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Three-dimensional force sensor by novel alkaline etching technique

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Abstract

Silicon based three-dimensional (3D) force sensor was designed and fabricated for detection of normal and shear forces. The sensor contains a rectangular rod emerging out of the centre of the membrane. The technology involves ion-implanted piezoresistors formation on the backside and a novel anisotropic etching on the front side of an n-type wafer. The two-component, two-step anisotropic etching process forms the rectangular side-wall rod and the membrane simultaneously, using a double layer silicon oxide and nitride mask. A mask-less alkaline etching in the second step results in the central rod protruding over the chip surface while leaving a frame of reduced thickness around the membrane providing mechanical stability. The cavity underneath the membrane was formed by bonding, facilitating also the signal read-out from the ion-implanted strain gauge resistors at the bottom (backside) of the membrane. The results of the mechanical test of the realised 3D Si force sensors are in good agreement with the theoretical predictions.

Keywords: Tactile sensing; Force sensors; Alkaline bulk micromachining

1. Introduction

Tactile sensing in robotic application and qualification of surface textures requires arrays of high sensitive force measuring elements. In contrast to the requirements of high resolution mapping in fingerprint identification, in these applications the emphasis is primarily on the 3-dimensional (3D) force detection. In all the proposed structures the shear sensitivity is generally enhanced by a rigid rod or stick mounted on the deforming membrane for transferring the load. Regardless of the selected piezoresistive [1] or capacitive [2] transduction principle, the main difference among the demonstrated structures is the processing technique and the material selected for the formation of the load-transferring element. Several authors propose SU8 resist [1,3], others form Si pyramids by alkaline etching [2] or by bonding them to the membrane in an additional processing step [4]. Recently, high-density plasma etching was also successfully applied in a nine-mask process using SOI wafers [5].

The present work describes a novel, simple process [6] for the formation of Si *mono-block*, three-axial force sensors. The alkaline etching technique can easily be implemented into the conventional six-masks process.

2. Sensor design

The sensor is built up from two parts, the single crystalline Si sensing element and the carrier printed circuit board (PCB). In the Si element, a column like rod at the centre of a deforming rectangular membrane protrudes over the top surface of the device. Piezoresistors with their reference counterpart, placed at the non-deforming frame 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 Si chip is bonded to a PCB, thereby

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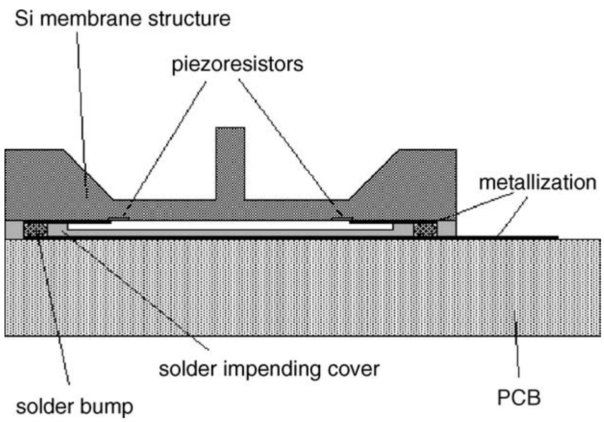

Fig. 1. Cross-section of the three-axial force sensor element.

providing both the contacts to the resistors and the cavity underneath the membrane (Fig. 1).

The Cosmos/M package was used for finite element modelling (FEM) the full membrane structure of the sensor.

A 3D model was built up using eight-noded SOLID elements to calculate the mechanical stresses and displacements caused by the external force (Fig. 2). The external load was taken as a force concentrated at the end of the central rod. This causes singularities in the FEM calculations, therefore,

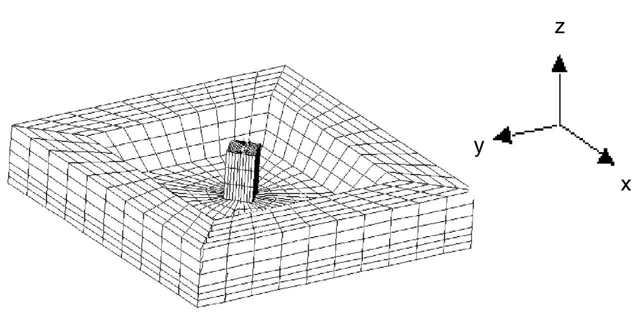

Fig. 2. The 3D meshing for FEM calculations of the mechanical stresses and displacements caused by the external force.

the node at the attacking point and its direct neighbours must be neglected. It can be done without consequences, since the stresses in the membrane are much more important, and these nodes are far away from the concentrated load.

In order to avoid the fracture of the membrane, the equivalent stress should not exceed 660 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.

Three different load cases were considered. Both normal force and shear forces were applied. The results for 100 and 130 μm membrane thicknesses are listed in Table 1.

The stress field (σ_x) for load F_z (1 N force applied normal to the membrane) is presented in Fig. 3.

The suitable positions for the resistors were determined by FEM calculations as well. Unlike to conventional piezoresistive pressure sensors, all four piezoresistors were aligned perpendicularly to the edges of the membrane. They were placed at the region of maximum stress, while their reference elements were formed in the non-deforming frame.

Piezoresistors act as independent sensing elements and variable legs of resistive half-bridge circuits as shown in Fig. 4. The force applied at the load-transferring rod deforms the membrane. The total strain arisen in the resistors causes change of their resistance. By measuring the node voltages of each half-bridges, the change of resistance can be determined and the force components can be calculated as described in ref. [1].

3. Experimental

3.1. The etching solution

The applied etching solution contained a mixture of saturated sodium hypochlorite (NaOCl) and sodium hydroxide (NaOH) aqueous solution [6] at a ratio of 1:1. This

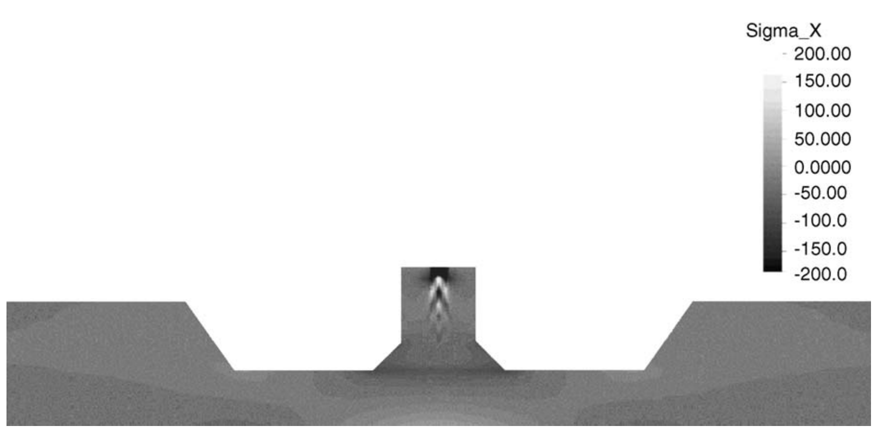

Fig. 3. The stress field (σ_x) of the sensor in response to 1 N force applied in the z-direction on the top of the force concentrating rod. The membrane thickness is 130 μm, the size of the square shape rod: 120 μm × 120 μm base with 290 μm height (protrusion over the frame: 80 μm). The chip size is 2 mm × 2 mm.