A Compact Eight-terminal Piezotransducer for Stress Measurements in Silicon

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***Abstract*— Deformations in the crystalline structure have an important impact in electric characteristics of the semiconductors, like carrier mobility and concentration. Since mechanical stress and strain are related, an induced stress in silicon chips compromise the performance and structural integrity of Integrated Circuits (ICs). Reason why stress-sensing devices are becoming important tools to detect and correct stress related problems, improving the performance and yield of ICs. This work shows the design and characterization of an Eight Terminals Silicon Piezotransduzer (8TSP), a stress sensor device based on the piezoresistive effect and designed to estimate the stress state over the (100) silicon surface. The multi-terminal device integrates a resistor rosette in a single octagonal plate, allowing to change the bias direction and to take measure in different orientations, the relationship between those observations can be used to estimate both direction and magnitude of the stress in a certain area. In order to characterize the device, a four-point-bending apparatus using a circular substrate has to be designed to have control of both magnitude and direction of the applied uniaxial stress. The device was attached to a disk and stress was applied in the main crystallographic directions to observe the piezoresistance characteristics and calibrate the sensor. We applied stress in some other directions and the stress behavior fit the predicted by the theory. Those results confirm that the 8TPS can be used to find the stress state over the surface of a silicon chip.**

Index Terms— Piezoresistance Sensors, Strain-Stress Chip.

Introduction

Strain induced by mechanical stress compromise not only the structural integrity, but also the performance of integrated circuits, since carrier mobilities, intrinsic carrier concentration and other important electric characteristics that define the circuit behavior are affected by deformations in the crystalline structure. Stress over the silicon surface is inevitable because it is induced during the fabrication process, chip packaging and even due to operation conditions, mainly because the differences between Coefficients of Thermal Exp ansion (CTE) and the Coefficient of Moisture Expansion (CME) of the different materials used in the electronic industry, those differences in the dilatation rates between attached interfaces generate an internal stress in the solids. Nowadays, more attention is given to identify and reduce the stress, since it has an increased impact in innovative IC technologies adopted by the industry, as ultra-thin dices, nanometric gate lengths, strained-silicon devices, Flip-Chip and 3D-IC packaging [1, 2].

Stress-sensing devices are becoming important tools to analyze the stress effects over the ICs due to electronic packaging. Traditionally, the Piezoresistive effect in silicon have been used to design transducers for stress-measuring purposes, with the main advantage that diffusion resistors are components of commercial IC fabrication process [2, 3], then, no extra layers or an specific purpose process are required and the circuitry to bias the device and process the output can be monolithically integrated.

Piezoresistors have been previously used by circuit designers, particularly for pressure sensor applications [4, 5]. For those kind of transducers, there is no need to get detailed knowledge of the individual stress components, since membranes or other kinds of micro-structures are used to concentrate and orientate the stress over the sensing device. On the other hand, we are interested in measure all the components of the stress state at a point on the silicon surface, and since stress is defined as a vector and has both magnitude and orientation, it is necessary to use devices with different orientations to observe all the stress components.

A well-known piezotransducer is the Resistor Rosette, a set of diffusion resistors with different alignments showed in Figure 1, which allows to determine the stress in a particular region. However, those resistors are separated and spread over an area, which could compromises the accuracy of the stress measurement, limiting its spatial resolution.

Instead of several devices, we decide to integrate, in the same device, all the resistors with different alignments, increasing the accuracy in a certain spot, since all directions share the same active area. The Eight Terminal Silicon Piezotransducer - *8TSP* showed in Figure 1. A multi-terminal device also can be configured in other operation modes, since it can be used like a two terminal piezoresistor rosette or as Four Terminal Silicon Piezotransducer - *FTSP*, and have advantages compared with traditional Rosette, since a stress-sensible output voltage can be observed directly in the contacts, without need of external calibrated circuits as Wheatstone bridges.

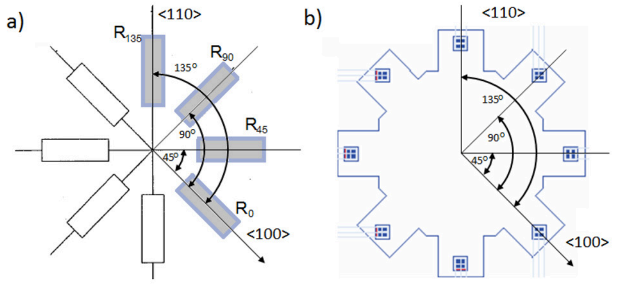

Fig.1 Stress-sensing devices: a) Resistor rosette and b) Eight Terminal Silicon Piezotransducer (8TSP).

The 8TSP can be used to characterize the stress state in integrated circuit chips and electronic packages. In order to get a precise measure, the device should be correctly characterized and calibrated. This work will focus on the characterization of the piezoresistance coefficients, the relative change in resistance and sensitivity of the 8TSP applying uniaxial stress through a special designed four-points-bending apparatus.

First, we present the theoretical development of the stress dependence of the diffusion resistors in monocrystalline silicon. Then, we show the designed experimental set-up used to generate the strain in the desired direction, a four-points bending test based in a circular disk, and the characterization results observed for piezoresistance of the designed 8TSP. We use those results to build an electric circuit equivalent to the sensor device, modeling the piezotransducer as a four terminal resistor bridge sensible to the mechanical stress which can be used in a circuit simulator. Finally, the simulation results of equivalent circuit model are compared with the measured output voltage of the multi-terminal device in order to validate the model. We conclude with the possible designs and future applications for stress-sensing chips based on a matrix of these compact piezotransducers.

II. The Piezoresistive Effect in Silicon

A generic semiconductor resistor, fabricated on the surface of a (100) silicon wafer, is subjected to an uniaxial mechanical stress σ, as shown in Figure 2. The internal forces are going to deform the material and the change the electrical resistivity of the crystalline semiconductor, effect known as piezoresistive effect.

The resistor has an active rectangular area of width W, length L and thickness t, and the material has a resistivity ρ_0 without any applied force. We will consider the crystallographic direction [100] as the reference axis, the device is orientated at an angle φ and the stress is orientated at angle λ. The relative change of resistance $(\Delta R)/(R)$ is calculated using both piezoresistive effect and geometrical deformation. However, in monocrystalline silicon the piezoresistive effect is several orders greater that the influence of the geometrical deformation [6, 7], then we can approach the change of resistance to the change in the resistivity as $(\Delta R/)/(R) \approx (\Delta\rho/)/(\rho_0)$. Also monocrystaline

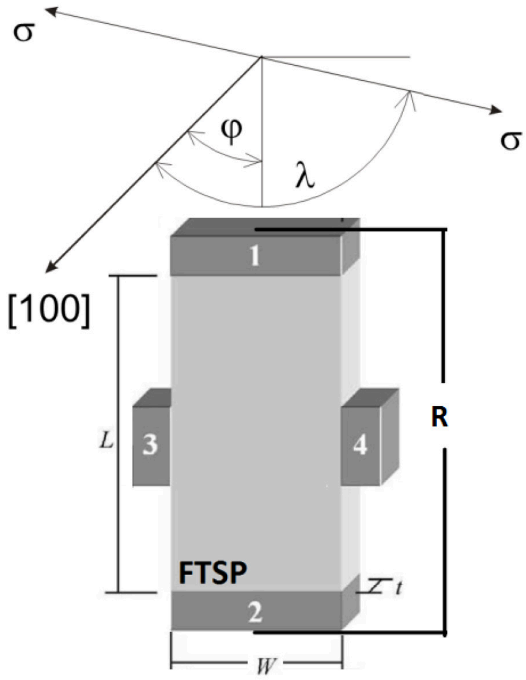

Fig. 2 Arbitrarily oriented silicon resistor.

silicon shows an interesting mechanical response, it has an anisotropic behavior, that means that a sample will stretch in different rates for the same mechanical stimulus up to the applied force direction, it also affects the piezoresistance, reason why the device orientation is extremely important for the design.

The piezoresistance of a material is often modeled by a set of empirical constants known as piezoresistive coefficients π_{ij}. If the stress on the surface is under 200MPa, the piezoresistivity effect can be linearized using only the first-order piezoresistive coefficients (*FOPR*): longitudinal coefficient π_{11}, which is describes the effect of the strain aligned with reference orientation; transverse coefficient π_{12}, which is perpendicular to the orientation; and shear coefficient π_{44}, which quantifies the effect of the stress that is coplanar the cross section. The values for the FOPR π_{11}, π_{12} and π_{44}, measured by Matsuda[7] and Smith[6], are presented in Table I. However, these values represent upper bounds on the coefficients, since FOPR are strongly dependent on the doping concentration and temperature [8, 9], and it is well known that the magnitudes decrease significantly for heavy doping levels [10].

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

	p-Type		n-Type	
FOPR [π_{ij}]	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

Using the piezoresistive coefficients, the relative change of resistance of the generic piezoresistor can be mathematical modeled as:

$$\frac{\Delta R}{R} \approx \frac{\Delta \rho}{\rho_0} = \frac{\sigma}{2}[\pi_{11}(1 + cos2\varphi cos2\lambda) + \pi_{12}(1 - cos2\varphi cos2\lambda) + \pi_{44}(sin2\varphi sin2\lambda)] \quad (1)$$

The stress-sensing devices in Figure 1 are aligned with the main crystallographic at the surface of (100) silicon wafer, for this reason, we are going to focus in the angles: $\varphi = 0°$ parallel with reference direction <100>; $\varphi = 90°$ perpendicular to reference; $\varphi = 45°$ and $\varphi = 135°$ aligned with the <110> direction. Then we can rewrite the equation up to the orientation as:

$$\frac{\Delta R_0}{R_0} = \frac{\sigma}{2}[\pi_{11} + \pi_{12} + (\pi_{11} - \pi_{12})cos2\lambda] \quad (2)$$

$$\frac{\Delta R_{45}}{R_{45}} = \frac{\sigma}{2}[\pi_{11} + \pi_{12} + \pi_{44}sin2\lambda] \quad (3)$$

$$\frac{\Delta R_{90}}{R_{90}} = \frac{\sigma}{2}[\pi_{11} + \pi_{12} - (\pi_{11} - \pi_{12})cos2\lambda] \quad (4)$$

$$\frac{\Delta R_{135}}{R_{135}} = \frac{\sigma}{2}[\pi_{11} + \pi_{12} + \pi_{44}sin2\lambda] \quad (5)$$

Notice that the piezoresistance at the devices aligned with the <100> crystallographic direction ($\varphi = 0°, 90°$) are not related to the shear coefficient π_{44}, only to the longitudinal π_{11} and transverse π_{12}. This observation will lead to an important design decision, since in p-type silicon, π_{11} and π_{12} are negligible compared with π_{44}, p-type devices show a very low sensitivity if aligned to the <100> direction. Since we are interested in measuring through all possible directions, n-type silicon will be used for the active area of the 8TSP.

III. An Octagonal Sensing Device

Instead of building several devices with different orientations, a single 8 terminals device shown in Figure 3 was designed and manufactured using a commercial technology, the XFAB 0.6µm CMOS process. The 8TSP was built as an octagonal shaped n-well layer over the p-type substrate, same layers used for the n-type diffusion resistors. That device looks like an "eight point star", since we overlap all the resistors in the Rosette in the same area, however a few modifications were included to avoid sharp angles which can generate Design Rules problems.

The resistance will be measured between opposite terminals. The resistor R_0 is measured between the terminals C1 → C5, aligned with the <100> ; the resistor R_{45} is measured between terminals C2 → C6, at angle $\varphi = 45°$ with the reference direction; R_{90} is between C3 → C7 and R_{135} is between C4 → C8, which are orientated at $\varphi = 90°$ and $\varphi = 135°$.

Since it is a very symmetric component, we can expect that the resistivity and the measured resistances in between the terminal will be the same for all the direction, however, since anisotropic behavior of the silicon, the sensibility to the mechanical stress will be different for every direction.

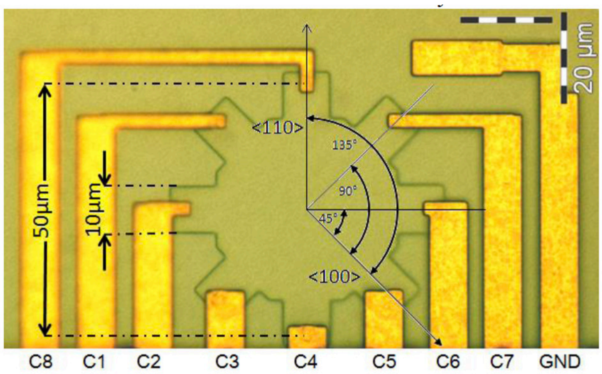

Fig. 3 Layout of the fabricated octagonal Hall plate.

A. Piezoresistor bridge model

In order to relate the change in resistance with an electric signal, like an output voltage related to the stress level, external set-up is required, like the Wheatstone bridge used with the strain gauges. This resistor bridge has to be carefully matched with the piezoelement, and usually shows some temperature drift and other errors related to the mismatch. However the multi-terminal device has a very interesting characteristic, it can be modeled as a four terminal device which behaves like a resistor bridge, as shown in Figure 4. A circuit level model will be very useful to simulate the sensor behavior within an EDA tool, this will be very helpful to design the circuitry that will be used to bias the device and process the output signal, and could be integrated in the same chip.

For this Four Terminal Silicon Piezotransducer - *FTSP*, an input voltage is applied in between terminals 1 and 2, called current-contacts, while an output voltage sensible to the stress is observed in the other 2 perpendicular sensor-contacts 3 and 4.

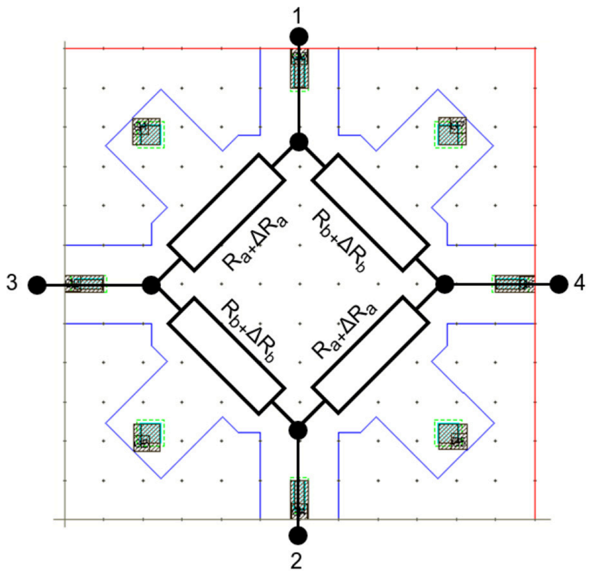

Fig. 4 Octagonal 8TSP modeled as a resistor bridge.

We model the FTSP as a resistor bridge using the Piezoresistors R_a and R_b, which change with the stress and have different orientations. For a symmetric device, R_a and R_b will be equal without applied strain. The device is bias by a voltage V_s at the current-contacts 1 and 2 and generates an output voltage V_{out} at the perpendicular sensor-contacts equal to:

$$V_{out} = \frac{\Delta R_a - \Delta R_b}{2R + \Delta R_a + \Delta R_b} V_s \approx \frac{\Delta R_a - \Delta R_b}{2R} V_s \qquad (6)$$

Any pair of opposite terminals can be used to bias the device and measure the output voltage, since we have 8 terminals, we will have at least 4 different possible orientations (φ = 0 °; 45 °; 90 °; 135 °). R_a and R_b can be substituted by R_0, R_{45}, R_{90} and R_{135}, up to the orientation of the current-contacts, for example, if the device is biased in between terminal $C1 \rightarrow C5$, aligned with the <100> direction and angle $\varphi = 0$ °, R_a will be R_{45} and R_b will be R_{135}, as can be observed in the Figure 4. Then we can find an expression for the output voltages for 8TSP up to the angle φ as:

φ[°]		$V_{out}(\varphi,\lambda)/V_s$
0	$\frac{\Delta R_{45} - \Delta R_{135}}{2R} =$	$\frac{1}{2}\sigma(\pi_{44} sin2\lambda)$
45	$\frac{\Delta R_{0} - \Delta R_{90}}{2R} =$	$\frac{1}{2}\sigma(\pi_{11} - \pi_{12})\cos(2\lambda)$
90	$\frac{\Delta R_{135} - \Delta R_{45}}{2R} =$	$-\frac{1}{2}\sigma(\pi_{44}\sin2\lambda)$
135	$\frac{\Delta R_{90} - \Delta R_{0}}{2R} =$	$-\frac{1}{2}\sigma(\pi_{11} - \pi_{12})\cos2\lambda$

The bridge model and the equations are equivalent to the models developed by other research groups, who worked with the four terminal piezotransducers [11, 4].

If the piezoresistivity coefficients are identified, two complementary measurements in different directions (spaced by 45°) are enough to estimate both the magnitude and the direction of an uniaxial stress on the surface of the devices, as can be observed in the equations. Since the 8TSP allows more different possible bias direction, extra measures can be used to determine an other stress components, like the share stress normal to the silicon surface for example, a complete methodology that uses measures in all the directions to determine the stress state and other applications of the device are going to be explored in future works.

IV. The Four-Point Bending Apparatus Design

Many of the monocrystalline silicon characteristics are anisotropic, which means that they shows different behaviors for different directions. Then, to study the response to mechanical deformation, it is necessary to control both the magnitude and direction of the stress, this leads to one main challenge: how to apply a precise and accurate strain in the surface of semiconductor chips with a particular orientation.

Previous research groups have used different methodologies to apply an uniaxial Load, like the Tensile test [12, 13], hydrostatic pressure [10 , 14], torsion test [15], cantilever beam bending test [9], three-point bending test and four-point bending test [11,3]. All of them require to cut several samples from semiconductor wafers, each one in a particular desired direction and then apply a mechanical load, which took an important amount of time and resources, and compromise the accuracy, since several different samples are used to observe the anisotropic behavior. Also, since semiconductors are brittle materials, clean cuts, special clamping structures and polished surfaces are required to reduce cracks and other defects which can lead to stress concentration and fragile fracture, which increase the time and care required to prepare the samples.

Instead of use several samples, we were looking for a methodology that allows to change the stress orientation. A bending apparatus specially designed for a four-inches silicon wafer was designed, allowing to spin the sample and have an accurate control over the deformation. If it is not possible use a complete wafer, a disk metal can be used as substrate and the silicon chip can be attached using a chipbounder adhesive. A quick introduction of the apparatus and the experimental setup, including the most important design consideration, is presented in order to explain the methodology used to characterize the stress sensors.

A. Bending test

In solid mechanics, strain is a measurement of deformation of the material and stress is a way to quantify internal forces. Most of solid materials, including metals and semiconductors, show an elastic behavior, a linear relationship in between the strain and the stress, summarized by the elastic theory of solids and the Hooke's law. Then, if a solid is deformed in a controllable way, it will be possible to find a complete stress distribution within the material. Stress is represented as a vector that has 6 components, 3 normal to the planes, called normal stress, and 3 parallel to the surfaces, the shear stress. It is desirable for the stress-tests with semiconductors to work with only one of the normal components of the stress, an uniaxial stress, canceling out the forces in other directions and avoiding the shear components.

There are several ways to deform a sample, it can be stretched, bent or twisted. In Tension testing [1], the sample is stretched with a tensile load, which generates an uniform normal stress along the material. This kind of test is specially useful for metals and plastics, however it is not recommended brittle materials, since the tensile stress will propagate failures and a special preparation of the sample is required to proper clamping and load.

A more suitable way to induce controlled deformation will be bend the material. In a bending test, a sample is placed horizontally while it is loaded with vertical forces, which generates a shear force and bending moment in the material. The bending moment deflects the sample, while the shear force induces shear stress in the solid. The deflection in beam have been widely study and the stress profile, surface and load-carrying characteristics are modeled by linear elasticity and Euler–Bernoulli beam theory.

In the Four-points bending test, load is applied two symmetric points at the middle of the beam for the four-point bending, as shown in the diagram in Figure 5. There is an area in the middle of the beam with a constant maximum bending moment and a very low shear force. This middle area provides the desired conditions to test semiconductor material, since the constant bending moment generates an accurate constant stress along the surface, without the shear stress induced by the shear force which can propagate a rapid fracture.

Based in the mechanics of materials and static force analysis, it is possible to find a relationship in between applied force, vertical displacement, deflection and stress in four-point setup showed in Figure 5. The sample has a thickness *t* and it is made of an elastic material with Young's modulus Y_λ; x_1 and x_2 are the distances in between the supports; I_x is area moment of inertia; *F* is the applied load and the maximum bending momentum is equal to $M_{max} = {F(x_1 - x_2)}/{4}$ at the central area. The stress at the surface in a solid under a bending momentum is $\sigma = {Mt}/{2I_x}$, then four-points fixtures applies uniform uniaxial stress in the central region

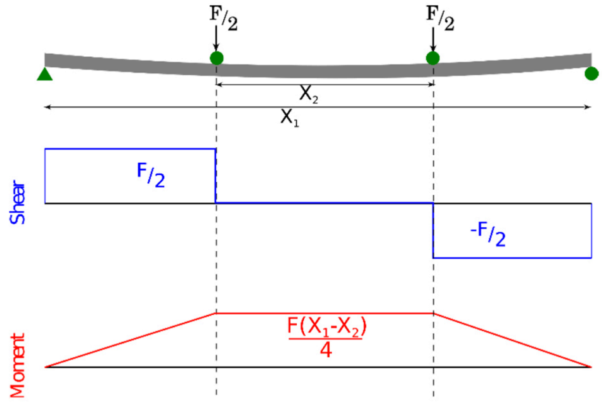

Fig. 5 Four-points bending test diagram showing the bend profile, shear stress and bending momentum along the sample.

equal to:

$$\sigma = \frac{F(x_1 - x_2)t}{8I_x} \tag{7}$$

The vertical displacement Δ_y between the support points and the strain ε at the surface of the beam can be calculated solving the differential equation from the Euler–Bernoulli beam theory, $\left({d^2y}/{dx^2} = {M(x)}/{Y\, I_x}\right)$, as:

$$\Delta_y = \frac{M_{max}(x_1 - x_2)(x_1 + 2x_2)}{6Y_\lambda I_x}$$

$$= \frac{F(x_1 - x_2)^2(x_1 + 2x_2)}{24Y_\lambda I_x} \tag{8}$$

$$\varepsilon = \frac{\sigma}{Y_\lambda} = \frac{6\Delta_y}{(x_1 - x_2)(x_1 + 2x_2)} \tag{9}$$

Those equations are important for the design of the apparatus, since they model a relationship between the linear displacement and the stress.

B. Bending test of a circular sample

Design a test to apply controlled stress over the semiconductor IC surface while at the same time measure the electric behavior is a challenging task, since it will be required to have a precise control over the direction and magnitude of the applied deformation and free space for the electrodes and connections is required.

The standard bending test in beams does not allows to change the angle in which the stress is applied, in this work we introduce the four-points bending apparatus, showed in Figure 6, designed to induce a constant uniaxial stress in the middle area of the disk, and since the sample is circular and it is not clamped, it is possible to rotate the sample and to aligned in different orientations. The same device can be tested in different orientations instead of slice different samples in several directions.

The apparatus was manufactured in aluminum and inox steel and specially designed for a four inches silicon wafer. It is composed of a base, three columns, an upper cover, where the fixed fixtures are positioned, and linear actuator which moves the inner supports. The geometry is the inverse of traditional Four-point bending setup to leave free area at the top, where the electrical connections and measurement instrument have access to the chip. The distance between columns is equal to the 4 inches wafer diameter, which allows to easily swap the disk and place it in the same position. The columns are used as rails for the displacement of the mobile base, also linear bearings were added to reduce friction and ensure smooth motion.

A 2mm pitch lead screw and a NEMA-23 stepper motor were used to build a linear actuator with a 5µm/step maximum resolution. The actual force on the actuator is not monitored, since the strain and surface stress are related to the vertical displacement. An external motor driver and regulated power source are required to bias and control the actuator.

C. FEM models, simulations and analysis of the circular substrate

The standard bending test in beams does not allow to change the angle in which the stress is applied. Instead of using a regular rectangular sample, we propose to use a disk, which allow us to spin the sample in any desired direction, which means that we can characterize the very same device in different orientations instead of cut different samples in several directions.

However, different from the conventional beam where the transverse area and the area moment of inertia I_x are constant along the beam, the circular substrate have some geometric particularities.

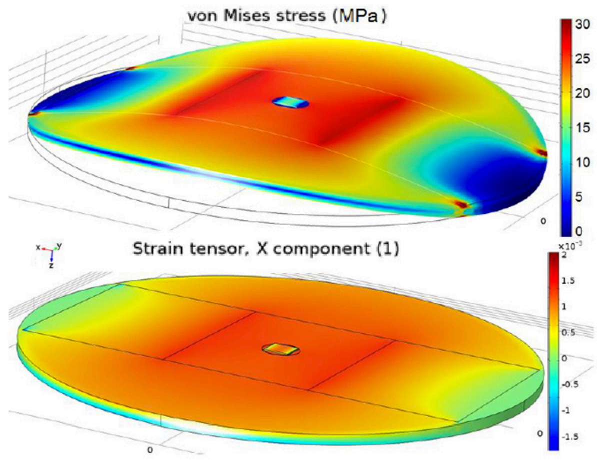

Fig. 7 FEM simulations results in a circular disk for 1mm deflection: a) bend profile and surface stress and b) uniaxial strain at the surface.

To simulate the behavior of the disk substrate and the semiconductor chip attached to the surface, Finite Element Models - FEM and COMSOL MULTIPHYSICS are used. Figure 7 shows the simulation results for stress distribution in the Four-points bending setup for a circular aluminum substrate and the Silicon die attached. Notice that in between the supports, the middle of the disk, strain is constant, however the surface stress is slightly different in between the disk and the die, difference that can be explained since the Young's modulus of both materials, aluminum and silicon, are different. Furthermore, notice that there is lower strain and stress levels at the borders of the silicon chip, stress sensor device should be placed in the middle of the chip to avoid the stress concentration or the lower strain level at the edges of the device.

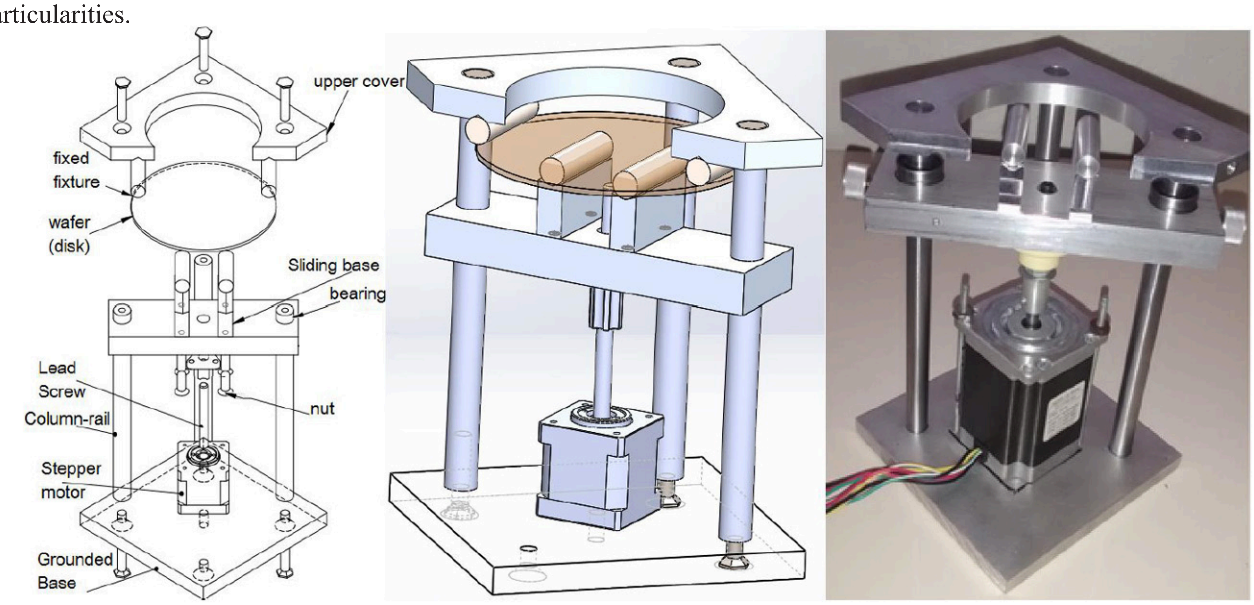

Fig. 6 Exploded view, assembled view and photo of the Four-points bending apparatus.

There will be the same deformation in the disk surface and the chip attached to the substrate, the stress at the surface of the chip can be calculated by the Hooke's law as:

$$\sigma = \varepsilon Y_\lambda = G_f \frac{6\Delta_y Y_\lambda}{(x_1 - x_2)(x_1 + 2x_2)} \quad (10)$$

The constant G_f is included in the equation as a correction factor to compensate the differences induced by the circular substrate and the attaching compound used to fix the silicon die to the surface. A value of the $G_f = 0.788$ factor was estimated using FEM simulations using aluminum as substrate and the selected attached method.

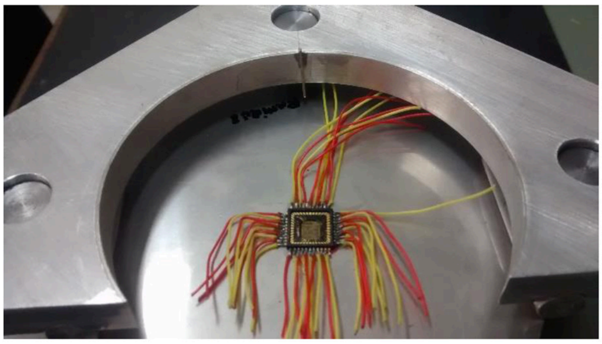

Fig. 8 Silicon device attached to metal disk substrate to be tested in Four-point bending apparatus.

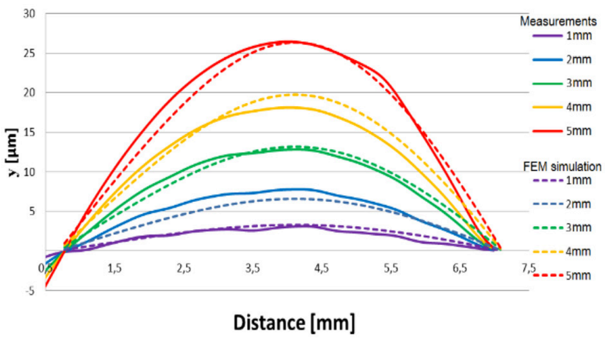

Fig. 9 Surface of an attached silicon chip under bending for different vertical displacements.

D. Silicon Devices attached to a metal disk

Chips already diced or packaged can also be tested with the setup, in those cases, the samples have to be careful attached to a circular substrate using standard electronic packaging technology, as shown in Figure 8.

We used tried adhesive substances and found that the LOCTITE ECCOBOND XE1218 underfill has excellent characteristics: it does not add remaining stress to the chip after curing and have a good strain transmission from the metal surface to the silicon sample. Attached silicon samples were tested under bending conditions, and a BRUKER Dektak surface profiler was used to measure the deflection at the surface. Figure 9 shows the surfaces profile for different vertical displacements of the Four-points bending setup, solid lines are the measurements with the Dektak profiler while dashed lines are the results simulated using FEM.

The behavior of a silicon piezotransducer under stress in the attached chip was also modeled. The stress generates a change of resistance and a distortion in the equipotential along the device, which can be observed in Figure 12.

V. Experimental Results

A. Characterization of the Piezoresistors

Samples of the devices were tested using the bending test with the main objective of validate the four-points bending methodology, but also to observe the behavior of the resistance between the terminals of the 8TSP and calibrate the device. Since the piezoresistive coefficients are highly dependent of the doping concentration, the test will be also useful to determine the values of π_{11}, π_{12} and π_{44} for the XFAB 0.6µm CMOS process.

Initially, we applied a deformation in the samples in two different relevant directions, the angles $\lambda = 0°, 45°$. Those angles are quite interesting since they will be aligned with the main crystallographic directions at silicon surface. Controlled stress was applied while the 4 Resistors R_0, R_{45}, R_{90} and R_{135} were measured using four-points measurement of impedance at room temperature of 300K (~27°C). Figure 10 shows the change in resistance in every case, it can be observed a strong linear dependence of the resistance with the stress.

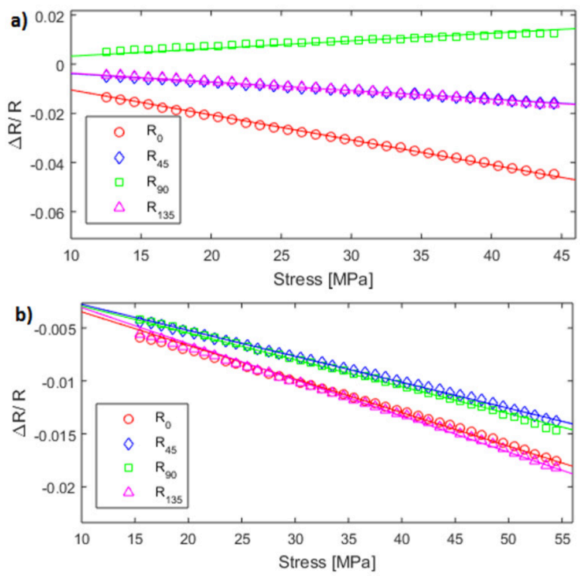

Fig. 10 Experimental result for stress orientated at angles: a) λ = 0º and b) λ= 45º.

We estimated the longitudinal, transverse and shear piezoresistive coefficients using the experimental measurements as: $\pi_{11} = -9.3 \times 10^{-10}\,Pa^{-1}$, $\pi_{12} = 4.7 \times 10^{-10}\,Pa^{-1}$ and $\pi_{44} = -1.5 \times 10^{-10}\,Pa^{-1}$. The differences between the values and the coefficients on Table I can be explained by the geometrical particularities of the 8TSP, the difference in doping concentration and temperature.

We test the devices in other intermediary angles for stress, using $\lambda = 22.5°$, $67.5°$, $90°$ and $112.5°$. Table II shows the results for the slope of the $\Delta R/_{R}$ versus stress under those testing conditions. The results fit the equations from the piezoresistance effect in silicon.

Table II Mechanical-stress-induced relative change in resistance [$10^{-10}\,Pa^{-1}$] for some particular uniaxial stress direction.

λ[°]	$\Delta R_0/R_0$	$\Delta R_{45}/R_{45}$	$\Delta R_{90}/R_{90}$	$\Delta R_{135}/R_{135}$
0	-9.29	-3.45	3.20	-3.48
22.5	-7.06	-4.02	0.46	-3.78
45	-3.50	-4.23	-3.52	-4.31
67.2	0.53	-3.26	-6.89	3.21
90	3.17	-3.50	-9.31	-3.43
112.5	-7.01	-3.92	0.66	-3.98

B. Characterization of the device as a four terminal resistor bridge

Once we characterize the piezoresistive effect and estimate the values for the coefficients π_{11}, π_{12} and π_{44}, we are going to validate the circuit model of the 8TSP as a piezoresistor bridge. This model will be very useful to simulate the transducer within an analog circuit design environment.

A 5V input voltage V_s was used to bias the sensor, while the output voltage is observed. We repeated the test under controlled condition, applying a deformation in the samples in two different relevant directions, with stress orientated at angles $\lambda = 0°$, and 45°, which are aligned with the main crystallographic directions at silicon surface. The 8TSP was biased in 4 different direction, which current-contacts orientated at angles $\varphi = 0°$, $45°$, $90°$ and $135°$, and the output Voltages V_{out0}, V_{out45}, V_{out90} and V_{out135} were measured for different levels of strain. Figure 11 shows the results in every case, notice that there is strong linear dependence with stress. Finite Element model of the octagonal device with the same geometry and piezoresistivity was build and simulated using COMSOL MULTIPHYSICS as solver. The mechanical stress generates a distortion in the equipotential, as it can observed in Figure 12, the behavior of the output voltage was the same as the measured in the characterization of the device.

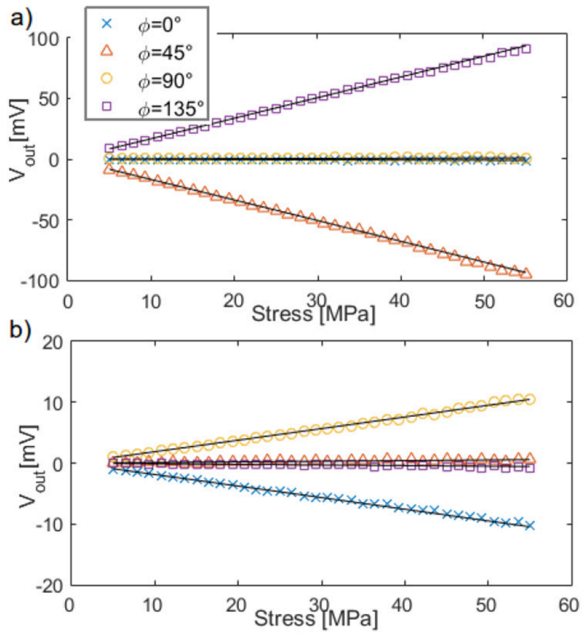

Fig. 11 Experimental result for the output Voltage for stress orientated at angle: a) $\lambda = 0°$ and b) $\lambda = 45°$.

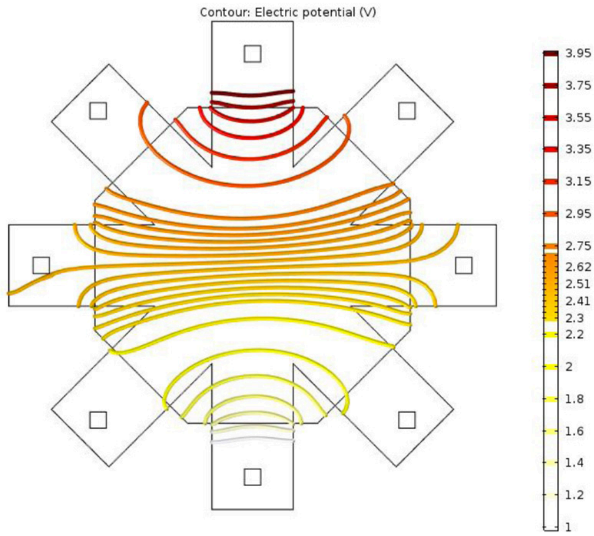

Fig. 12 FEM simulation results for equipotentials under mechanical stress.

We test the devices in other intermediary angles for stress, same as for the change in resistance, a stress aligned with angles $\lambda = 22.5°$, $67.5°$, $90°$ and $112.5°$ was applied. Table III shows the results for the sensibility $^{Vout}/_{Vs}$ versus stress. The results fit piezoresistor bridge model of the device.

Table III Sensitivity to Mechanical stress V_{out}/V_s for some particular uniaxial stress direction.

λ[°]	V_{out_0}/V_s	$V_{out_{45}}/V_s$	$V_{out_{90}}/V_s$	$V_{out_{135}}/V_s$
0	0.75	0.61	-0.74	-0.61
22.5	0.52	5.35	-0.53	-5.44
45	-0.01	7.67	-0.02	-7.66
67.2	-0.53	5.32	0.54	-5.32
90	-0.73	0.11	0.73	-0.10
112.5	-0.52	-5.40	0.53	5.41

VI. Conclusions

This work introduces the 8TSP, a single and compacted device fabricated with a commercial CMOS process. This device was successfully used to measure the magnitude an mechanical stress applied in a Silicon die in several directions. We observed a significant variation in all the possible directions, and maximum sensibility of the device were detected when the stress is aligned with the <100> direction, which is in agreement with the piezoresistece theory.

A chip-attached-on-disk and the four-points bending test techniques were successfully used to apply a stress over the surface of the device, and finite-element simulations of the die strain distribution agree well with the measured stress. It was possible to calibrate the sensors and determine the values for the piezoresistence coefficients $\pi_{11} = -9.3 \times 10^{-10}$ Pa^{-1}, $\pi_{12} = 4.7 \times 10^{-10}$ Pa^{-1} and $\pi_{44} = -1.5 \times 10^{-10}$ Pa^{-1}. Some spreading comparing the values experimentally obtained and the coefficients from previous works can be explained by the difference in doping concentration and temperature.

The Four-point bending apparatus is reliable and simple to use. It was possible the monitor the piezotransducer and the responses fits the expected linear behavior. However, a few minor problems were observed. The actuator has shown a hysteresis during increasing and decreasing cycles. The displacement of the actuator is affected mainly by tolerance between the lead screw and the polymeric guide nut and the force along the motor, which compress the shaft. This actuator hysteresis influence can be completed reduced if the vertical displacement of the sample is monitored or by adding force-strain sensors at the shaft.

We modeled the 8TSP using a resistor bridge. The mechanical stress unbalances the bridge generating a proportional output voltage. The sensitivity of the bridge is related to the piezoresistive effect and it is function of the orientation of the bias current-contacts and the direction of the applied stress. Using measures with different orientations is possible to determine the complete uniaxial stress state at certain region on the silicon surface.

It is possible to determine both the magnitude and direction of the applied stress switching the current direction in the 8TSP. Since the output is a differential voltage, there is no need to design an external Wheatstone bridge, thermal calibration or compensation circuitry.

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