Stretchable Resistive Pressure Sensor based on CNT-PDMS Nanocomposites

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***Abstract*— Flexible pressure sensors attached conformably to skin are of great interest for wearable electronics and robotic applications. However, effective utilization of such devices often requires them to be stretchable. Herein we report a stretchable pressure sensor based on carbon nanotube –polydimethylsiloxane (CNT-PDMS) nanocomposite. The sensors are based on interdigitated silver (Ag) patterns as bottom electrodes which are connected by a top conductive polymer made of CNT–PDMS composite. The sensors are developed on a PDMS substrate to achieve the required elasticity. The performance of the sensors is assessed by measuring change in the resistance of the device for applied mechanical stimuli. The minimal detectable pressure by our sensor is 500Pa. It is noted that the conductivity of CNT-PDMS composites and Ag electrode spacing are the two critical factors significantly influencing the performance of the sensors.**

***Index Terms*— CNT-PDMS nanocomposite, Piezoresistivity, Screen-printing, Stretchable Pressure Sensors.**

I. Introduction

The next evolutionary progression of the electronic industry is expected to result in flexible and stretchable electronics. The flexible electronics are not just expected to benefit the consumer electronics with some of the futuristic devices but also broaden the horizon of large area electronics applications into personalised health care system and robotics [1]. The realisation of such devices using traditional silicon wafer is a major challenge due to its brittle and rigid nature [2]. Until now, the mechanical robustness required for flexible electronics are achieved predominantly via two methods: (a) Smart structural engineering of conventional material [2, 3]; (b) Use of novel material to develop electronics [4]. Organic semiconductors fuelled the unprecedented growth of flexible electronics in the initial stages of the development, however with the technological progression a new class of materials called nanomaterials began to play an important role in the development of flexible electronics. Some of the nanomaterials and nanostructures include nanowire [5], metal nanoparticles [6] and nanocarbon allotropes such as carbon nanotube (CNT) [7] and graphene [8] .

The development of sensors especially pressure/strain sensing devices on flexible substrate are of great interest due to their potential applications in electronic skin (E-skin), displays and robotics [9-12]. The development of flexible sensors has been demonstrated using various nanomaterial and nanocomposites [13, 14]. Nanocomposites are materials consisting of polymers and nanomaterials. By incorporating the polymer with conductive nanomaterials the conductivity and mechanical elasticity of nanocomposites is enhanced. The CNT-PDMS composite is one of the widely used composites for pressure sensing applications [10, 15]. A significant advantage of CNT-PDMS nanocomposite is its low percolation threshold in comparison with other nanofillers such as metallic nanoparticles, carbon black etc. The low percolation threshold is a result of high aspect ratio and large surface area of CNT [16] However, a disparity in percolation threshold is observed in the literature. This is primarily due to variation in the quality of nanotube, which is affected by various factors such as process technique, dispersion technique, surfactants etc. [17]. To ensure the conductivity of the nanocomposite, it is critical to optimize the processing and dispersion techniques. Due to superior electrical conductivity, the multi-walled carbon nanotubes (MWNTs) have also been used for sensors [13]. The sensing mechanisms of the all reported pressure/strain gauge sensors can be broadly classified as capacitive [18], piezoelectric [19], piezoresistive [20] and triboelectric [21]. Herein, we report the development of resistive pressure sensor. Fig. 1 depicts the schematic of an array of developed pressure sensor. The performance of the device is evaluated by the change in resistance against an applied pressure. Furthermore, we also investigate the impact of top PDMS-CNT composite on the device performance by varying the CNT weight ratio in the composite. The effect of the electrode spacing on the device resistivity change is also investigated in this study.

The paper is organised as follows: Section II presents an overview of the material and fabrication process flow of the

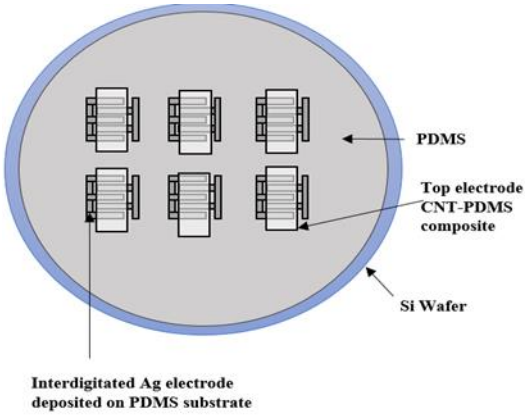

Fig. 1: Schematic of an array of sensors.

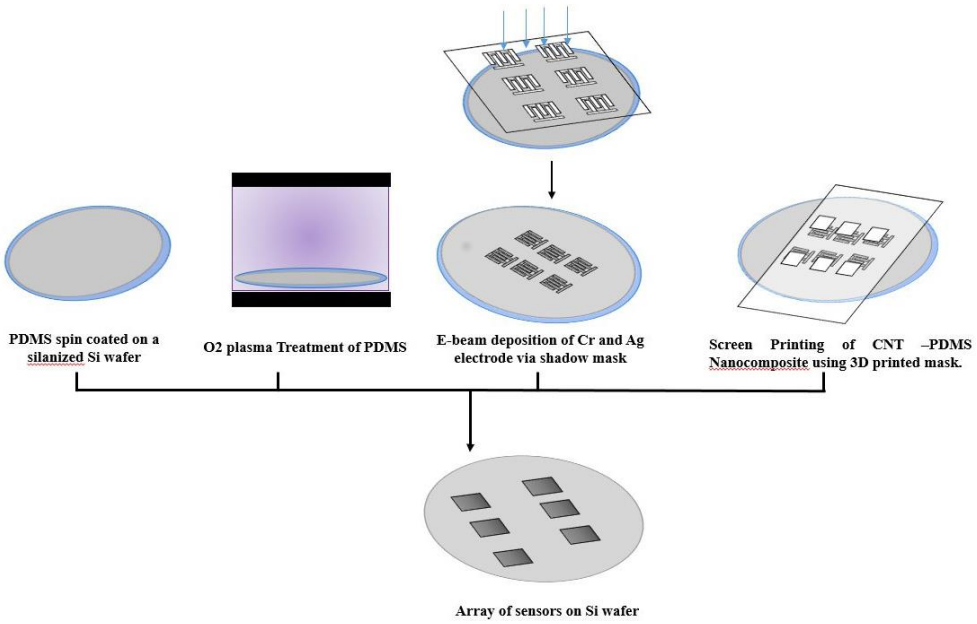

Fig. 2. The graphic representation of the key steps in the fabrication of the pressure sensors.

device. Device characterisation and results are reported in section III and the scope for future work and conclusion are in the Section IV.

II. Materials and Methods

The device comprises of a thin layer of PDMS as a substrate having interdigitated (IDEs) silver (Ag) electrodes and CNT-PDMS nanocomposite is printed as a resistive sensor layer on top of IDEs. The reasoning behind the choice of PDMS is attributed to its excellent mechanical elasticity, which is a critical parameter of the devices. Fig. 2 depicts an overview of key steps in the fabrication process flow of our device. The development of our pressure sensor can be broadly categorised into two major steps: (a) Fabrication and development of bottom PDMS substrate consisting of silver electrode; (b) Development of the top-layer of PDMS-CNT nanocomposite. The details of the steps are discussed in the following sections.

A. Fabrication of Silver electrode on the PDMS layer

The 4-inch silicon (Si) wafers are used as the carrier substrate during the fabrication process, which are cleaned using standard procedure to remove any surface contaminants. After the cleaning procedure, the wafers are silanized using chlorotrimethylsilane. This is to obviate any complexity associated with the removal of PDMS from the silicon wafer after completion of the fabrication process. The PDMS kit (Sylgard 184, from Dow Corning) consists of a polymer base resin and curing agent. These two are mixed thoroughly in a 10:1 ratio and degassed using a vacuum desiccator. The degassed mixture is then spin-coated on the wafer at 1100 rpm for 30s, resulting in an 80µm-thick PDMS layer. The spin-coated wafer was cured in an oven at 80°C for 2h. An oxygen plasma treatment was performed at 100 W for 30 seconds for the surface modification of PDMS. This ensures a better adhesion of metal electrode to be deposited by forthcoming e-beam evaporation [22]. Chromium (10nm thickness deposited at 5Å/s) and silver (100nm thickness deposited at 15Å/s) were e-beam evaporated successively via a 3D printed shadow mask at ~70-90°C. The use of shadow mask avoided any subsequent lithography steps generally required to achieve patterned electrode structure depicted in Fig. 1.

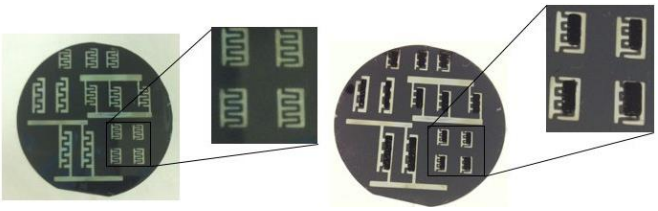

Fig 3: (a) Ag/Cr electrodes e-beam evaporated on a PDMS substrate. (b)Final Device structure with CNT-PDMS composite screen printed on top Ag electrodes

B. Synthesis of CNT- PDMS nanocomposite

The MWNTs (CVD, outer diameter 6-9nm, length ~5µm) used in this work were purchased from Sigma Aldrich (Product Number- 724769). The MWNTs were mixed at different ratios in the PDMS to obtain different weight percentage (7 wt.% and 8 wt.%). The weak van der Waals forces existing between CNTs could cause the agglomeration and thus may result in bundles of CNTs. Agglomeration of CNTs causes a poor dispersion of CNTs within the PDMS and therefore has a detrimental effect on the composite conductivity. The initial dispersion of MWNTs in PDMS was achieved via mechanical mixing for 10 minutes. The dispersion of CNTs in polymer matrix was further enriched by a sonication treatment for 30 minutes at 42 kHz. A higher weight percentage of CNTs in the composite increases the conductivity of the nanocomposite; however, it also has a negative impact on the stretchability of the final developed layers on substrates. Therefore, to enhance the stretchability of the nanocomposite, the ratio of polymer resin to curing agent of PDMS was increased to 30:1. The developed composite was deposited on top of Ag electrodes via

manual screen printing technique using a mask developed via a 3D printer [23]. Finally, the CNT-PDMS composite was cured at 80ºC for 2h in an oven. Fig.3 shows the developed sensor on Si wafer.

C. *Characterisation of pressure sensors*

The performance of the sensors was evaluated by measuring the change of device resistance for an applied compressive force. A normal compressive force was applied across a glass slide placed on top of sensing area. This was done to ensure even distribution of applied force across the sensor and to acquire an accurate measurement as the sensitivity of the sensor is affected by the random distribution of MWNTs. The change in the device resistance was measured across the two IDE during the application of force.

During the characterisation of the device, the two parameters that were evaluated are: (a) influence of the CNT filler wt. % on the sensitivity of the sensor; (b) effect of electrodes spacing on the sensor sensitivity. Resistance of individual sensors were also measured under no external force. The force applied to the sensors was increased from 0 to 1.4N in steps of 0.35N. The eventual change in the device resistance was determined by taking the average of resistivity change of the device within a period of 30s. The recovery time of the device was also evaluated by reducing the applied force from its maximum value of 1.4N to 0N in the steps of 0.35N.

III. Results and Discussions

The operation principle of our device is based on the resistive mechanisms where an external force applied on the device causes a change in the resistivity of the CNT-PDMS composite. The conductivity of composite is determined by the formation of conductive path by CNTs within the PDMS matrix. An application of external force deforms this conductive path thus resulting in an increase in the resistance of the device. The impact of an external force on the conductive path within the PDMS matrix is depicted schematically in Fig. 4. Through experimental analysis it was determined that the minimum of 7wt% of CNTs was required to achieve the prerequisite conductivity for the sensor suitable for sensing applications.

A. *Impact of CNT filler concentration*

The CNT-PDMS composite exhibits a piezo-resistive behaviour, i.e. the composite's resistance changes under application of mechanical stimulus. The electrical conductivity of the composite is due to formation of a conductive path by CNT within the PDMS matrix. Therefore, as expected the conductivity of the composite with higher concentration of CNTs is much higher due to an increased probability of conductive path within the matrix. The performance of the sensor is evaluated by measuring the change in the resistance of the device as a function of pressure. Fig.5 depicts the change in the resistances of the devices consisting of 7 and 8 wt.% of CNT. The change in the resistance of the devices consisting of 7wt.% CNT composite is larger than in 8wt%. This is due to the immediate distortion of fewer conductive paths present within

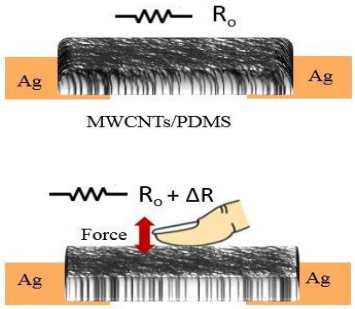

Fig 4: Impact of an external force on the CNT conductive path within the PDMS matrix. Application of compressive force causes the deformation of CNT conductive path resulting in an increases device resistance.

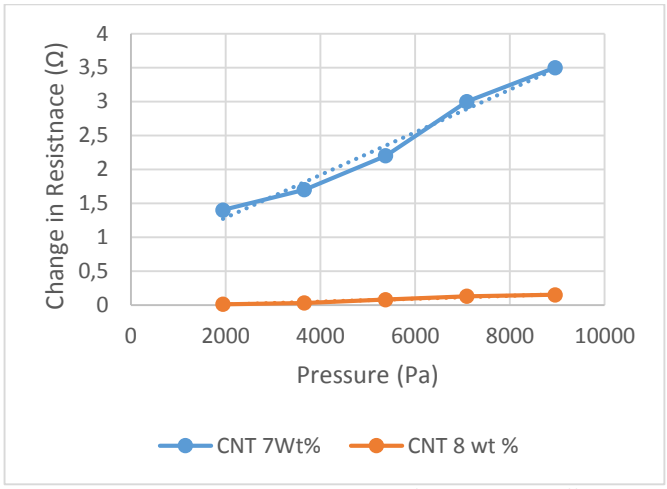

Fig 5: Change in resistance vs applied pressure for device with different CNT concentrations.

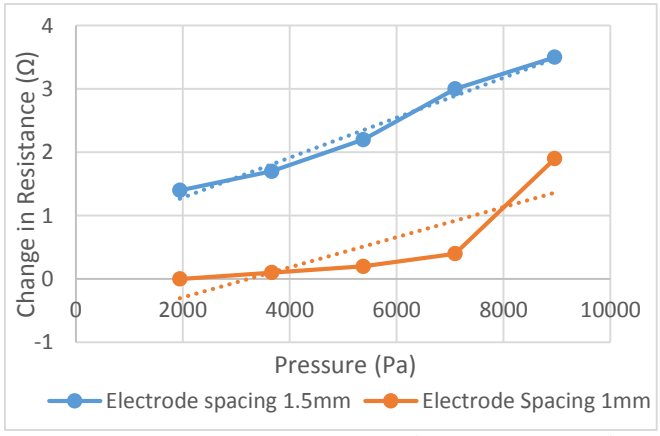

Fig 6: Change in resistance vs applied pressure for device consisting of same CNTs wt% but with different electrode spacing.

the PDMS matrix. Therefore, a composite with lower CNT concentration is preferred due to noticeable change in the resistance. A lower filler concentration is also advantageous to obtain a better stretchability3. Furthermore, our device is capable of detecting a pressure as small as 500Pa, which is still much smaller the pressure generated by gentle touch on a human skin (10kPa) [20, 24]. The non-uniform change in the resistance of the device could be attributed to agglomeration of CNTs within the matrix. Furthermore, cyclic pressure can have a significant impact on the sensor performance. To study this

phenomenon, we assessed the restoration of sensors to its initial value of resistance after removal of the applied force. It was observed that restoration of sensors consisting of 8 wt.% of CNT was faster than its counterpart. This is again due to the higher probability of conductive paths within the 8wt.% in comparison with 7wt.%.

B. Impact of electrode distance on the sensor Performance.

In order to study the impact of the electrode spacing on the sensor performance, the change in the resistance of sensors with different electrode spacing but consisting of same CNT-PDMS composite was studied. The measurements were carried out on devices with electrodes spacing of 1mm and 1.5mm (both in horizontal and vertical directions) for an applied pressure. The results of the study are shown in Fig.6. The closer proximity of the electrodes means, fewer conductive paths are required between the electrodes. Therefore, the change in the resistance of the device is much smaller for a given pressure in comparison with the devices with larger electrode spacing. This is beneficial for sensor application, due to reduced probability of the required conductive path in comparison with device with larger electrode spacing.

IV. Conclusion and Future works

In summary, we have reported a skin attachable resistive pressure sensors based on a simple architecture. The sensor devices comprised of e-beam evaporated interdigitated silver electrodes, and CNT-PDMS composite as top conductive composite. The cost associated with the device was reduced with the use of 3D printed shadow mask and manual screen-printing. Our device was capable of sensing a pressure as small as 500 Pa. The simple device architecture, easy fabrication and high sensitivity permit the device to be utilised in large area pressure sensing applications. Furthermore, we have also studied the impact of CNT concentration and electrode spacing on the sensing performance. These parameters could be further optimised to realise a highly sensitive device. We believe the reported architecture of the device has the capability to be used for strain sensing. Therefore, in the future, investigation will be carried out to realise such feasibility of the device in strain and other mechanical stimuli sensing purposes. These sensors could be optimised for integration into various sensing applications in robotics, e-skin and medical prosthetics.

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