STRUCTURAL AND ELECTRICAL BEHAVIOR OF INTEGRATED DIAPHRAGM MICRO-PRESSURE-SENSOR BASED ON MOSFET TRANSISTOR

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ABSTRACT

In this paper, the MOSFET transistor performance as sensible element and the structural and electrical behavior of integrated diaphragm micro-pressure-sensor has been described. ANSYS software has been used as a tool to design the mechanical properties and ANALOG INSYDES software has been used to predict the electrical behavior of transistors. The incorporation of MOSFET transistors on maxim stress regions has been explored to enhance the drain current under pressure. In addition, we found a more control of the electrical characteristics in the pressure sensor. For the pressure sensor, the difference of voltage was found to increase by 70mV for each 50kPa.

1. INTRODUCTION

In the last decades, the micro-sensor based on microelectromechanical techniques has been used to produce a wide range of system in automotive, biomedical and industrial applications. Due to for biological systems, the pressure are lower, for example, the arterial pressure is around 14-20kPa, the sensor must be small. The IC fabrication technologies and the possibility of on-chip circuitry benefit to microsensors due to can provide functionalities as the self testing, among others. It revealed that microelectromechanical techniques using CMOS commercial IC fab is a feasible approach.

Typically, the pressure sensor uses the piezoresistance effect in a homogeneously-doped silicon strip attached to a membrane of silicon. Resistors are diffused to measure the maximum stress at the surface. By etching away part of the silicon under the resistors until a thin membrane is left, it is possible to obtain a higher stresses and therefore a higher sensitivity. The piezoresistors are connected in Wheatstone bridge configuration. It consists of 4 elements (piezoresistors) arranged in each side of the diaphragm border. In order to obtain the differential output [1], an input DC voltage, or excitation voltage is applied between the top of the configuration and the output voltage is measured across the middle. The output voltage of such a transducer is sensed by an interface circuit usually based on operational amplifiers [2]. The piezoresistors have the disadvantage of being highly sensitive to temperature changes while featuring comparatively small relative stress dependent signal amplitude changes.

In this study, the piezoresistors are substituted by MOSFET transistor. The transistors are more controllable than the piezoresistors. The temperature dependence can be optimized with the polarization and the power consumption can be reduced choosing a lowest bias current. Also, the area consumption is benefit due to the advantage in order to incorporate a resistive channel controlled with a polarization.

The main purpose of this paper is to report the structural properties and the analytical results of diaphragm micro pressure-sensor by using MOSFET transistors as sensible element. Also, we describe the design procedure for 15kPa pressure application, presenting the overcoming temperature dependence of the electrical property. The analysis was made using finite element analysis software ANSYS [3] and numerical level transistor software ANALOG INSYDES [4].

2. MATHEMATICAL MODEL

Many studies were made in solid state concerning the piezoresistive effect and the dependence of electrical properties. Under stress, some materials exhibit changes on resistivity (or carrier mobility). In this regards, the doped silicon has been utilized to form strip of material to shape piezoresistors. In which, put under pressure (applied stress), they will show changes in its resistivity. The description of the piezoresistivo effect thought mathematical model considers a three-dimensional anisotropic crystal. Because the symmetry of the crystal, for a three-by-three resistivity tensor the piezoresistance effect can be described by relating each of the six fractional resistivity changes to each of the six stress components . Resistivity change (Δρ) by external stress (σ) can be represented for the below matrix expression,

$$\frac{1}{\rho}\begin{pmatrix}\Delta\rho_{11}\\ \Delta\rho_{22}\\ \Delta\rho_{33}\\ \Delta\rho_{12}\\ \Delta\rho_{13}\\ \Delta\rho_{23}\end{pmatrix}=\begin{pmatrix}\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \pi_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & \pi_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & \pi_{44}\end{pmatrix}\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ 2\sigma_{12}\\ 2\sigma_{13}\\ 2\sigma_{23}\end{pmatrix} \quad (1)$$

where ρ_{ij} is the resistivity tensor, π_{ij} is the piezoresistivo coefficient and σ_{kl} is the mechanical stress.

Typically, the piezoresistors are almost always placed along certain crystallographic orientation (e.g.,<100> or <110>), because of that, is possible to define another important parameters: longitudinal and transverse piezoresistance. When mechanical stress is applied, assuming that shear stress is negligible, therefore when the piezoresistor is placed along principal axes, the longitudinal resistivity change is expressed by

$$\left.\frac{\Delta\rho}{\rho}\right|_{l}=\pi_l\sigma_l+\pi_t\sigma_t \qquad (2)$$

If the piezoresistor is not placed along principal axes, the transversal resistivity change is expressed by

$$\left.\frac{\Delta\rho}{\rho}\right|_{t}=\pi_l\sigma_t+\pi_t\sigma_l \qquad (3)$$

since π_l is longitudinal piezoresistive coefficient, σ_l is longitudinal mechanical stress, π_t is transverse piezoresistive coefficient and σ_t is transverse mechanical stress. For a long and narrow piezoresistor with crystallographic orientation <110> direction in {100} wafer, the piezoresistive coefficients can be expressed by

$$\pi_l=\tfrac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44})$$
$$\pi_t=\tfrac{1}{2}(\pi_{11}+\pi_{12}-\pi_{44}) \qquad (4)$$

It is noted that the above equation are only valid for uniform stress fields or if the piezoresistor dimensions are small compared to the diaphragm size. For sensible elements, the stresses will vary across of them and have to be computed. That can be done most efficiently by finite element analysis simulation programs which be mention to continue.

3. METHODOLOGY OF DESIGN FOR DIAPHRAGM AND MOS ELEMENT

Hence, the design methodology consisted of simulating the mechanical stresses in the silicon diaphragm using ANSYS release 10.0. Due to diaphragm symmetry, it is divided in four quadrants with a normalized distance referred to the longitude, as is showed in Fig. 1.

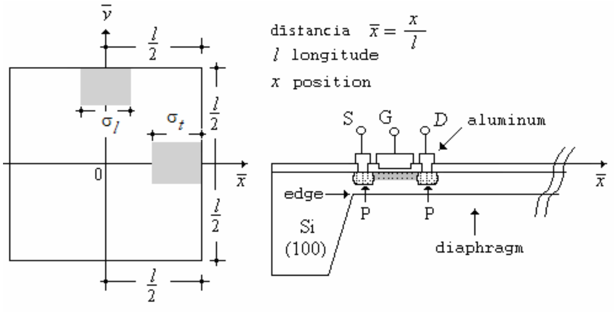

Figure 1. Vertical and cross-sectional view of diaphragm sensor.

Table 1. List of parameters used in the simulation study and dimensions for the diaphragm, as shown in Fig. 1.

Parameters and dimensions [5]	
Silicon properties	p-type $N_A = 10^{15}$ cm^{-3}
	$\rho = 7.8\ \Omega$-cm
	Y = 130GPa
	N = 0.28
	$\pi_{11} = +6.6\text{X}10^{-11}$ Pa^{-1}
	$\pi_{12} = -1.1\text{X}10^{-11}$ Pa^{-1}
	$\pi_{44} = +138.1\text{X}10^{-11}$ Pa^{-1}
Diaphragm dimensions	$l = 1000\ \mu$m
	$t = 15\ \mu$m
Pressure analysis	15kPa

After, we obtain the mechanical stress along the length of the element (channel transistor). In this way, it is possible to obtain a list of values of stress for a fixed applied displacement, or force. The normalized values obtained can be longitudinal or transverse as is shown in Fig 2.

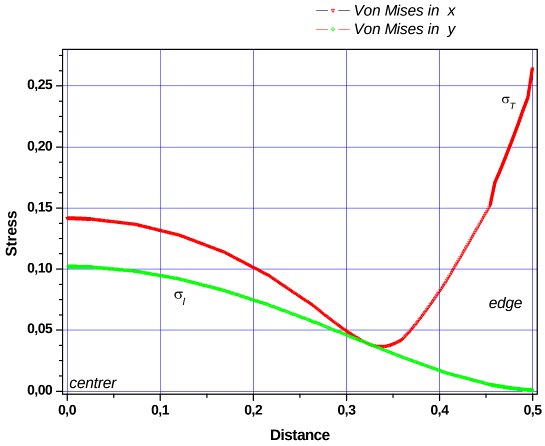

Figure 2. Plot of the von-Mises stress versus distance, as obtained from ANSYS.

We can distinguish a stress distribution between edge and center of diaphragm. For transverse component, the maximum stress is 25.428MPa which is localized in the edge of the diaphragm. The von Mises plot shows the color representation of the stress (Fig. 3).

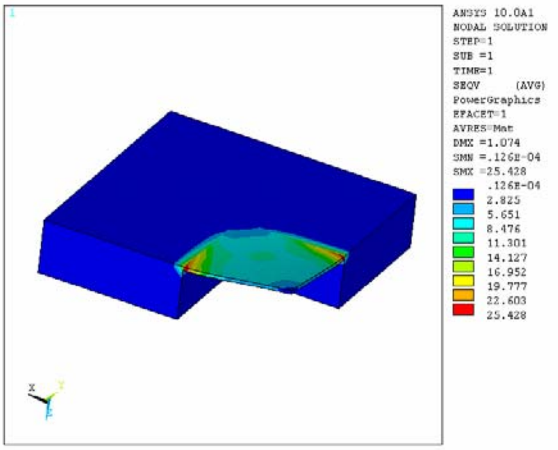

Figure 3. Plot of the von-Mises stress countours on diaphragm, as obtained from ANSYS.

The longitudinal stress is lowest and some authors do not consider it.

The linear region nears of the border allows us to define the size of the sensible elements, in our case, the channel length of PMOS. The linear interpolation give us a linearity range of $\overline{x}$ = 0.45 to 0.5, which is defined by $(-a+bx)\left(\frac{l}{t}\right)^{2}P$ where a and b are constants dependents of piezoresistive coefficients whose value are $320 \cdot 10^{-10}$. and $960 \cdot 10^{-10}$ respectively. For our case, the diaphragm length is 1000µm therefore we have 50µm to position the transistor.

In the other hand, to increase the sensitivity we needed to limit the size of the transistor as we see in the next section.

In order to analyze in biological application the effect of the pressure on diaphragm, we simulate the deformation in Z axe, Fig. 4.

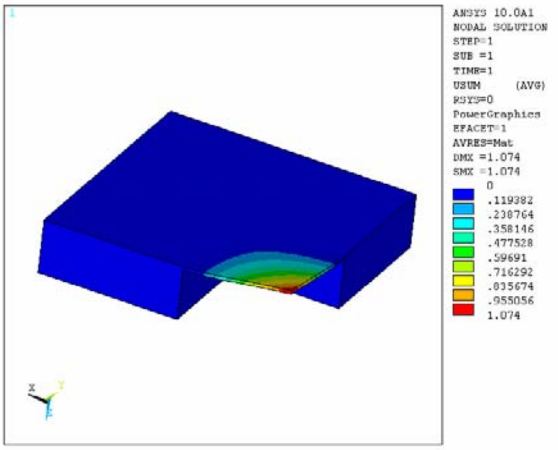

Figure 4. Plot of the deformation on diaphragm, as obtained from ANSYS.

The maximum displacement of 1.074µm is found in the center of diaphragm. The effect in the border is lower; we obtain approximately 1.8 x10^{-4} µm.

4. SYMBOLIC ANALYSIS OF MOS-ELEMENTS

Due to the diffused resistors have the disadvantage of being highly sensitive to temperature changes, is necessary to choose another sensible element that replaces the resistor and we can to control this temperature dependence. Classical I-V characteristics of MOS transistors can obtain from the physics of the MOS system when coupled to the drain and source doped regions. As we know, the current flow characteristics are referenced to the threshold voltage, which is set by technology process. Temperature variations in the I-V behaviour occur the surface mobility varies with temperature as well as the threshold voltage. The simple model for the threshold voltage dependence is given by

$$I_D(T) = \frac{\beta(T)}{2}\left(V_{GS} - V_T(T)\right)^2 (1 + \lambda V_{DS}) \qquad (5)$$

where β is the device transconductrance and V_T is the threshold voltage. The basic temperature dependence of a PMOS (diode connected) used is illustrated in the Fig. 5. The variation of temperature was 273, 300 and 327°K.

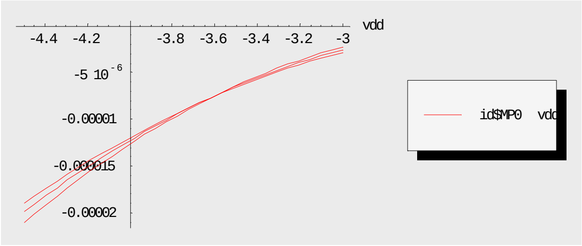

Figure 5. Temperature variation in saturated PMOS, as obtained from ANALOG INSYDES.

As we can see, the curves PMOS exhibit a zero temperature point. If our device is biased at this point, the variation in mobility is balanced by the variation in V_T . We use the electrical parameters from MOSIS for AMI Semiconductor 0.5micron run t66h.

The variation of electrical properties of MOS transistor under pressure, can be determined by using the conductance change (inverse of resistivity change) due to mechanical stress as

$$\frac{\Delta\mu}{\mu} = -\frac{\Delta\rho}{\rho} \qquad (6)$$

The equations 2 and 3 can be sustituited in (6) and we can obtain the mobility change due to the mechanical stress which must be sustituited in the drain current expression. If the position of our transistor is from de border to the center (transverse stress effect), we can integrated de variation of drain current over distance between x1=l/2 to x2= l/2 –W, the result is

$$I_{D_{presión}} = I_D\left[1+\left[-\frac{b}{2}\left(1-\frac{W}{l}\right)+a\right]\pi_l\left(\frac{l}{h}\right)^2 P\right] \quad (7)$$

Where I_D is the drain current without mechanical stress, l and h are length and thickness of diaphragm, P is the pressure and W is channel width.

The effect of pressure of a drain current PMOS is showed in Fig. 6. The range of pressure used was from 15kPa to 150kPa.

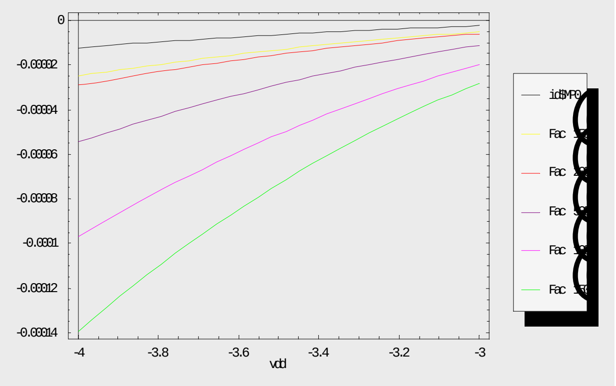

Figure 6. Drain current variation in saturated PMOS under mechanical stress, as obtained from ANALOG INSYDES.

In the Wheatstone bridge configuration (Fig. 7a), the output will be the difference between V_{DS}(T1) and V_{DS} (L1). The result obtained for temperature dependence of drain current PMOS, as showed in Fig. 7, the range of temperature used was 273, 300 and 327°K.

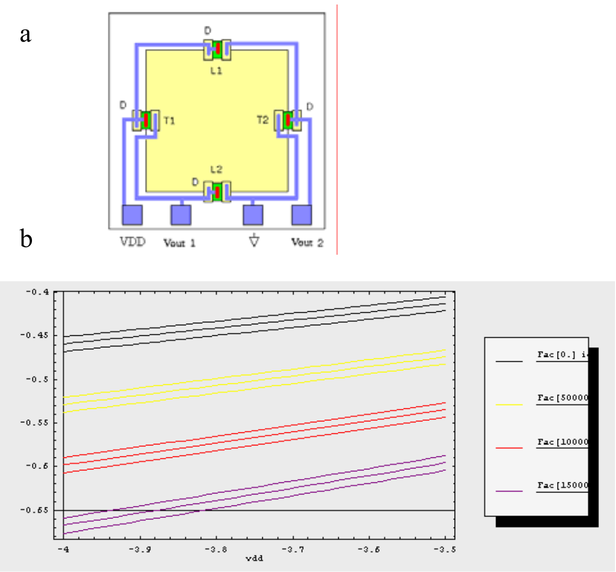

Figure 7. Temperature dependence of drain current variation in saturated PMOS under mechanical stress, as obtained from ANALOG INSYDES.

5. CONCLUSIONS

In this project, the design of silicon based diaphragm has been described. The PMOS transistors as sensible elements gave flexibility to the design obtaining a dependence control with the temperature through the polarization of the channel. The ANSYS release 10.0 was used as the basis to simulate the mechanical properties of diaphragm. The simulations for mechanical stress give us the optimal region to position of the sensible elements. The placement of the PMOS was found to be critical and optimal placement can result in a significant improvement in sensibility of the sensor. Post-process challenges associated of fabrication under VLSI process for the micro-pressure-sensor are our present work.

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6. REFERENCES

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