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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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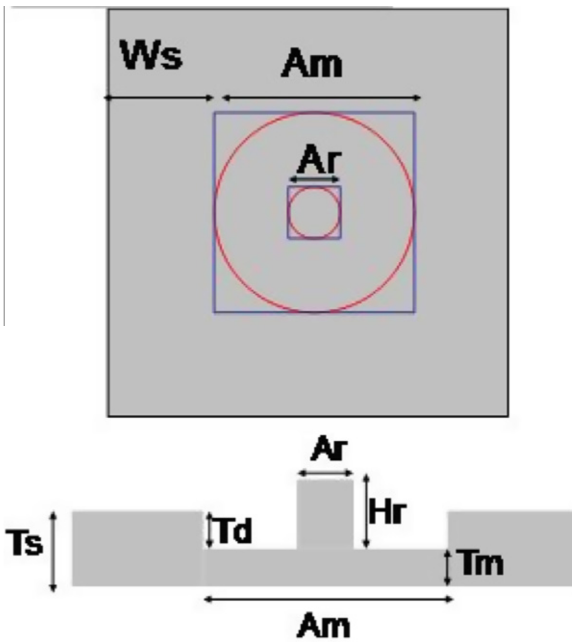

Fig. 1. Top and cross sectional schematic view of the simulated and realized sensors. Membrane with square shape and its circular equivalent is marked by dotted and continuous lines, respectively.

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)

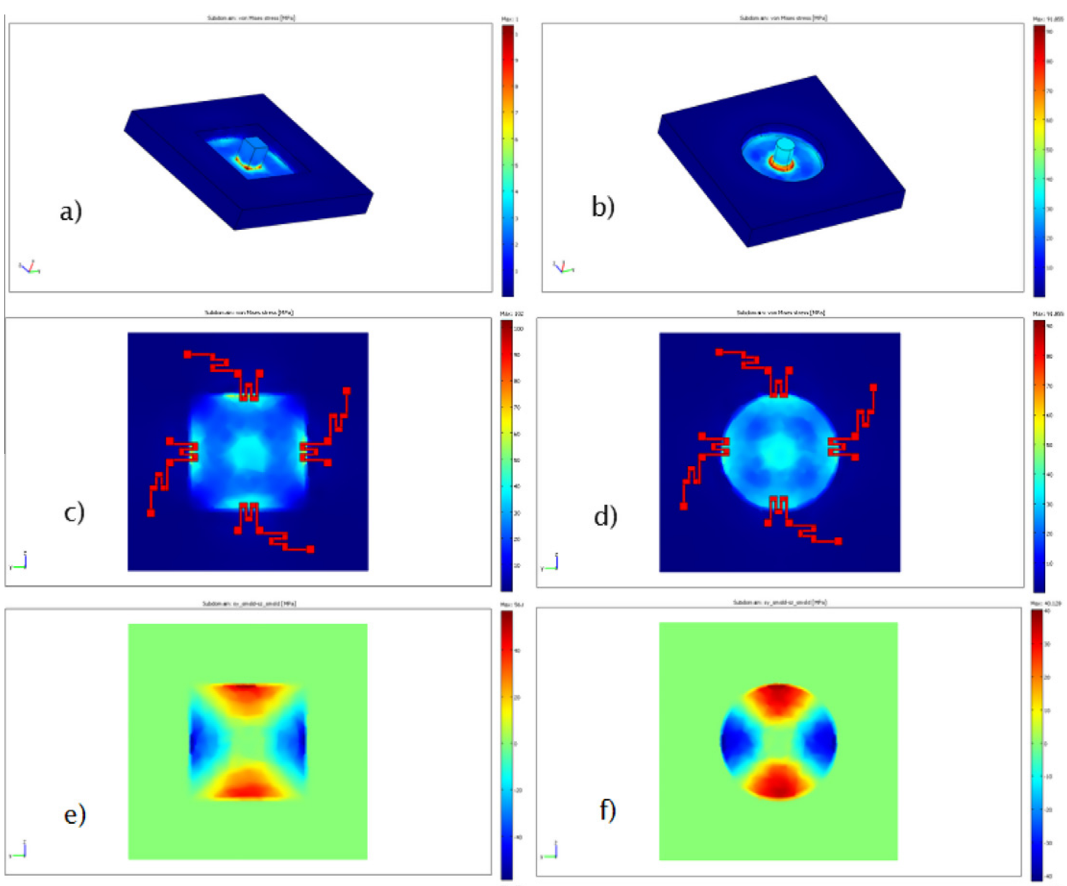

Fig. 2. (a and b) Implemented 3D model of a sensor with square shaped and circular membrane, respectively. (c and d) Calculated von Mises stress distributions and the designed sensing and reference resistors on square shaped and circular membranes. (e and f) Calculated stress distribution on the back-side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