Multimodal Measurement of Proximity and Touch Force by Light- and Strain-Sensitive Multifunctional MEMS Sensor

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***Abstract*—A multimodal sensor with Si micro-cantilever embedded in PDMS elastomer for measurement of proximity and touch forces has been fabricated and characterized. DC resistance of the strain gauge on the cantilever changes in proportion to the indentation depth of the object. On the other hand, the AC ($>$ 0.5 MHz) impedance including photo-sensitive component of Si increases with increase of distance between the sensor surface and the object because of decrease of light intensity reflected on the object surface. Moreover, the AC impedance is different between grounding and floating of the proximate object because of difference of distribution of electrostatic field between electrodes, so that it is suggested that proximity can be detected as the impedance change by light as well as the electric field.**

I. Introduction

In late years, human support robots have attracted much attention. To ensure safety and workability for human, these robots should detect proximity, touch, and slip to work objects. Various sensors have been proposed and developed to detect touch forces and proximity, and a robotic hand with multimodal function to detect touch and proximity using these "discrete" sensors has been reported [1]. In addition, a measurement method using a single sensor for detection of touch and proximity has been proposed [2]. However, the sensor size should be reduced because they are too large to be mounted on the fingertip of human support robots. We have developed the miniature multi-axial tactile sensor fabricated by micro-electro-mechanical-systems (MEMS) technology, which can detect normal and shear forces using micro-cantilevers with NiCr strain gauge film embedded in polydimethylsiloxane (PDMS) elastomer [3], [4]. In this work, the light-sensitivity has been given to the tactile sensor for multimodal detection of proximate distance and touch force.

II. Detection Principle

Fig. 1 shows conceptual diagrams of multimodal sensing of proximity and touch forces. As shown in Fig. 1 (a), three micro-cantilevers are fabricated by surface micromachining process on Si wafer inside of a 1 mmϕ circle. These micro-cantilevers are embedded in the cylindrical elastomer for protection of fragile structures and flexibility of a contact site. When the object contacts with the elastomer surface, as shown in the right-hand side of Fig. 1 (b), the micro-cantilever is bent by deformation of the elastomer, so that the resistance of the NiCr strain gauge is changed. The micro-cantilevers have inclined shapes and are arranged in the different direction, so deflection of each cantilever depends on the force direction applied by the object, e.g., all cantilevers are deflected similarly for normal force application, and deflections of opposite cantilever are different for shear force application. Therefore, both amplitude and direction of applied contact force can be obtained simultaneously [5].

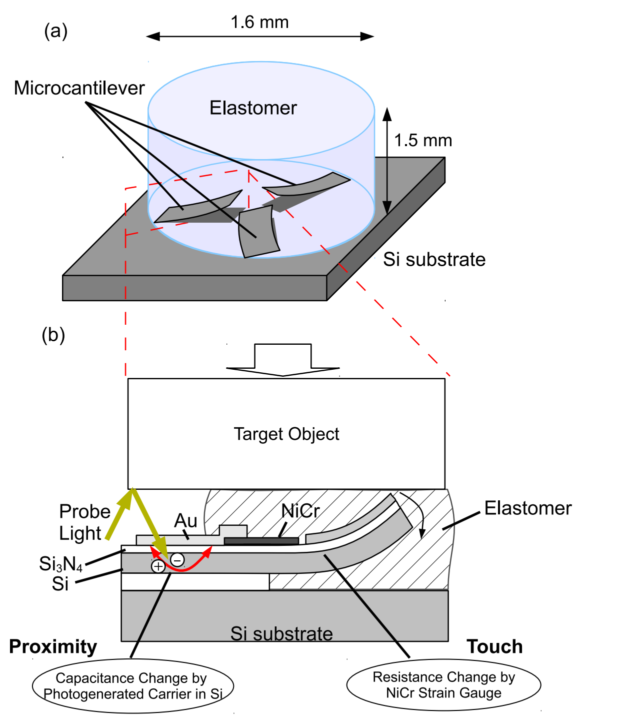

Fig. 1. Conceptual diagrams of multimodal sensing of proximity and touch force, (a) schematic view and of the sensor and (b) response to proximity and touching of the target object.

On the other hand, the proximity is detected as the impedance change in Si by light intensity reflected from the object as shown in left-hand side of Fig. 1 (b). A cross-

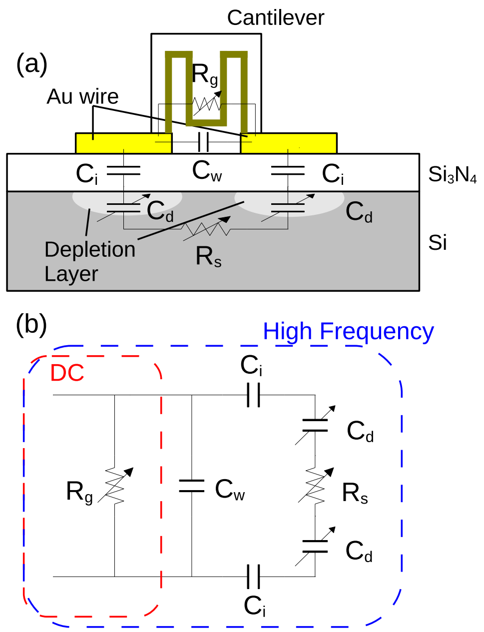

Fig. 2. (a) A cross-sectional schematic view of the sensor and (b) an equivalent circuit diagram of the sensor.

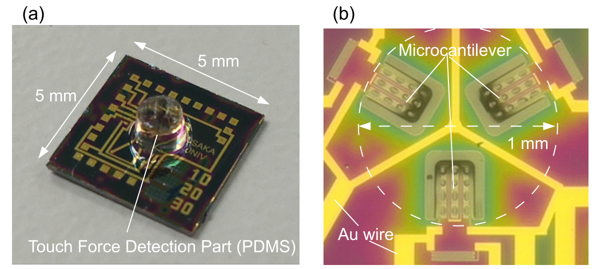

Fig. 3. (a) A photograph of the fabricated sensor and (b) a microscopic image of micro-cantilevers.

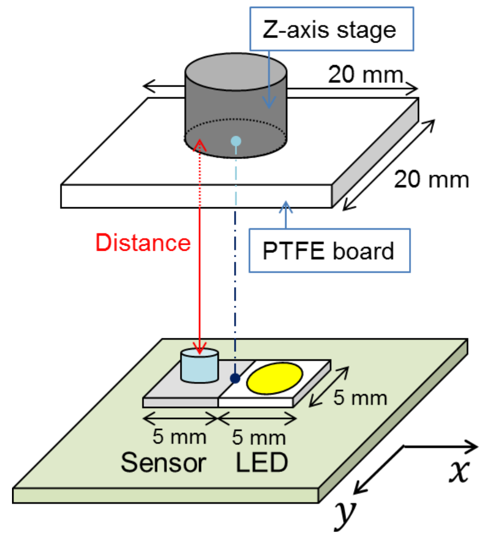

Fig. 4. A measurement setup for proximity and touch force sensing.

sectional schematic view and equivalent circuit of the sensor are shown in Fig. 2. The touch force can be detected by measurement of DC resistance as the NiCr strain gauge (R_g). The impedance measured at high frequency includes an electrical pathway through Si_3N_4 insulating layer and Si under Au electrodes, as shown in Fig. 2 (a), and so resistance (R_s) and capacitance of the depletion layer (C_d) depending on the photoconductive effect in Si can be measured through high-frequency impedance [6]. Consequently, contact force and proximity can be detected as the DC resistance and the AC impedance changes respectively by a single sensor element.

III. Experimental

A. Fabrication Process

The sensor was fabricated by the surface MEMS process using Si on insulator (SOI) wafer. At first, through via holes in Si wafer were fabricated by deep reactive ion etching (DRIE), then Cu was filled in via holes by electroplating after chemical vapor deposition (CVD) of Si_3N_4 thin film. This via electrode is formed to obtain the output signal from the backside of the wafer [7], as well as to increase the sensitivity to light with increasing the capacitance between electrode and Si. Next, Au electrode, NiCr strain gauge, and Cr stress control layer were deposited sputtering or vacuum evaporation and then patterned by the photolithography, respectively. The micro-cantilevers were released from the Si substrate by sacrificial etching of buried SiO_2 layer with the buffered HF solution. Finally, micro-cantilevers were embedded in the cylindrical elastomer (polydimethylsiloxane; PDMS). A photograph of the fabricated sensor is shown in Fig. 3 (a). The size of the fabricated sensor chip is 5 mm square. The height and diameter of cylindrical force detection part are 1.5 and 1.6 mm, respectively. Fig. 3 (b) shows the microscopic image of micro-cantilevers. It is found that the micro-cantilevers have inclined shapes because the end parts of three cantilevers become dark tips by the irregular reflection of probe light, as shown in Fig. 3 (b).

B. Measurement Setup

Fig. 4 shows a measurement setup for proximity and touch force sensing. The fabricated sensor and the object were fixed on the xy and z axis stage, respectively, and the object was moved closer and touched to the sensor surface. A polytetrafluoroethylene (PTFE) board (20 mm square and 1 mm thick) and an LED chip (EK Japan, LK-1WH-6) were employed as the target object and the probe light, respectively. The resistance change of the strain gauge by touch force was measured by precise digital multimeter (ADCMT, R6581). For the proximity measurement, the AC impedance change induced by the reflected light from the object was measured by LCR meter (Hioki, 3532-50) at more than 500 kHz because the effect of an electrical pathway through Si becomes pronounced from frequency characteristics of impedance [6].

IV. Results and Discussion

A. Proximity and Touch Detection

Fig. 5 shows DC resistance and AC impedance (at 0.5–2 MHz) change rates as a function of distance between the sensor surface and the PTFE board, where the y-axis shows change rate to the value at 0 mm and the negative value of

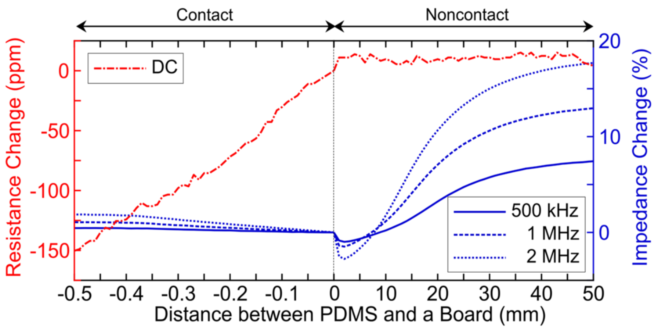

Fig. 5. DC resistance and AC impedance change rates as a function of distance between the sensor surface and a PTFE board.

x-axis shows the indentation depth of the object to the sensor surface. The DC resistance is almost constant when the object do not contact with the sensor surface, but decreases linearly as a function depth of indentation. The elastomer is deformed by the indentation of PTFE board and the micro-cantilever is deflected, therefore, it is demonstrated that the touch force can be obtained by DC resistance measurement.

By contrast, the AC impedance increases with increase of distance as shown in the right-hand side of Fig. 5. It is considered that the resistance and width of the depletion layer in Si decrease with increase of photogenerated carrier excited by reflected light from the PTFE board, because light intensity decreases in inverse proportion to the square of the distance [6]. Moreover, the impedance change becomes larger with higher measurement frequency because the capacitance of depletion layer increases. So we can detect approximation of the object as the AC impedance change of the sensor.

B. Effect of Environmental Light and Temperature

The effect of the environmental temperature of the AC impedance was characterized, because the carrier density in Si depends on the temperature. Fig. 6 shows the impedance change rate (at 1 MHz) as a function of temperature, when the sensor is heated by the ceramic heater. The impedance decreases with temperature increase because of increase of carrier density by thermal excitation. The slope of impedance to temperature is $-0.5\%/^{\circ}$C obtained from the linear approximation by the least-square method. Compared with results in Fig. 5, the error by 1°C temperature change is estimated to be 1 mm in the distance with the highest sensitivity ($x \sim 15$ mm). Therefore, in the case of approximation of the hot object and measurement in an environment with drastic temperature change, it is considered that temperature compensation, e.g., using the reference element sealed in an opaque material, is needed.

As the proximity is detected as an impedance change by reflected light from the object, the effect of environmental light should be concerned. Fig. 7 shows the impedance change rate (at 1 MHz) as a function of illuminance of environmental light at the sensor surface without LED probe light, where the illuminance was changed by adjusting the distance from the light source (fluorescent lamp). The impedance decreases with increase of illuminance, and the change of impedance by environmental light of 500 lx is -8%. However, since the environmental light is intercepted by the object, the actual

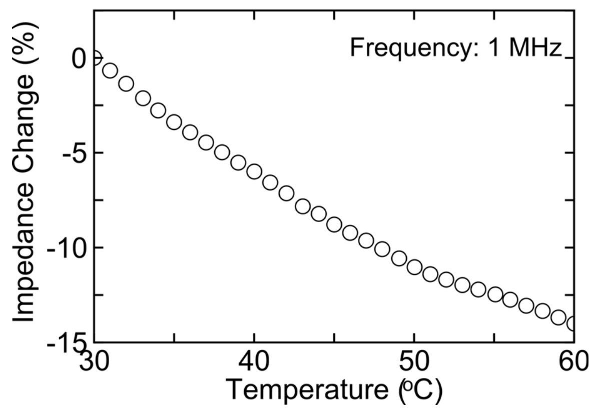

Fig. 6. Impedance change as a function of temperature.

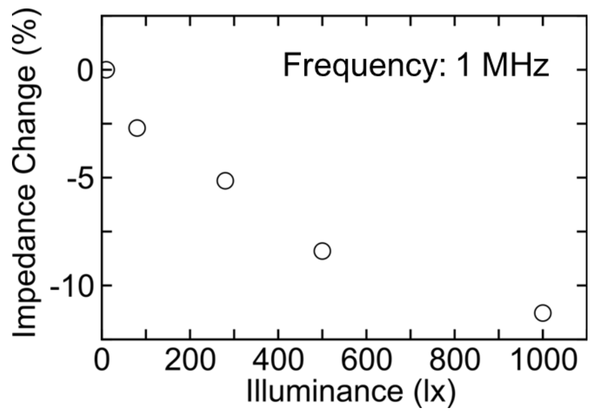

Fig. 7. Impedance change as a function of illuminance of environmental light.

illuminance at the sensor surface is smaller than that of environmental light. Fig. 8 shows attenuation rate of illumination at the sensor surface to environmental light as a function of proximate distance from the PTFE board. Actually incident light to the sensor surface is 15% of environmental light so that the actual impedance change by environmental light of 500 lx is estimated to be -1.2% Standard illuminance in office rooms is specified 500 lx by ISO international standard [8]. The impedance change discussed above is corresponding to the case of turning on-off light in these environments, so the error by environmental light is enough small under steady light environment.

C. Effect of Capacitance between Electrodes

In proximity measurement using probe light as shown in Fig. 5, accurate detection of the object contact is difficult because the reflected light decreases at an extremely short distance from the sensor surface. Moreover, the transparent object is hardly detected by optical methods. Here, the capacitance between Au wires, C_w, as shown in Fig. 2 depends on distribution of the electric field. The distribution of electric field may be changed by approximation of dielectric or conductive materials; proximity sensor using these effect has already been put to practical use [9]. In this section, possibility of proximity detection by similar measurement using fabricated sensor without probe light is examined. Fig. 9 shows the impedance change (at 1 MHz) caused by grounding

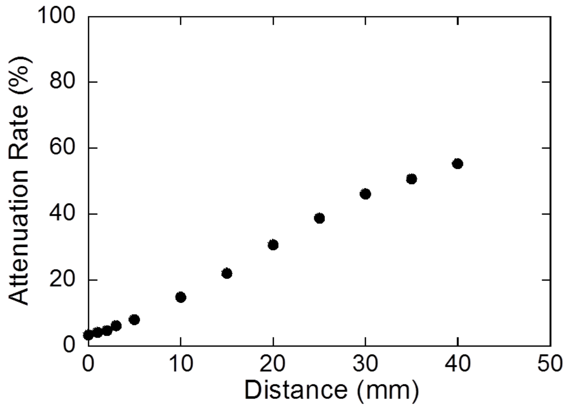

Fig. 8. Attenuation of illuminance of environmental light by proximity of the target object.

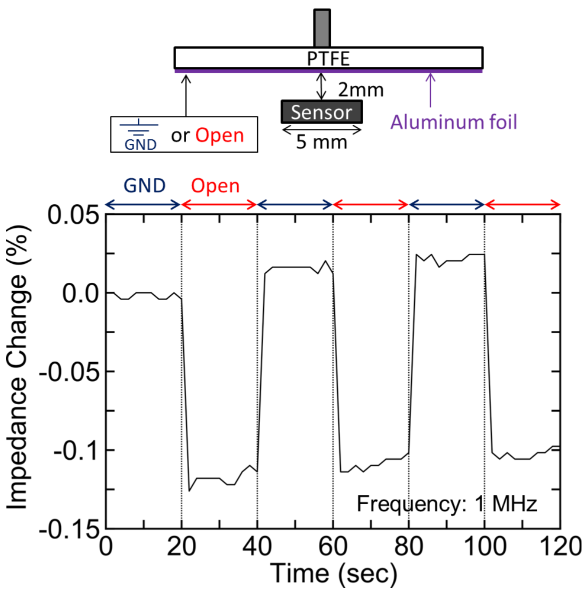

Fig. 9. Impedance change caused by grounding and floating the target object.

and floating an aluminum foil attached to the PTFE board, where the distance from the sensor surface is fixed to 2 mm. The impedance for floating state is 0.1% smaller than that for grounding state. It is considered that the distribution of the electric field depends on electric potential of the aluminum foil so that the capacitance between wires is changed, therefore, it is suggested that proximity can be measured as the impedance change induced by light as well as electric field. In addition, material (e.g., metal or resin) of the object might be identified by the capacitance change because the distribution of the electric field depends on the conductivity and dielectricity of the object.

V. Conclusion

The miniature sensor which can multimodally detect proximity and touch forces of the object has been fabricated and characterized. Touch force is detected as the DC resistance change of strain gauge on the micro-cantilever fabricated by MEMS process, and proximate distance is detected as the AC impedance change ($\geq$ 500 kHz) of photosensitive Si substrate induced by reflected light from the object. The DC resistance increases linearly with increase of indentation depth of the object and do not change in non-contact state. On the other hand, the AC impedance increases with increase of distance to the object. Therefore, it is demonstrated that both touch force and proximate distance can be measured by a single element. The error of measured proximate distance induced by environmental temperature and light (illuminance: 500 lx) are $<$ 1 mm/°C and $<$ 2 mm, respectively. Moreover, the AC impedance of the sensor for the object floating electrically is 0.1% smaller than that for the grounded object because of the capacitance change between electrodes, consequently, it is suggested that detection proximate and electrical state of the object can be also obtained without probe light.

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