Highly Sensitive Flexible Capacitive Pressure Sensor with ZnO NW interlayers

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Abstract **—Pressure or force sensors that can reliably detect a broad range of pressure with high sensitivity are prerequisite for applications such as human-machine interface, electronic skin in robotics, and health monitoring. This paper presents a novel approach to fabricate a highly sensitive capacitive pressure sensor by introducing a zinc oxide nanowire (ZnO NW) interlayer between the polydimethylsiloxane (PDMS)/electrodes interface in the conventional metal-insulator-metal architecture. The sensing performances of PDMS-based pressure sensors with and without ZnO NW interlayers were investigated. The ZnO NW interlayer reinforced the electrical connection from metal to PDMS to significantly enhance the device performance with ~ 50 times improvement in sensitivity (from 0.125 kPa^{-1} to 5.6452 kPa^{-1} at a low-pressure range (0-10 kPa)) with respect to conventional PDMS only dielectric-based capacitive sensors.**

Keywords — Flexible pressure sensors; Capacitive sensors; ZnO NW; Electronic skin; PDMS; Soft touch sensors.

I. INTRODUCTION

Human skin consists of numerous receptors located at different depths inside the soft tissues to sense external stimuli such as temperature, pressure, and strain etc. [1-3] In order to realise electronic skin (e-skin) capable of mimicking the transduction mechanisms of the human skin, a network of flexible and stretchable sensors, that convert the external stimuli into electrical signals, are highly desired. In fact, the e-skin research has inspired a rapid development of sensing technologies, particularly the flexible pressure sensors. This is due to their wide range of applications of soft e-skins in areas such as wearable systems, tactile displays, health monitoring, human-machine interfaces, etc. [4-9]. Various transduction mechanisms used for the development of pressure sensors include piezoelectric, capacitive, piezoresistive, and triboelectric [10-14]. Among them, capacitive pressure sensors are widely explored owing to their simple fabrication, low cost, high sensitivity, and remarkable environmental stability [15, 16].

Among various structures and morphologies, the most common capacitive pressure sensors are comprised of a dielectric sensing material sandwiched between two conductive metal layers [17]. The sensitivity of these devices is highly dependent on the materials of the dielectric layer. The elastomeric or rubber materials such as polydimethylsiloxane (PDMS), Ecoflex, and polyurethane (PU) are commonly used dielectric materials. This is due to their good thermal and chemical stability, effective dielectric property, biocompatibility and excellent mechanical property to undergo a reversible deformation [18-20]. To realise high-performance capacitive pressure sensors, using these dielectric materials, following techniques are usually adopted: 1) introduction of microstructures such as pyramid, pillars or wrinkles in the elastomeric or dielectric material; 2) utilisation of nano-fibre dielectric materials with porous structures; 3) development of composite dielectric materials by incorporating filler materials such as carbon nanotubes, silver nanowires etc., to the elastomer matrix [12, 21-25]. For example, capacitive pressure sensors using the micro-arrayed PDMS structure demonstrated an increase in sensitivity (0.6-2 kPa^{-1}), 60 times more than the flat PDMS counterparts (0.01-0.016 kPa^{-1}) at the low pressure region (0-2kPa) [26, 27]. Although the sensitivity was enhanced, the working pressure range of this microstructure-based capacitive pressure sensor was limited [28, 29]. Alternatively, electronic fillers such as carbon nanostructures, graphene nanoplatelets, silver nanowires, high k dielectric nano particles etc., are embedded inside the elastomer matrix to enhance the sensitivity along with a broad working pressure range. Likewise, piezoelectric nanomaterials such as ZnO nanoparticles are incorporated in the composite material to improve the sensitivity [18]. However, a uniform dispersion of the filler inside the elastomer matrix for a repeatable sensing performance is highly challenging to achieve.

To address the existing challenges, we present a novel capacitive pressure sensor by introducing two ZnO NW interlayers, each between a PDMS/electrodes interface. Two PDMS-based capacitive pressure sensors, with and without the ZnO NW interlayer structure, were fabricated and the performances of the sensors were compared by investigating the relative change in capacitance under an applied pressure. With ZnO NW interlayers, the capacitive pressure sensor revealed a 50 times higher sensitivity than the standard PDMS counterpart, with a sensitivity of 5.6452 kPa^{-1} in 0-10 kPa range. The is a significant advancement in terms of sensitivity in comparison with recent reports.

This paper is organised as follows: Section II presents the fabrication steps for the pressure sensors. The results related to the device characterisation are discussed in Section III and the key outcomes are summarised in Section IV.

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II. MATERIALS AND METHODS

To investigate the impact of ZnO NW on PDMS-based flexible capacitive pressure sensors, two different devices in a metal-insulator-metal architecture were fabricated with and without ZnO NW interlayers. The device without ZnO NW interlayers is labelled as sample 1 and the other is sample 2, as shown in Fig. 1. Firstly, 10/80nm-thick Ti/Au contact electrodes were deposited on a ~175µm-thick polyvinyl chloride (PVC) sheet using an electron-beam (E-beam) evaporator. Sequentially, the metal coated PVC sheet was diced into small pieces of 2cm x 1 cm dimensions for top and bottom metal electrodes. The PDMS dielectric layer was prepared by mixing the PDMS elastomer and curing agent at 10:1 ratio.

In the case of sample 1 (i.e. PDMS-based flexible capacitive pressure sensor), a 150 µm-thick PDMS was directly spin-coated on top of one of the electrodes (Fig. a1) and annealed at 80ºC for 15mins. Successively the top electrode was placed over the semi-cured PDMS to ensure a firm adhesion (Fig. a2). Likewise, sample 2 (PDMS embedded by ZnO NW flexible capacitive sensor) was assembled by drop-casting ZnO NW on both the electrodes prior to spin-coating the PDMS layer. Firstly, the drop casted ZnO NW was annealed at 80ºC for 10 mins (Fig. b1). Sequentially, a 150 µm-thick PDMS was directly spin-coated on top of the ZnO NW/bottom electrode (Fig. b2). Finally, the ZnO NW coated top electrode was placed on top of the semi-cured PDMS/ZnO NW-bottom electrode (Fig. b3). By taking advantage of the ZnO NW piezoelectric property, the electrical signal from the contact electrodes to the dielectric material was enhanced. Therefore, the ZnO NW layers were placed closely next to the electrodes to maximise the electrical signal sent by the electrical contacts.

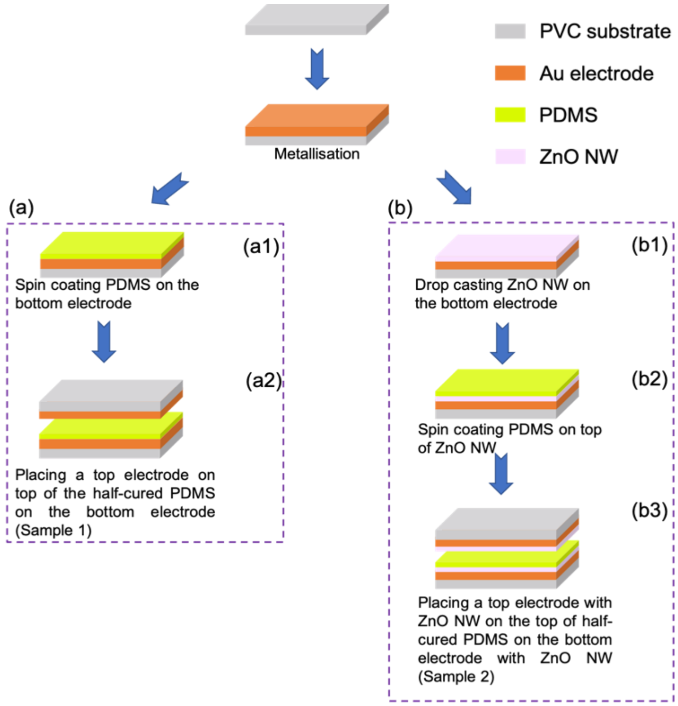

Fig. 1 Schematic representation of PDMS-based capacitive pressure sensors (a) without and (b) with ZnO NW interlayers.

The device characterisation was conducted by placing the fabricated pressure sensors under a single point 1004 aluminium load cell with a square plastic probe on a linear moving stage connected to a motor with a resolution of ~0.1mm. The set up was connected to an E4980AL precision LCR meter (Keysight Technologies, Santa Clara, CA, USA) and a PC program, LabVIEW 2018 Robotics v18.0f2 (National Instruments, Texas, USA) to measure and record the change in the capacitance of samples.

III. RESULTS

To assess the device performance, the sensing properties were firstly evaluated by measuring the relative change in capacitance at different pressure ranges varied from 0 to 50kPa, as shown in Fig. 2(a) and (b). The standard sample (sample 1 without interlayers) revealed a relative change in capacitance of less than 7% between the applied pressure range (0-50kPa). On the other hand, the sample with ZnO NW interlayers (sample 2) revealed a relative change in capacitance of ~100% for the same pressure range.

From these results, it is clear that the addition of ZnO NW layers have played a significant role leading to an improvement of the device performance. This enhancement in the sensing performance is attributed to the piezoelectric effects introduced by the ZnO NW interlayer. As mentioned earlier, the purpose of placing the ZnO NW layers next to the electrodes is to reinforce the electrical connection from the electrodes to the dielectric material.

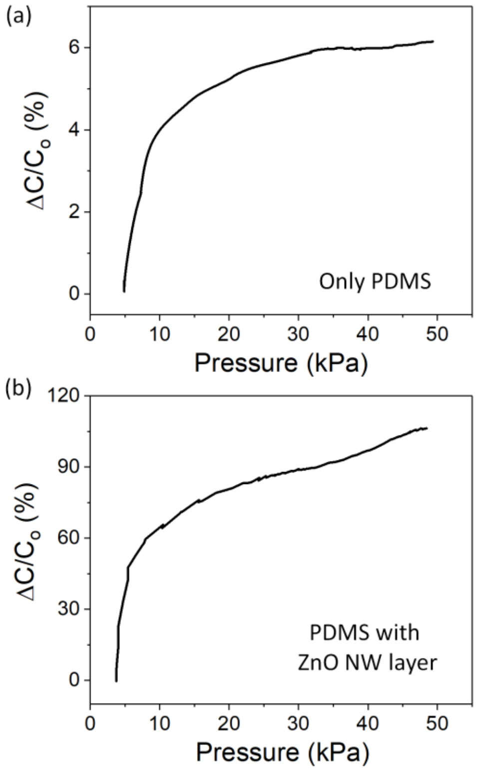

Fig. 2 Sensor characterisation: (a) relative capacitance change vs. applied pressure for sample 1; (b) relative capacitance change vs. applied pressure sample 2.

In addition, ZnO is known to become polarised under an external electric field due to its non-central symmetrical structure [30, 31] In this case, under the influence of the vertical pressure, ZnO NWs become more compact. Meanwhile, the induced charge carriers are generated because of the polarisation effect which sequentially interact with PDMS and strengthen its dielectric property due to the Maxwell-Wagner-Sillars interfacial polarisation [32]. The working mechanism is illustrated in Fig. 3. Consequently, the PDMS-based capacitive pressure sensor with ZnO NW interlayers layers experiences a significant improvement in its relative change in capacitance.

Additionally, the device sensitivity was extracted from Fig. 2 by using the equation (1) [33]:

$$S = \delta\,[(C - C_0)/C_0]\,/\,\delta P \qquad (1)$$

Where C and C_0 are the capacitances with and without the applied pressure, and P is the amount of pressure applied. The sensitivity for different pressure ranges (1-10 kPa, 10-20 kPa, 20-50 kPa) was then derived from Fig. 2(a) and (b). As shown in Fig. 4(a), the PDMS-based capacitive pressure sensor with ZnO NW interlayers shows a higher sensitivity for all the pressure ranges varied from 0 to 50 kPa, indicating a dramatically improved sensing performance. Especially at the lower pressure range, from 1-10 kPa, sample 2 demonstrates the highest sensitivity of 5.6452 kPa^{-1}, compared with that of 0.1251 from sample 1.

Moreover, the reliability of two samples were assessed by carrying out a cyclic loading test by loading and unloading the samples using 1N force at a frequency of 0.33Hz. It is noticeable from Fig. 4 that sample 2 shows a higher stability and reliability by not only presenting a full recovery response and less noise but also a larger range of capacitance change by a factor of ~21.42%.

IV. CONCLUSION

In this work, a simple and cost-effective fabrication method is used for the development of capacitive pressure sensors. Two PDMS-based capacitive pressure sensors were fabricated with and without ZnO NW interlayers to investigate the effect of ZnO NW for pressure sensing. The device performance was then evaluated by comparing the experimental results of the two sensors. The pressure sensor with ZnO NW interlayer exhibited an enhanced capacitance, sensitivity, and reliability due to its piezoelectric effects. A high-sensitivity (5.6452 kPa^{-1}) of the capacitive pressure sensor was demonstrated in the pressure range of 1-10kPa. The effect of the ZnO NW alignment for the device performance will be further explored in our future work.

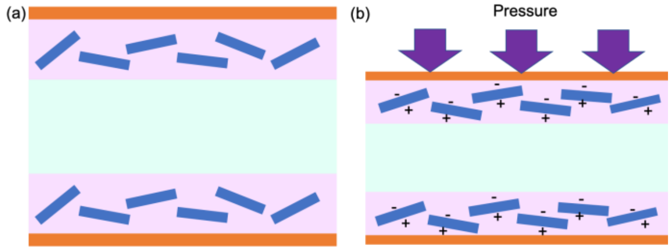

Fig. 3 The illustration of the device with PDMS embedded by ZnO NW: (a) without any external pressure; (b) with a vertically applied pressure.

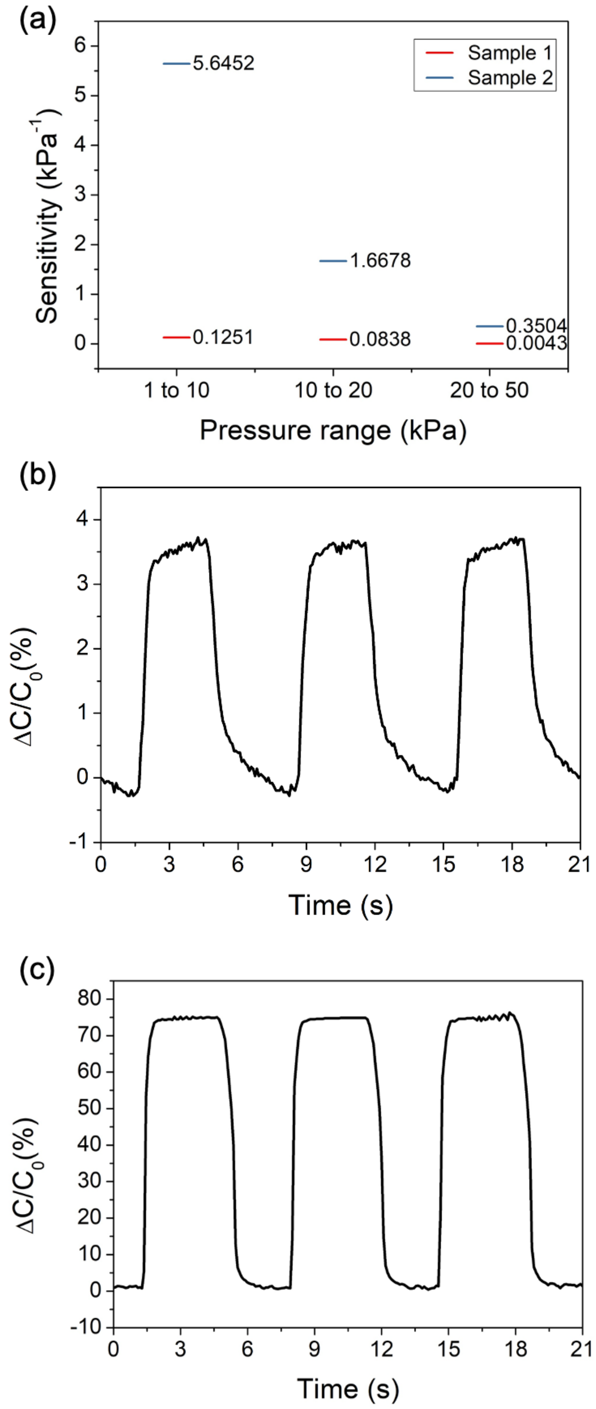

Fig. 4 (a) Sensitivity comparison for sample 1 and 2; Cyclic tests for (b) sample 1 and (c) sample 2.

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