Sensors and Actuators A 188 (2012) 103–110

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Integration and packaging technology of MEMS-on-CMOS capacitive tactile sensor for robot application using thick BCB isolation layer and backside-grooved electrical connection

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ARTICLE INFO

Article history:
Received 31 August 2011
Received in revised form 23 April 2012
Accepted 24 April 2012
Available online 2 May 2012

Keywords:
MEMS-CMOS integration
Chip-size packaging
BCB
Tactile senor
Molding

ABSTRACT

This paper describes a novel wafer-level integration and packaging technology for a chip-size-packaged integrated tactile sensor. A MEMS wafer and a CMOS wafer were bonded with a thick (50 μm thick) BCB (benzocyclobutene) adhesive layer, and a capacitance gap for capacitive force sensor is formed between the wafers. The large thickness of BCB is advantageous to capacitively isolate the CMOS circuit and the capacitance electrodes. The thick BCB layer was formed on the CMOS wafer and molded with a glass mold to make a flat surface and via holes simultaneously. For surface mounting, bond pads are located on the backside of the sensor chip by drawing electrical feed lines through the chip edge. To make the feed lines in wafer level, tapered grooves were fabricated along the scribe lines by TMAH (tetramethyl ammonium hydroxide) wet etching, and half dicing was done along the grooves to access electrodes on the BEOL (back end of line) layer of the CMOS. Finally, the tactile sensor was completed and preliminarily evaluated.

1. Introduction

In recent years, there has been a great interest of tactile sensors for social robots such as nursing care robots, security robots and pet robots. The tactile sensors enable not only accurate manipulation but also collision detection and tactile communication, which are important for the robots to work with human [1].

The developed tactile sensors can be classified into two types based on soft and hard materials [2,3]. Soft tactile sensors are generally made of polymer, which often not only works as a flexible structural layer but also a sensing material with piezo-resistivity or piezo-electricity. The advantages of the soft tactile sensor are flexibility, large area coverage and low cost potential, while the disadvantages are limited sensing accuracy and difficulty in internal signal processing. Hard, especially Si-based, tactile sensors have a possibility of integration with circuits, which leads to high functionality as well as high sensitivity. For example, multi-axis force sensing, digital output and self testing are possible by the integrated circuit (IC) [4]. However, distributing many sensors over a large area leads to problems related to wiring, packaging, physical installation etc.

The problems common to both soft and hard tactile sensors are a large number of wires and data volumes to be processed [5]. It may become a bottleneck for large-area, high-density installation of the tactile sensors on a robot body. Some recent tactile sensors have a signal processor and a communication circuit to address these problems [6,7]. In such a sensor, tactile data is processed and sent using a serial bus network, which considerably reduces the number of wires. At present, however, the integration is still in printed circuit board level.

To realize a smaller, high-performance tactile sensors allowing denser installation, we have proposed the one-chip tactile sensor which has a signal processing and communication circuits [8]. The tactile sensor is composed of a MEMS structure and a CMOS circuit, and is packaged as it can be directly mounted on a signal line. As discussed in the next section, the tactile sensor must fulfill some requirements including stacking type integration with a foundry-made standard CMOS wafer, electrical feed-through to backside pads, and the use of reliable crystalline Si for a sensing structure. However, to fulfill these requirements for the tactile sensor is difficult based on existing MEMS-CMOS integration and packaging technology. In this study, therefore, a novel "MEMS-on-CMOS" process was developed. A commercial sense amplifier IC was used to

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0924-4247/$ – see front matter.
http://dx.doi.org/10.1016/j.sna.2012.04.032

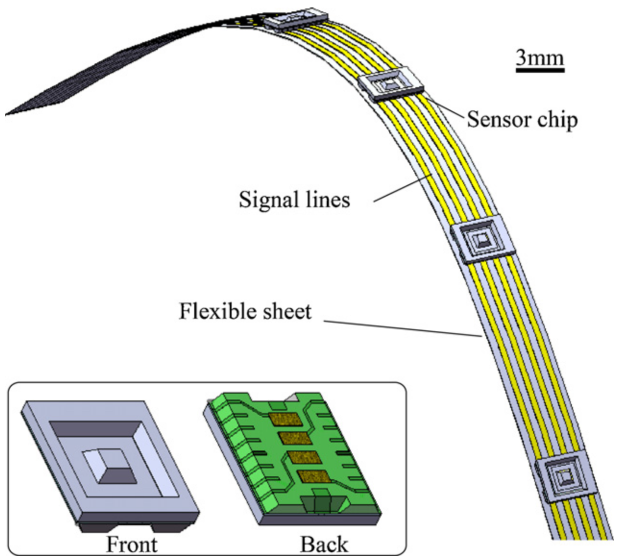

Fig. 1. The tactile sensors mounted on flexible printed circuit.

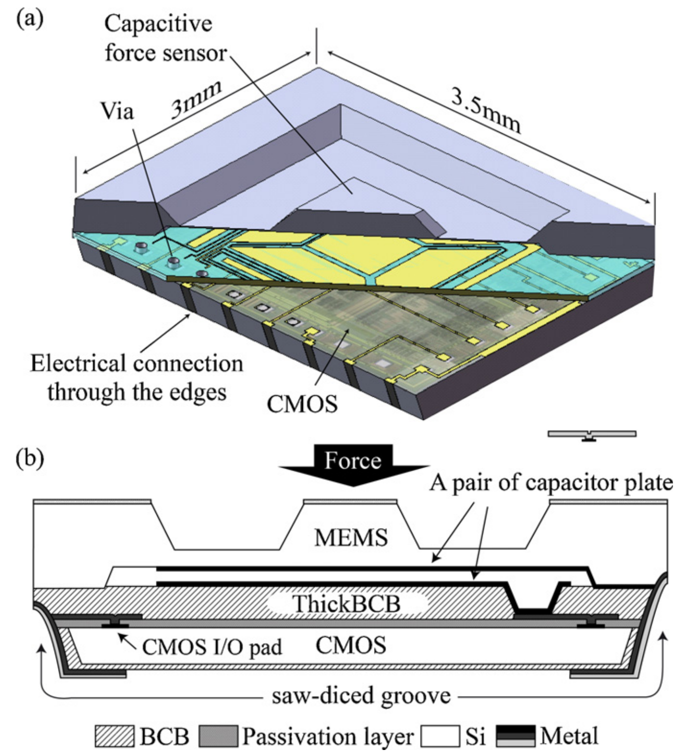

Fig. 2. Structure of the MEMS-on-CMOS capacitive tactile sensor. (a) Bird's eye view. (b) Cross section.

demonstrate the feasibility of the MEMS-on-CMOS process. Finally, the prototyped integrated tactile sensor was preliminarily evaluated.

2. Device structure

2.1. Technological requirements

Fig. 1 illustrates how to install the tactile sensors on the robot body. The tactile sensors are directly mounted on a flexible printed circuit, on which a power line, a ground line and two differential signal lines, i.e. 4 lines in total, are fabricated. This bus style installation method enables the dense and wide installation of the tactile sensors without increasing the number of wire. For this type of device installation and mounting, the tactile sensor must fulfill the following requirements.

1) The front side of the tactile sensor must be a sensing part, which is touched with objects, and the backside must have bond pads to be connected with the flexible printed circuit e.g. by soldering.
2) For the above configuration, the sensing part, i.e. MEMS, must be mounted on top of the IC.
3) The IC must be a standard one, which can be commercially available in a CMOS foundry from a practical point of view.
4) The sensing part must be made of a mechanically reliable material such as crystalline Si.

Up to date, a large number of MEMS-CMOS integration methods have been studied with various structures and materials [9,10]. They can be classified into lateral (in-plane) and vertical integration. Typical lateral integration is based on poly-Si surface micromachining [11] and SOI MEMS technology [12], and adopted by commercial accelerometers and gyroscopes [13]. However, the lateral integration does not fulfill the requirements 1 and 2. Also, the poly-Si surface micromachining needs high temperature annealing (e.g. $1100\,^{\circ}\mathrm{C} \times 30$ min) for stress release and dopant activation, but this temperature is much higher than one allowable for standard IC.

From the requirements 1 and 2, the vertical integration is a natural selection. For this type of integration, a MEMS structure must be fabricated within the thermal budget of CMOS circuits (<400–500 °C). Under this limitation, sputter-deposited metal alloy [14], SiGe deposited by plasma-enhanced chemical vapor deposition (PEVCD) [15] and single crystal Si film transferred by wafer bonding [16] are used. Because the tactile sensor need to detect a few N or larger on a mm-scale sensing area, a diaphragm as thick as several 10 μm or thicker is required [4]. Such a thick structure is difficult to fabricate based on thin-film-based technology. In this study, therefore, a wafer-bonding based integration was selected, and a bulk-micromachined Si sensing structure was stacked on a CMOS wafer using polymer adhesive. As a result, the requirement 4 is also satisfied.

To fulfill the second part of the requirement 1, it must be straightforward to use silicon-through-vias (TSV) in the CMOS wafer [17]. However, TSV is not yet commercially available or common for foundry-made standard IC. To fulfill the requirement 3, a new "TSV" technology must be developed. In this study, electrical connection between the bond pads and the I/O pads of CMOS circuits was established by chip edge wiring method [18]. The developed "MEMS-on-CMOS" technology fulfills all requirements of 1–4, which are difficult to fulfill simultaneously by the conventional integration and packaging technology.

2.2. Structure of the tactile sensor

Fig. 2 shows the structure of the tactile sensor designed in this study to fulfill all of the above requirements. A Si sensing structure with a bulk-micromachined diaphragm is attached on a CMOS chip. The Si sensing structure and the CMOS chip are bonded with a polymer adhesive layer, on which aluminum sensing electrodes are formed and connected to the CMOS circuit through via holes. The capacitive gap is formed between the diaphragm and the sensing electrodes, and sealed by adhesive bonding. The sealing is not hermetic, but a large spring constant of the diaphragm and a large capacitance gap (10 μm) avoid sticking problem.

For the surface mounting of the sensor chip, the bond pads must be located on the backside of the sensor chip. Electrical connection between the bond pads and the I/O pads of CMOS circuits is