A Novel Fully Printed and Flexible Capacitive Pressure Sensor

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***Abstract*—A novel fully printed flexible capacitive pressure sensor was fabricated using conventional screen and gravure printing techniques. The sensor was successfully printed on a flexible polyethylene terephthalate (PET) substrate with silver (Ag) nanoparticle (NP) ink as the metallization layer and polydimethylsiloxane (PDMS) as the dielectric layer. The capacitive response of the sensor demonstrated a percentage change of 5 % and 40 % for minimum and maximum detectable compressive forces of 800 kPa and 18 MPa, respectively when compared to the base capacitance of 26 pF. At the minimum detectable pressure, the stability measurements resulted in a maximum variation of ± 0.15 % from the average capacitance value of 28 pf. The response of the printed device demonstrated the feasibility of employing traditional printing techniques for the fabrication of flexible pressure sensing devices.**

I. Introduction

Recently, there has been a growing interest in the development of pressure sensors on flexible substrates for applications in the aerospace, automotive, and biomedical engineering fields [1-3]. Pressure sensors are typically manufactured using conventional CMOS processes which are often expensive and fabricated on rigid substrates [4-7]. Almost all pressure sensing systems built to date utilize hanging structures or cavity based sensor design configurations [8-12]. However, none of these configurations offer the high flexibility, stability and conformability, required for various pressure sensing applications. A continuous layer-on-layer configuration is envisioned as a promising approach that will overcome the drawbacks associated with conventional pressure sensing systems. The development of fully flexible and conformal pressure sensors, due to the availability of diverse manufacturing materials and the rapid development of modern fabrication techniques, is thus poised to have a significant impact on the modern society.

Over the last decade, a steady and considerable effort has been directed towards the development of printed electronics using conventional printing technologies. To name a few, organic thin film transistors (OTFT's) using inkjet printing [13-15], flexible displays by means of screen printing [16-18] and electrochemical sensors by rotogravure printing [19, 20]. The use of printing technologies overcomes some of the drawbacks associated with conventional silicon technology, which involves high-vacuum and high-temperature deposition processes along with sophisticated photolithographic patterning techniques [21]. The advantages of printing include improved cost efficiency, reduction of material wastage during fabrication, flexibility in the substrate and low manufacturing temperatures. Even though a steady and considerable effort has been directed towards the development of flexible electronics, there have been no reports on fully printed flexible pressure sensors. This has led to the research of traditional printing techniques for the manufacture of flexible pressure sensors.

Gravure printing is known for its high quality and high printing speed; use of low viscosity inks and robustness of the process [22, 23]. Screen printing has an added advantage of producing a relatively larger wet film thickness which is difficult to attain by other print methods [24]. A typical gravure system is comprised of an engraved gravure cylinder (image carrier), doctor blade, impression roller and ink pan whereas a screen printer consists of a squeegee and a screen printing mask which consists of a frame (steel or aluminum), screen fabric and stencil. Gravure printing is a direct ink transfer process while screen printing is a push through process in which the substrate is not in direct contact with the mask.

In this work, conventional screen and gravure printing techniques were used to fabricate a fully printed flexible capacitive pressure sensor. A laboratory scale gravure press was used to print highly a conductive silver (Ag) nanoparticle (NP) based ink as the electrode metallization layer on a flexible polyethylene terephthalate (PET) substrate. A dielectric layer of polydimethylsiloxane (PDMS) was deposited using a screen printer. The capability of the fabricated device to be used as a pressure sensor was demonstrated by investigating the capacitive response based on varying compressive forces applied.

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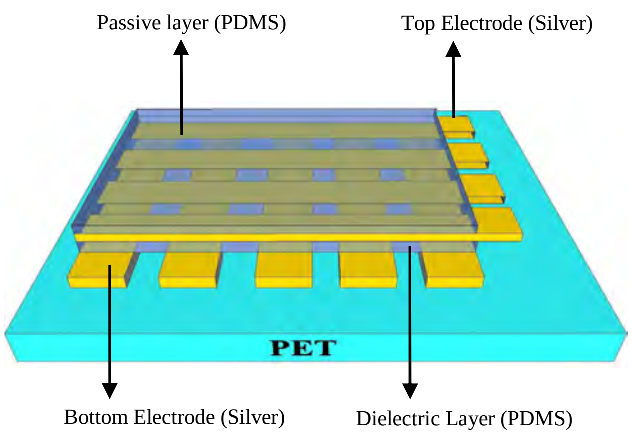
II. Experimental

A. *Chemicals, and Sample Preparation*

A 130 µm thick flexible PET film (Melinex ST 506) from DuPont Teijin Films was used as the substrate. A Ag NP ink, with an average particle size of 20-50 nm (Inktec, TEC-PR-020) was used as the metallization ink for the top and bottom electrodes layers. PDMS (Sylgard® 184 Silicone Elastomer) from Dow Corning was used for the fabrication of the dielectric and passivation layers. The liquid PDMS pre-polymer was mixed thoroughly with a curing agent at a ratio of 10:1 and degassed for 1 hour.

B. *Sensor Fabrication*

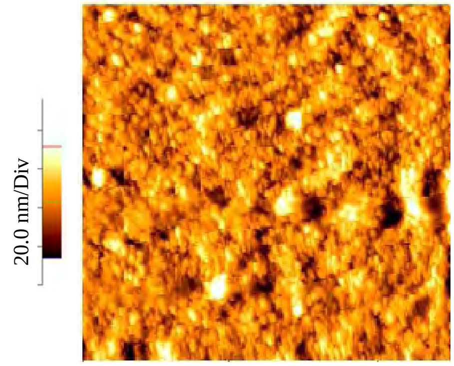
The schematic design of the flexible pressure sensor is shown in Fig. 1(a). The fabrication of the sensor was performed at the Center for the Advancement of Printed Electronics (CAPE) in Western Michigan University using a laboratory gravure press (K-Printing Proofer) from Testing Machines Inc. and a screen printer (AMI MSP 485) from Affiliated Manufacturers Inc. Initially, an array of 4 bottom electrodes with dimensions of 4 cm × 0.5 cm and 0.5 cm spacing were gravure printed on PET. A 4 cm × 4 cm PDMS dielectric layer was then screen printed on top of the electrodes. This was followed by the gravure printing of an array of 4 top electrodes, with similar dimensions to that of the bottom electrode, but at a 90° rotation in angle when compared to the bottom electrodes. This resulted in the grid structure shown in Figure 1(a). Finally, a passivation layer of PDMS was screen printed on top of the electrodes (Fig. 1(b)). The Ag NP and PDMS printed layers were cured at 120 °C for 15 minutes and at 100 °C for 45 minutes, respectively after each layer was printed. The average overall thickness of the printed pressure sensor was measured to be 200 µm.



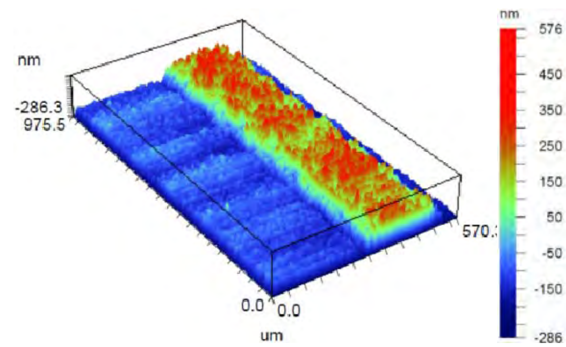
(a)

(b)

Fig. 1: (a) Schematic of pressure sensor. (b) Photograph of fully printed pressure sensor.



(a)



(b)

Fig. 2: (a) AFM image and (b) 3D output of the vertical scanning interferometry of printed Ag NP ink on PET.

Atomic force microscopy (AFM) and vertical scanning interferometry with a WYKO RST-plus optical profiler were used for the roughness and thickness measurements, respectively of the gravure printed Ag NP ink. A 10 × 10 µm AFM image and 3D output of the interferometry is shown in Fig. 2. An average thickness of 300 nm and RMS roughness value of 82 nm was measured.

C. *Experimental Procedure*

The experiment setup is shown in Fig. 3. The printed pressure sensor was placed between a force gauge (Mark-10 model M5-200) and vertically movable platform (Mark-10 ESM 301 motorized test stand). The capacitive response of the sensor was then tested by applying varying compressive forces, perpendicular to the sensor. The sensor was connected to an Agilent E4980A precision LCR meter with wires which were attached using a silver conductive epoxy paste (Circuit works CW2400). The change in capacitance was measured using a custom built LabVIEW™ program on a PC connected to the LCR meter via a USB cable.

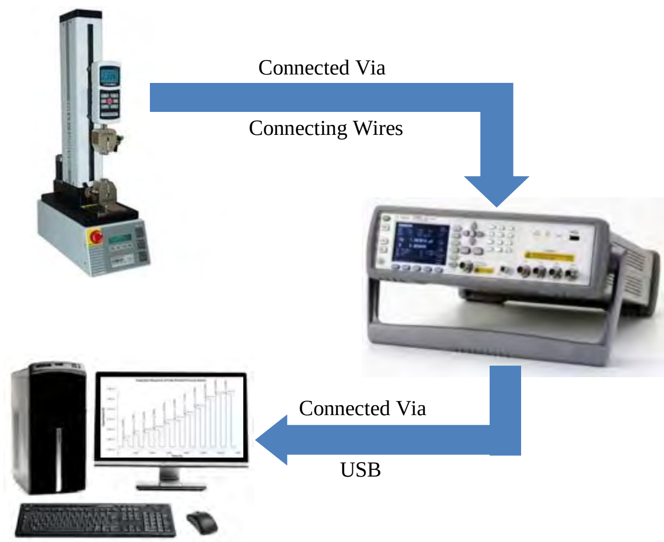


Fig. 3: Experimental Setup.

III. Results And Discussions

The capacitance of the fully printed pressure sensor, which is similar to a parallel plate capacitor, is inversely proportional to the thickness of the dielectric layer. Figure 4 shows the change in capacitance for the different compressive forces applied to the printed pressure sensor. It was observed that the smallest detectable pressure was ~800 kPa for which the base capacitance increased from 26 pF to 28 pF. The capacitance increased further for the different increasing compressive forces applied on the sensor and a capacitance as high as 37 pF was measured for an applied pressure of 18 MPa. A 5 %, 10 %, 17 %, 24 %, 36 %, and 40 % change in capacitance was observed as the pressure increased from 0.8 MPa to 2.6 MPa to 4.9 MPa to 7.7 MPa to 11.2 MPa to 18 MPa, respectively. These responses can be attributed to the shortening of the distance between the electrodes due to the application of the varying compressive forces. A study based on a similar non-printed structure has been reported for the detection of pressures within a dynamic range of upto 1 MPa [25]. The dynamic range made possible by the printed pressure sensor was 18 MPa.

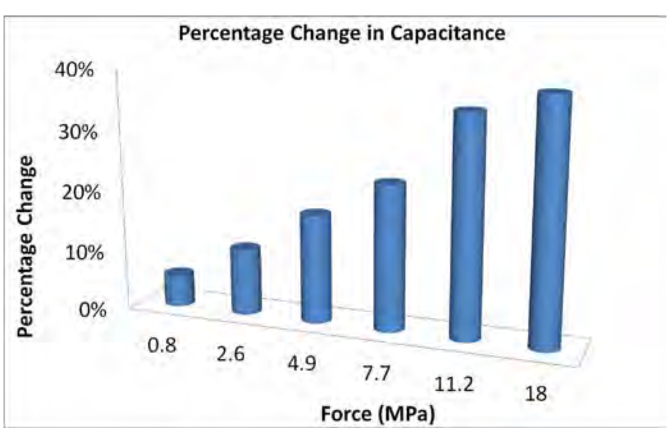


Fig. 4: Percentage change in the capacitive response of the fully printed pressure sensor towards varying compressive forces when compared to base capacitance.

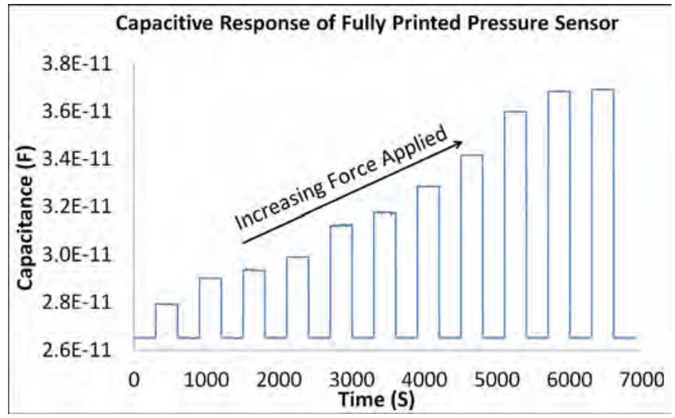


Fig. 5: Capacitive response of fully printed pressure sensor towards varying compressive forces.

Figure 5 shows the dynamic capacitive response of the printed pressure sensor towards varying compressive forces. Initially, the capacitance of the pressure sensor was recorded for 5 minutes with no force applied. Then, the sensor was subjected to the minimum detectable pressure of 800 kPa for 5 minutes, after which the compressive force was released. The response of the sensor was again recorded for another 5 minutes. This cycle was continued for different increasing compressive forces upto the maximum detectable compressive force of 18 MPa. It was observed that the sensor was rendered reversible, after each compressive force was released, due to the fact that the capacitance always attained its base capacitance value of 26 pF. The printed pressure sensor showed a maximum variation of ± 0.15 %, from the average capacitance value of 28 pf, at the minimum detectable pressure of 800 kPa. This result demonstrates the stability of the printed sensor.

IV. Conclusion

In this work, we have successfully employed gravure and screen printing to fabricate a fully printed pressure sensor. The top and bottom electrodes of the sensor were gravure printed on a flexible PET substrate using a Ag ink. A dielectric layer, screen printed using PDMS, was sandwiched between the electrode layers. The average overall thickness of the fully printed pressure sensor was 200 µm, with electrode dimensions of 4 cm × 0.5 cm and 0.5 cm spacing. The capacitive response of the pressure sensor was investigated by varying the compressive forces applied. It was observed that the minimum and maximum detectable pressure was 800 kPa and 18 MPa, respectively. A 5 % and 40 % change in capacitance was measured for the 800 kPa and 18 MPa, respectively. The stability measurements demonstrated a maximum variation of ± 0.15 %, at the minimum detectable pressure of 800 kPa, from the average capacitance value of 28 pf. The results obtained show the potential use for fully printed flexible sensors in pressure sensing applications. Future studies include research to enhance the sensitivity of the printed pressure sensor for a wider range of applied pressures.

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