FLIPPED CMOS-DIAPHRAGM CAPACITIVE TACTILE SENSOR SURFACE MOUNTABLE ON FLEXIBLE AND STRETCHABLE BUS LINE

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ABSTRACT

The following novel configuration has been developed for a MEMS-CMOS integrated tactile sensor on a flexible and stretchable bus for covering a social robot body: 1) a sensing diaphragm is formed on a CMOS substrate by backside etching, and 2) the CMOS substrate is flip-bonded to a low temperature co-fired ceramic (LTCC) substrate. By this configuration, no through-silicon vias (TSVs) are needed, simplifying the fabrication process. The flipped CMOS substrate and the LTCC substrate were bonded and electrically connected using Au-Au bonding, which also formed differential capacitive gaps. A flexible and stretchable wire was fabricated by metal etching and polyimide laser cutting. The tactile sensors, which were mounted on the surface of the flexible bus, sent coded digital signals according to applied force.

KEYWORDS

Tactile sensor, MEMS-CMOS integration, Wafer-level packaging, Au-Au bonding, Surface mounting, Stretchable wire

INTRODUCTION

For social robots such as nursing care robots, home assistant robots and pet robots, tactile sensors play important roles in manipulation, collision detection, and communication with humans. Unlike industrial robots, the social robots should have dense tactile sensing on their whole body like humans in order to operate safely and appropriately without fences or other safety measures. Up to date, tactile sensors using various detection principles have been developed [1].

For a robot skin with high-speed and fine-resolution sensing over the entire surface, we have developed a bus-based event-driven tactile sensor network of chip-size-packaged sensors with integrated MEMS and CMOS (Figure 1 (a)) [2]. Each tactile sensor has a differential capacitive sensor, a sensor readout circuit, a signal processor and a data transmission controller. To facilitate practical installation on a robot, the tactile sensors are surface-mounted on a flexible and stretchable meandering bus line [3], as shown in Figure 1 (b). In general, the fabrication processes of TSVs and through-silicon grooves (TSGs) [4] are complicated. The motivation of this study is to develop a surface-mountable integrated tactile sensor without TSVs or TSGs in order to simplify the fabrication process. Also, this study demonstrates a practical solution for implementing a tactile sensing system to robot applications.

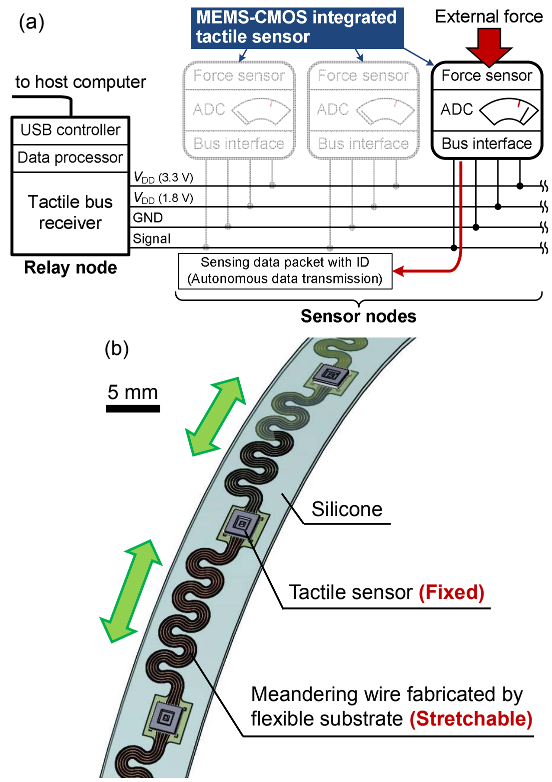


Figure 1: Concept of (a) networked tactile sensor system and (b) its physical implementation.

DEVICE STRUCTURE

Figure 2 shows the structure of the prototyped tactile sensor. The ground (GND) electrode is formed on the passivation layer of a CMOS substrate to reduce the effect of parasitic capacitance due to CMOS interconnections. A LTCC substrate [5] is used to provide interconnections to the backside. On this substrate, a sensor electrode and a reference electrode are formed. Using Au-Au bonding, these two substrates are electrically connected by Au bumps and packaged with an Au seal ring. Differential capacitive force sensing is realized by a CMOS-diaphragm. To provide a fixed reference capacitance and avoid the piezoresistive effect on the sensitive circuits, the reference electrode and

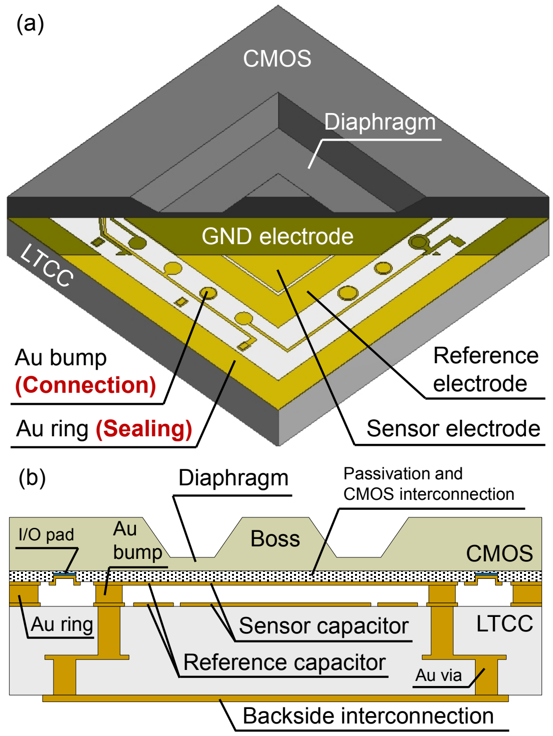


Figure 2: Structure of CMOS-on-LTCC differential capacitive tactile sensor. (a) Bird's eye view. (b) Cross-sectional view.

the analog circuits are placed outside the CMOS-diaphragm. The sensor capacitance changes according to the external force applied to the center boss.

FABRICATION

Device Fabrication

Figure 3 illustrates the process flow for fabricating the tactile sensor. In this study, a 20 mm^2 diced CMOS substrate and the LTCC substrate were used for in-house fabrication. The thickness of the CMOS and LTCC substrates are 300 µm and 350 µm, respectively. The CMOS substrate was thinned by back grinding and polished into mirror finish before dicing.

First, Au bumps and rings were formed by electroplating on the CMOS substrate using a seed layer of Au/Cr (Figure 3 (a)). The height of the electroplated Au was 10 µm. To reduce the surface roughness and variation of the Au bump, a surface planer (DAS8920, Disco Corp.) was used for planarizing the surface by fly cutting (Figure 3 (b)) [5]. The heights of the Au bumps were 5 µm, and the peak-to-valley roughness was about 100 nm after planarization. The seed layer of Au/Cr was patterned by wet etching for wiring and GND electrode formation (Figure 3 (c)). The Au bumps, Au rings, reference electrodes, and sensor electrodes were also formed on the LTCC substrate (Figure 3 (d)). After surface activation by Ar ion bombardment [6], the CMOS and LTCC substrates were bonded by Au-Au bonding at 180°C applying bonding pressure of 22 MPa (Figure 3 (e)).

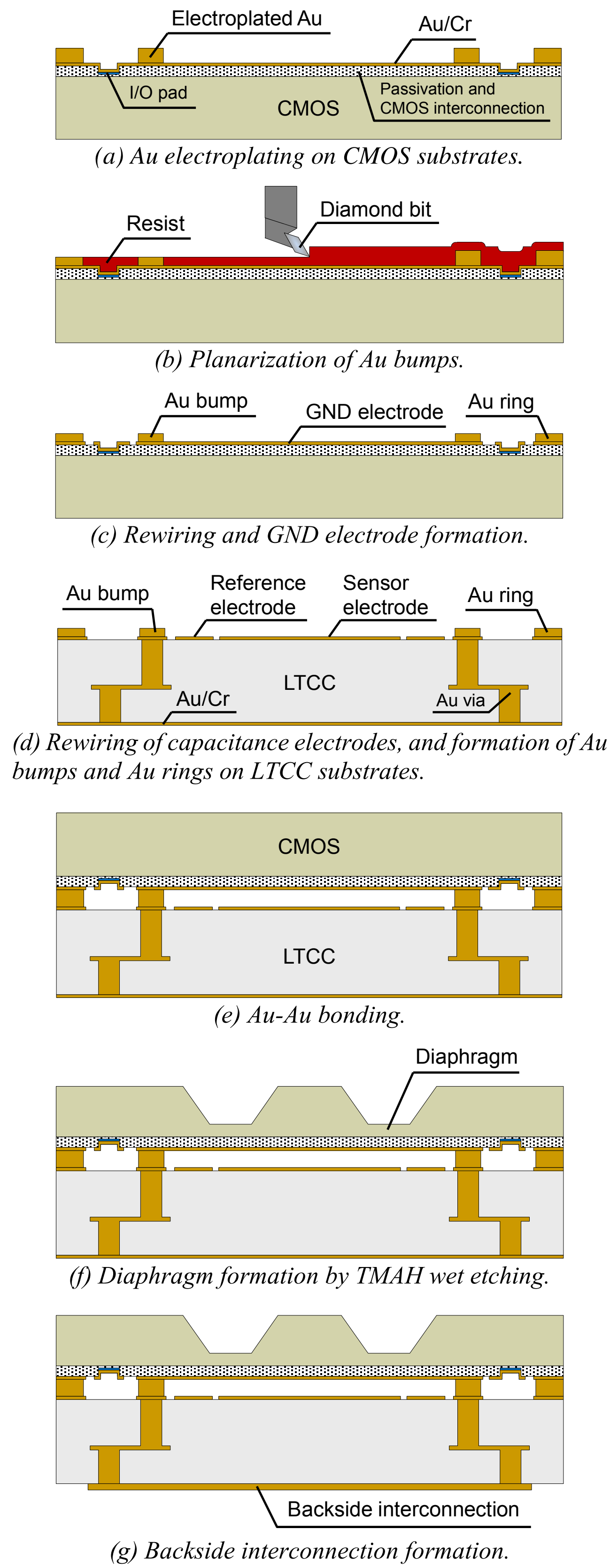


Figure 3: Fabrication process of CMOS-on-LTCC differential capacitive tactile sensor.

To make the Si substrate thin and remove a grinding-damaged layer, the Si of the bonded CMOS substrate was etched by 100 μm using a tetramethylammonium hydroxide (TMAH) solution. To form the diaphragm, a double layer mask of photoresist (ProTEK PSB-23, Brewer Science, Inc.) and SiO_2 deposited by plasma-enhanced chemical vapor deposition (PECVD) was used [7]. The TMAH solution with 0.1% Triton X-100 was selected as an etchant to reduce the etching rate of Si{110} [8] (Figure 3 (f)). Finally, the backside interconnections for surface mounting on bus lines were formed by electroplating and etching (Figure 3 (g)).

The integrated tactile sensor was successfully fabricated via the above process. Figure 4 shows optical micrographs of the CMOS and LTCC substrates before Au-Au bonding and photographs of the fabricated tactile sensor.

Surface Mounting on Flexible Wire

For the fabrication of the flexible and stretchable bus, a flexible substrate made of 8 μm thick Cu, 25 nm thick Ni-Cr, 35 μm thick polyimide and 60 μm thick polyethylene terephthalate (PET) was used. The metal was etched by a metal etchant. Then, the polyimide layer surrounding the wire was cut by a frequency tripled Nd:YVO_4 355 nm laser with laser power of 0.1 W and peeled off from the PET. Due to the thermal budget, an anisotropic conductive film (ACF) was used for surface-mounting the tactile sensor on the bus line (Figure 5 (a)). Diced tactile sensors were mounted by flip-chip bonding at 170°C (Figure 5 (b)).

Figure 6 (a) shows a photograph of the surface-mounted tactile sensors on the stretchable wire and an optical micrograph of a part of the stretchable wire. The ACF contact resistance was determined as less than 1 Ω. The fabricated wire covered with silicone was capable of stretching to 140% of its original length (Figure 6 (b–c)).

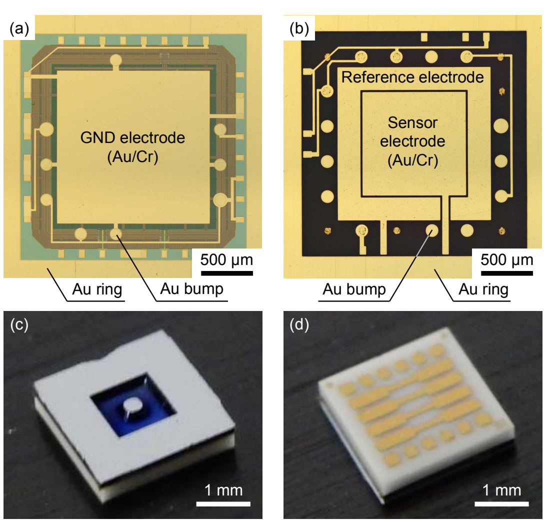
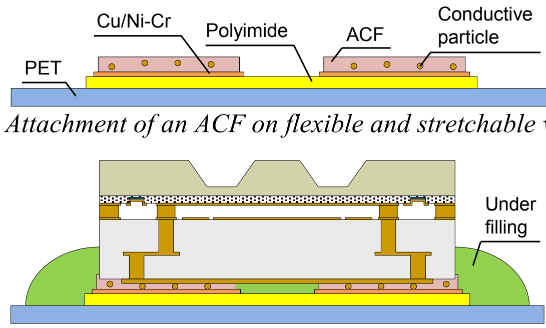


Figure 4: Fabrication results. (a–b) Optical micrographs of a CMOS substrate and an LTCC substrate with electrodes. (c–d) Top and bottom views of completed tactile sensor.



(a) Attachment of an ACF on flexible and stretchable wire.

(b) Surface mounting and fixing.

Figure 5: Surface mounting process of tactile sensor onto flexible wire.

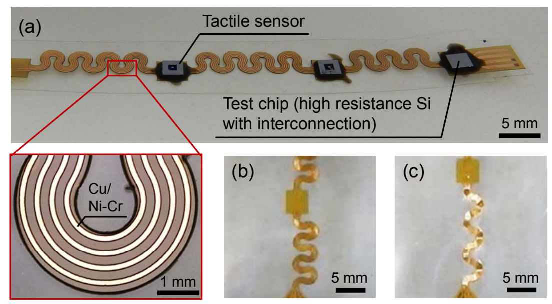


Figure 6: (a) Photograph of surface mounted tactile sensor on stretchable wire. (b–c) Stretch test of stretchable wire.

RESULTS

Figure 7 (a) shows the experimental setup. The external force was applied by a pin and a Z-stage and measured by a force sensor (MX020-10N, Minebea Co., Ltd.) and a transmitter (CSA-524, Minebea Co., Ltd.). By using a software host and a relay node circuit, the sensor node was controlled and a large amount of sensing data was analyzed (Figure 7 (b)). Figure 8 shows the relationship between external force and decoded sensor output, where ksps indicates kilo samples per second. The sensing data rate based on the desired response time or the force resolution can be set by sending configuration data to the sensor. For example, at sensing data rates of 2 kHz and 0.5 kHz, the force resolution is 4.6 mN and 1.1 mN, respectively.

A human-inspired threshold and adaptation operation was also demonstrated (Figure 9). By setting a threshold value of 500, which corresponds to 0.3 N, data below this value are eliminated, as shown in Figure 9 (b). In addition to the threshold operation, the transmission interval can be controlled by adaptation operation. The interval increased linearly from 1 ms to 11 ms by applying a constant strong force over the threshold.

CONCLUSION

We implemented a surface-mountable integrated MEMS-CMOS tactile sensors with a size of 2.6 mm × 2.6 mm × 0.56 mm. The developed sensor enjoys a simple

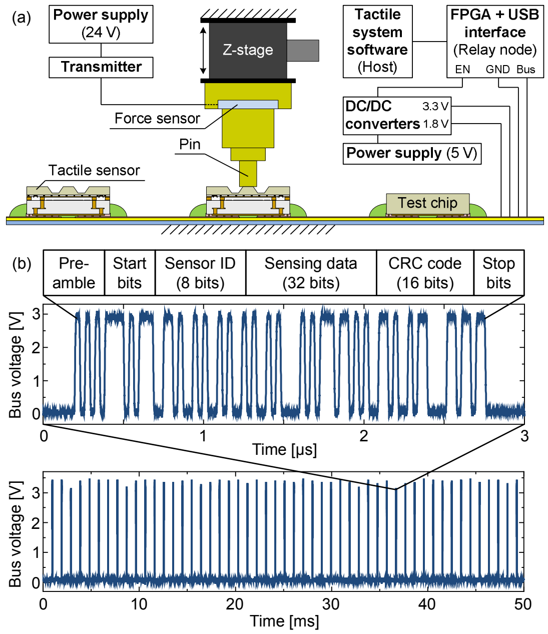


Figure 7: (a) Measurement setup and (b) digital signal output waveforms.

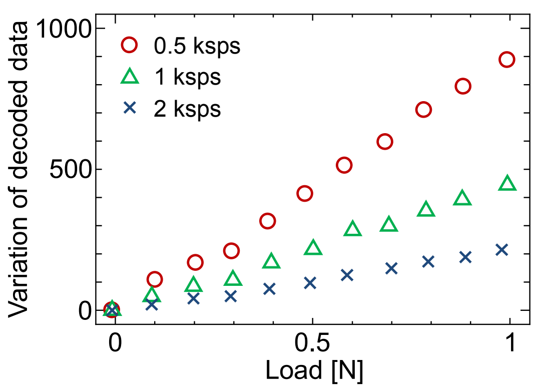


Figure 8: Measured relationship between external force and decoded sensor output.

fabrication process compared to sensors with TSVs and TSGs. The prototyped tactile sensor and a flexible and stretchable wire fully functioned as designed.

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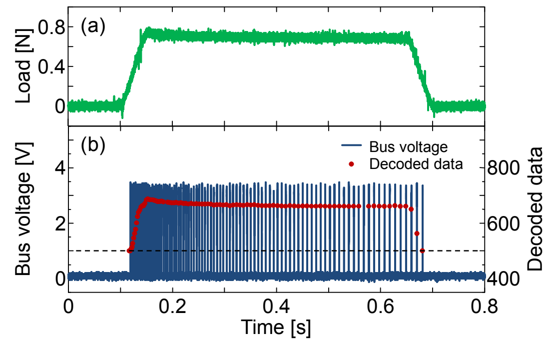

Figure 9: Human-inspired threshold and adaptation operation. (a) Input stimulus to the sensor. (b) Pulses and decoded sensing data from the sensor on the bus line (The threshold value is 500, which corresponds to 0.3N).

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