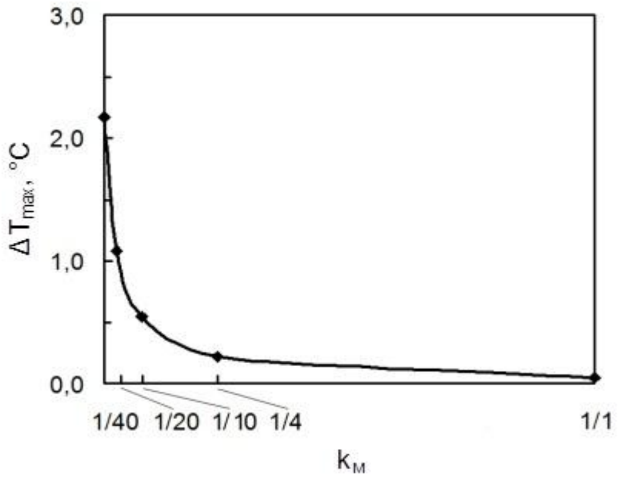

Figure 6: The maximum temperature drop of piezoresistors.

Figure 7 presents the pressure transducer main characteristics change in relations to the piezoresistors self-heating for the model with surface piezoresistors.

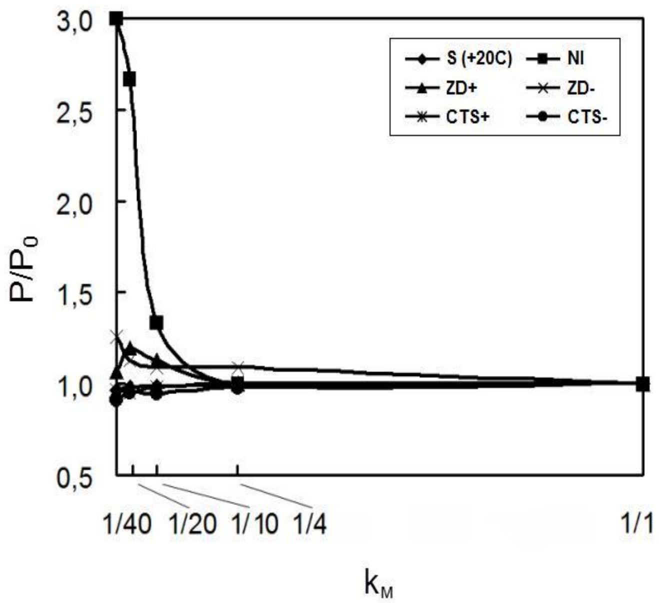

Figure 7: The change in the main characteristics of the pressure transducer during piezoresistors self-heating for the model with surface piezoresistors placement.

The obtained results allow us to conclude that the piezoresistors self-heating has a significant effect on the main characteristics of the pressure transducer based on SOI structure. Piezoresistors self-heating leads to a change in the basic characteristics of the transducer, in particular, to the nonlinearity increase. Thus, piezoresistors self-heating should be considered as one of the significant factors that must be taken into account when developing pressure transducers based on SOI structure [12, 13].

CONCLUSION

In this paper finite element modeling was used to calculate the effect of piezoresistor self-heating on the characteristics of the pressure transducer based on SOI structure. The three-dimensional model of the silicon pressure transducer with the piezoresistor on the membrane surface was developed. The calculation of the pressure transducer characteristics, taking into account temperature changes in the piezoresistor resistance and fundamental piezoresistive coefficients, was made. It is shown that the piezoresistor self-heating leads to the changes of the transducer main characteristics, in particular to the significant increase in the nonlinearity. This effect should be taken into account in the development of pressure transducers based on SOI structure.

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