3D-printed elastomer foam-based soft capacitive pressure sensors

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***Abstract*—The field of tactile sensing has exploded in recent years with the development of sensors using a wide variety of composite materials and fabrication techniques to meet the varying requirement of applications such as robotics, wearable, and interactive systems. Often these applications require touch sensors over large areas, and this calls for a simple manufacturing route such as additive manufacturing. Herein we present fully 3D printed highly sensitive capacitive touch sensors with an elastomeric foam-based dielectric layer (a blend of PDMS and $BaTiO_3$) and PEDOT: PSS and AgNWs composite based electrodes. The device is encapsulated with PDMS. The sensor was tested under dynamic and static conditions, and the sensitivity was found to be 0.918 $\%kPa^{-1}$ with excellent linearity (99.77%). The presented approach for realizing soft and flexible electronic skin (e-Skin) in one single automated step has potential to transform applications such as wearables, health monitoring, and rehabilitation with low-cost and easily manufacturable high-performance sensors.**

Keywords—tactile sensor, flexible sensors, soft sensor, porous PDMS, direct ink writing, 3D printing

I. Introduction

Tactile or electronic skin (e-Skin) and touch-based interfaces are widely used in robotic, prostheses, and haptic feedback-based interactive systems[1-4]. Often the e-Skins with tactile sensors are developed in such a way that they can be wrapped around or placed on the external curvy surfaces of these systems and real-world objects [5-7], but recently they have also been embedded in 3D printed smart structures [8], or concealed in wearables such as smart gloves, to prevent wear and tear [9]. Whilst several types of touch sensors have been explored, the ones working on the capacitive transduction method are most popular due to their simple structures and readout electronics [10]. Capacitive-based sensors offer high sensitivity for static or quasi-static contacts in the low-pressure range, which is typically needed in object handling [10-13]. To improve the conformability, soft and stretchable capacitive touch sensors have also been reported recently using elastomeric materials as dielectric or stretchable substrates [14-19]. Most of these sensors rely on traditional microfabrication techniques, such as etching, spin-coating, electroplating, photolithography, etc. Whilst, these methods have helped to obtain high density and spatial resolution e-Skins, they are also time-consuming, costly, and complex. Since many e-Skins applications require touch sensors over large areas, there is a need for a simple manufacturing route such as additive manufacturing (AM).

The AM processes provide an attractive alternative method for the fabrication of transducers and smart structures [20, 21]. Techniques such as fused-Deposition-Modelling (FDM) and direct ink writing (DIW) using multi-material 3D printing show increasing interest. 3D printing allows the seamless realisation of complex design, structures, and shapes without complicated multi-step processes. New 3D printers have emerged with more sophisticated controls and the possibility to print multi-materials (not just polymers, but also conductive inks and composites). These allow simple manufacturing of devices with higher resolution as well as their integration with readout electronics [8, 22, 23]. This is especially important for DIW printers as the rheological properties of different composites require different printing parameters. These AM systems have been demonstrated to be able to print smart devices and intrinsic sensors.

Herein, we present fully 3D printed highly sensitive capacitive touch sensors with an elastomeric foam-based dielectric layer (a blend of PDMS and $BaTiO_3$) and PEDOT: PSS and AgNWs composite based electrodes. For soft capacitive tactile sensors, elastomers such as polydimethylsiloxane (PDMS) have been well used as the dielectric because of their good mechanical strength, stretchability, elasticity, and conformability [13, 24-27] along with conductive materials such as PEDOT: PSS and conductive fabric [3, 27]. However, the sensitivity of bulk PDMS structures is insufficient for fine texture detection, and as a result, a blend of PDMS and other high dielectric materials such as barium titanate [28], zirconium [29], and ZnO nanowires [18], *etc.* have been used to improve performance [26]. In parallel, porous PDMS active layers have also been explored. The porous structures in these cases have been obtained using sodium chloride (NaCl), sugar cubes, potassium chloride (KCl), and ammonium bicarbonate (NH_4HCO_3) to improve further the sensor's sensitivity [30-32]. Building on these advances, here we have an innovative 3D printing approach to develop capacitive pressure sensors with 3D printing of a dielectric layer based on porous PDMS and $BaTiO_3$. The sensors are developed with porous layers at a weight ratio of PDMS: NH_4HCO_3: $BaTiO_3$ 80:20:1 and 16:4:1. The results, presented in this paper, showcase the exceptional characteristics of the porous layers and the influence of the different concentrations of $BaTiO_3$ on the capacitive responses of the sensors.

This paper is organised as follows: Section II describes the materials and the fabrication procedure used for the capacitive sensors. Section III explains the experimental process and performance of the 3D printed devices. Section IV summarizes the results.

II. Materials and Methods

A. Design of the capacitive sensor

Fig. 1 shows the design of the sensor and its fabrication by DIW. The device has two electrodes that are 20 mm wide, 15 mm long, 0.5 mm thick, and an extended square contact pad of 5 mm. The dielectric layer has the same design as the electrodes. The device was encapsulated with PDMS in a

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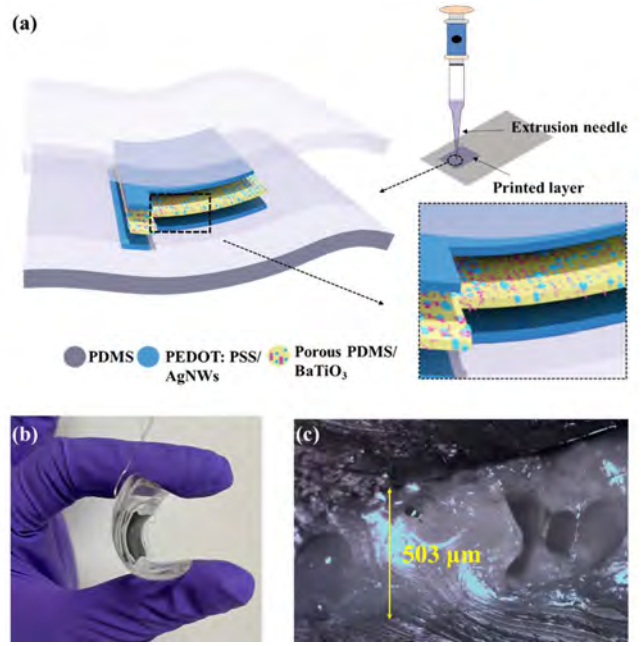

Fig. 1. (a) Schematic illustration of the sensor's design and printing of various layers, (b) 3D printed flexible capacitive sensor and (c) microscopic image of the dielectric layer.

square pattern of 30 × 30 mm. The thickness of the entire device is 20.15 mm.

B. Material Preparation

1) Dielectric Layer: The curing agent was mixed with the PDMS prepolymer (the weight ratio of prepolymer and curing agent is 10:1). After mixing, the PDMS was placed in the desiccator to eliminate its bubbles. Bulk PDMS was used for the encapsulation of the device, while a portion of that was used as the matrix for the porous dielectric layer. The porous PDMS was obtained by mixing bulk PDMS with 1 wt. %. NH_4HCO_3 and stirring the solution for 5 minutes. The $BaTiO_3$ was also added to the PDMS: NH_4HCO_3 solution. Two different ratios of $BaTiO_3$ were added to porous PDMS to develop Sensor1 (1 wt. % of $BaTiO_3$) and Sensor2 (5 wt. % of $BaTiO_3$). Fig. 2a illustrates the preparation of the solution for the dielectric layer.

2) Electrode: 1 wt. % of polyethylene oxide (PEO) was added to the PEDOT: PSS solution and was stirred at room temperature until PEO was dissolved. After that, 10 % (v/v) of DMSO was added to the conductive solution to improve the conductivity of the ink. The solution was stirred for 1 hour at 200 rpm at room temperature until the dopant was well-dispersed. Lastly, 2 % (v/v) of AgNWs were added. The ink was stirred for another 30 minutes at ambient temperature to achieve uniformity. Fig. 2b presents the preparation process for the conductive ink used here to form the electrodes.

C. Device Fabrication

The five-layer device was fabricated using DIW techniques. The 3D printer used in this study is a state-of-the-art 3D printer (Brinter, Turku, Finland) able to print paste-like materials. Firstly, the PDMS (top and bottom layers) of the device were printed on a heated printed bed at 80°C. The PDMS was filled in a syringe with 18G nozzle size (internal diameter of 0.84 mm), and the system was able to deposit the material at a pressure of 500 mbar. When the PDMS layers were cured, a syringe with the conductive ink was placed in the pneumatic printing tool (from Brinter) to print on top of the two PDMS layers. For the conductive ink, 120 mbar was applied using a 21G nozzle (internal diameter of 0.51 mm). When the conductive layers were dried, the syringe was filled with the porous PDMS/$BaTiO_3$ mixture solution. This solution was printed on top of only one of the two electrodes, using a 14G nozzle (internal diameter of 1.54 mm). Two different pressures were applied to obtain two dielectric layers with different concentrations of $BaTiO_3$ in porous PDMS. More specifically, 3000, and 5000 mbar were applied to print the porous mixture with 1% and 5% wt of $BaTiO_3$, respectively. Immediately after the printing, the structures were placed in the oven for 1 hour at 90°C to enable the formation of pores. When NH_4HCO_3 is heated, it decomposes into carbon dioxide (CO_2), ammonia (NH_3), and water (H_2O) [24, 30]. Eq. 1 illustrates the decomposition of the annealed NH_4HCO_3 at 90 °C in an endothermic process. After this the structure with the porous layer and the one without it, were attached and bonded together with a small amount of PDMS on the edges. Copper wires on the side of the top and bottom electrodes were attached with silver paste and epoxy resin.

$$NH_4HCO_3 \rightarrow CO_2\uparrow + NH_3\uparrow + H_2O \quad (1)$$

III. Results and Discussion

A. Performance and Evaluation

The fabricated devices were tested for their transducer characteristics. All the experiments were conducted using a linear actuator that applied controlled pressure to the devices. The actuator was controlled by custom-made LabVIEW software. The sensors were placed on top of a load cell to measure the forces applied by the linear motor. A circular

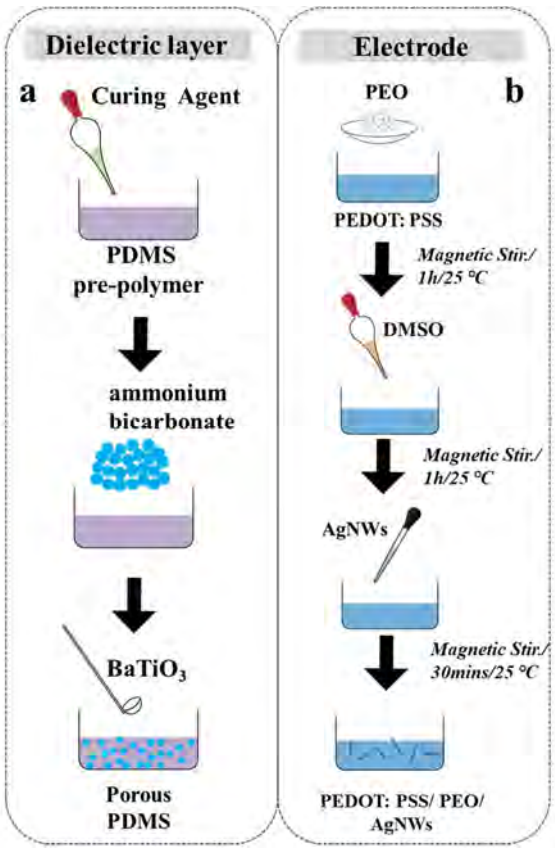

Fig. 2. Schematic illustration of the preparation of solutions for various layers needed in the sensor.

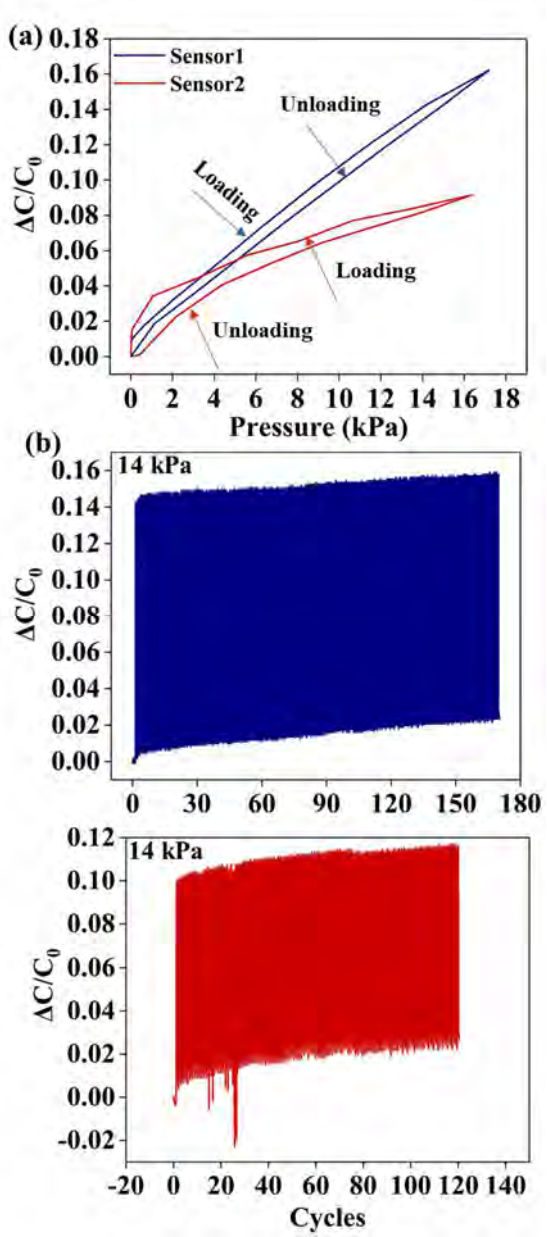

Fig. 3. (a) Capacitive responses under different loading and unloading conditions and the stability of sensors over time for (b) Sensor1 and (c) Sensor2.

probe was attached to the linear motor with a diameter of 2 cm and that was the object in contact with the device. The change in the capacitance was measured using a Keysight (E4980AL) LCR meter.

The devices were tested for their response to static stimuli. In that regard, the devices were tested for pressure between 0-17 kPa. Fig. 3a presents the relative change of capacitance with respect to applied pressure under loading and unloading conditions. From the results, it may be noted that Sensor1 exhibited a sensitivity of 0.918%kPa^{-1} (with linearity (R^2) of 0.99768), and Sensor2 showed a considerably lower sensitivity of 0.556%kPa^{-1} (with a slightly less linear fit of 0.95856). In order to observe the stability of the sensors, dynamic stimuli were applied, and the response was recorded. Fig. 3 (b-c) presents the relative change of capacitance with respect to pressure loading-unloading cycles. The devices were tested for 120 cycles with each cycle lasting for 3 s. The pressure was applied from 0 to 14 kPa. From the experimentation, we can conclude that the devices show a minor deviation (0.587% for Sensor1 and 0.663% for Sensor2) from one cycle to the following one with a slight upwards trend. This can be attributed to the viscoelastic creep effect that PDMS possesses [33]. Sensor2 showed some inconsistency for some of the cycles at the beginning of the measurements.

TABLE I. SUMMARY CHARACTERISTICS OF EACH SENSOR

Sensor	Hysteresis [%]	Linearity [%]	Standard Deviation [%]	Sensitivity [%/kPa]
1	1.427	99.77	0.587	0.918
2	5.83	95.58	0.663	0.556

Table I summarizes the characteristics of the two pressure sensors. The hysteresis showed by Sensor1 was found to be 1.427% and 5.83%. for Sensor2, calculated using the reported method [30]. Each sensor's response also varies (Fig. 3a), especially with increasing pressure. This difference in the response can be explained by the porosity of the dielectric layers in each device. The porous layer of Sensor1 consisted of a larger number of pores than the porous layer of Sensor2. The addition of $BaTiO_3$ improves the capacitive responses of the sensors due to its high dielectric constant [28, 34]. However, it occupies some of the area in the PDMS matrix, when the porous layer is annealed to form the pores, resulting in a less porous structure. In other words, $BaTiO_3$ creates an agglomeration in the PDMS matrix which reduced the compressibility of the dielectric material. This explains the difference in the response of each device. Moreover, since Sensor1 consisted of a more porous dielectric layer, it has a lower Youngs Modulus, which improved the sensitivity [30].

Table II presents the comparison of the performance of devices developed using our approach with other works reported in the literature. This includes devices developed using different fabrication techniques. The data clearly show that Sensor1 has much greater sensitivity in this series of devices, with the next best-performing device being twofold less sensitivity.

TABLE II. COMPARATIVE TABLE

Fabrication Method	Dielectric Layer	Sensitivity [% kPa^{-1}]
SLS [35]	CNT-TOU	0.549 (17-100 kPa) 0.146 (100-240 kPa) 0.035 (240-515 kPa)
DIW[36]	Graphene Nanoplates (GNPs)/MWCNT	0.164 (>70 kPa)
FDM [8]	Ecoflex 00-30	0.348 (>10 kPa) 0.134 (<50 kPa)
Drop-casting [34]	Porous PDMS	0.18 (0-400 kPa)
Drop-casting [37]	CNF/Porous PDMS	0.60 (0-1kPa)
Drop Casting [38]	Porous PDMS	0.0083 (4-200 Pa) 0.0124 (44 Pa-2 kPa) 0.0012 (2.2-120 kPa)
DIW [39]	PDMS	0.31 (0.248–500 kPa)
DIW [This work]	**Porous PDMS/$BaTiO_3$**	**0.918 (>20 kPa)**

IV. CONCLUSION

This paper presents fully 3D-printed capacitive touch or pressure sensing devices, based on a porous dielectric layer. The first fully printed porous PDMS based sensor exhibited high sensitivity, stability, and low hysteresis. In the future, devices with different ratios of porous PDMS: $BaTiO_3$ will be printed to deeply examine the effect of $BaTiO_3$ in the sensor's response.

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