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Development of a Biomimetic MEMS based Capacitive Tactile Sensor

H.B. Muhammad[1,] *, C.M. Oddo[2], L. Beccai[2], M. J. Adams[1], M.C Carrozza[2], D.W. Hukins[1], M. C. Ward[1]

[1]*Department of Mechanical Engineering, University of Birmingham, Birmingham, United Kingdom*
[2] *ARTS Lab, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, Italy*

Abstract

This paper presents the development of a low-cost MEMS based biomimetic tactile device intended to be incorporated as the core element in a biomimetic fingerpad. The developed silicon based sensing devices consist of an array of capacitive sensors with optimized design to measure force ranges encountered during tactile exploration of surfaces with different textures. As with the biological finger, the sensor array contains sensors of different sensitivity and position/orientation, guaranteeing a high informative content of data obtained from surface-finger interaction. This paper presents the design of the device, fabrication processes used and experimental results of sensor performance.

Keywords: MEMS; tactile array; biomimetic; capacitive sensor

1. Introduction

Tactile sensing has been defined as a form of sensing that can measure given properties of an object through physical contact between the sensor and object [1]. In robotics, there is a need for robotic hands to detect geometry, texture, slip or other contact conditions to allow enhanced dexterity of manipulation [2]. A challenging aspect in designing a suitable tactile sensor is in developing a device that can be mounted within the required space constraints and also be able to sense a distributed stimuli at high spatial resolution over a large area of contact [3]. In humans, tactile perception is obtained by interpreting responses from various units responsible in the mechanotransduction process. The mechanoreceptors differ mainly in their mechanical excitation thresholds, dynamic behaviour, locations and distribution within the skin. Artificial tactile sensing systems aim to emulate the mechanism of human touch perception [4]. Micro Electro Mechanical Systems (MEMS) technology enables fabrication of tactile sensing devices with microscale features and arrayed structures, that are inspired from biological mechanoreceptors located in the finger pad [5, 6]. Significant developments in flexible microscale sensors have been shown in literature as well [7, 8]. This work shows the design and development of a tactile device containing sensors of different sensitivity and position/orientation and organised in an arrayed fashion, so

* Haseena Muhammad. Tel.: +44 0121 4144217; fax: +44 0121414 3958
E-mail address: hbm768@bham.ac,uk

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guaranteeing a highly informative content of data recorded during surface-finger interaction. The approach was based on implementing a robust packaged tactile array that has the required sensitivity to encode contact force distribution arising at the interface with the probe and to provide information on texture related attributes.

2. Concept and structure of tactile sensor array

The schematic of a single sensor structure is shown in Figure 1. It consists of a thin silicon diaphragm, a cavity formed by sacrificial layer releasing and a bottom electrode made of silicon. The diaphragm is deflected by any applied pressure and the deflection is monitored electronically by detecting the capacitance between the diaphragm and the substrate. The main design features of the tactile sensors are listed below:

1. Thin diaphragm (2 µm) – for fabrication of highly sensitive device and also to allow ease of visualization of silicon dioxide etch profile during sacrificial etching(see Section 3).
2. Small capacitance gap (2 µm) – a small gap enlarges the magnitude of capacitance change for a given pressure
3. Dimensions - the dimensions of the sensor were optimized to allow the required force range to be measured. Four capacitive sensors were formed differing in diaphragm geometric dimensions.
4. Boundary conditions of diaphragm – In order to tune the sensors to measure a range of forces, the diaphragms formed were either clamped or fixed-fixed structures.
5. The diaphragm of each sensing element includes 5 µm radius holes for allowing access to sacrificial layer etching. The presence of etch holes also reduces squeeze film effects.
6. Reference capacitors were included in close proximity to each individual sensor having the same magnitude of capacitance however with an oxide dielectric layer to prevent deformation of the membrane with pressure.

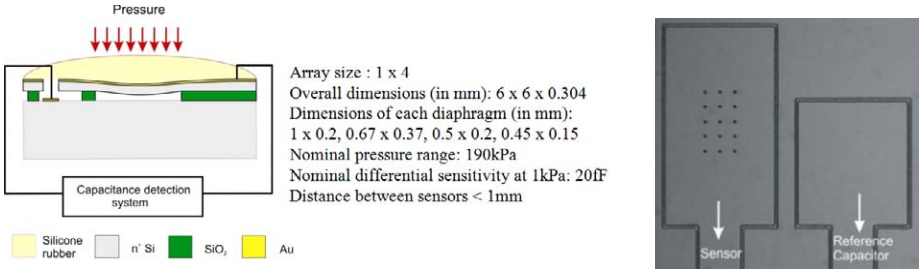


Fig. 1. Left: Cross sectional schematic of sensor; Right: Image of a single sensing element and reference capacitor

The analytical solution for large displacements of the diaphragm is complex non linear expression that is subject to various constraints[9]. However finite element analysis (FEA) can be used to confirm the analytical model and to provide more reliable solutions especially for larger deflections. FEA was carried out (Comsol Multiphysics) on models of each sensing element and both membrane displacement and working range of sensors were estimated. Figure 2 shows the simulated change in capacitance with pressure for each sensing element.

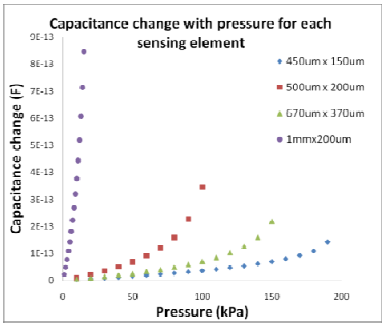


Fig. 2. Change in capacitance with applied pressure simulated for each sensing element. The sensor array has been designed to have wide dynamic range of forces. Response from the sensors is non-linear as expected.

3. Sensor fabrication

The fabrication process was applied to a Bonded and Etched-back Silicon-on-Insulator (BESOI) wafer with 2 μm silicon device layer, 2 μm silicon oxide layer and 300 μm highly conductive silicon substrate layer. The silicon layers were highly arsenic doped (n+) with resistivity < 0.006 Ωcm. The device layer was patterned to create the sensor structure using photolithography. Holes were also patterned on the top plate to allow access to the silicon dioxide layer for sacrificial release. The top layer was then etched using Deep Reactive Ion Etching (DRIE) Bosch process. The wafer was diced into 6mm x 6mm individual chips. Regions of the SiO2 layer were then etched using HF solution. Consequently, the chips were coated with 20 nm of Titanium (using e-beam deposition) followed by 200 nm of Gold using thermal evaporation process. The sensor was hosted on a PDIP carrier and wiring was performed by means of a wire bonder using 25 μm Al wires that were bonded to the sensor Au electrodes and to the Au pads of the carrier. The wires were then coated with epoxy resin. The tactile sensor array was packaged by means of a layer of Dragon Skin™ Q (Smooth-On, PA, USA). The packaging was performed by pouring, and after the curing process a thickness of ~1mm was obtained.

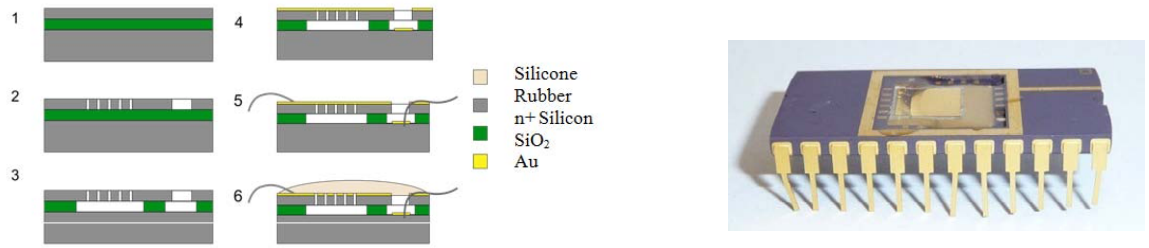


Fig. 3. Left: schematic representation of sensor fabrication process; Right: Sensor array wire bonded to a PDIP carrier and packaged

4. Design of sensing electronics

The readout electronics for the tactile sensor array was implemented in a Printed Circuit Board (PCB). It encompasses four high resolution capacitance-to-digital converters (AD7747, Analog Devices). This device has nominal resolution down to 20 aF and accuracy of 10 fF, thus being coherent with the design inputs given by the FEM simulations. The design of the electronics took into consideration the sensor layout and in particular the use of the reference capacitor integrated into each capacitive sensing element in order to avoid drift and common mode variations due to proximity and parasitic capacitance coupling between the sensor and surface. Consequently, both the positive and negative inputs of the capacitance-to-digital converter were used within the PCB and the reading was differential. Moreover, in order to increase the signal to noise ratio, the 4 pairs of tracks from the socket of the sensor array to the converters were shielded by using the dedicated pin of each capacitance-to-digital converter. Data from the converters was acquired with a soft-core processor (NiosII, Altera) instantiated onboard a FPGA (CycloneII, Altera) and then transmitted to a PC (running a Graphical User Interface) by means of Ethernet communication.

5. Characterization methods and preliminary results

The characterization apparatus, shown in Figure 4, consists of a loading system that integrates three orthogonal manual micrometric translation stages (A) with crossed roller bearing (M-105.10, PI, Karlsruhe, Germany), that allowed the positioning of a loading probe close to the sensor under test. The sensor prototype (B), connected to the sensing electronics, was secured to a mechanical fixture. Normal load tests were applied by means of an aluminium probe with a spherical head (∅ 2 mm) (C). Contact between this part and the sensor was obtained by a servo-controlled micrometric translation stage (M-111.1, PI, Karlsruhe, Germany) (D), which allowed the position of the probe to be finely controlled in the normal direction. In order to measure and record both magnitude and direction of the force applied to the microsensor, a six-component load cell (ATI NANO 17 F/T, Apex, NC, USA) (E) was placed at the interface between the loading probe and the servo-controlled micrometric translation stage. The

indentation experiments consisted of a load cycle (F) at constant velocity (69 μm/s) for 621 μm, followed by a steady state of 2 s (G) and by an unload cycle (H) at the same constant velocity.

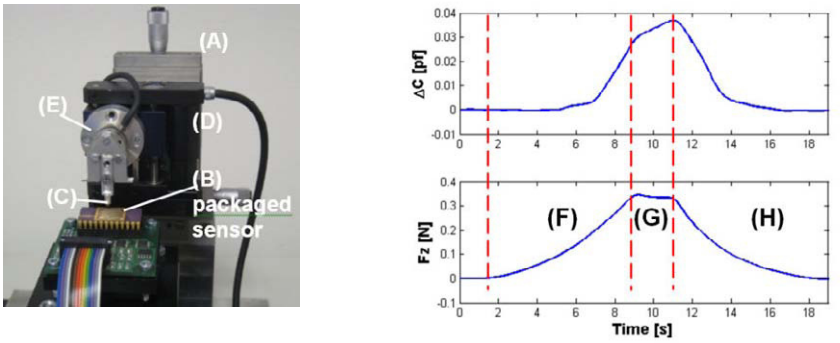


Fig. 4. Left: Characterization apparatus. Right: A load-unload cycle; the variation of measured capacitance from one sensing unit or the array is shown in the top graph, while the bottom graph shows the contact force measured by means of the load cell.

6. Conclusion

A tactile sensor array with large force range and spatially varying sensitivity was fabricated using MEMS technology. Readout electronics was designed and tested to measure the capacitance of each individual sensor in the array. Load-unload cycles with a spherical probe applied with constant indentation velocity, showed a general coherence (Figure 4, right) between the profile of the measured capacitance variation and contact force. The experimental modeling of sensor outputs combined with the effects of packaging and loading conditions is an on-going issue, as pointed out in Figure 4 phase G. In this phase, the stress relaxation arising in the lower subplot was not accompanied by a similar behavior for the measured capacitance. As a matter of fact, such behavior is not due to experimental errors, given that multiple runs of the same load-unload cycle showed the same phenomenon. Finally, the sensor array will be tested by dynamically applying textured stimuli in order to evaluate the suitability of the developed technology for roughness encoding.

Acknowledgements

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