

Basic Study for Tactile and Visual Texture Measurement by Multimodal MEMS Sensor with Force and Light Sensitivity

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Abstract— The tactile and visual texture measurement by multimodal MEMS sensor is reported. This MEMS sensor has two function in a structure: force-sensitivity of resistance of microcantilevers embedded in the elastomer and light-sensitivity of a MOS structure on the Si substrate. Deflection of the cantilever induced by applied force depends on the tactile texture including hardness, thickness, and roughness of the object, and is detected as DC resistance change of the strain gauge film. On the other hand, incident light depends on the visual texture of the object, and is detected as AC impedance change at 5 MHz. It is confirmed that the resistance and impedance changes depend on the physical and optical properties of the object, respectively. Therefore, it has been demonstrated that multimodal texture can be characterized by a single MEMS sensor.

Keywords—Tactile Sensor; Optical Sensor; Microcantilever; Multimodal Sensing

I. INTRODUCTION

In late years, texture design for a high-value-added product have become very important. Generally, texture of the object is characterized by human sensory evaluation, however, it lacks quantitativeness and reproducibility. In our previous works, we have already developed the multi-axial MEMS tactile sensor, which can detect normal and shear forces using microcantilevers with NiCr strain gauge film [1] and was applied to tactile texture measurement enabling qualitative classification of many kinds of objects [2], [3]. However, more quantitative tactile characterization is required to inspect physical properties such as hardness, thickness, and roughness of the object. Moreover, texture of the object is evaluated by tactile and visual senses, so multimodal sensing of physical and optical properties is needed to characterize the object texture more accurately. We have also developed the multimodal MEMS sensor which is sensitive to force and light [4]. In this paper, dependence of the sensor output on hardness, thickness, and roughness of the object and textural characterization of the object by the multimodal sensor has been reported.

II. MULTIMODAL SENSING

A. Structure of Multimodal MEMS Sensor

Fig. 1 shows a conceptual illustration of the tactile sensor, a microscopic image of the microcantilevers, and a cross-

sectional structure of the microcantilever. The microcantilevers are embedded in Polydimethylsiloxane (PDMS). The microcantilever has an inclined shape to have sensitivity of normal and shear forces. Three microcantilevers are located within $\phi 1$ mm circle, as shown in Fig. 1(b). The microcantilevers were fabricated on the Si-on-insulator (SOI) wafer by the surface MEMS process. Si_3N_4 , Cr, NiCr, and Au/Cr thin films were formed as shown in Fig. 1 (c) for insulation, shape control, strain gauge, and electrode, respectively.

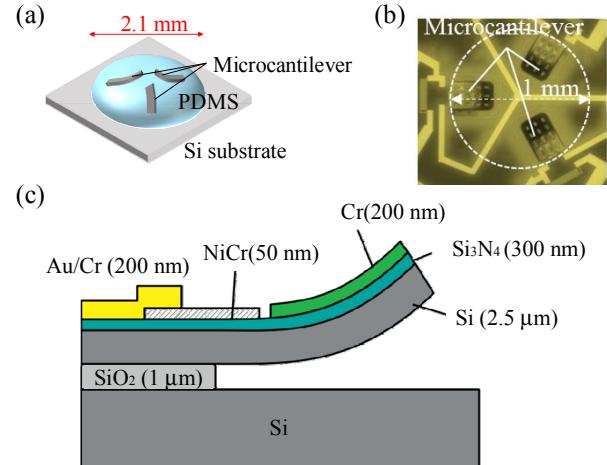


Fig. 1. (a) A conceptual illustration of tactile sensor, (b) a microscopic image of the microcantilevers, and (c) a cross-sectional structure of a microcantilever.

B. Principle of Tactile Sensing

Fig. 2 shows conceptual diagrams of multiaxial force sensing. Deflection change of the microcantilever by force applying is detected as DC resistance change of the NiCr thin film strain gauge. When normal force is applied to the surface of the sensor, microcantilevers are deformed upward because of lateral deformation of PDMS. On the other hand, in the case of shear force application, the microcantilevers are deformed into the shear force direction. Therefore, multiaxial force can be detected because the deflection change of the cantilevers depends on force direction.

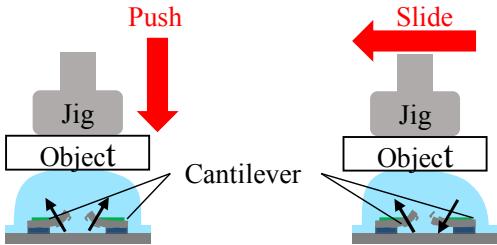


Fig. 2. Conceptual diagrams of sensing of multiaxial force (normal force (a) and shear force (b)).

C. Principle of Visual Sensing

Fig. 3 shows conceptual diagrams of light sensing. When the sensor surface is irradiated with light, the AC impedance between electrodes is decreased by the photoconductive effect in the upper part Si layer of the SOI wafer [4]. So, the intensity of light can be measured as the impedance change of the sensor.

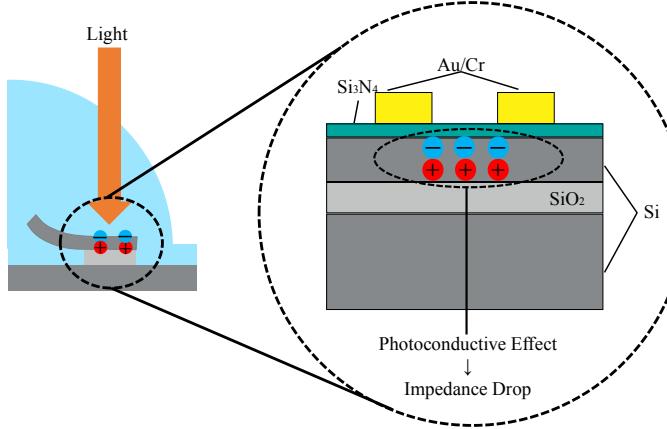


Fig. 3. Conceptual diagrams of sensing of light.

D. Multimodul Sensing

Fig. 4. shows relative resistance change of the strain gauge on the microcantilever as a function of normal and shear forces and impedance (at 5 MHz) change between electrodes as a function of LED light illuminance. The resistance changes are proportional to both normal and shear forces. On the other hand, the impedance decreases with increasing of illuminance of LED light. Therefore, it is demonstrated that the fabricated sensor have sensitivities to both multiaxial forces and light.

III. EXPERIMENT METHOD

A. Characterization of Tactile Texture

Fig. 5 shows experimental methods of the tactile texture characterization. The measurement methods are constructed from indentation and pull-up test (Fig. 5 (a)) and sliding test (Fig. 5 (b)). In the indentation and pull-up test, the object is indented onto the sensor surface with depth of 200 μm and then pulled up using a z -axis stage. In the sliding test, the sensor is moved 100 μm horizontally after indenting the object into the sensor surface with normal force of 0.5 N. The chronological features of resistance change in these tests have been characterized.

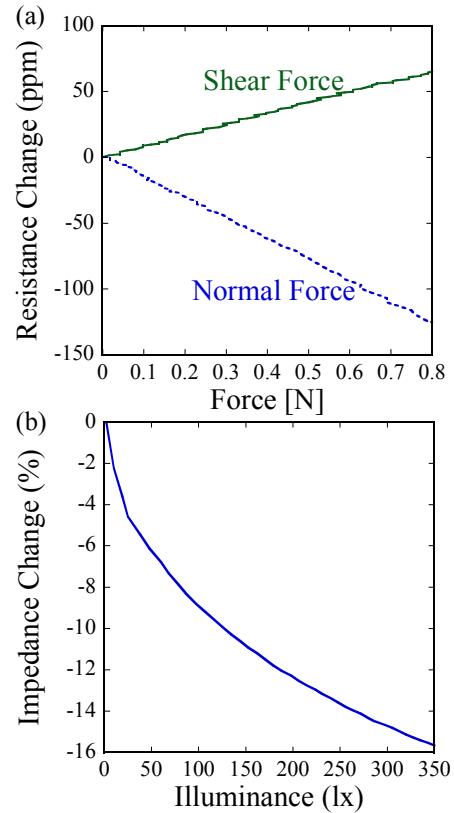


Fig. 4. (a) Relative resistance change as a function of normal and shear forces and (b) impedance change as a function of light illuminance.

As objects for texture measurement, various kinds of rubber (chloroprene, silicone, polyurethane, and others) with hardness of 25-90 (Shore A) and thickness of 1-10 mm were employed. To standardize surface characteristics of the object, they were covered with a thin-flat glass plate. In addition, glass plates with surface roughness of $R_z=0.03 \sim 3.49 \mu\text{m}$ are fabricated by hydrogen fluoride etching to investigate the effect of the object surface.

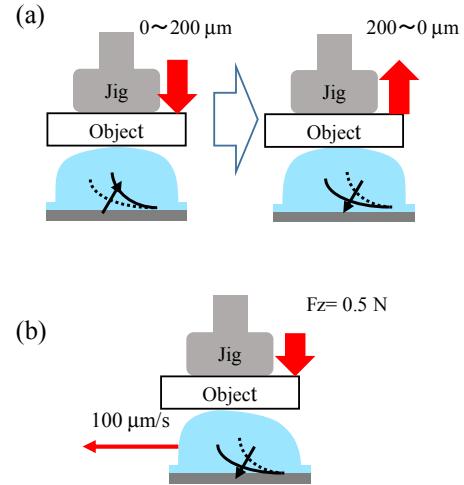


Fig. 5. Schematic illustrations of measurement methods for the tactile sensing, (a) indentation and pull-up test, (b) sliding test.

B. Characterization of Visual Texture

Fig. 6 shows a schematic illustration of the measurement system for the visual texture of the object. The object is irradiated with probe light from a white LED installed at a lateral position to the multimodal sensor. The sensor is 10 mm away from the object and the LED. The impedance of the sensor depends on surface reflective characteristic of the object because it decreases with increase of light illuminance as shown Fig. 4(b). In this work, the impedance change (at 5 MHz) from that without light irradiation (in dark environment) are measured.

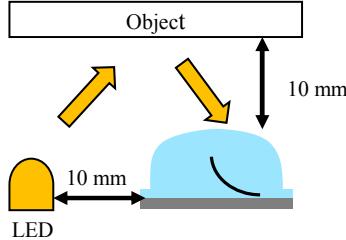


Fig. 6. A schematic illustration of a measurement system for the visual sensing.

IV. RESULT AND DISCUSSION

A. Tactile Texture

Fig. 7 shows relative resistance changes of the sensor, $\Delta R_p/R$ as a function of time when the objects are indented on the sensor surface and then pulled up. Fig. 8 shows relative resistance changes of sensor, $\Delta R_s/R$ as a function of time when the sensor is slid on the objects. It is found that the resistance changes in Figs. 7 and 8 depend on the characteristics of the object including thickness and hardness. Fig. 9 shows four types of resistance changes corresponding to texture features. $(\Delta R_s/R)'$ is time-derivative of $\Delta R_s/R$ and σ_s is standard deviation of sliding. Table I shows coefficients of correlation between resistance changes as shown in Fig. 9 and characteristics of the object (thickness, hardness, and R_z). It is obvious that the resistance changes obtained from the indentation and sliding tests of the sensor are correlated quantitatively with physical characteristics of the object including hardness, thickness, and roughness. Therefore, we can characterize the tactile texture of the object by analyzing of the resistance changes of the fabricated sensor.

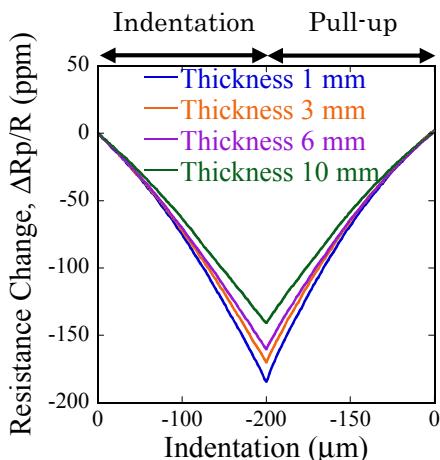


Fig. 7. Relative resistance changes of the sensor as a function of time when the objects are indented on the sensor and then pulled up

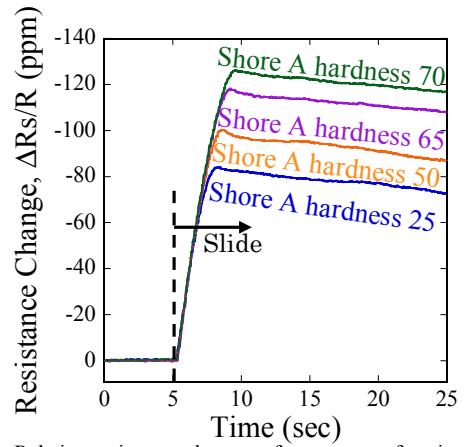


Fig. 8. Relative resistance changes of sensor as a function of time when the sensor is slid on the objects.

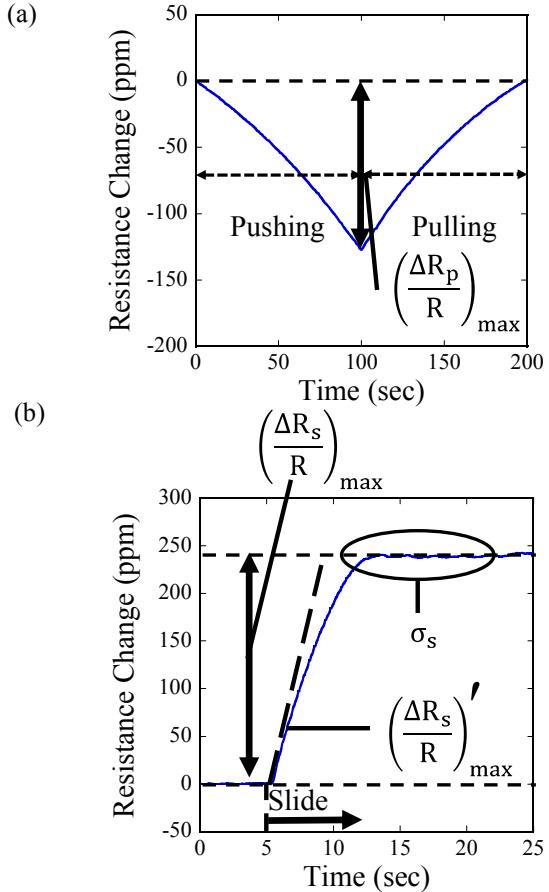


Fig. 9. Four types of resistance change depending on texture features, for (a) indentation and pull-up test and (b) sliding test.

TABLE I.
COEFFICIENT OF CORRELATION OF THE SENSING
OUTPUT AND THE PARAMETER

	$(\Delta R_p/R)_{\text{max}}$	$(\Delta R_s/R)_{\text{max}}$	σ_s	$(\Delta R_s/R)'\text{max}$
Hardness	-0.841	0.136	-0.428	0.761
Thickness	0.953	0.005	0.830	-0.860
$R_z < 1 \text{ mm}$	-0.834	0.964	-0.353	0.907
$R_z > 1 \text{ mm}$	0.848	-0.345	0.852	0.533

B. Visual Texture

Fig. 10 shows relative impedance change of the sensor induced by reflected light from rubbers with various colors to that without light. This result shows that the impedance change by reflected light depends on the color of the material. Although the objects have similar tactile texture (hardness and thickness), the impedance decrease is different because of difference of the color.

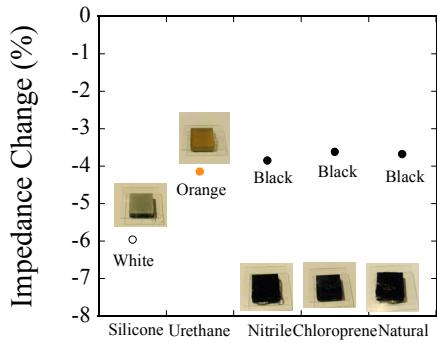


Fig. 10. Relative impedance change of the sensor, induced by reflected light from rubbers with various colors.

C. Multimodal Texture

Fig. 11 shows a radar chart of normalized feature resistance and impedance changes of three kinds of rubber. $(\Delta R_p/R)_{\max}$ for Chloroprene and Rubber Sponge, which has different hardness and similar color, are obviously different as contrasted with the other parameters. On the other hand, the impedance change for silicone is different from other rubbers because of different color. So, this single sensor is sensitive to both tactile texture (hardness) and visual texture (color). Because multimodal texture includes tactile and visual features of the object, both physical and optical sensing should be measured synthetically. Therefore, it is demonstrated that the single MEMS sensor is useful for the multimodal texture sensing.

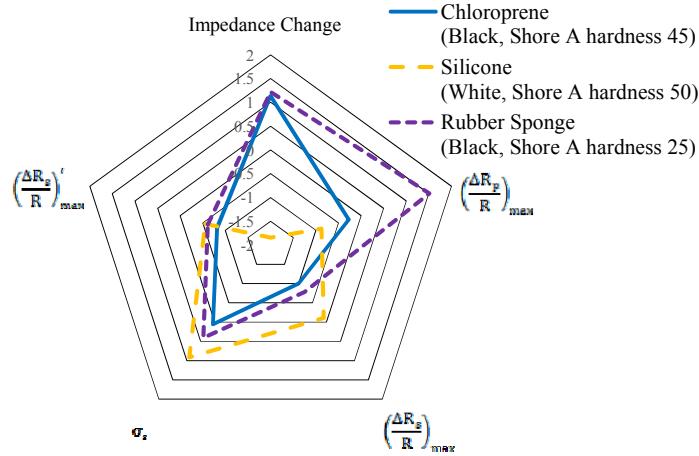


Fig. 11. A radar chart of normalized resistance and impedance changes..

V. CONCLUSION

A MEMS sensor with force and photo sensitivities has been fabricated and applied to quantitative measurement of multimodal (tactile and visual) texture of the objects. In tactile sensing, it is found that the resistance change of the strain gauge on the microcantilever embedded in the elastomer depends on hardness, thickness, and R_z , which constitute the tactile feature of the object. On the other hand, the impedance change by reflected light from the object depends on the color of the object. Therefore, it has been demonstrated that multimodal texture can be characterized by a single MEMS sensor.

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