Micromachined Piezoresistive Tactile Sensor Array
Fabricated by Bulk-etched MUMPs Process

Adisorn Tuantranont[1,2], Tanom Lomas[1], and V. M. Bright[3]

[1]National Electronics and Computer Technology Center (NECTEC)
[2]National Nanotechnology Center (NANOTEC)
112 Thailand Science Park, Pahol Yothin Rd., Klong Laung, Pathumthani 12120 Thailand
Tel: +662-564-6900, Fax: +662-564-6771, Email: adisorn.tuantranont@nectec.or.th
[3]CAMPmode, Dept. of Mechanical Engineering, University of Colorado at Boulder, USA
Tel: 303-735-1763, Fax: 303-492-3498, Email: brightv@colorado.edu

ABSTRACT

The design, fabrication and testing of a 5×5 micromachined tactile sensor array for the detection of an extremely small force (micrometer-Newton range) has been discussed. An anisotropic etching of silicon substrate of a MUMPs process chip forms a central contacting pads that are trampoline-shape suspended structures and sensor beams. A piezoresistive layer of polysilicon embedded in sensor beams is used to detect the displacement of the suspended contacting pad. Each square tactile has dimension of 200 μm × 200 μm with 250 μm center-to-center spacing. The entire sensor area is 1.25 mm × 1.25 mm. The device was tested characterized under various normal force loads using weight microneedles. The individual sensor element shows the linear response to normal force with good repeatability.

Keywords: Tactile Sensors, Piezoresistive, MEMS, MUMPs, Force Sensor Array, bulk-etching

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) technologies have found the broad field in intelligent solid-state microsensors, the sensing devices that are batch-fabricated by micromachining techniques and integrated with electrical circuits on the same chip. A micromachined tactile sensor is a promising area in the field of physical MEMS sensors. It has a function similar to the surface of a human fingertip. The measurement and processing of a contact stress found useful in robotic dexterous manipulation applications. When a robot grasps object, information on contact, shear force and torque determination are needed for feedback control of robot. Other potential applications of this sensor would be such as sensing of organic tissue on a small scale at the end of catheter or on the fingers of an endoscopic-surgery telemanipulator [1]. Recently, varieties of micromachined tactile sensors capable of measuring normal and shear stress are individually developed by many research groups [2,3] but none of them are foundry-fabricated. In this paper, we present a novel piezoresistive tactile sensor array designed for measurement in medium-density sub-millimeter tactile sensing and fabricated by a commercial available Multi-Users MEMS Process (MUMPs) with bulk etching in post processing step.

2. SENSOR DESIGN

2.1 Sensor Configuration

The individual sensing element in the array is a trampoline-shape structure composed of a central contacting plate suspended by four beams over an etched pit. Embedded in each of beams is a polysilicon piezoresistor (2.8 μm wide and 168 μm long). Each tactile sensor element has dimension of 200 μm × 200 μm with 250 μm center-to-center spacing. Each of four sensor beams has geometry of 90 μm long and 10 μm wide. The central contacting plate is a square plate of 40μm× 40 μm. The entire sensor area is 1.25 mm × 1.25 mm. Figure 1 shows the scanning electron micrograph (SEM) of the micromachined piezoresistive tactile sensor array and the configuration of an individual sensor element.

2.2 Piezoresistive Sensor

An applied normal force causes the deflection of the central plate in a direction normal to the plane of substrate and induces equal tension and axial elongation in each of the four beam elements. For a small deflection of the central plate, the beams can be modeled as solid bars with pin joints at both points where the beam joins the central plate and the substrate [3].

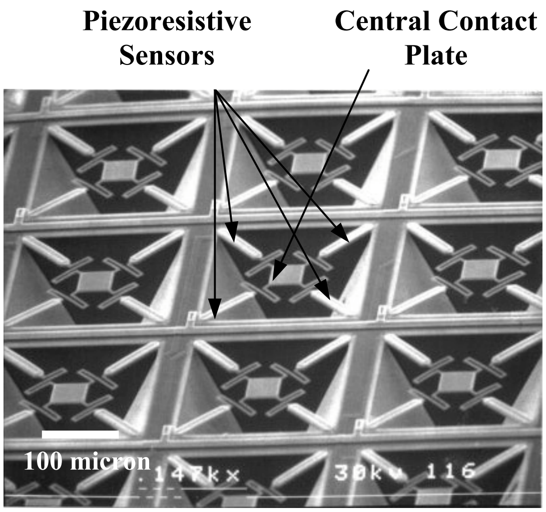

Figure 1: Scanning electron micrograph of the micromachined piezoresistive tactile sensor array and configuration of a sensor element.

We assume that the applied normal force is uniformly distributed on the central plate of each element.

With this simplified model, the strain induced in each beam due to applied normal force is characterized as:

$$\varepsilon_n = \frac{L}{2(EA)d} F \qquad (1)$$

where

ε_n	strain induced in a beam due to an applied normal force
L	the length of the sensor beam
F	the applied normal force
d	the normal deflection of the central plate or of the tip of the beam
E	Young's modulus of beam composite
A	cross-section area of the sensor beam

The working principle of the piezoresistive tactile sensor is piezoresistivity, which is the property of materials to change their resistivity under strain. The sensitivity to strain of a certain material is referred to as the Gauge factor (G). The gauge factor is defined as the ratio between the fractional change in resistance ($\Delta R/R$) and the strain (ε_n) induced in the resistor by an applied stress [4]. Longitudinal gauge factors (G_l) in which the direction of an electrical current flow is parallel to the applied strain is of interest here. The change of resistance due to strain in the beams is given by:

$$\frac{\Delta R}{R} = \varepsilon_n \times G_l \qquad (2)$$

From the mechanical beam theory, the deflection d at the tip of the cantilever beam is given by:

$$d = \frac{1}{2} k L^2 \qquad (3)$$

where k is the beam's spring constant and L is beam length. Thus, combining Eq.(1)-(3), the change of resistance as a function of the applied normal force is given by:

$$\frac{\Delta R}{R} = \left[\frac{G_l}{k(AE)L} \right] \cdot F = S \times F \qquad (4)$$

where S is sensitivity of the piezoresistive beam. The linear relationship of resistivity change and applied force is proven.

A commercially finite element analysis tool, MARC, was used to simulate the deflection of the structure under applied normal force [5]. When normal force is applied on the central plate, the sensor beams bend toward the pit as shown in Fig. 2 and the maximum stress is at the bases of the beams where piezoresistors are embedded. Figure 3 shows the stress distribution of the piezoresistive beam. The response of the sensor structure to pure normal stress loading was evaluated.

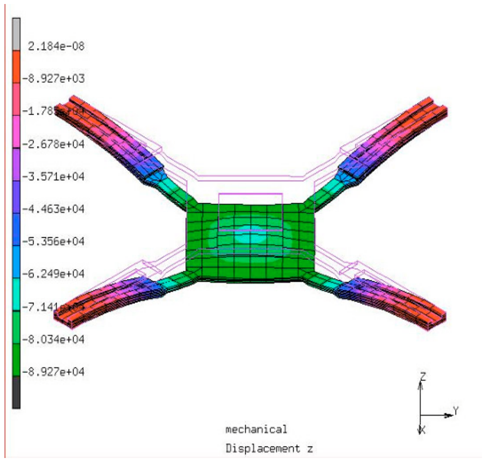

Figure 2: FEM result showing the deflection of the structure under normal force load.

3. DEVICE FABRICATION

3.1 Bulk-Etched MUMPs Process

The tactile sensors have been fabricated through the commercially available Multi-Users MEMS Process (MUMPs) [6]. This is a three-layer surface micromachining polycrystalline silicon (polysilicon) process.

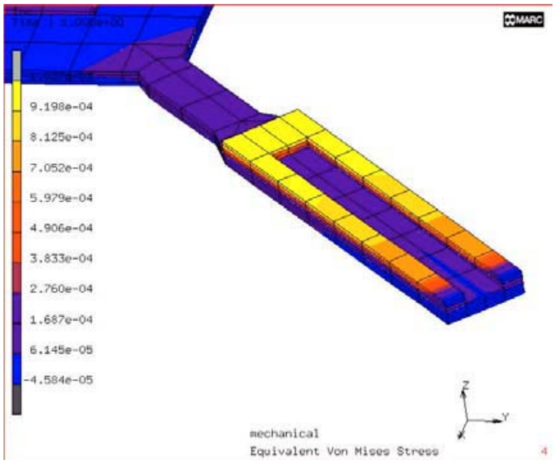

Figure 3: FEM result showing the stress distribution on the piezoresistive beam.

To suspend trampoline-shape structures over cavities, the bare single-crystal silicon substrate is exposed to chemical etchant using the superimposition of “Anchor1”, “Anchor2”, Poly1-poly2 via”, “Dimple”, “Hole1” and “Hole2” layers on top of each other to create “cut through substrate” mask.

By this method, the nitride and all the oxide layers above nitride are thoroughly opened during regular MUMPs process, leaving exposed bare silicon while the other area of the chip has covered with oxide and nitride layers [7]. The silicon substrate is selectively etched in-house using the method of anisotropic etching by EDP (ethylene diamine pyrochatechol and water). The polysilicon structures are not effected by EDP etching because the etching rate of polysilicon in these chemical etchants is much slower than single-crystal silicon. By this method, the bulk micromachining can be done on the surface micromachining chip (MUMPs) using only a maskless post-processing etching step.

3.2 Tactile Sensor Array Fabrication

The sensor array was fabricated using a bulk-etched MUMPs process as discussed in 3.1. Silicon nitride layer comprised the base layer of the free-standing sensor structures. The thinnest polysilicon, POLY0, is used to construct the piezoresistive structures and embedded in silicon dioxide layer of OXIDE1 and OXIDE2. The piezoresistor is located at the base of all four beams where the induced strain due to beam bending is at maximum. On the top layer, polysilicon, POLY2, was used to encapsulate silicon dioxide and increase the total thickness of the beams (total beam thickness = 5.35 μm). Figure 4 shows the cross-section of the piezoresistive sensor beam. The central plate was constructed with the same structure as the beam except there was no piezoresistors embedded. The sensing structures were then released from the underlying silicon substrate using bulk silicon wet etching with an EDP solution at temperature of 90 °C for 30 minutes. The single crystal silicon is anisotropically etched in the area opened by the combination of “cut through substrate ” layer (as discussed in section 3.1) until the central plate was undercut. The pits are formed underneath structures and their depths were controlled by etching time. The device was packaged in a ceramic DIP package and the read-out signal is electrically connected by gold wire bonding. A thin protective layer of polyvinyl chloride (PVC) or elastomer rubber can be adhered to the polysilicon surface of the sensor to provide interpolation of normal load between elements and protect the sensor array.

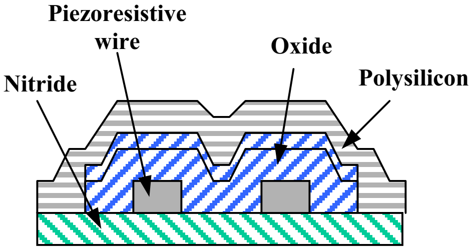

Figure 4: The cross section of the piezoresistive sensor beam.

4. TEST AND CHARACTERIZATION

First, High-resolution X-Y-Z micromanipulator is used to position the pre-known weight microneedle on the bare sensor (without protective layer) directly for force testing. The entire setup was placed under a microscope for visual inspection. The tactile sensor array was connected to the external circuit on a board to measure the resistance and voltage change when force is applied. Figure 5 shows the experimental setup of piezoresistive sensitivity measurement with the applied normal force.

A wheatstone bridge circuit is used to measure the extremely small change in the resistivity of piezoresistors. The resistivities of R_1, R_2, R_3 are adjusted evenly until equal to resistivity of the sensor, R_M, of 9.4kΩ. Therefore read-out voltage, V_0 , is equal to zero before normal force is applied. Plot of the change in read-out voltage correspond to applied normal force is shown in Fig. 6. Sensor response shows linearity behavior with 0.02 mV/μ N sensitivity gain.

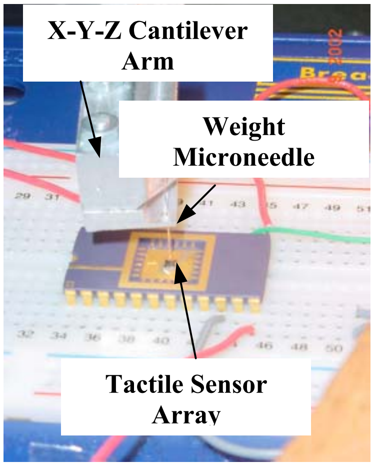

Figure 5: Experimental setup of piezoresistive sensitivity measurement with applied normal force by using pre-known weight microneedle.

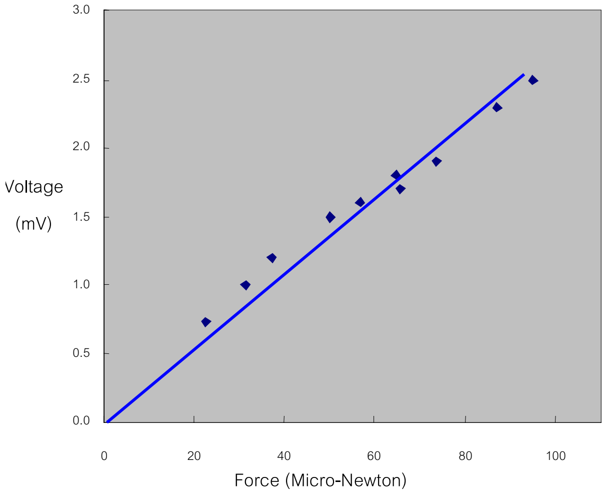

Figure 6: Plot of read-out voltage versus applied normal force.

5. CONCLUSIONS

The micromachined piezoresistive tactile sensor array has been successfully fabricated by the commercial available surface micromachining foundry (MUMPs) with bulk-etching post-processing technique. The bulk etching of silicon substrate through "cut through substrate" mask is successfully done with a complete undercut of a central contacting plate and create a suspended structures. The response of the sensor structure to pure normal stress loading was experimentally evaluated. Linear sensitivity of the sensors with normal force load was approximately 0.02 mV/μN as tested with pre-known weight microneedle. More tests on operating temperature dependence and hysteresis behavior when the various protective layers are applied need to be studied further. Moreover, the packaging issues of the sensor must be addressed before the sensor can be considered useful for practical applications.

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