3-AXIS FULLY-INTEGRATED SURFACE-MOUNTABLE DIFFERENTIAL CAPACITIVE TACTILE SENSOR BY CMOS FLIP-BONDING

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ABSTRACT

This paper reports a 3-axis MEMS-CMOS integrated tactile sensor for surface-mounting on a flexible bus line. This 3-axis sensor uses a bran-new CMOS LSI with capacitive sensing circuit and other extended functionalities (e.g. configurability and a robust clock data recovery algorithm). The sensor is composed of a flip-bonded CMOS substrate with a sensing diaphragm and a special low temperature co-fired ceramics (LTCC) substrate with vias. These substrates are electrically and mechanically connected by Au-Au bonding, forming sealed differential capacitive gaps. The completed sensor outputs coded 3-axis digital signals according to applied 3-axis force with small cross-sensitivity and hysteresis.

INTRODUCTION

Social robots for non-industrial areas such as nursing care, housework support, and entertainment are now being developed all over the world. These robots must be safe, but they are also required to manipulate various objects appropriately and communicate with humans friendly. For these purposes, social robots must equip many tactile sensors on their whole body like human tactile receptors. Until now, tactile sensors and systems have been developed using many kinds of force detection methods [1][2]. However, there are problems: 1) increase of wires connecting sensors to detection circuits, 2) low sensitivity and signal delay caused by distance between sensors and signal processing circuits, 3) large hysteresis error, 4) installation on curved and bendable parts such as robot arms and hands, and 5) force direction and slip detection.

As a solution of these problems, we propose a flexible and stretchable 3-axis MEMS-CMOS integrated tactile sensor, as shown in Figure 1. Each tactile sensor has 3-axis differential capacitive sensing electrodes, a readout circuit, a signal processor and a data transmission controller. The sensors are surface-mounted on a meandered flexible and stretchable bus line [3] for installation on a robot. In the previous papers [4][5], we presented a 1-axis tactile sensor using the 1st generation of CMOS LSI with limited functionalities. In this study, we have developed the new 3-axis tactile sensor with the 2nd generation of CMOS LSI.

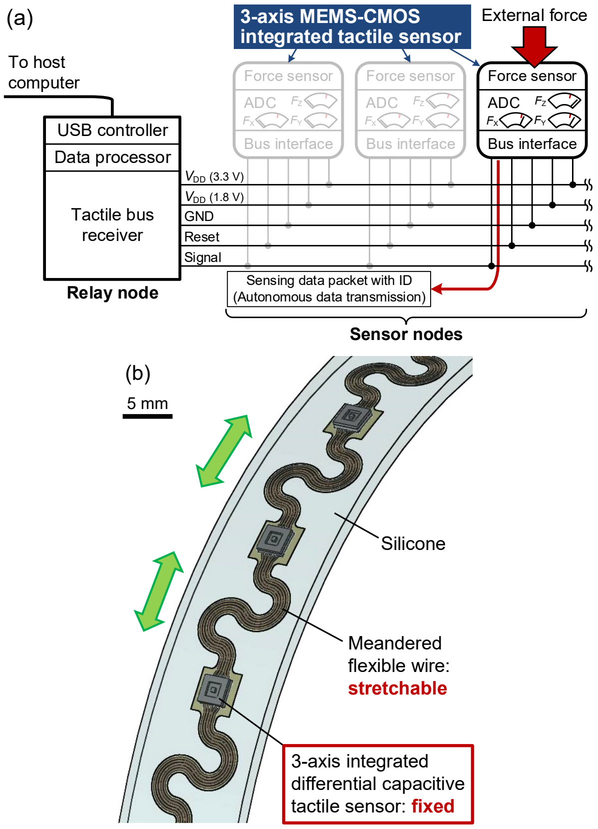


Figure 1: Concept of (a) a networked 3-axis integrated tactile sensor system and (b) its physical implementation.

SENSOR STRUCTURE AND WORKING PRINCIPLE

Figure 2(a) shows the structure of the 3-axis integrated tactile sensor. The sensor size is designed to 2.5 mm × 2.5 mm × 0.66 mm. A sensing diaphragm is formed from the backside of a flipped CMOS substrate, which is electrically connected and sealed with a LTCC substrate. This structure has an advantage of simple fabrication by providing interconnections to the sensor backside for surface-mounting without using through silicon vias (TSVs). The structure and the fabrication process are almost similar to the previous 1-axis tactile sensor [4], but there are some modifications as follows: 1) the capacitor gap is reduced from 10 µm to 5 µm for higher sensitivity. In order to enhance X and Y-axis sensitivities, 2) the side wall of the diaphragm boss is not tapered but vertical, 3) differential capacitive sensing like seesaw for X and Y-axis although one capacitance changes and another is fixed for Z-axis, and 4) the electrode areas of X and Y-axis are about twice larger than that of Z-axis.

The working principle of the tactile sensor is shown in Figure 2(b) and (c). When normal force (F_Z) is applied to the diaphragm boss, the diaphragm is deformed and the capacitance increases except for the fixed capacitor (C_{Zref}). In this case, differential capacitance of only Z-axis appears due to the symmetry of the electrode layout. On the other hand, the diaphragm boss tilts by shear force (F_X and F_Y). As a result, capacitance of only the force direction changes and differential capacitance of only that direction also

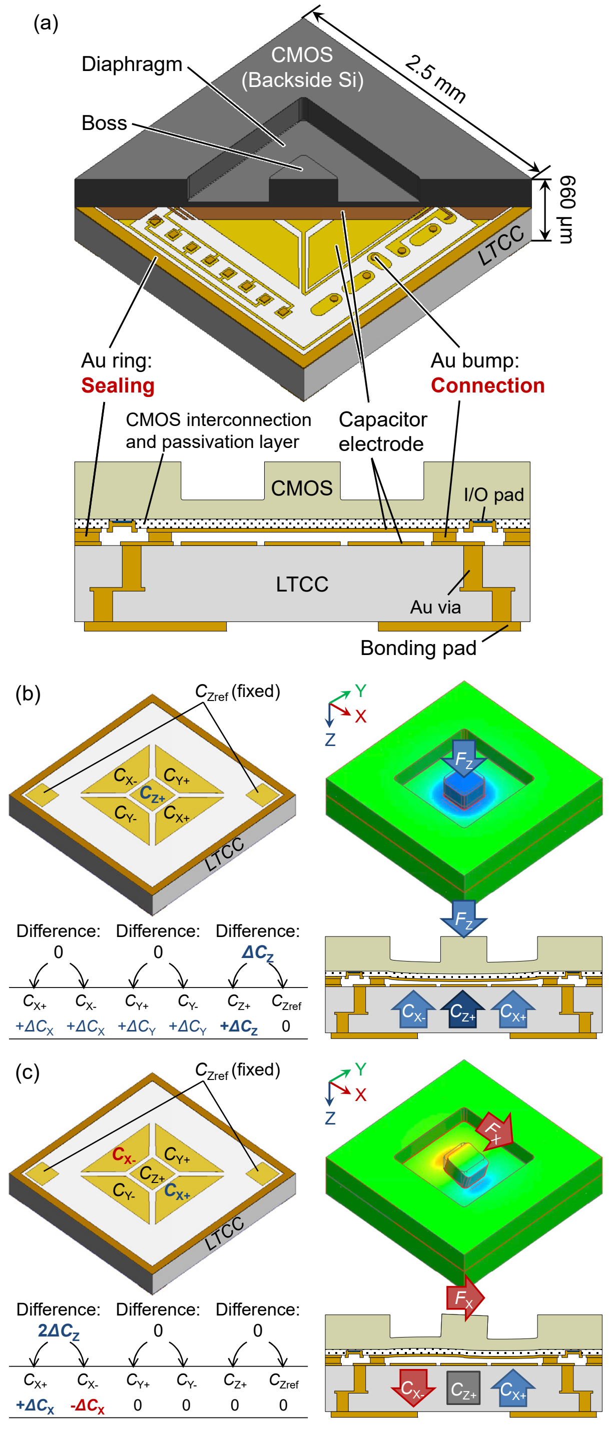
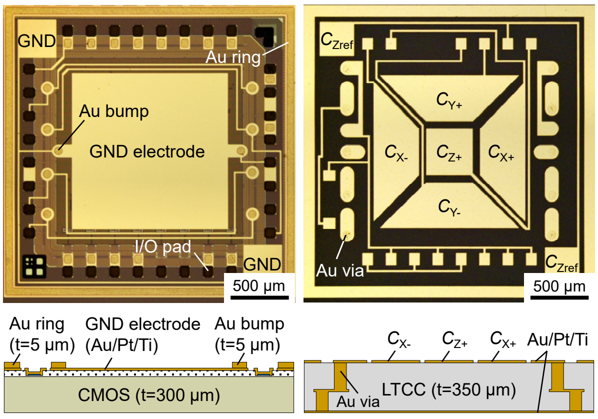


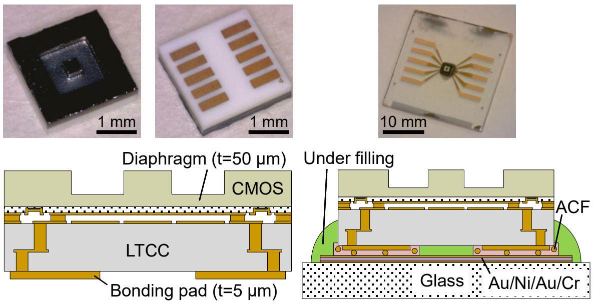
Figure 2: (a) Structure of the 3-axis integrated tactile sensor (top: bird's eye view, bottom: cross-sectional view). Capacitor electrode layout and working modes induced by (b) normal force of F_Z and (c) shear force of F_X.

appears. For every six capacitors, the capacitance is detected by oscillation circuits which are included in the CMOS LSI. The differential type sensor output for each axis is acquired by the difference of the two counter values which are given by the oscillation frequencies of the two capacitors with a certain sensing conditions.



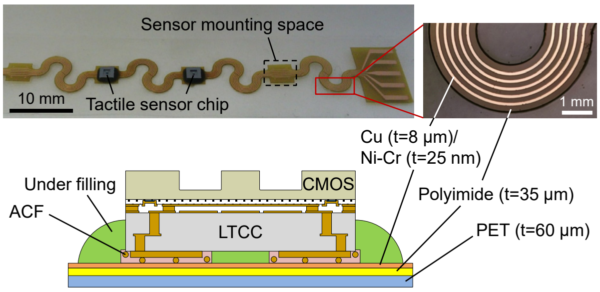
(a) Preparation of a CMOS substrate with Au bumps, an Au ring and a GND electrode.

(b) 3-axis differential capacitor electrode formation on an LTCC substrate.



(c) Integration by Au-Au bonding and diaphragm/bonding pad formation.

(d) Surface mounting of a tactile sensor chip on a glass substrate by ACF.



(e) Surface mounting of tactile sensor chips on a flexible bus line.

Figure 3: Fabrication and surface-mounting process of the 3-axis integrated tactile sensor.

FABRICATION

Figure 3 illustrates the fabrication process. The CMOS substrate used in this study is fabricated by a multi-project wafer which contains a laser ablated area with large surface roughness of about 20 µm in peak-to-valley. For fabrication, the surface is smoothed by chemical mechanical polishing after depositing a 20 µm thick SiO$_2$ film by plasma enhanced chemical vapor deposition. The thickness of the CMOS substrate is reduced to 300 µm by back grinding. The CMOS substrate and a 350 µm thick LTCC substrate are both diced into 20 mm square size for in-house fabrication.

Au bumps and a seal ring are formed on the CMOS substrate by electroplating. The substrate is annealed at 350°C in vacuum to remove contamination in the electroplated Au, and then planarized by fly cutting with a diamond bit (DAS8920, Disco Co.) [6]. A ground (GND) electrode is formed by patterning an Au electroplating seed layer (Figure 3(a)). 3-axis differential capacitor electrodes are formed on the LTCC substrate (Figure 3(b)). After flip-bonding the CMOS substrate to the LTCC substrate by

Au-Au thermo-compression bonding at 300°C with a bonding pressure of 130 MPa, a 50 µm thick sensing diaphragm is formed by deep reactive ion etching in the CMOS substrate, and then backside bonding pads are formed by electroplating (Figure 3(c)).

A diced tactile sensor chip is surface-mounted on a glass substrate with interconnections using an anisotropic conductive film (ACF) for characterization (Figure 3(d)). The bonding temperature and the applied bonding load are 170°C and 3 N, respectively. Two tactile sensor chips are also surface-mounted on a meandered flexible bus line (Figure 3(e)). This bus line is fabricated by wet etching of the metal layer and laser cutting of the polyimide layer [4].

EXPERIMENTAL RESULTS

Figure 4 shows an experimental setup. Initially, power and configuration data are provided to the tactile sensor on the glass substrate (Figure 3(d)) through a field programmable gate array (FPGA) based relay node. The tactile sensor recognizes the configuration data via our original clock data recovery system [7], and starts transmitting 3-axis sensing data packets (Figure 5), which is decoded by the relay node (Figure 4(a)). The packet data rate is set to about 80 Hz. Normal/shear force is applied to the sensor by pushing/pulling a 3D-printed pin using a movable stage with a reference force sensor (MX020-10N, Minebea Co., Ltd.) and a transmitter (CSA-524, Minebea Co., Ltd.). These 3D-printed pins are used for applying force to only a target side of the diaphragm boss.

Figure 6 shows sensor output characteristics for normal force (F_Z) and shear force (F_X and F_Y). The sensor detected each direction of 3-axis force with small cross-sensitivity and hysteresis. The sensitivity is 62.7 kCount/N for Z-axis, 15.8 kCount/N for X-axis, and 14.2 kCount/N for Y-axis. The force resolution calculated from standard deviations is 0.15 mN for Z-axis, 5.9 mN for X-axis, and 8.7 mN for Y-axis.

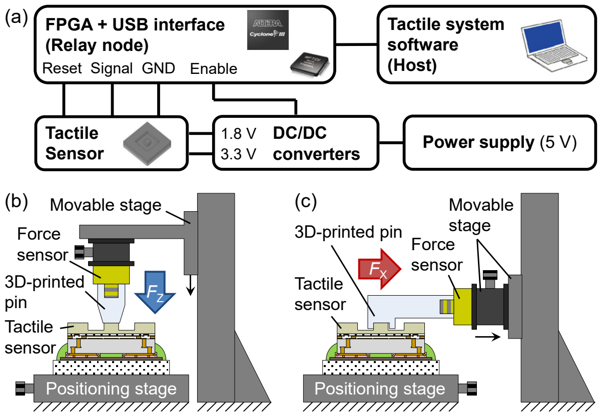


Figure 4: Experimental setup. (a) Measurement system diagram. Measurement setup for applying (b) normal and (c) shear forces to the tactile sensor.

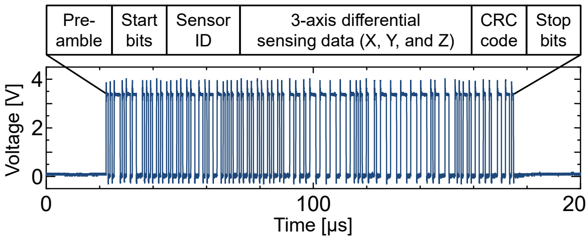


Figure 5: Digital signal output waveform from the completed 3-axis integrated tactile sensor.

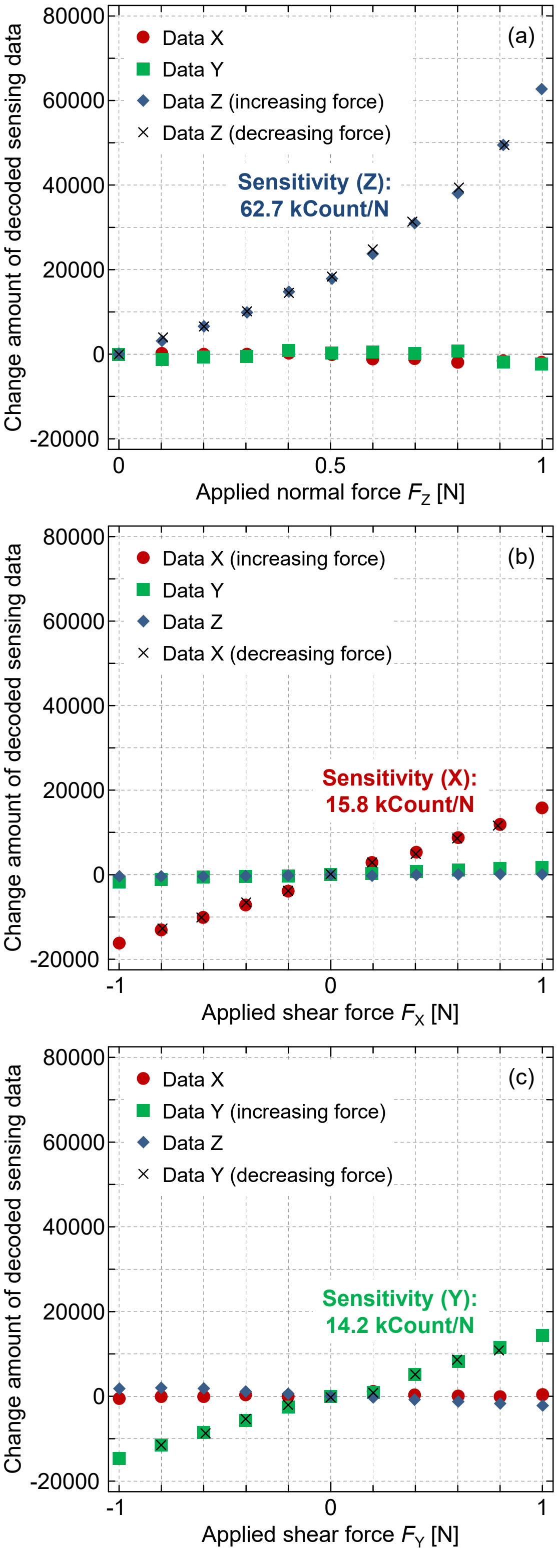


Figure 6: Sensor output changes by applying (a) F_Z, (b) F_X, and (c) F_Y.

The operation of the two bus connected sensors is also demonstrated, as shown in Figure 7. Without applying

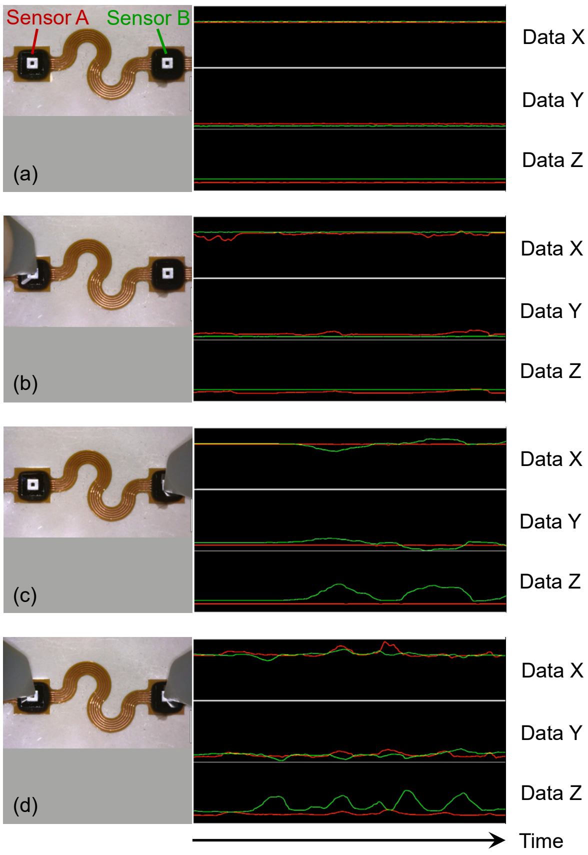


Figure 7: Operation test results of the two bus connected sensors. (a) Initial state. Push only (b) sensor A and (c) sensor B. (d) Push sensor A and B at the same time.

force, the sensors send stable 3-axis sensing data (Figure 7(a)). When force is applied to the diaphragm boss of each sensor, data of the pushed sensor changes (Figure 7(b) and (c)). Simultaneous force sensing of the two sensors is also demonstrated (Figure 7(d)).

CONCLUSION

We have developed a 3-axis surface-mountable integrated tactile sensor and evaluated its characteristics. In order to simplify the fabrication process, a CMOS substrate with capacitance detection circuits was flip-bonded on a LTCC substrate with vias, and then the sensing diaphragm was formed from the backside of the CMOS substrate. For evaluation of the surface-mounted tactile sensor, normal and shear forces were applied by 3D-printed pins and movable stages. The fabricated tactile sensor demonstrated 3-axis force detection not only with small cross-sensitivity and hysteresis but also with good force resolution less than 10 mN. The two bus connected sensors correctly sent sensing data according to the applied force. These results demonstrate that the 3-axis integrated tactile sensor developed in this study will be useful for robot tactile sensation.

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