# A NEW TYPE OF TACTILE SENSOR DETECTING CONTACT FORCE AND HARDNESS OF AN OBJECT

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## ABSTRACT

We propose a new type of tactile sensor that can detect both the contact-force and hardness of an object. It consists of a diaphragm with a mesa structure, a piezo-resistive displacement sensor on the diaphragm, and a chamber for pneumatical actuation. An array of these sensors can detect the two-dimensional contact-force-distribution and hardness-distribution information, and the surface texture of the contacted object. We theoretically analyzed the operation of the tactile sensor, and designed its specifications for a device for detecting the touch of a human finger. We fabricated the device's sensor element by micromachining technologies to prove the principle. The size is 3.0 mm x 3.0 mm x 0.4 mm, and it has a displacement sensor element of piezo-resistance at the periphery of the diaphragm structure.

## INTRODUCTION

MEMS (Micro-Electro-Mechanical-Systems) technologies have opened the door to many kinds of intelligent solid-state microsensors, in which the sensing devices are integrated with electrical circuits on the same wafer. A tactile sensing device is a promising area in the field of physical sensor systems, because we can make a sensing device that has functions similar to the surface of a fingertip by integrating micro-scale sensing devices in an array.

Several types of tactile sensors have already been proposed for handling objects in robotics and automation systems [1-6]. Such devices basically detect the contact-force between the sensor and objects. Those systems cannot, however, measure the hardness of the contacted objects. Therefore, it is difficult for them to handle soft and fragile materials. Maezawa et al. proposed a hardness detecting system using a piezoelectric resonator [7], but it has difficulty detecting the contact force as well as the hardness of the contacted object.

This paper proposes a new type of tactile sensor that can detect both the contact-force and hardness of an object. Setting multiple sensor devices in an array also enables them to detect the two-dimensional contact-force-distribution, hardness-distribution, and surface texture of the contacted object.

## PRINCIPLE OF TACTILE SENSOR

The structure of our tactile sensor is shown in Fig. 1. It consists of a diaphragm with a mesa at the center, a piezo-resistance displacement sensor at the periphery, and a chamber for pneumatical actuation. Figure 2 shows an array of three sensor elements.

*(a) Contact-force distribution and 2D surface texture image detection*

When the tactile sensor array makes contact with an object having a bumpy surface (Fig. 2(a)), the surface profile of the object causes some of the mesa structures on the diaphragms to contact the object, so their diaphragms deform downwards. From the displacement and location of the deformed diaphragms, the system can detect the contact-force distribution and 2D surface texture image of the object.

*(b) Hardness distribution detection*

In the second mode, the contacted mesa elements are pneumatically driven towards the object (Fig. 2(b)). The contacted regions of the object are deformed according to the driving force of the mesa element and the hardness of the object (Fig. 2(c)). Therefore, we can detect the hardness distribution of the object by measuring the relationship between the displacements of the diaphragms and the actuation force of the mesa elements.

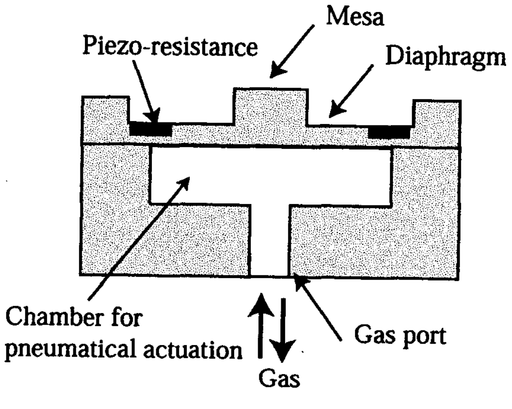
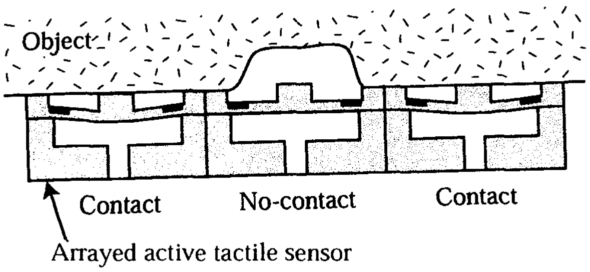
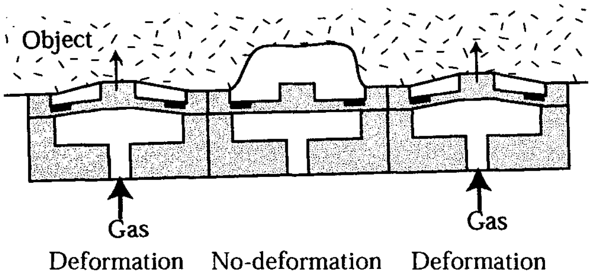


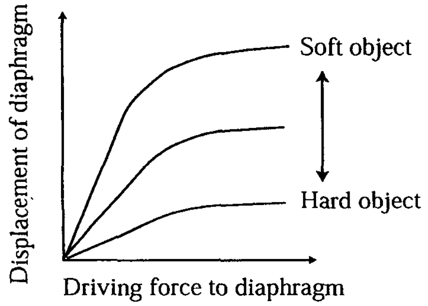
*Fig. 1. Structure of the proposed tactile sensor.*



(a) Detecting contact force distribution and two dimensional surface image



(b) Detecting hardness distribution



(c) Displacement of a diaphragm as a function of hardness of the object

*Fig. 2. Detecting principle of the proposed tactile sensor.*

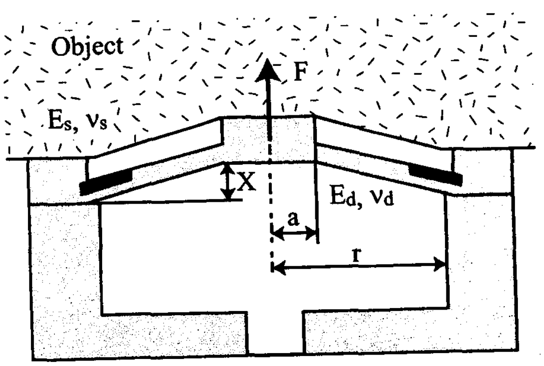


*Fig. 3. Functional model of sensing element.*

## DEVICE DESIGN

We theoretically analyzed the operation of the sensor, and designed its specifications to detect the touch of a human finger. First, we modeled the tactile sensor as shown in Fig. 3. We assumed that the contacted object is an elastic material. The relationship between the deformation $X$ of the object and applied force $F$ is given by

$$F = (K_d + K_s) \cdot X \quad , \tag{1}$$

where $K_d$ and $K_s$ are the elastic constants of the diaphragm and object, respectively. To obtain $K_s$, we used the contact-model in which the surface profile of the object changes according to the pushing depth of the mesa structure toward the object. In this condition, $K_s$ is given by

$$K_s = \frac{2aE_s}{1-\nu_s^{2}} \quad , \tag{2}$$

where $a$ is the radius of the mesa structure and $E_s$ and $\nu_s$ are the elastic modulus and Poisson's ratio of the object, respectively. The elastic constant of the diaphragm structure with mesa is given by

$$K_d = \frac{2\pi E_d}{3(1-\nu_d^{2})} \cdot \frac{h^3}{a^2} \left[ \frac{1}{2}(1-t^2) - \frac{2t^2}{1-t^2}(\ln t)^2 \right]^{-1} , \tag{3}$$

where $h$ is the thickness of the diaphragm, $t$ is the ratio at the radius between mesa and diaphragm (t=a/r), and $E_d$ and $\nu_d$ are the elastic modulus and Poisson's ratio of the diaphragm with mesa structure, respectively.

Using equation (1), we investigated how the deformation $X$ of the object changes with $K_s$ (Fig. 4). We obtained the following results.

(a) $K_s << K_d$
In this region, the elasticity of the object is much smaller than that of the diaphragm. Therefore, the diaphragm always deforms by the same amount under a constant force even if the hardness of the object changes. As a result, the sensor cannot detect the change in hardness according to the touched material in this region.

(b) $K_s >> K_d$
The elasticity of the object is too large compared with the applied force, so the diaphragm cannot deform. This means that the sensor cannot detect the change in hardness of the object in this region.

(c) $K_s \cong K_d$
The elastic constant of the object is in the same range as that of the diaphragm. Therefore, the deformation of the diaphragm changes with the hardness of the touched object. The sensor can detect the change in hardness of the object in this region.

We conclude that in order to detect a change in the hardness of the touched object, the elastic constant of the diaphragm should be almost the same as that of the touched object. Based on this result, we obtained equation (4), which lets us determine the diaphragm size. From equations (2) and (3), and the choice of $K_d=K_s$, the relationship between the radius and thickness of the diaphragm is given by equation (4).

$$r^3=\frac{\pi}{3}\cdot\frac{E_d}{E_s}\cdot\frac{\left(1-\nu_s^2\right)}{\left(1-\nu_d^2\right)}\cdot\frac{h^3}{t^3}\left[\frac{1}{2}\left(1-t^2\right)-\frac{2t^2}{1-t^2}(\ln t)^2\right]^{-1} \qquad (4)$$

The procedure for determining the diaphragm specifications is as follows.

(1) First, we determined from another experiment that $K_s$ of a fingertip is 330a (kN/m).

(2) Using $K_s$=330a (kN/m), we plotted the relationship between diaphragm radius and thickness (equation (4)) to determine the size of a sensor device that can detect the hardness of a fingertip (Fig. 5).

(3) We determined that its minimum thickness is 6.0 μm because of the diffusion depth of the piezo-resistance layer formed on the diaphragm.

(4) Finally, we chose the diaphragm radius as 1.0 mm, and designed three different types of sensors, which are shown in Fig. 5.

Table 1 shows the typical specifications of the sensor designed for detecting the touch of a fingertip.

## FABRICATION PROCESS

We developed a fabrication process for the sensor element of the proposed tactile device system to confirm the principle (Fig. 6). The process is summarized as follows.

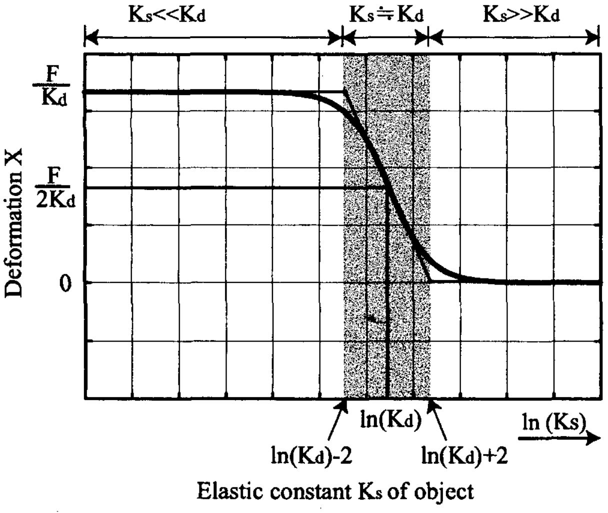


*Fig. 4. Relationship between the deformation and elastic constant of the object. $K_s$: elastic constant of the object, $K_d$: elastic constant of the diaphragm.*

(a) An n-type 4" silicon wafer with resistivity of 20.4 Ωcm was used for fabricating the sensor. First, we formed a silicon oxide layer 500 nm thick on the surface by thermal oxidization. We patterned it to define the area of the piezo-resistance sensing elements. Then, we diffused boron into the opened area of the silicon oxide layer to form p-type silicon. The diffused area works as the displacement sensor of the diaphragm.

(b) The surface was covered with an oxide layer 800 nm thick. Then a silicon nitride layer was deposited on only the rear side of the wafer. This keeps the rear wafer surface flat during the following process.

(c) Contact holes were patterned on the front side surface. Then, for the electrical wiring, an Al layer 1.0 μm thick was deposited by sputtering and patterned by wet etching. Finally the surface was covered with a silicon nitride layer 300 nm thick for protection against the environment.

(d) The bonding pads for the electrical wiring were patterned on the front side of the wafer, and the rear side layers (silicon oxide and silicon nitride) were patterned to define the aperture of the diaphragm.

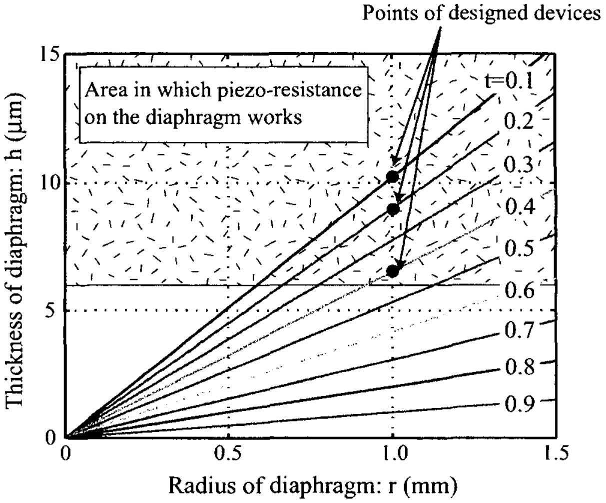


*Fig. 5. Relationship between the radius and the thickness of diaphragm suitable for detecting hardness of a human finger tip ($K_s=K_d$, $K_s$=330a (kN/m)).*

*Table 1. Specifications of sensor device.*

| | |
|---|---|
| Device | 3.0 mm x 3.0 mm x 0.425 mm |
| Diaphragm | 1.0 mm x 1.0 mm x 6.0 μm |
| Mesa (SU-8) | 0.1 mm x 0.1 mm x 30 μm |
| Piezo-resistance displacement sensor | 0.10 mm x 0.16 mm<br>(Resitance 920 Ω) |
| Elastic const Kd | 960 - 1400 N/m |

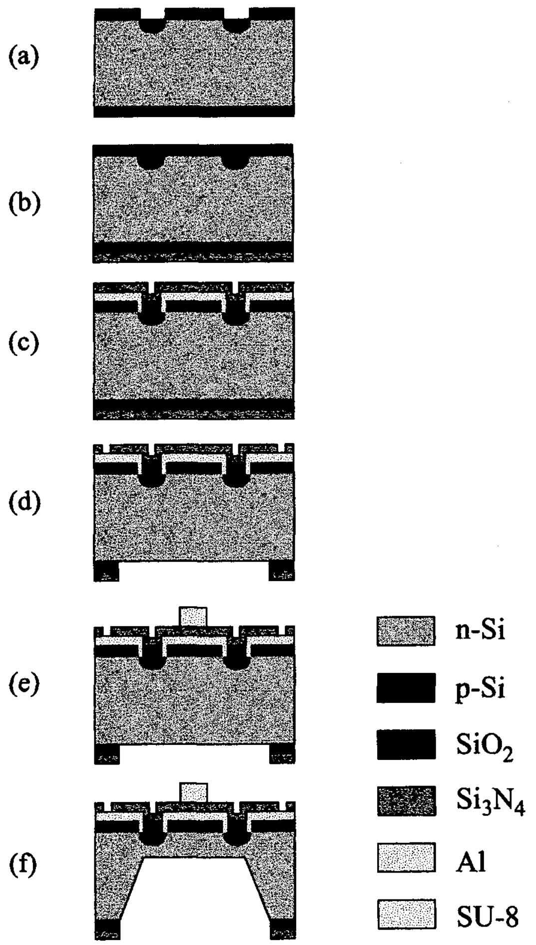


*Fig. 6. Fabrication process of a sensing element.*

(e) A mesa structure 30 μm high was formed using SU-8 photoresist.

(f) The diaphragm structure 10–15 μm thick was formed by wet etching using 30.5 wt.% KOH as the etching solution and an etching temperature of 90°C. The front side of the wafer was protected from attack by the etching solution.

The fabricated sensing device is shown in Fig. 7. It is 3.0 mm x 3.0 mm and has a displacement sensor of piezo-resistance at the edges of the diaphragm structure.

## CONCLUSION

We proposed a new type of tactile sensor that can detect both the contact-force and hardness of an object. We theoretically analyzed the operation of the tactile sensor, and designed its specifications for a device for detecting the touch of a human finger. We fabricated the device's sensor element by micromachining technologies to prove the principle. The size is 3.0 mm x 3.0 mm x 0.4 mm, and it has a displacement sensor element of piezo-resistance at the periphery of the diaphragm structure.

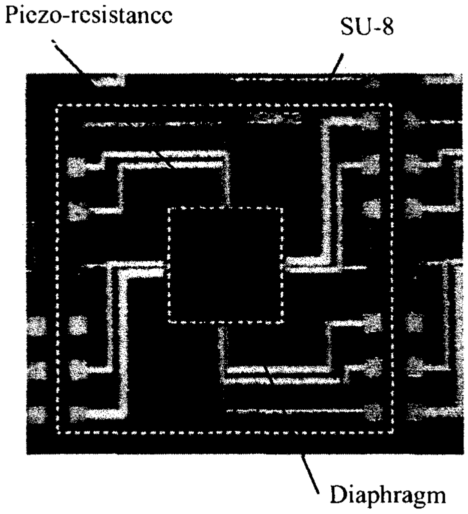


*Fig. 7. Fabricated sensor device.*

## ACKNOWLEDGEMENTS

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