Surface Texture Detection With a New Sub-mm Resolution Flexible Tactile Capacitive Sensor Array for Multimodal Artificial Finger

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***Abstract*— This work presents a flexible polyimide-based capacitive tactile sensing array with sub-millimeter spatial resolution. The sensor is conceived to be embedded in a multimodal artificial finger to detect and classify the texture morphology of an object's surface. The proposed tactile sensor comprises a 16 × 16 array of capacitive sensing units. Each unit is composed of a parallel square electrode pairs (340 µm × 340 µm) separated by a compressible air cavity and embedded into a flexible polyimide substrate. Standard MEMS microfabrication techniques were used to develop the sensor. The polyimide device was covered with a thin compressible PDMS layer to tune the normal pressure sensitivity and dynamic range (225–430 µm thin PDMS layer resulting in 0.23–0.14 fF/kPa). The detection of the surface morphologies of a regular grating stamp for different orientation and a small metallic nut placed on the sensor is demonstrated, showing a 420 µm spatial resolution. The proposed sensor represents a novel capacitive tactile sensing device with a sub-mm resolution of human fingertip sensitivity. [2020-0188]**

***Index Terms*— Tactile sensors, capacitance transducers, force measurement, sensor arrays, flexible electronics, polymer films, polyimides.**

I. Introduction

THE pleasant sensation transmitted by tactile perception influences how a user perceives not only the aesthetics and ergonomics but also a product's quality [1]. Automotive designers are increasingly interested in exploiting the tactile sensation provided by the surface finishing in vehicle's interiors. The selection of dashboard texture and material must provide a certain feeling to touch, which requires an iterative exercise including design, fabrication and focus group testing and appraisal [2], [3]. In an effort to virtualize the design and evaluation of new car interiors, a multimodal artificial finger is being developed to mimic human touch perception to textures.

Four kinds mechanoreceptors are embedded in the dermis of human fingertips at different depths, categorized in rapid adapting and slow adapting receptors [4], [5]. On static touch, a coarse texture reshapes the finger's surface, and this force distribution is detected by the slow adapting receptors close to the skin surface. Fine textures are detected by the fast adapting receptors which are sensitive to the vibration generated by the relative motion between the skin and the object when sliding the finger over its surface. On that premise, both fine and coarse texture sensing mechanisms are equally important to fully emulate the human touch perception on artificial sensor fingers.

This work focuses on the development and evaluation of the tactile sensing component dedicated to detect coarse surface texture morphology. The sensor was conceived to be integrated in an artificial multimodal finger, which will be used to digitalize the texture characteristics of real samples into a virtual environment.

Tactile sensors mimicking human touch sensitivity for texture discrimination must detect normal and tangential force distribution in the 0.01-10 N range with spatial resolutions below 1 mm [6]–[8]. Different transduction mechanisms, like piezoresistivity, piezoelectricity, and capacitive, have been used for tactile sensors. Among them, tactile sensors with capacitive matrices provide high sensitivity and resolution by exploiting the capacitance variation depending on the overlap area or separation distance between two electrodes due to an applied force. However, capacitive sensors are often restrained by their dielectric properties, hysteresis, parasitic effects, and complex measurement circuits. The resolution is one of the key requirement, but it is affected by the electrode size. Therefore, a trade-off must be found between sensitivity and resolution. Flexible tactile sensors have attracted increasing research attention in applications such as touch panels, prosthetic and robotic fingers, taking advantage of bendable and stretchable characteristics. Previous works have shown that electrode design, for instance floating electrodes embedded in

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flexible materials [9]–[12], and flexible microstructured dielectric materials [13]–[16] can be used to improve capacitive sensor sensitivity. Other devices include flat and bump-textured polymeric layers, combined with multiple sensing elements in a quadrant cell configuration, to increase sensitivity to both normal and sheared forces [15], [17], [18]. Despite providing tactile sensitive matrices capable of acquiring force distribution, none of the previous works have reached a spatial resolution of 0.5 mm, which is required for emulating the typical human tactile sensing.

This paper presents a novel flexible tactile sensor device conceived to extract surface morphology with a spatial resolution of 420 μm. The proposed device was fabricated on a flexible polyimide (PI) substrate and contains a 16×16 matrix of capacitive electrode pairs. Each pair is separated by an air cavity deformable by an applied force. A custom electronic readout was developed to address the individual cells and eliminate typical parasitic effects and external noise that jeopardize fF range measurements of small electrodes. A thin compressible polydimethylsiloxane (PDMS) cover was used to tune the pressure sensitivity and the dynamic range.

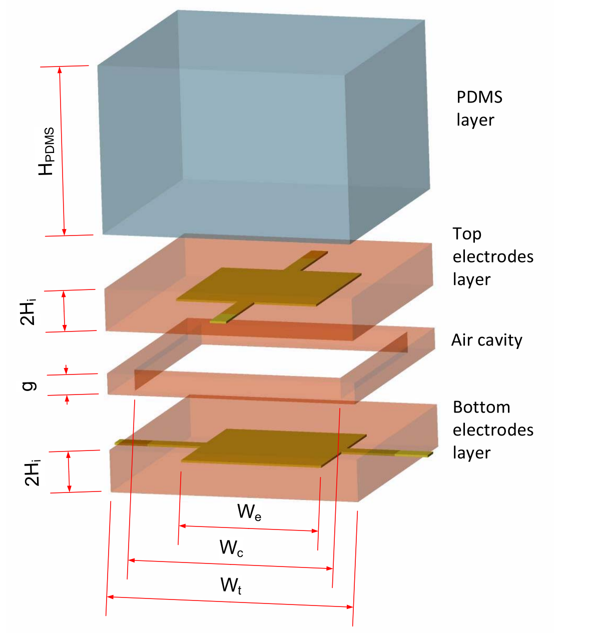


Fig. 1. Conceptual schematic of the sensing unit.

II. Sensing Modeling and Structure Design

In the proposed device, the transverse component of contact force is sensed through the parallel-plate capacitive mechanism. Fig. 1 depicts the main components of a sensing unit. The tactile unit is composed of a parallel electrode pairs (340 μm × 340 μm), each one embedded in a flexible and insulating PI layer and separated by a compressible 1 μm air gap cavity (380 μ m × 380 μm). The total capacitance C_T of a single cell can be approximated by a lumped sum of the insulating membranes and the air cavity contributions, resulting in

$$C_T = \left(\frac{1}{C_{PI}} + \frac{1}{C_{AIR}}\right)^{-1} = \frac{\varepsilon_{PI}\varepsilon_0 A}{2H_i + \varepsilon_{PI} g}. \quad (1)$$

Being $C_0 = \varepsilon_0 A/g$ the capacitance of the air gap at rest, the theoretical total capacitance ranges between 23% C_0 with an undeformed electrode (g=1 μm), and 30% C_0 when the top membrane is totally collapsed (g=0 μm). The resulting maximum change of capacitance is 64 fF.

During the design of pressure sensors, another important factor to consider is the force required to deform the sensor membranes so that they touch, which is characterized by the incipient touching pressure of the capacitor plates. When pressure is applied over that limit, the upper membrane deforms and the capacitance increases until the top membrane is totally collapsed. Indeed, based on the studies reported in [19]–[21], the behavior of the membrane can be simplified in two main distinct operating modes: the normal mode (region 1), when the membrane is freely suspended on the cavity and characterized by a linear and high sensitive response; the touch mode (region 2), at a pressure over a transition point (incipient touch), the membrane goes in direct contact with the base of the cavity until it totally collapses.

An investigation to characterize the mechanical behavior of the sensing unit was made by means of a finite element (FE) analysis, by using COMSOL Multiphysics®. This study was performed to validate the design and the principle of operation and to provide a reference behavior for the experimental validation of the core component of the sensor.

The loading modality was simulated by imposing an uniform pressure on a small area representing the contact region with the probe's tip. A contact pair was implemented between the top and the bottom surface of the cavity. The side boundaries of the top membrane and the bottom surface of the model were set to be fixed in all directions. We also exploit the two symmetry planes, X and Y, to reduce the computational time. The thicknesses of the top and bottom PI insulating membranes in the stack (as shown in Fig. 1) are the same ($2H_i$), in order to have the electrode plane in the neutral mechanical plane of the moving membrane. As an approximation, we assumed an electrode layer thinner than the PI layer and lying on the neutral plane so that the total bending stiffness of the membrane is mainly resulting from the polymeric materials. Therefore, the electrodes were neglected while the PI material was simulated as an elastic linear model. The geometrical dimensions and the material's property are reported in the Table I, with reference to Fig. 1.

The FE model was implemented to simulate the membrane deformation during both the normal and the touch mode. Considering the ratio between the electrodes area and the thin gap, the fringe field can be neglected. So, the capacitance can be reasonably approximated by

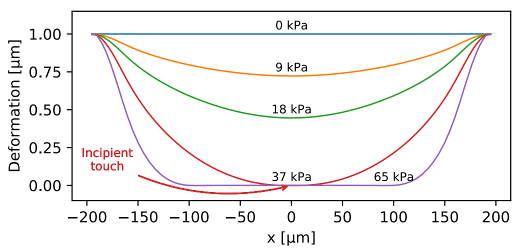
$$C_e = \iint \frac{\varepsilon_{PI}\varepsilon_o}{\varepsilon_{PI}\left(g - d\left(x, y\right)\right) + 2Hi} dx dy \quad (2)$$

over the quarter of electrode surface. ε_o is the permittivity in vacuum, ε_{PI} the dielectric constant of the insulating material, $d\left(x, y\right)$ represents the deformation of the neutral layer of the top membrane, Hi is half of the top membrane thickness, and

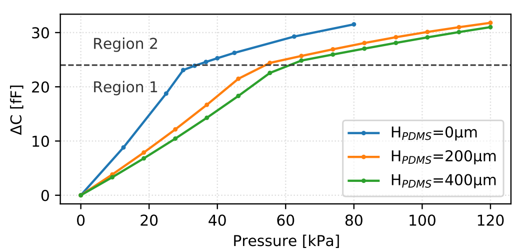
TABLE I

GEOMETRICAL AND MATERIAL PARAMETERS FOR THE FE MODEL

	Value	Description
Hi	5 [μm]	PI insulation layer thickness
g	1 [μm]	Cavity height
We	340 [μm]	Electrodes width
Wc	380 [μm]	Cavity width
Wt	420 [μm]	Sensing unit width
	PI-2611 material	
E_{PI}	8.5 [GPa]	Young's modulus
ν_{PI}	0.3	Poisson's coefficient
ε_{PI}	2.9	Dielectric constant (@ 1kHz)
	PDMS (10:1) material	
E_{PDMS}	800 [kPa]	Young's modulus
ν_{PDMS}	0.49	Poisson's coefficient



(a)



(b)

Fig. 2. Results from the FE simulation. In (a), the deformation of the upper membrane due to the applied pressure for the bare sensor, and in (b) the capacitance-pressure curves with and without the PDMS layer on top. Region 1 indicates the linear behavior before touching.

g is the initial gap between the two membranes. Given the two symmetries, the total capacitance C_T is equal to 4 times C_e.

We hypothesized that the PDMS substrate plays a significant role in controlling the sensitivity and the linear region. The advantage provided by this elastomeric layer regards its behavior as a mechanical filter that conforms to the external object's surface and uniformly spreads the contact pressure over the sensing unit underneath. In fact, by adopting PI alone it is hard to reach the same level of adaptability to the external object's surface approaching the sensor. Therefore, two types of cells with different PDMS thicknesses (200 and 400 μm) were also implemented in the FE model. The PDMS was modeled as a linear elastic material with the parameters reported in Table I.

Fig. 2a shows the deflection of the top membrane of sensor as a function of the x coordinate for different pressures,

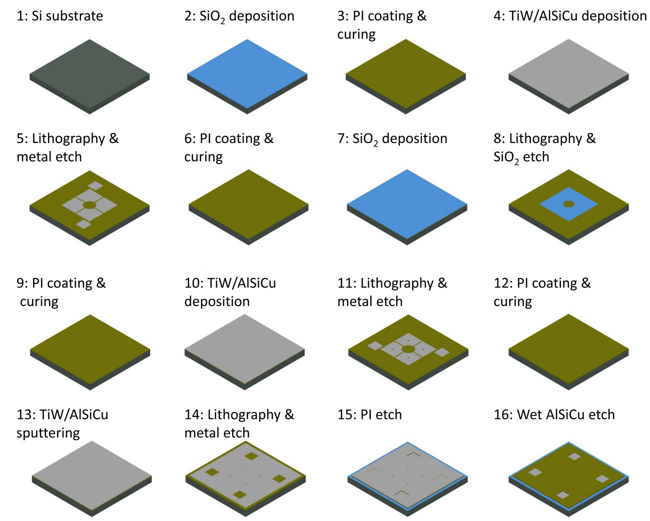


Fig. 3. Schematic depicting each step of the fabrication process.

whereas Fig. 2b shows the results of the capacitance-pressure (C-p) response of the sensing unit provided by the FE model. As observed, the sensor capacitance increases linearly with the pressure (region 1) up to the incipient touch pressure threshold, where the sensitivity is altered (region 2) due to the different mechanical deformation of the membrane. Moreover, the sensitivity of the sensor is increased by reducing the thickness of PDMS layer, which reduces the stiffness of the sensing element. On the other hand, increasing the PDMS thickness also increases the linear range of the sensor. These results demonstrate how adding a thin elastomeric layer provides a way to tune the sensitivity and the dynamic range of the sensor.

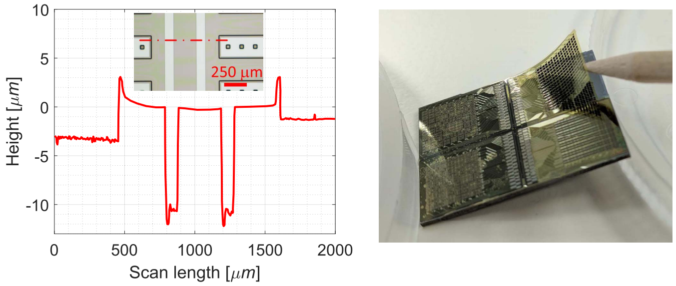
III. FABRICATION

One of the typical commercial fabrication process employed to develop flexible electronics is based on the removal process of Kapton®, where the individual circuit layers have to be built separately and then bonded together with adhesive in a heated vacuum press. This process allows the development of thin and small structures on a repeatable and scalable way, using materials and processes common in microfabrication. Additionally, a strong bonding between PI layers is also reported as a main advantage.

The fabrication process used for the capacitive tactile sensor, sketched in Fig. 3, makes use of standard 8 inch silicon wafer as mechanical support for device implementation (step 1 in Fig. 3).

The process starts with the deposition of a 0.75 μm thick SiO_2 layer obtained by plasma enhanced chemical vapour deposition (PECVD). This layer will be used as sacrificial release layer enabling the sensor release at the end of the process (step 2 in Fig. 3).

A first PI layer (PI-2611 from HD MicroSystems) is then spin coated to achieve a 5 μm thick film and then cured at 250 °C for 14 h (step 3 in Fig. 3). The 1.15 μm TiW/AlSiCu metal multilayer used as bottom electrode is then deposited



(a) (b)

Fig. 4. (a) Shows the surface profile acquired through the mechanical profilometer along the segment shown in the inset. In (b) the flexible sensor is released from the die.

by means of DC magnetron sputtering (step 4 in Fig. 3). The first lithography is then performed to outline the bottom electrode by using a dry metal etch process on an Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE) tool (step 5 in Fig. 3). At this point, a PI layer is spin coated and cured at 250 °C for 14 h to achieve a second 5 µm thick film embedding the bottom electrode (step 6 in Fig. 3). A 1 µm thick SiO_2 PECVD sacrificial layer is then deposited to define the future capacitor air gap (step 7 in Fig. 3). The second lithography is used to outline the SiO_2 sacrificial layer by means of a dry SiO_2 RIE etch process (step 8 in Fig. 3). At this point, the process sequence used to implement the bottom electrode (steps 3-6 in Fig. 3) is replicated, including the third lithography to form the top electrode (steps 9-12 in Fig. 3). Once the top electrode is embedded on the last PI film, a 0.65 µm TiW/AlSiCu metal layer is deposited by sputtering to be used as a hard mask for the PI etch process (steps 13 in Fig. 3). A fourth lithography step is used to outline the pads using a dry metal etch process on an ICP RIE tool (steps 14 in Fig. 3), and subsequently the PI films are etched with a dry RIE etch process based on a O_2/CF_4 plasma until reaching the two embedded electrodes (steps 15 in Fig. 3). The remaining AlSiCu hard mask layer is finally removed using an aluminum wet etch process, while the electrode pads are protected by a TiW layer embedded om the electrode multilayer stack (steps 16 in Fig. 3). Devices are finally released (see Fig. 4b) and detached from the supporting substrate using an HF vapour process to remove the SiO_2 sacrificial layers. Due to the change in wafer topography at each step, possible variations on the PI thickness are expected. Therefore, after each spin coating process, the wafer underwent a measurement for PI thickness validation. The final PI thickness of 10 µm is shown on the profile measured across the pads and release trenches after APS O_2/CF_4 etch in Fig. 4a.

The external top elastomeric layer was made of Sylgard 184 (Dow Corning) that was mixed in the standard 10:1 ratio and degassed before being poured. The film thickness was achieved by spin-coating the PDMS on a 4-inch wafer. On the base of the open-loop manner for spin-coating, as reported in [22], [23], we defined the best estimate thickness (with a 30% of uncertainty) at either 150 and 250 rpm for 60 seconds, to yield thicknesses of 400 and 200 µm, respectively. The actual results for the thicknesses were 430 and 225 µm, respectively. The PDMS film was then cured in the oven for 5 h at 65 °C.

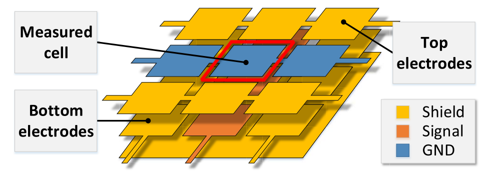


Fig. 5. Example of a 3×3 sensing element array and corresponding active shielded measurement connections.

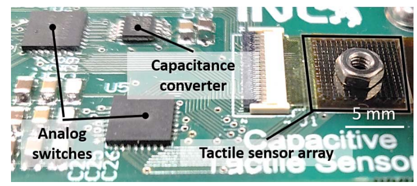


Fig. 6. Analog front-end electronics and tactile sensor array.

IV. Readout Electronics & Test Setup

The gap deformation applied to a single cell, proportional to the applied pressure, is measured through the capacitance variation between the electrodes. In this sensor configuration, the top and bottom electrodes are organized in rows and columns. The individual cells are addressed by measuring the capacitance between signal path connected to the bottom electrode and the grounded top electrode. The top external electrode is grounded, providing a low resistance path to external interference potentials, while an additional large electrode PCB plane underneath the sensor completely isolates the bottom measurement electrode. However, this configuration may contribute to parasitic capacitance arising between adjacent rows and columns as well as interference from floating potentials of the remaining cell electrodes.

To isolate the capacitance measurement to a single overlapping row-column cell, all the columns not being measured must be biased to the same potential of the excitation signal, which eliminates the interfering electric field between these electrodes, as illustrated in Fig. 5. This biasing signal provides an active shielding of the measurement signal path and electrodes, enabling the measurement of individual overlapping electrode cells configured in arrays of shunted rows and columns.

The analog front-end includes a capacitance to digital converter (CDC) and analog cross point switch to interface the row and column electrodes of the sensor. The FDC1004 CDC from Texas Instruments has a full scale range of ±15 pF, with 0.5 aF resolution and a programmable offset capacitance up to 100 pF and an active shielding signal output. The CDC has 4 multiplexed sensing channels and output rates up to 400 S/s. Two 8×12 analog cross point switches (ADG2128 from Analog Devices) interface the sensor and the CDC by configuring the connections between the sensor's rows and and columns, and the signal, ground or active shielding paths. The CDC and analog switches are configured through a shared I^2C bus line to an ESP32 microcontroller.

In this device, 12 rows and 12 columns are interfaced through the switches, while the remaining are always

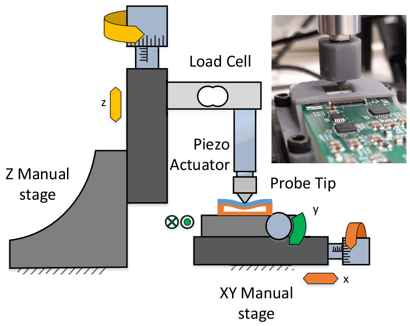


Fig. 7. Schematic of the setup to test the tactile sensor with a flat 250 μm probe tip.

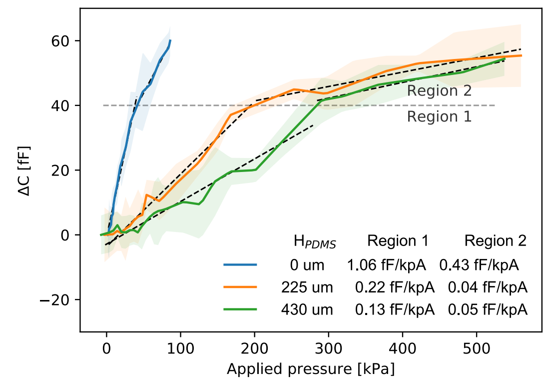


Fig. 8. Experimental tactile sensitivity results in different configurations. The vertical axis represents the variation of the measured capacitance to its initial value as a function of applied pressure. The graph shows the measured response of a sensing cell for the bare sensor alone and with two thicknesses (225 μm and 430 μm) of the upper PDMS layer.

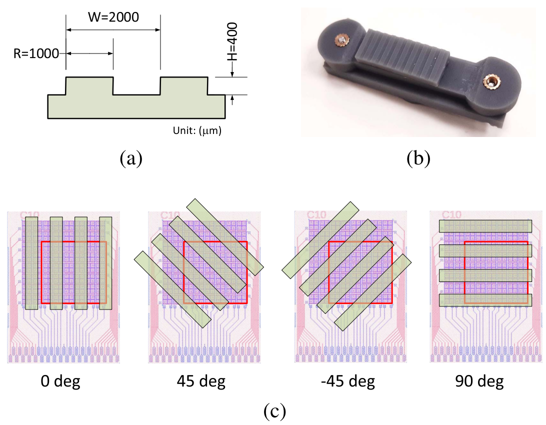


Fig. 9. Geometrical dimensions of the regular grating stamp used for the test (a); custom-made frame to fix the stamp to the load cell probe (b); different layouts tested to assess the sensor ability on recognizing tactile pattern (red border boxes delimit the 12×12 sensitive array.) (c).

connected to the active shielding signal, reducing the sensor sensitive area to a 12×12 frame. The frame measurement consists in measuring the relative capacitance in each of the sensor cells, corresponding to the local applied pressure, compared to the nominal capacitance at rest.

The CDC's programmable offset capacitance is calibrated to compensate for the long signal paths between the CDC and the sensor, as well as the cross point switch's channel capacitance. The 12×12 frame capture measures each cell sequentially by columns and rows. At start, all rows and columns are connected to the active shielding signal. For each cell, the respective row and column are connected to the CDC measurement and ground signals, and the capacitance is measured. Only the required connection changes between cell measurements are made to minimize I^2C communication bottlenecks and to optimize frame capture for speed. An acquisition rate of approximately 1.25 frame captures per second is achieved with this device.

We set up a custom-made equipment for contact force characterization to operate as the testbench for the proposed sensor, as schematically depicted in Fig. 7. The readout electronics with the tactile sensor array on board was fixed to a dual axis manual stage (Edmund Optics). The experimental testbench comprised a resistive beam load cell (capacity: 500 g, accuracy: 0.5 mN), a vertical axis manual stage (PT1/M, Thorlabs) and a piezo actuator (P-841.2, Physik Instrumente) operating in open loop with a displacement resolution of 0.3 nm, travel range of 30 μm and maximum pushing force of 1 kN. The acquisition system consists of a 32 bit microcontroller (Teensy 3.5, Kinetis K64F 120 MHz microcontroller) and an external 24-bit ADC converter (HX711, AVIA Semiconductor) to acquire the load cell. A graphical user interface was implemented in Python 3 to monitor and acquire the data of the applied loads and the capacitance measurements.

V. Results & Discussions

Preliminary tests were performed to measure the sensitivity of the capacitive sensor cell to an applied pressure. The displacement of the piezoactuator was gradually increased in small steps, and then the capacitance was captured at the refresh rate of the readout electronics.

Each data point in Fig. 8 represents the average result from 5 acquisitions, whereas the shaded regions represent two standard deviations from the average. In accordance with the behavior observed from the simulation results, a high sensitivity over a short operative range (around 1 fF/kPa between 0-30 kPa) resulted for the bare sensor. Moreover, as observed in the simulation, the presence of PDMS enlarge the operative range to the detriment of sensitivity: for the thinner PDMS we observed 0.23 fF/kPa up to 150 kPa, whereas for the thicker PDMS we have 0.14 fF/kPa until 300 kPa.

The 2D pressure distributions capacity of the sensor was tested by applying normal forces using a plastic stamp with a regular grating profile, as depicted in Fig. 9. During this test, the plastic stamp was pushed against the sensor with a gradually increasing force until a maximum value of 1.2 N, in four different orientations of the grating with respect to sensing array. Two sensors covered with 225 μm and 430 μm thick elastomer layers were used to acquire the tactile image of the regular grating, as shown in Fig. 10a and Fig. 10b, respectively. The orientation and pitch between the gratings can be qualitatively assessed from these images.

To demonstrate the sensor's ability to detect the surface morphology, the 2D image representation of an M2 nut is

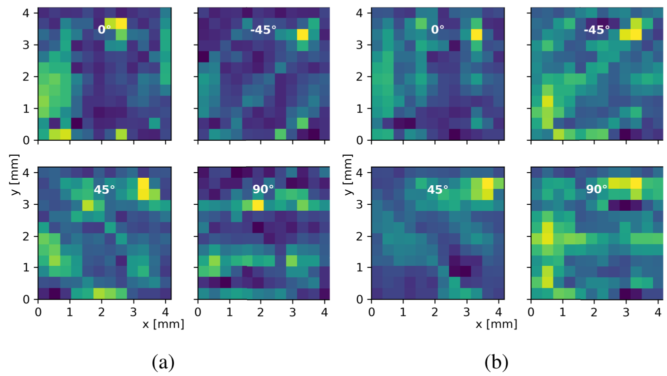


Fig. 10. Experimental morphology measurements of regular matrix using tactile sensor with 225 μm (a) and 430 μm (b) top membrane thicknesses under 1 N load.

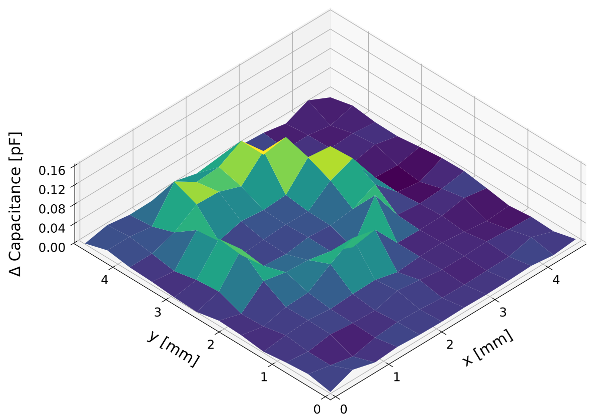


Fig. 11. Morphology of an M2 nut placed against the tactile sensor surface with a 0.72 N normal force.

depicted in Fig. 11. This M2 nut (shown in Fig. 6) was applied against the sensor with a 0.25 N normal force. The inner (2 mm) and outer (4 mm) nut diameters are clearly observed, demonstrating the sensor's high spatial resolution.

VI. Conclusion

In this paper we presented a novel flexible tactile sensor that comprises a 16×16 array of capacitive sensing elements, with 340 μm × 340 μm square electrodes separated by a compressible air cavity. The sensing array was fabricated on a flexible polyimide substrate using standard MEMS microfabrication techniques. The corresponding readout scanning electronics was designed and implemented. The polyimide device was then covered with PDMS layers, to tune the normal pressure sensitivities and dynamic range. While the sensitivity for the bare sensor was 1.05 fF/kPa, the sensitivity for 225 and 430 μm thick PDMS layers resulted in 0.23 and 0.14 fF/kPa, respectively. The linear region of the bare sensor was increased nearly as 6 and 10 times, respectively. We also tested the sensor concerning the ability to distinguish the orientation and spacing of a regular grating stamp pressed against it. Finally, the surface morphology induced by an M2 nut placed on the sensor was demonstrated with a 420 μm spatial resolution.

A natural progression of this work is the design of new electrodes shape and matrix layout to improve the sensing performance. Moreover, the work is also ongoing to design a new readout electronics capable of higher sampling rate.

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