Design of an Eight-Terminal piezotransducer using Multiphysics simulators

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***Abstract*—Numerical methods and multiphysics simulation have been used to predict the behavior of the sensor and estimate the piezoresistivity coefficients of eight-terminal silicon piezotransducer (8TSP). Finite Element Models and specialized solvers are suitable tools to design these devices with unique geometry and anisotropic behavior, where is not feasible to find an accurate analytic solution. The piezotransducers were fabricated using a commercial CMOS process (XFAB 0.6µm) on a monocrystalline semiconductor wafer and were characterized. Simulation results are compared against real measurements from implemented sensor, and seems to have a similar behavior, which demonstrates the utility of this technique for sensor design.**

1. Introduction

Silicon piezotransducers are widely used MEMS devices, with successful commercial applications as pressure sensor and accelerometers. Most of these devices are based on piezoresistivity effect, due to a simpler integration with ICs and more linear response compared with piezocapacitance or other technologies. The piezoresistivity effect was first discovered by Smith [1] and mathematical modeled by Matsuda and Kanda [2, 3], those fundamental researches describe the silicon as an anisotripic material, and the behavior under a mechanical strain is highly dependent of the device main crystallographic orientation, the doping concentration in the material and the stress conditions.

It is possible to find analytic solutions for simple devices, but the development of complex geometries to improve the sensitivity or performance increase the complexity of the calculations. In these cases, Numerical methods and computational solvers become very useful to estimate and visualize the behavior under various stress conditions. In this work, Finite Element Methods (FEM) and multiphysic simulation have been used to design an Eight Terminal Piezotransducer (8TSP), which is shown in Fig.1. We show in this paper the simulation results compared with the experimental measurements from the characterization of the fabricated device.

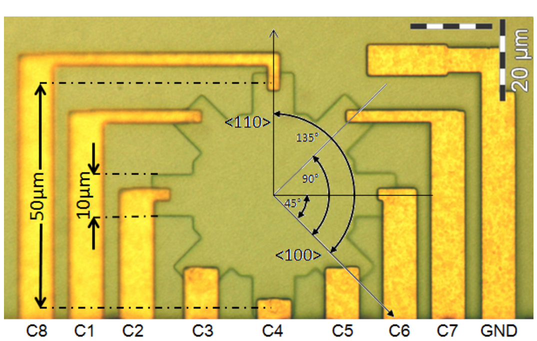

Fig. 1. Eight Terminal Silicon Piezotransducer (8TSP)

2. The Piezoresistivity effect in Silicon

The piezoresistance is the change in resistivity due mechanical stress, and can be modeled by a set of empirical constants known as the First Order piezoresistive coefficients (FOPR): the longitudinal π_{11} , the transverse π_{12}, and the shear coefficient π_{44} . The values for the FOPR measured by Matsuda[3] and Smith[1] are presented in Table I. An analytic solution for generic rectangular resistor can be mathematical written as:

$$\frac{\Delta R}{R} \approx \sigma \frac{\pi_{11} + \pi_{12} + (\pi_{11} - \pi_{12}) \cos 2\varphi \cos 2\lambda + \pi_{44} (\sin 2\varphi \sin 2\lambda)}{2}$$

Where σ and λ represent magnitude and direction of an uniaxial stress and the device orientated at angle φ with the referenced crystallographic direction [100]. This solution partially describes the behavior of the resistance measured in between opposite terminals of the 8TSP, however, the electric field and flow inside the octagonal geometry is different form the rectangular device, then, computational models has been used to observe the exact behavior of the designed transducer.

Table I
First Order Piezoresistive Coefficients $[10^{-10}\text{Pa}^{-1}]$.

FOPR $[\pi_{ij}]$	p-Type		n-Type	
	Smith	Matsuda	Smith	Matsuda
π_{11}	0.7	-0.6	-10.2	-7.7
π_{12}	-0.1	0.1	5.3	3.9
π_{44}	13,8	11,2	-1.4	-1.4

3. FEM Simulation of an Octagonal sensor

The main challenge with the computer simulation is how to solve at the same time the mechanical behavior and the electrical response of the devices, for this purpose we build Finite Element Model and used COMSOL Multiphysics 5.2a interface, which solve for piezoresistivity in anisotropic materials, like the monocrystalline silicon. An 8TSP was placed in the middle of a silicon substrate, and a tensile force is applied along the desired direction. At the same time, the device is biased with 5V across 2 opposite terminals. The input electric current is measured, and the equivalent input resistance of the devices is estimated.

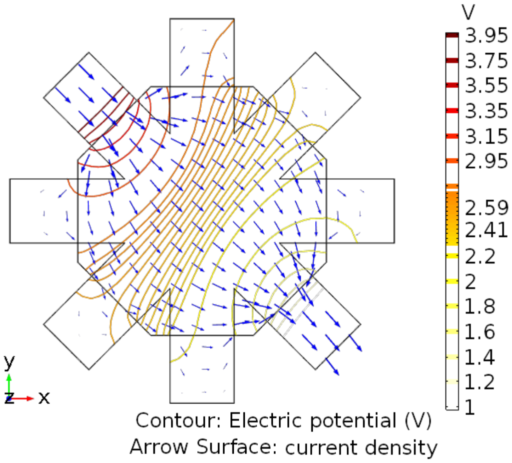

Fig. 2. Simulated current flow and equipotential lines distorted due stress

Because of the piezoresistivity, the stress generates a distortion in the current flow and equipotencial lines with in the devices, this behavior observed in Fig.2. Notice that there is a transverse piezoeffect: an output voltage proportional to the stress can be measured at the terminals perpendicular to the bias direction. This setup as four terminal piezotransducer has been widely used in the design of pressure sensors [4, 5].

4. Experimental characterization of the device

The devices were experimental characterized applying stress aligned with the main crystallographic (stress angle $\lambda = 0°$ for$\langle 100 \rangle$ direction and $\lambda = 45°$ for $\langle 110 \rangle$). The resistance between opposite terminals and the output voltage were recorded for different directions and stress levels. The measurements for the device aligned in different directions (φ of 0°, 45°, 90° and 135°) are shown in colored circles in the Fig.3. With the FOPR measured by Smith[1], same stimulus and conditions were replied in COMSOL Multiphysics, the simulation results are shown in black solid lines. It is possible to identify a linear behavior in both the experimental measures and simulated results, and a very similar behavior.

Actually, the FEM simulations were used to estimated the values for the piezoresistivity coefficients for the technology as $\pi_{11} = -9.3 \times 10^{-10}\text{Pa}^{-1}$, $\pi_{12} = 4.2 \times 10^{-10}\text{Pa}^{-1}$ and $\pi_{44} = -1.5 \times 10^{-10}\text{Pa}^{-1}$. Some spreading comparing the values experimentally obtained and the coefficients from previous works [1, 3] can be explained by the difference in temperature and doping concentration.

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5. Conclusions

COMSOL Multiphysics was employed to simulate a Finite Element Model of a multi-terminal Piezotransducer. Simulation allows us to estimate the values of the piezoresistivity coefficients and to visualize the current flow and equipotencial lines in the devices, and the behavior of the sensor. Results are very close to the experimental measurements of the fabricated device, which demonstrates the accuracy of this simulation methodology.

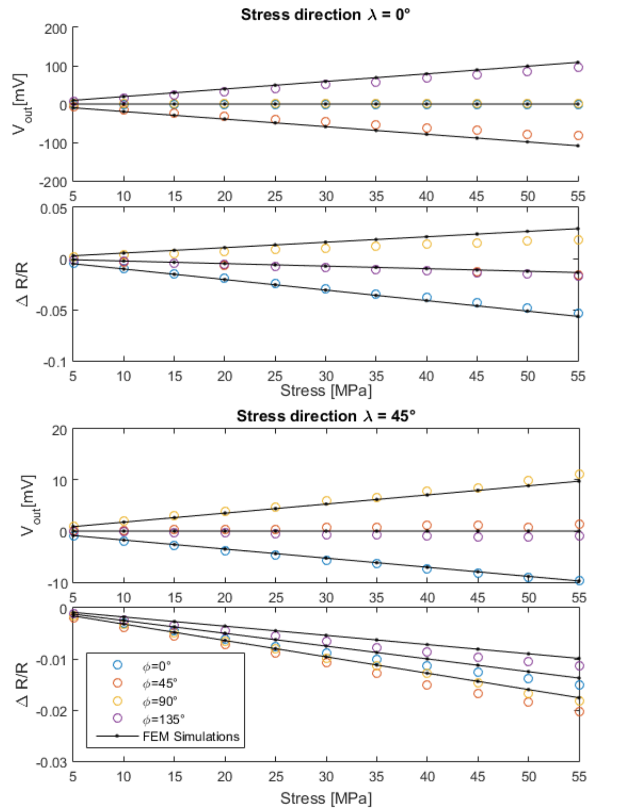

Fig. 3. Comparison between experimental measures (round circles) and FEM Multiphysics simulation results (straight black lines)

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