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# Sensitivity tuning of A 3-axial piezoresistive force sensor

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ABSTRACT

Design and development of a Si based full membrane piezoresistive 3D force sensor is presented in this paper. Four piezoresistors are formed by ion implantation on the back side of a thin Si membrane, while on the front side a 380 μm high Si mesa is produced by subtractive dry etching (deep reactive ion etching). The external force is applied on the top of the mesa. The applied force vector, i.e. its normal and shear force components are determined by combining the responses of the four piezoresistors. The effect of different parameters – the shape and thickness of the membrane, the cross section of the mesa – on the sensitivity of the sensor is analyzed systematically by finite element methods. Comparison of the characteristics of the different sensor designs obtained from simulations and from experimental measurements is also presented.



## 1. Introduction

There is a critical need for miniature force sensors for a large number of applications ranging from semiconductor processing to medical devices to material characterization. Most of the proposed structures the shear sensitivity is generally enhanced by a rigid rod mounted on the deforming membrane for transferring the load using wet alkaline etching [1,2] or wafer bonding [3,4] techniques. Some of the developed micro-electromechanical sensors are too fragile and the sensitivity can cover only a narrow range [5].

The present work describes a Si mono-block, full membrane, three-axial force sensor using deep reactive ion etching (DRIE) technology with a design which makes the sensitivity and robustness easily scalable. In the Si element, a column like rod at the centre of a deforming membrane protrudes over the top surface of the device. Piezoresistors placed on the backside of the membrane, provide the signals for resolving the vector components of the load. The mono-block Si structure guarantees the perfect transmission of the attacking force to the sensing elements.

The advantage of the developed fabrication technology is the ease of the sensitivity tuning of the sensor by adjusting two lithographic steps defining the geometry of the sensor. Effect of membrane thickness, shape of the membrane and fill factor (the area of the rod/area of the membrane) on the sensitivity of the sensor was analyzed systematically by finite element methods. Based on the simulation results photolithographic masks were designed and force sensor elements were realized. Experimental results were compared to simulations and good agreement was found.

## 2. Simulation results

The COMSOL Multiphysics 3.5 software package was used for finite element modeling (FEM) the full membrane structure of the sensor. A stationary stress analysis is presented for the sensitivity calculations in Structural Mechanics Module using time independent Navier equation for stress [6]. Ortotropic elasticity matrix was used to describe the anisotropic properties of Si. (1 0 0) orientation of the substrate and ⟨1 1 0⟩ directionality of the piezoresistors were taken into account [7]. As boundary conditions the frame of the membrane ($W_s$ on Fig. 1) was considered to be fixed, whereas other elements are free to move with zero initial displacement.

A 3D model was built up using tetrahedral elements to calculate the mechanical stresses and displacements caused by the external force. The external load was taken as a force distributed at the end of the central rod, as the realistic loads in this size range are not point loads.

In order to avoid the fracture of the membrane, the equivalent stress should not exceed 250 MPa [7]. Therefore, the von Mises equivalent stress was also calculated. The estimated sensitivity can be obtained from the stresses in the $x$ and $y$ directions, as they are the longitudinal and transversal stresses depending on the orientation of the resistors.

The schematic geometry of a sensor element is shown on Fig. 1. The initial parameters are summarized in Table 1. In the following, effect of membrane thickness and fill factors on sensitivity was analyzed. One parameter was varied at a time, while others were kept constant.

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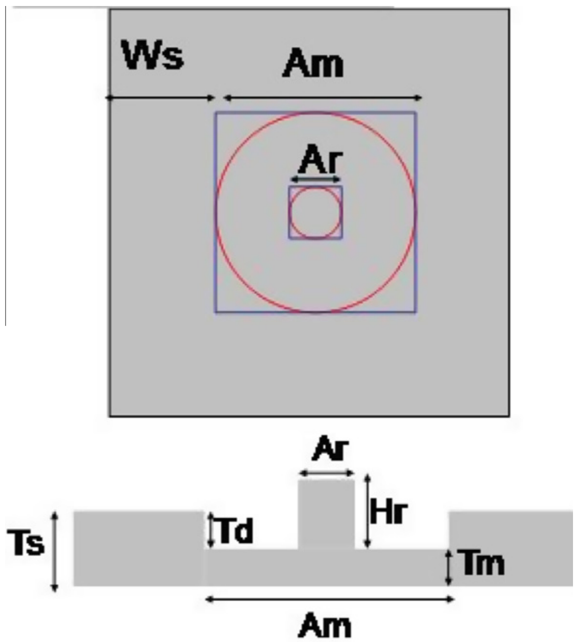


**Fig. 1.** Top and cross sectional schematic view of the simulated and realized sensors. Membrane with square shape and its circular equivalent is marked by dotted and continuous lines, respectively.

Suitable positions for the piezoresistors on the membrane were analyzed by FEM calculations in order to get largest change in resistivity, which is equivalent to find the positions, where the largest mechanical stresses occur [7]. Stress distributions do not change qualitatively, if vary the structural parameters, while using the same loads and boundary conditions for the chips.

**Table 1**
Initial parameters of the investigated sensor.

| Parameter name | Reference value (μm) |
|---|---|
| $A_r$ (rod's radius/side length) | 200 |
| $H_r$ (height of the rod) | 120 |
| $T_d$ (difference between thickness of the membrane and suspension frame) | 150 |
| $T_m$ (thickness of the membrane) | 110 |
| $A_m$ (membrane's radius/side length) | 940 |
| $W_s$ (width of the suspension frame) | 500 |
| $T_s$ (thickness of the suspension frame) | 260 |

Planar technology allows us to form the resistors on the back side of the mesa, so in the following we investigate the back side of the membrane.

Fig. 2 shows some of the implemented geometries with rectangular and circular structures (2a, b), the von Mises equivalent stress distribution on the back side of the membranes (2c, d) and the distribution of the mechanical stress which is proportional to the resistance change (2e, f).

Above simulations show that the edges of the membrane (Fig. 2c and d) are convenient positions for the piezoresistors. They were placed at the region of maximum stress aligned perpendicularly to the edges, while their reference elements were formed in the non-deforming frame.

Sensitivity of one resistor was analyzed as a function of membrane thickness (50–230 μm) while applying 1 N normal (Fig. 3a)

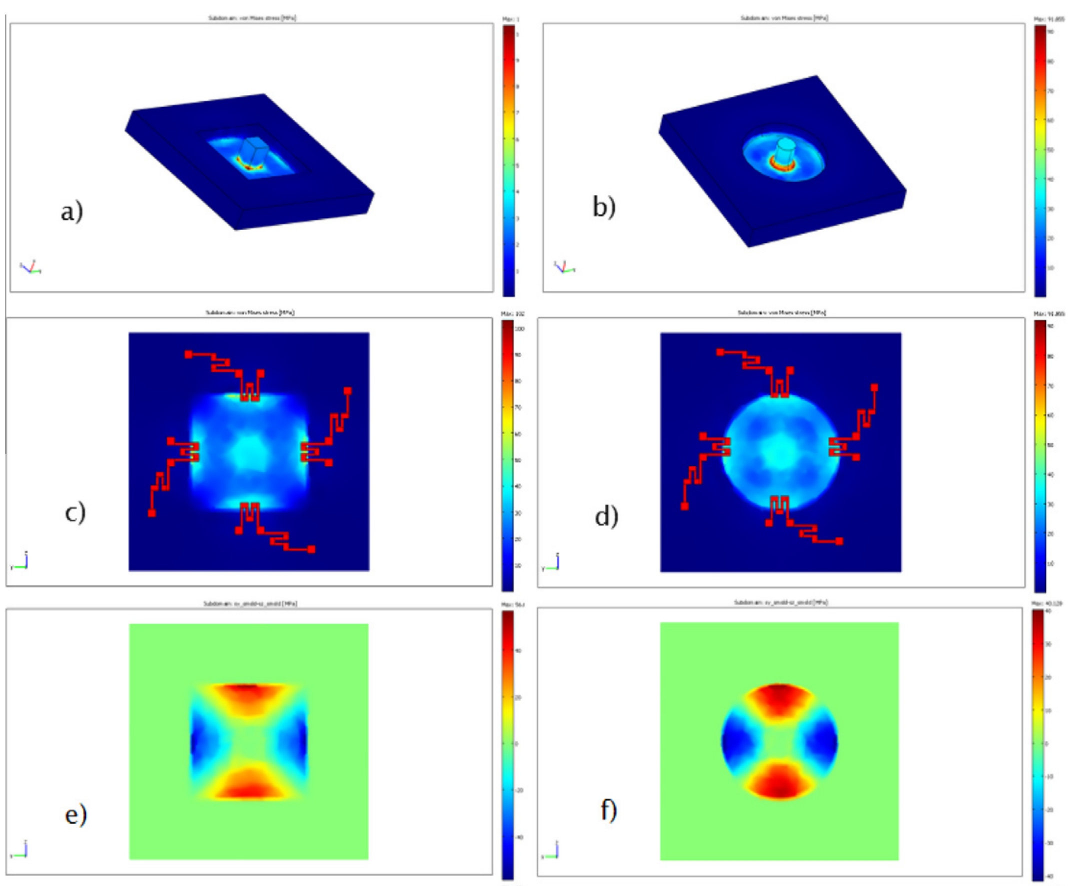


**Fig. 2.** (a and b) Implemented 3D model of a sensor with square shaped and circular membrane, respectively. (c and d) Calculated von Mises stress distributions and the designed sensing and reference resistors on square shaped and circular membranes. (e and f) Calculated stress distribution on the back-side of a square shaped/circular membrane proportional to the resistance change.

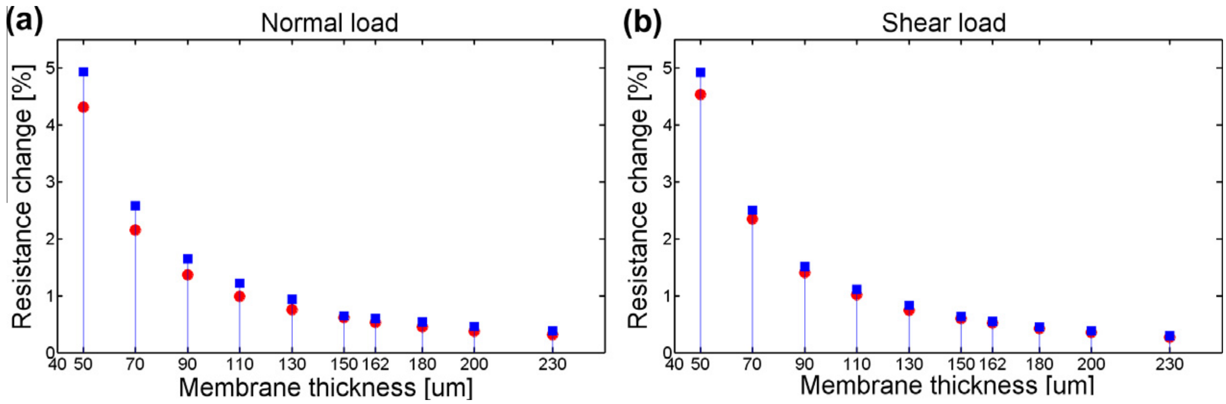


**Fig. 3.** Relative resistance change versus membrane thickness for 1 N normal (a) and shear (b load on square shaped (marked with blue squares) and circular (marked with red circles) sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

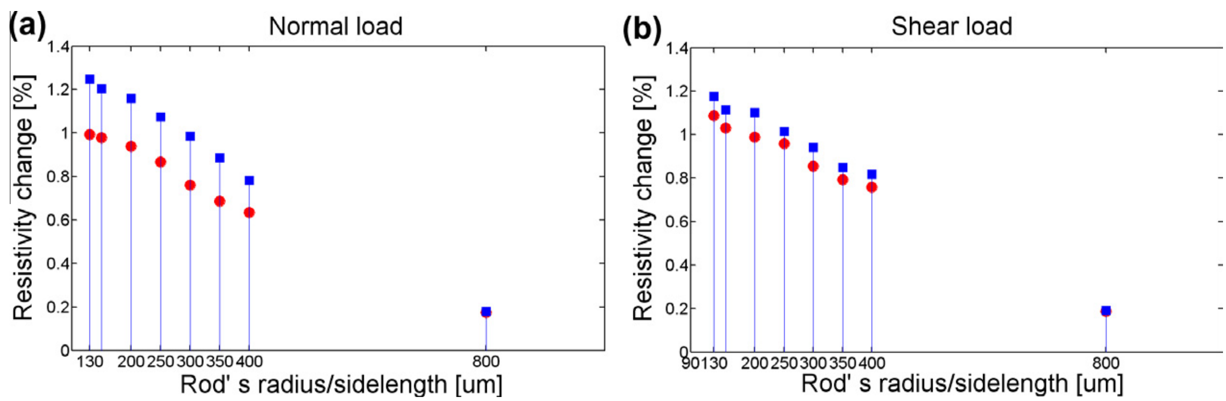


**Fig. 4.** Relative resistance change versus fill factor for 1 N normal (a) and shear (b) load on square shaped (marked with blue squares) and circular (marked with red circles) sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

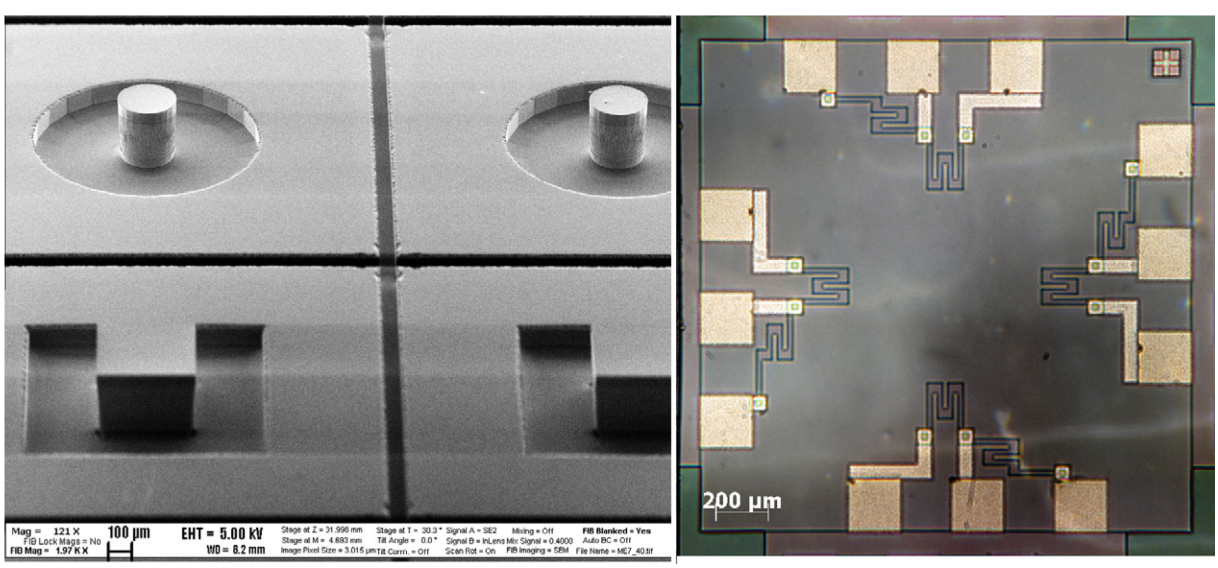


**Fig. 5.** Front (a) and back-side (b) images of the fabricated sensors.

and 45° shear (Fig. 3b) force load. Sensitivity decreases with increasing membrane thickness, as resistivity change is inversely proportional to the square of the membrane thickness. It means that just by varying the thickness of the membrane, we could tune the sensitivity of a chip, in a range of one order of magnitude. Another important conclusion is that the square shaped sensors are more sensitive, than their circle shaped equivalents.

Fill factor of the membrane was also analyzed by FEM. The diameter (in circular case) or side length (in square shaped case) of the rod was varied in the 130–800 µm range. Sensitivity of one resistor was analyzed while applying 1 N normal (Fig. 4a) and 45° shear (Fig. 4b) force load, respectively. Simulations show that by increasing the fill factor the sensitivity is decreasing approximately linearly.

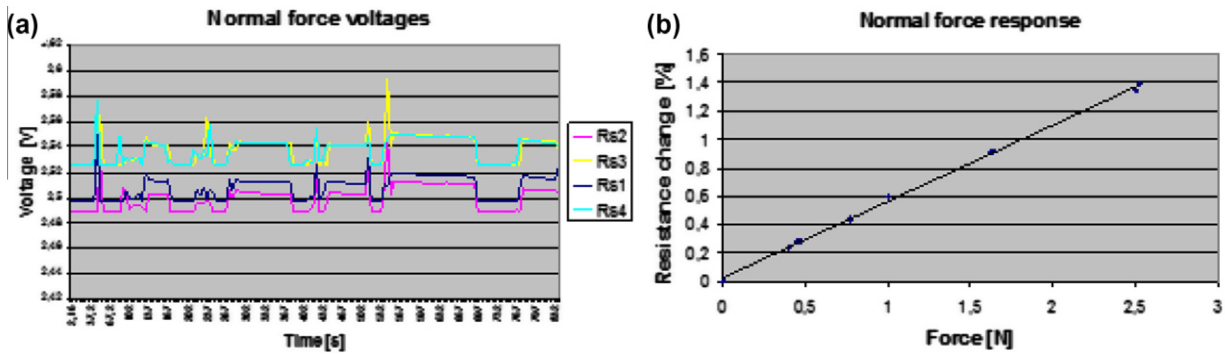


**Fig. 6.** (a) Voltage response of the resistors to normal loadings versus time. (b) The linear input–output characteristic of the sensor with square shaped 162 μm thick membrane and rod with side length of 200 μm.

## 3. Experimental results

Fig. 5a and b shows the realized sensor front and back side, respectively. In the fabrication process for the formation of the 3D geometry two masks were used. These masks define the shape and fill factor of the sensor while the membrane thickness and overhang of the rod is defined by the deep reactive ion etching steps.

On the back side *p*-type piezoresistors were fabricated by ion implantation. Contact pads were formed by Al deposition and patterning.

The packaging had to be carried out with great precision, considering that the membrane and the piezoresistors need to move freely, while other parts should be fixed. A PCB board, with a hole on it, only in the position of the membrane was used; later the chip was attached to this. Hence we could guarantee the good agreement between the conditions of the simulations (boundary conditions) and of the experimental measurements.

The experimental set-up consisted of a loading instrument, signal measuring system and data processing. Piezoresistors with their reference pairs were arranged in a half-bridge configuration to provide a direct voltage reading proportional to the strain [2,8]. The node voltages were measured by a Keithley 617 Programmable Electrometer switched subsequently by a Keithley 705 Scanner to each node. LabView 6.0 package was applied for controlling and data acquisition via IEEE-488 bus. The bias voltage was 5 V.

Sensors realized with the following parameters were tested using Andilog Centor force gauge: side length of the membrane is 940 μm, side length of the transmitting rod is 200 μm, thickness of the membrane is 162 μm, and height of the rod is 310 μm. Characterizations followed a simply way, such that the force gauge was fixed, while the sensor was moved towards it.

In response to normal loading, the sensor outputs were recorded at different force magnitudes in the 0–2.5 N range.

Responses to the normal loading in all four elements are approximately equal, since the stress and the arising strain at the position of all the symmetrically arranged piezoresistors in the membrane is similar.

The input–output characteristic was linear, as expected, resulting in a sensitivity of 5.98 mV/V/N, which is in good agreement with the calculated 6.01 mV/V/N value for a sensor with 162 μm thick square shaped membrane. Measured responses for different loading conditions are plotted in Fig. 6.

## 4. Conclusions

Sensitivity tuning of a full membrane mono-block 3D force sensor was shown by varying geometrical parameters of the structure. The process flow allows the batch fabrication of sensors with different sensitivity by simply changing the fill factor and the membrane thickness in the configuration. The different fill factor designs can be placed on the very same photolithographic mask, while membrane thickness is defined by the DRIE process, which is usually done wafer by wafer.

Finite element simulations show that sensitivity depends on membrane thickness, shape of the membrane and ratio of the transmitting rod/membrane area, too. Calculated sensitivity forecasted by FE analysis was compared with experiments on realized sensors. The measured input–output characteristic was perfectly linear in the investigated range, resulting in a sensitivity of 5.98 mV/V/N, which is in good agreement with the calculated 6.01 mV/V/N value for a sensor with 162 μm thick square shaped membrane. The sensitivity range for micro-electromechanical membrane or bridge-type piezoresistive sensors are often in the mV/V/mN range [1,9,10]. In our case the device parameters was chosen to fulfill the requirements of a specific automotive application, where higher loads are applied. With special packaging using elastomeric covering the load range could be further extended [10].

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