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Parameter extraction scheme for silicon pressure sensors in standard CMOS technology

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Abstract

Forming a part of the CAD/CAE attempts to simulate and design microsystems, the process of parameter extraction for a pressure sensor macromodel from layout is presented. The pressure sensor was integrated on a silicon chip by means of a standard CMOS technology (1.0 μm from Atmel-European Silicon Structures) followed by micromechanical structuring of the device. A tool for analysing the physical layout of the sensor is also described. From the results, an electrical model of the sensor was obtained for use in conventional CAD tools.

1 Introduction

Microsystems can combine analog and digital circuits, along with mechanical elements, in a single package. The monolithic integration of a sensor element and the electronic interface circuit so that the sensor signal can be conditioned on a single chip has proved to be a good approach to the efficient adaptation of sensor elements to electronic systems and to the reduction of external interference [1,2], thus, the merging of the IC and micromechanical worlds has led directly to the development of on-chip integrated systems. Due to its material and electronic characteristics, silicon is preferred for this integration.

However, direct access to these technologies is still limited, due to a lack of standardized design and manufacturing procedures. For a fast design of the total system, the well-known ASIC design method would have to be transferred to the development of microsystems. This supposes the performance of several tasks not yet completely established. There can be summarized as making compatible the standard CMOS process and the micromachining technology needed to build the sensor, the implementation of sensor models in conventional electronic simulators and the preparation of sensor cells for use in commercial CAD tools.

In this context, this paper is focuses on the development and application of a macromodel for pressure sensors based on a standard CMOS technology. The parameters of the macromodel are deduced from the process-dependent material properties of CMOS technology and the geometrical dimensions of the sensor layouts. Although the work has been conducted with the help of the restricted analog behavioral capabilities of a SPICE simulator, it is clear that the model can be easily implemented in a more flexible VHDL-A simulator [3].

2 Sensor Working Principle

The piezoresistive silicon pressure sensor is one of the most frequently used sensors. It is usually designed as a diaphragm with piezoresistors using bulk micromachining technology [4]. It shows high sensitivity, good linearity and good stability [5].

The basic features of the layout of a pressure sensor are shown in Fig. 1(a). The simplest sensor circuit that can be built using piezoresistors is the Wheatstone bridge, shown in Fig. 1(b). When pressure, P, is applied to one of the sensor ports, and while the other port is maintained at a reference level, a non-isotropic resistance change with stress is produced. Two of the resistors, R_{P2} and R_{P3} , increase and the other two, R_{P1} and R_{P4}, decrease in value. The resulting output, V_a-V_b, is given by:

$$V_a - V_b = V_{pol} \left(\frac{R_{P2}}{R_{P1}+R_{P2}} - \frac{R_{P4}}{R_{P3}+R_{P4}} \right) \tag{1}$$

V_{pol} is the bias applied to the sensor. The output is proportional to the applied pressure and can be written as:

$$V_a - V_b = S\ (P - P_0) \tag{2}$$

The coefficient of proportionality or sensitivity, S, relies on a number of parameters that can be divided into three groups, mechanical, electrical and geometrical parameters. The temperature, T, dependency of these parameters must also be included.

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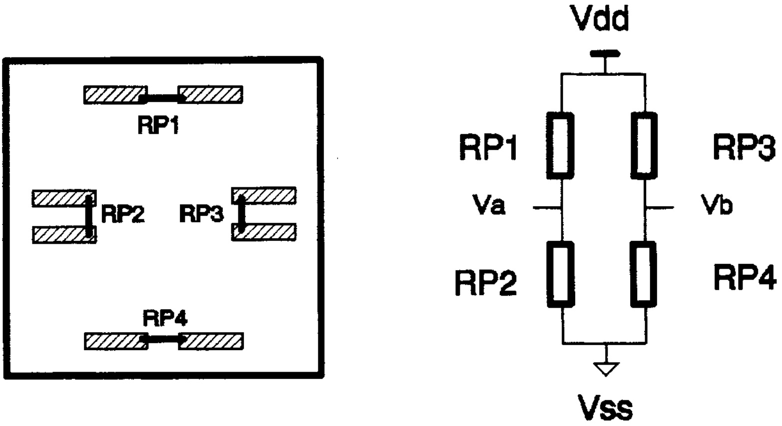

Fig. 1. (a) Sensor layout (b) Electric model

3 Sensor Macromodel

For the automation of the design process, the extraction of a model from the sensor layout for an efficient and accurate simulation of realistic microstructures becomes indispensable. In semi-custom design environments, developed for a wide range of applications, it is not practical to address the simulation of the complete microsystem at the physical level because of the vast number of degrees of freedom necessary to represent the system accurately.

Fig. 2 represents the symbol for the developed model. As these sensors show a large temperature coefficient, the input variables of the model are V_{pol}, P and T.

The model consists of a Whetstone bridge, in which each piezoresistance is described by [2]:

$$R^{+}(P,T) = R_0(T_0,P_0)\ [1 + \alpha[T-T_0]][1+S_0^{+}[1+\beta[T-T_0]][P-P_0]] \qquad (3)$$

$$R^{-}(P,T) = R_0(T_0,P_0)\ [1 + \alpha[T-T_0]][1+S_0^{-}[1+\beta[T-T_0]][P-P_0]] \qquad (4)$$

The macromodel comprises seven parameters, R_0, the resistance at the reference conditions, S_0^+, S_0^-, the sensitivity for the negative and positive piezoresistors, α^+, α^-, collects the temperature coefficient of the resistance and β^+ and β^-, the temperature coefficient for the sensitivity. The associate sensitivity includes the contribution of sensor topology, sensitivity also depends on the average stress at the piezoresistor location.

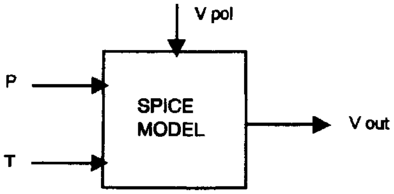

Fig. 2. Sensor macromodel

4 Integration Technology

Accurate values of material properties are a prerequisite for the design and simulation of microsystems. When IC layers are used, physical properties other than those monitored in the IC process play a role. For the extraction of these properties, a set of test structures was fabricated (Fig. 3).

The standard 1.0 μm CMOS technology from Atmel-ES2 was used. The technology features one polysilicon and two metal levels. A post-processing technology allows the building of membranes by anisotropic etching from the back side of the wafer, what is defined by a double-side aligned photolithographical step [6].

Prior to this, the behaviour of the membranes constituting these pressure sensor test structures, was simulated in order to estimate the sizes to be adopted, and, so as, to avoid buckling effects and the loss of sensitivity [5].

5 Physical level parameters

A set of parameters at the physical level are needed to extract the final macromodel directly from the layout. These parameters are divided in three groups:

5.1 Mechanical parameters

The longitudinal and transversal piezoresistive coefficients, π_L and π_T, of the piezoresistor layers are the most relevant mechanical parameters from which the average sensitivity can be derived. Although the Young modulus and Poisson coefficient of crystalline silicon and passivation layers, were collected from the literature, π_L and π_T were measured by fitting the experimental results obtained from the test structures, where each piezoresistor was considered as an isolated device.

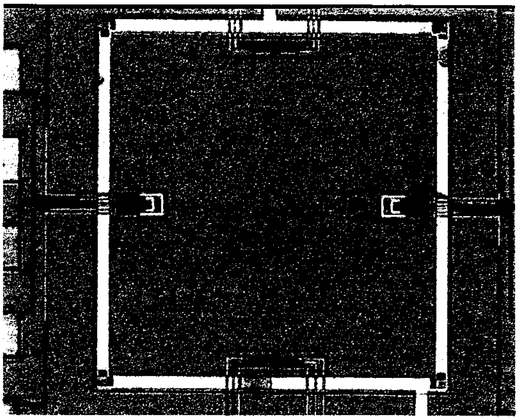

Fig 3. Test structure, containing three independent Wheatstone bridges.

5.2 Electrical parameters

The sheet resistance, the resistivity and the temperature coefficients of the doped silicon, polysilicon and metal layers were measured using the same test structure. To avoid the effects of pressure, the measurement was performed before the micromechanical structuring step.

5.3 Geometric parameters

Important layout information is related to piezoresistance location and size, membrane thickness, membrane size and the non-alignment tolerances. These were collected from the layout or by optical inspection of the processed device. Geometric parameters are summarized in table I.

Parameter		Size (μm)
H	Membrane Depth	3.5
L	Membrane size (square)	600
A	Piezoresistance width	3
LR	Piezoresistance length	77
DCPA	Parallel piez. to membrane axis	7
DBPA	Parallel piez. to membrane edge	15
DCPE	Transversal piez. to membrane axis	4
DBPE	transversal piez. to membrane edge	15

Table I. Geometric parameters of the test structures

6 Model extraction

When the set of the parameters described above were obtained, a model extraction process was performed for other sensor layouts. The process was divided in two stages:

6.1 Physical level

The sensitivity of each piezoresistor is the key parameter. In order to determine S_0^+ and S_0^-, the resolution of the Timoshenko equation for anisotropic thin shells was resolved to obtain the normalized average stress at the piezoresistor location, σ_L and σ_T. The parameters from table I are needed at this stage. The sensitivity of each piezo-resistor was computed as:

$$S = \left(\frac{L}{H}\right)^2 (\pi_l \cdot \sigma_l + \pi_t \cdot \sigma_t) \tag{5}$$

6.2 Phenomenological level

The characteristics of each of the resistances: the sheet resistance, $R_\square$, at 273 K, the temperature coefficient of the piezoresistive sensitivity and the temperature

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coefficient of the resistance were added to complete the model represented by equations (3) and (4)

Experimental Values for $R_\square$, α, and β, are reported in Table II.

Parameter	Negative Piezoresistance	Positive Piezoresistance
$R_\square$	53 Ω	53 Ω
α	$1.1\ 10^{-3}\ {}^{\circ}K^{-1}$	$1.1\ 10^{-3}\ {}^{\circ}K^{-1}$
β	$-8.0\ 10^{-3}\ ({}^{\circ}K\cdot bar)^{-1}$	$-1.2\ 10^{-2}\ ({}^{\circ}K\cdot bar)^{-1}$

Table II. Experimental results.

7 Results and discussion

The extraction process was applied to the longest Wheatstone bridge which is shown in Fig. 3. At the physical-level step, we obtained $S_0^- = -2.3.10^{-2}\ bar^{-1}$ and $S_0^+ = 1.8.10^{-2}\ bar^{-1}$.

The differences observed between the negative and the positive sensitivity, suggest that a model formed by four resistors, with a behaviour described by the equations (3) and (4), should be used.

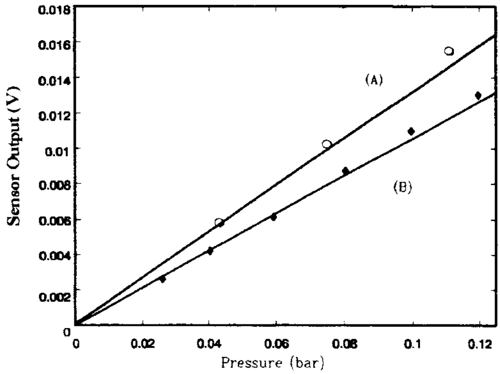

Fig. 4. Comparison between experimental (dots) and simulation behaviour (line) of CMOS based silicon pressure sensors (A) 273 °K (B) 298 °K.

Fig. 4, compares the experimental behaviour at two different temperatures (dots) and the model result from HSPICE simulation (lines). Design Framework II (from Cadence) was used as the design environment. So, in this framework, the additional facilities of the technology, such as analog and digital libraries could be used to design and build integrated microsystems [7].

To evaluate the performances of our mixed simulation environment, we implemented a monolithic integrated pressure sensor with a current conveyor based instrumentation amplifier. A good concordance between the simulation with our model and experimental results was observed.

8 Conclusions

The strategy presented in this work would seem to be a valuable tool for the simulation of microsystems containing pressure sensors. It combines low level physical simulations based on Timoshenko equations to extract the parameters describing the behaviour of the sensor. This permits a rapid simulation of the complete microsystem at a higher level of abstraction and, moreover, the inclusion of such a model in a mixed simulation environment including analog-digital and mechanical parts, all of which are described with the emerging VHDL-A. Due to these design possibilities, more complex sensor systems for advanced applications can be developed and build, directly from semi-custom design environments.

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