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Flexible Graphene-on-PDMS Sensor for Human Motion Monitoring Applications

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***Abstract*— In this work, a 4-step method of developing flexible, stretchable, and thin graphene-on-polydimethylsiloxane (PDMS) piezoresistive strain sensors is presented. The proposed sensor utilizes the piezoresistive property observed in a dense graphene-nanoflakes percolation network sandwiched between two flexible PDMS layers for strain sensing applications. A gait monitoring system comprising of two identical sensors integrated on the knee region of a sports leggings is developed and demonstrated for real-time human motion monitoring.**

Keywords—Graphene nanoflakes; piezoresistivity; flexible sensors; gait monitoring; polydimethylsiloxane (PDMS)

I. Introduction

Human monitoring in individuals suffering from various neurological and other locomotor disorders like Parkinson's disease, multiple sclerosis, and Huntington's disease can provide valuable information regarding the progression of the disease. Continuous home-based monitoring of physical movement, and in particular gait characteristics can help in tracking disease progression, thereby enabling healthcare professionals to develop personalized treatment plans for patients suffering from the aforementioned conditions [1]. Continuous yet non-invasive monitoring of human locomotion necessitates the availability of thin, flexible, lightweight and wearable sensors tailored for human motion monitoring applications.

With the advancement of telemedicine and the constantly growing demand for patient-specific personalized treatment plans, the last decade has seen a surge in the demand for flexible and wearable sensors targeted towards monitoring of human vitals such as gait, pulse, blood pressure etc. Thus, flexible and stretchable sensors utilizing piezoresistive property of nanomaterial-polymer composites has been a growing area of research for the last two decades. Nanomaterials such as carbon nanotubes (CNTs) [2], carbon nanofibers (CNFs) [3]–[5], silver nanowires [6], carbon black [7], [8], and graphene [9], [10] have been employed as piezoresistive sensing elements in many of the works reported in the past. Also, in most of those nanomaterial-polymer composite-based sensors, elastomers like polydimethylsiloxane (PDMS), ecoflex, and rubber have been the materials of choice mainly because of their superior flexibility, stretchability, and excellent response to torsion [11]–[13]. Continuous innovations have led to using alternative substrates like paper for producing inexpensive yet accurate biodegradable and environment friendly sensors [14].

In this work we present a facile and highly repeatable method of fabricating thin, flexible, and stretchable graphene-on-PDMS piezoresistive strain sensors tailored for human motion monitoring applications. Morphological studies and subsequent uniaxial tension tests are conducted on the developed sensor to understand the strain sensing mechanism. A series of experiments involving joint movement detection and phonation sensing have been conducted to assess the potential of the sensor for human motion monitoring applications. Finally, a sophisticated gait monitoring system comprising of two identical sensors working in tandem was used for obtaining the dynamic strain characteristics of the two knee joints of an individual, thus allowing for accurate real-time monitoring of the gait behaviour.

II. Experimental

A. Graphene-on-PDMS sensor fabrication

The sensor reported in this work consists of a graphene nanoflakes percolation network layer sandwiched between two thin layers of PDMS substrates. A quick and repeatable 4 step process is developed for fabricating the sensors, represented schematically in Fig. 1 (a). The method entails coating a 200 µm thick polydimethylsiloxane (PDMS) layer on top of a 2-inch silicon wafer and subsequent curing. Post curing of the bottom substrate layer, a rectangular patch of conductive solution of graphene dispersion in n-butyl acetate (acquired from Graphene supermarket, USA) is screen printed, dried and 9 mm wide copper tape electrodes are attached at two extreme ends to form electrical contacts. Finally, a 200 µm thick PDMS layer spin-coated on top and cured to achieve a complete encapsulation. The fully fabricated sensor is then stripped from the silicon wafer and diced into a compact rectangular shape. Fig. 1 (b) shows an image of a diced Graphene-on-PDMS sensor that was fabricated using the above-mentioned process.

B. Data Acquisition

The sensor responses in the characterization and motion monitoring tests were recorded using a data acquisition device (NI-DAQ USB-6003) connected to an appropriately designed

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Wheatstone bridge circuit. The signal was monitored and logged using NI Signal Express 2015 software.

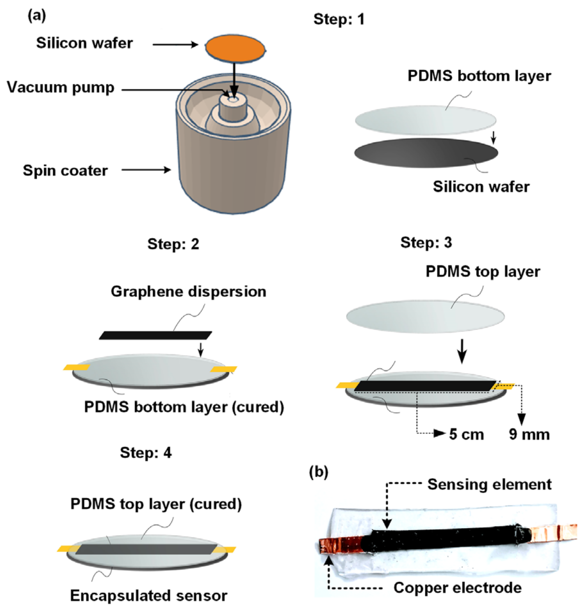

Fig. 1. (a) Schematic representation of the 4-step fabrication process using spin-coating of PDMS on a silicon wafer to obtain thin and flexible Graphene-PDMS strain sensors; (b) Image of an array of Graphene-PDMS sensors fabricated in this work.

III. Results and Discussion

A. Sensor morphology and mechanism

The morphological properties of the flexible graphene-PDMS strain sensor is studied using a scanning electron microscope (SEM). The sensor was diced longitudinally, thereby exposing the inner cross-section and secured on an SEM stub to observe the layered structure of the sensor. The imaging studies confirms the presence of a 220 µm thick graphene nanoflakes percolation network sandwiched between two 200 µm PDMS layers. The SEM micrograph in Fig. 2 (a) shows the interface of the top and bottom PDMS layers with the graphene nanoflakes confirming the binding of the polymer substrate with the nanoflakes percolation network. The piezoresistive strain-sensing mechanism in the graphene-PDMS sensor can be attributed to the conductive domain disconnection mechanism reported previously in other similar nanomaterial-polymer composite based sensors [3], [5], [9]. The SEM micrograph in Fig. 2 (b) shows the overlapping of the graphene nanoflake domains forming a dense nanomaterial percolation network which provides a conductive path for charge transport. When an external strain is applied, the overlapping area between the nanomaterial domain changes leading to a change in resistance which is schematically represented in Fig. 2 (c).

To understand and confirm the strain-induced resistance modulation of the sensor, a simple experiment was conducted wherein the sensor was subjected to uniaxial tension and localized tapping. The sensor was coupled to a Wheatstone bridge circuit (with two 4.7 kΩ fixed resistors and a 0 - 4.7 kΩ variable resistor) and voltage change response was continuously monitored using NI DAQ as shown in Fig. 3 (a). The response plots in Fig. 3 (b) & (c) demonstrate the sensor output when it is subjected to periodic uniaxial tension and localized tapping every 5 seconds for 12 cycles.

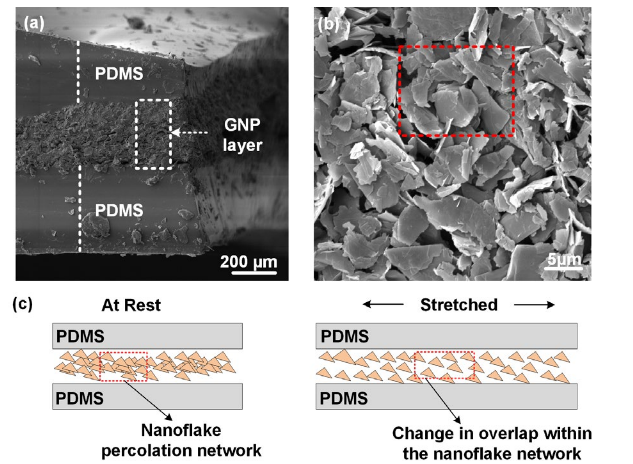

Fig. 2. (a) SEM micrograph depicting the interface of the polymer layer with the graphene nanoflake percolation network; (b) SEM micrograph of the overlapping nanoflake domain in the grapene-PDMS strain sensor; (c) Schematic diagram illustrating the conductive domain disconnection mechanism explaining strain-induced resistance modulation in the sensor.

By comparing the plots from the experiments, it can be observed that the sensor-response to uniaxial loading stimuli is much larger in comparison to localized tapping. This can be attributed to the fact that the binding between the PDMS substrate and graphene nanoflakes percolation network ensures a change in the overlapping area of the nanoflakes network when strain or pressure is applied to the PDMS substrate. Thus, when the sensor is applied with uniaxial tension, there is a greater decrease in the overlapping area of the graphene nanoflake domains and thereby the increase in the overall resistance is higher as compared to the sensor being tapped locally at the centre.

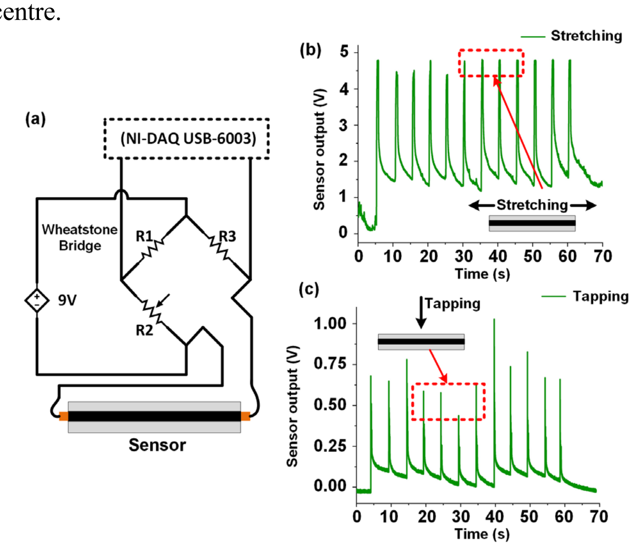

Fig. 3. (a) Schematic representation of setup used for condcuting the streching and tapping experiments; (b) Plot showing the sensor-response from the stretching experiment; (c) Plot showing the sensor-response from the tapping experiment.

B. Application in human motion monitoring

To demonstrate the applicability of the sensor for human motion monitoring, a series of tests involving joint movement monitoring, gait characterization, and phonation analysis were conducted. To demonstrate applicability in phonation sensing, the sensor was firmly secured on the laryngeal prominence region of the neck (Fig. 4 (a)). The test subject gulped in a repetitive pattern with an interval of 5 seconds between two consecutive gulps. As evident from the plot in Fig. 4 (b), the sensor demonstrated repeatable voltage response characteristics for the test thus confirming its potential as a phonation analyser.

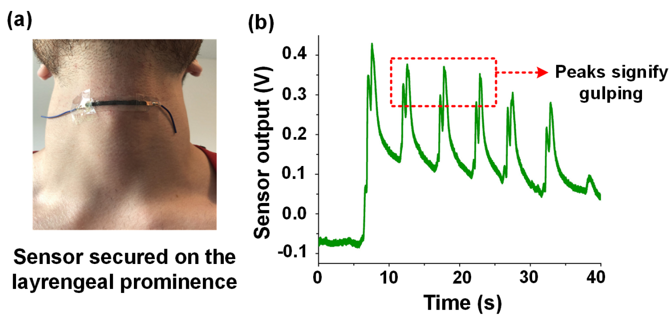

Fig. 4. (a) Photograph of the sensor secured on laryngeal prominence region of the neck; (b) Plot of the sensor-response from the repititive gulping test.

Furthermore, the sensor was secured on a wearable sport training legging which was then worn to demonstrate its applicability in joint movement monitoring. The photo collage in Fig. 5 (a) shows two identical graphene-on-PDMS sensors mounted and secured on the knee regions of a sport leggings and worn by a test subject.

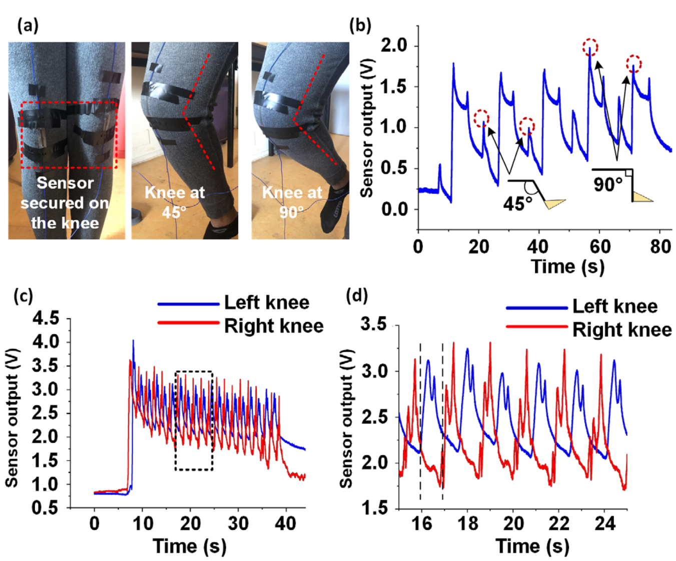

Fig. 5. Plots showing the sensor's response to human motion; (a) Photograph collage showing two identical sensors mounted on the knee regions of a sports leggin; (b) Sensor output for different angles of the knee joint; (c, d) Sensor output for the gait monitoring experiment normal and zoomed in plot.

To demostrate the capability of the sensor to differentitate between different knee-joint positions/strain levels, the left knee was bent at an angle of 45° immediately followed by 90° angle, repeated for 5 cycles. The plot in Fig. 5 (b) shows the distinguishable peaks of the sensor-response obtained at both the angles demonstrating the ability of the sensor to distinguish between different joint positions.

As stated earlier, continuous monitoring of gait characteristics can prove to be crucial in the home-diagnosis and progression-tracking of locomotor disorders such as Huntington's disease, multiple sclerosis, and Parkinson's disease. To assess the potential of the sensors for reliable gait monitoring, the test subject was directed to walk while the voltage response of the pair of sensor working in tandem was logged continuously. The plots in Fig. 5 (c) & (d) show the sensor-responses from both knees when walking normally for 30 seconds. The phase lag between the sensors from both knees signifies the gait pattern specific to a particular individual. With multiple sensors attached to different regions of the limbs of an indiviudal, a more sophisticated gait monitoring system can be developed in the future. The motion monitoring experiments conducted demonstrate the feasibility of these sensors to be integrated in smart suites, robotics and also in wearable biomedical devices used for health care monitoring applications.

IV. CONCLUSION

In summary, this work established a facile method of fabricating a class of highly flexible Graphene-PDMS piezoresistive strain sensors targeted for human motion monitoring applications. The sensor comprised of a 220 µm thick nanomaterial layer of Graphene Nanoflakes sandwiched between two thin layers of PDMS (200 µm thick). The fabrication method which comprised of spin-coating the substrate PDMS layers, ensured repeatable sensor characteristics by employing spin-coating to accurately control the sensor dimensions. The sensors fabricated in the work were utilized for demonstrating applicability in practical human motion monitoring applications involving phonation sensing, gait characterization and joint locomotion. The sensor design and fabrication method presented in this work lays down the foundation for a future class of accurate and repeatable flexible sensors targeted for wearable sensor applications.

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