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Study, design, microfabrication and characterization of a new CMOS compatible multi-terminal pressure sensor with enhanced sensitivity

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ABSTRACT

This paper presents the design, microfabrication and characterization of a CMOS compatible multi-terminal pressure sensor (MTPS). The design is supported by an analytical as well by a numerical study. This sensor is an alternative to the pressure sensors based on both: the conventional silicon Wheatstone Piezoresistive Bridge (WB) and Four-Terminal Pressure Sensors (FTPS). The layout of the MTPS is designed in such a way that the sensor sensitivity is effectively improved and the short-circuit effects, which are modeled by the geometrical correction factor (G), can be minimized. The effect of a polysilicon gate over the active region of the sensor is studied in order to further enhance its sensitivity. The MTPS was fabricated using two different foundries: one academic (CCS-UNICAMP) and another commercial (0.35 μm CMOS AMS). The MTPS sensor sensitivity amounts to 4.8 and 0.24 mV/psi, respectively. The influence of temperature on the sensors transfer function is also studied.

1. Introduction

Silicon pressure sensors are an extremely successful product. Since when they first came up in 1962, many studies were being carried out considering the piezoresistive effect in diffused piezoresistors on a cantilever beam [1]. After that, the piezoresistive effect in silicon has been extensively used for pressure sensors in the form of a Wheatstone Piezoresistive Bridge (WB) [2]. However, more recently, Four-Terminal Pressure Sensors (FTPS) have been an alternative method for design of sensors in the mechanical domain [3–5].

An important characteristic of the FTPS is the dependence of its output parameters on the geometry of the current and electrical potential terminals and also on the geometry of its current-spread region (CSR). Therefore, the sensitivity of conventional FTPS is limited by the well-known short-circuit effects, which may be modeled by the geometrical correction factor (G). Thus, an accurate analysis of this type of pressure sensor cannot be based only on both the Ohm's law [4] and the semiconductor anisotropic conductivity. The boundary conditions nearby the ohmic contacts of the CSR must be taken into account. Hence, an accurate analysis of G is suitable for the layout optimization of FTPS devices.

G can be calculated both analytically and numerically. However, an analytical analysis for G requires arduous mathematical technique of conformal transformations and it is very time-consuming [6–8]. On the other hand, numerical analysis can be performed and provides a suitable approach to the solution of differential equations with well-known boundary conditions. Thus, Finite Element Method (FEM) was carried out not only to amount G but also to predict the sensor's sensitivity.

Aiming the maximization of both sensitivity and G, we propose an alternative for the FTPS, which was already presented by us in former works [9,10]. This topology is referred to as multi-terminal pressure sensor (MTPS). This sensor is formed by merging four FTPS together. The MTPS requires a specific biasing circuit, which is also presented. In addition, a theoretical introduction about the noise sources in the FTPS and their influence on both the sensor sensitivity and resolution is presented.

Experimental results were carried out using two different foundries: our own in-house foundry (Center for Semiconductor Components – CCS/UNICAMP) and a commercial 0.35 μm CMOS Austrian Microsystems Technology^{TM} (AMS). Using our in-house foundry, we just fabricated the piezoelements while the biasing circuit was discrete. On the other hand, using the AMS foundry, an entire system (piezoelements plus on-chip biasing circuit) was fabricated. Our experimental results present a comparison between the characterizations of both sensors at room temperature over a differential pressure ranging from 0 to 10 psi. Finally, the influence of temperature on the transfer function of both sensors (FTPS and MTPS) is also presented.

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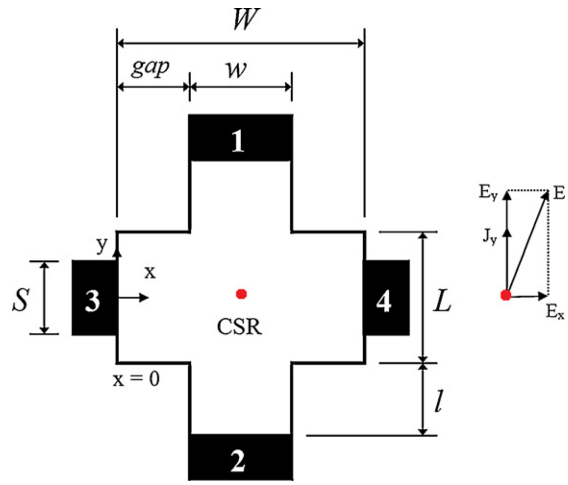

Fig. 1. FTPS geometrical parameters (left) and electrical field and current density vectors at coordinate $x = W/2$ and $y = 0$, supposing sensor under electrical bias and mechanical-stress conditions (right).

2. Theory

The sensor for the mechanical domain presented in this paper is based on the transversal piezoresistive effect. When the cubic symmetry of silicon lattice is broken, the conductivity is no longer isotropic. As a result, the current density vector is no longer parallel to the electrical field vector. Thus, the electrical field can be split up into a vector parallel to the field direction and one transversal to it [11]. This anisotropic resistivity is depicted in right-hand side of Fig. 1. Mechanical stress therefore has a similar effect to the silicon anisotropic resistivity, as the magnetic field in the Hall Effect. Thus, part of our work was based on previous researches carried out for the magnetic domain by Popovic [12] and Kammerer *et al.* [13]. In addition, the piezoresistive effect regards to the resistivity change of a piezoresistive sensing element (PSE) when under the influence of a mechanical stress.

The main characteristics of both four and multi-PSEs are determined by: the geometry of the MTPS, the geometry of the micromachined membrane, the type of the silicon (p or n), the impurity concentration, the alignment of the PSE related to the crystallographic plane of the membrane, the location of the PSE at the maximum stress region and the misalignment of the photolithography [14].

For our analytical analysis, we consider that the CSR of the PSE is made of a uniform p-type silicon layer. This CSR is located at a region of maximum normal and uniaxial mechanical stress on the micromachined membrane's surface.

2.1. Geometrical definitions for the sensor layout

In order to understand the terms and the topology of the MTPS, the layout of a four-shaped PSE, which we denote by Adapted-FTPS, is first explained. The Adapted-FTPS layout and its current density and electrical field vectors with origin at the center of the CSR are shown in Fig. 1. The current contacts (terminals 1 and 2) are supplied by a constant bias current I_s. Terminals 3 and 4 are the sensing terminals where a mechanical-stress-dependent voltage can be measured.

L and W are the length and the width of the device, respectively. l and w are the length and the width of the current terminals, respectively. S is the width of the sensing contacts. *Gap* is the distance between the current terminal border and the edge of the CSR.

2.1.1. An analytical study for the sensor output voltage

By considering that the majority of the current flow is confined on the CSR surface, the output voltage of four-terminals PSEs can be calculated using a two-dimensional coordinate system (x–y). For an accurate result, the thickness of the CSR should also be as small as possible in order to achieve a minimum of current flowing toward the substrate. Thus, Ohm's law can be expressed as follows:

$$\begin{bmatrix} \vec{E}_x \\ \vec{E}_y \end{bmatrix} = \left(\rho_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} \Delta\rho_{xx} & \Delta\rho_{xy} \\ \Delta\rho_{yx} & \Delta\rho_{yy} \end{bmatrix} \right) \begin{bmatrix} \vec{J}_x \\ \vec{J}_y \end{bmatrix} \tag{1}$$

where ρ_0 is the resistivity of the non-stressed silicon and $\Delta\rho_{ij}$ is the stress-induced resistivity change.

The piezoresistance of a material is often represented by a set of experimental constants: the piezoresistive coefficients. Considering a simplification of indexes in reduction of notation [10], the relation between the first-order piezoresistance coefficients and the mechanical stress can be written as [16]:

$$\frac{\Delta\rho_i}{\rho_0} = \sum \pi_{ij}\sigma_j, \tag{2}$$

where π_{ij} is the piezoresistive tensor and σ_j is the stress in an arbitrary coordinate system.

The symmetry of the silicon lattice structure reduces the number of first-order piezoresistance coefficients (FOPR) to three: π_{11}, π_{12} and π_{44}. For p-type silicon, the π_{11} and π_{12} coefficients are much smaller than π_{44} [15,16] and, hence, FOPR can be reduced to π_{44}.

If now we consider that the voltage-sensing contacts are connected to a high impedance voltmeter, then it is a fact that the current density in the x direction is null ($\vec{J}_x = 0$). As a result, Eq. (1) can be written as:

$$\vec{E}_x = \frac{\Delta\rho_6}{\rho_0} \frac{\vec{E}_y}{(1 + \Delta\rho_2/\rho_0)}. \tag{3}$$

The relation between the output voltage and the bias source is calculated by integrating $\vec{E}_x$ along the x direction and $\vec{E}_y$ along the y direction, respectively. Thus, considering that the current contacts are supplied by a constant bias current I_{bias}, the stress-dependent voltage measured between the voltage-sensing contacts is given by:

$$V_{out} = \frac{\Delta\rho_6/\rho_0}{(1 + \Delta\rho_2/\rho_0)} \rho_s I_{bias}, \tag{4}$$

where ρ_s is the sheet resistance of a non-strained silicon.

From Eq. (2), we can calculate the resistivity change. In order to reach the maximum sensitivity, the components π's and σ's must be calculated for an arbitrary Cartesian system. This is accomplished by performing a transformation of the coordinate system through Euler's angles [15]. Based on Eq. (4), we can calculate the FTPS output voltage fabricated using a p-type layer on a (1 0 0) silicon wafer and aligned to an arbitrary in-plane direction as follows:

$$V_{FTPS} = \left[\frac{(1/2)\pi_{44}(\sigma_1 - \sigma_2)\sin(2\varphi))}{1 - (1/2)\pi_{44}(\sigma_1 - \sigma_2)\cos(2\varphi)} \right] \rho_s I_{bias}, \tag{5}$$

where π_{44} is the shear piezoresistive coefficient for p-type silicon, $(\sigma_1 - \sigma_2)$ is the resultant uniaxial mechanical stress along the $\langle 1\,1\,0 \rangle$ crystallographic orientation and φ is the Euler's angle.

Eq. (5) presents an output voltage regardless the influence of the ohmic contacts. However, we can add the geometrical correction factor G in order to consider the short-circuit effect present in this type of sensor. In addition, it is clear that for a maximum sensitivity, φ must be 45° and thus, the FTPS output voltage can be simplified to:

$$V_{FTPS} = \frac{1}{2}\pi_{44}(\sigma_1 - \sigma_2)\rho_s I_{bias} G. \tag{6}$$