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3D printed mould-based graphite/PDMS sensor for low-force applications

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ABSTRACT

This paper concerns the design, fabrication and characterization of graphite/PDMS sensors for low-force sensing applications. Exploiting the design flexibility of 3D printing, moulds of specific dimensions were prepared onto which graphite powder and PDMS were cast, to develop sensor patches. The sensor patches were highly flexible with repeatable responses to iterative bending cycles. The patches were tested in terms of stretchability, strain and bending-cycle responses. The sensor patches had interdigitated electrodes operating on capacitive sensing, where the effective capacitance changes with an applied force because of changes in their dimensions. Forces ranging from 3.5 mN to 17.5 mN were applied to determine the capability of these sensor patches for low-force sensing applications. The sensor patches had a quick recovery having a sensitivity and SNR per unit force of 0.2542 pF mN^{-1} and 10.86 respectively. The patches were capable of differentiating the forces applied on them, when they were attached to different objects in daily use.

1. Introduction

The use of force sensors is a popular and convenient technique in sensing technology for monitoring different strain-induced applications. They have always been a popular choice due to their benefits for dynamic and quasi-static measurements. Different kinds of force sensors based on the processed materials, operating principle, and performance have been developed to date. The advantages of these force sensors lie in the longevity in their performances in terms of sensitivity, linear range of operation and durability with various loads. In earlier times, force sensors with silicon-based substrates were developed for industrial [1,2] and biomedical [3,4] applications. Even though they did serve a wide range of interdisciplinary applications like imaging and interventional fields [5], there were certain disadvantages attached to them. Some of them are high cost per unit, low output signal, high input power and high leakage current. As a result of these drawbacks, sensors with flexible materials [6] have been devised and formulated for force sensing [7,8]. In order to develop flexible sensor prototypes, a range of processing material have been used based on their electrical, mechanical and thermal properties. Different types of polymeric and elastomeric materials like polydimethylsiloxane (PDMS) [9], polyethylene terephthalate (PET) [10], polyimide (PI) [11], poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) [12], etc. have been used to develop the substrate of the flexible force sensors. Among these materials, PDMS has been a favourite choice [13–15] due to the low cost, hydrophobicity, biocompatible nature, easy handling in combination with a moulding process and ability to form nanocomposites due to the formation of exceptional interfacial covalent bonding with the electrodes [16]. Similarly, different types of conductive materials like carbon allotropes [17], silver [18], gold [19] have been used to develop the electrodes of the sensor patches. The choice of conductive material differs in terms of their electro-mechanical properties. Graphite, one of the allotropes of carbon, has been used predominantly due to its high electrical conductivity, porosity, and corrosion resistance compared to other allotropes of carbon as electrodes. They have been used for temperature sensing [20,21], electrochemical sensing [22,23], strain sensing [24], piezo-resistive sensing [17] and bio-sensing [25–28]. Among the fabrication techniques, different methodologies like photolithography [29], screen printing [30], laser cutting [31], 3D printing [32], etc. have been used for developing flexible prototypes. Among them, utilizing 3D printing to develop the moulds [33,34] provides a high degree of design flexibility, which could be exploited to optimize the sensor design for specific applications. This paper presents the design, develop-

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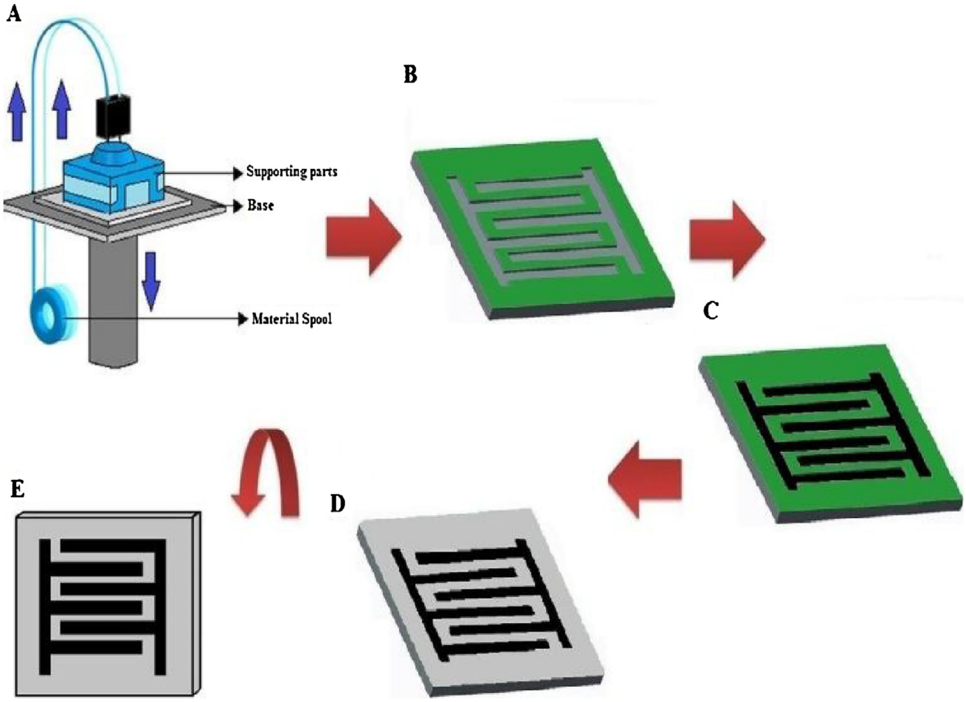

Fig. 1. Schematic diagram of the fabrication process. (A) 3D printing resulted in the reusable mould (B). Then, graphite powder was cast (C) onto the mould, filling its trenches. This was followed by casting of PDMS (D), which was cured to form the sensor patches (E).

ment, and implementation of novel sensor patches fabricated by combining 3D printing with a casting technique. 3D printing was used to produce a mould for the desired sensor shape into which a thin layer of graphite powder was filled followed by casting in PDMS. This process results in flexible sensor patches with conductive graphite electrodes at their top surface. After curing, the developed sensor was peeled out of the mould, characterized and used for force sensing.

Nowadays, flexible sensors incorporated with microelectromechanical systems (MEMS) have become a popular choice for researchers to develop micro-structured devices for force sensing. Some of the applications include their uses as tactile sensors for biomimetic application [35] and robotic applications [36], while some of the sensors, being capacitive in nature, offering the advantages of simplicity in design and fabrication, high sensitivity, and relatively low energy consumption [37]. The application of flexible sensors for [38] applied low-force sensing specially in the field of tactile sensing [39], used it for robotic and upper-limb prostheses, touch screens were made using it by [40] and soft tactile sensors were achieved using it by [41]. Although various materials have been used in this research, there have been certain limitations like high cost, complexity in design and rigidity associated with them. For example, even though [38] used a microfluidic multilayer sensor to measure forces up to 2.5 N, their disadvantages lie in the material cost and complexity of the structure. Although, the research from [42] on capacitive polymer tactile sensors is available, the detectable range of operation in this case is too high, especially for haptic robotic applications. Our work provides a conjunctive approach on the cost of fabrication, operating principle and detectable range. Our sensors can also detect forces within a low-force regime, ranging from 3.5 mN to 17.5 mN, which could lead to utilization of these sensors as wearables for rehabilitation purposes after the patient suffers from a stroke, muscle spasms, etc. In such cases the sensors would enable monitoring of even slight movements of a body part to determine the patient's recovery. The novelties of this paper lie in two specifics: (i) the development of a flexible, capacitive sensor patch fabricated using a 3D printed mould and (ii) the application of these sensor patches for low-force sensing.

2. Fabrication of the sensor patches

The fabrication of the sensor patches was done in the laboratory environment at fixed temperature and humidity conditions. Fig. 1 shows a schematic of the steps carried out for fabrication of the sensor patches. A 3D printer (3D PRINTING SYSTEMS, UP Plus 2) was used for creating the moulds, which were employed as reusable templates to fabricate the sensor patches. [43] showed the use of Acrylonitrile Butadiene Styrene (ABS), with a diameter of 1.75 mm being the best 3D printer filament. A printed-circuit board acted as the base onto which the mould was printed (Fig. 1(A)). The design of the electrodes was done with commercial software (CREO Parametric 2.0) that related to the printing system. The fabrication of a 3D printed mould (Fig. 1(B)) took around 25 min. The moulds were thoroughly cleaned with isopropanol before using them for casting purposes. The initial casting was done with graphite powder (Sigma-Aldrich 282863-25 G, <20 μm) onto the trenches of the 3D printed moulds (Fig. 1(C)).

The residual powder remaining on the moulds other than on the trenches was carefully scraped off. Then, a layer of PDMS (SYLGARD® 184 SILICONE ELASTOMER KIT) was cast onto the mould to form the substrate of the sensor patches (Fig. 1(D)). The height of the PDMS layer was adjusted to 1000 microns by a casting knife (SHEEN, 1117/1000 mm) (Fig. 1(D)). The sample was then desiccated for an hour to remove any trapped air bubbles on the surface of the PDMS (Fig. 1(D)). After curing of the sample in the oven at 70 °C for 2 h, it was peeled off to generate the final sensor patch (Fig. 1(E)). A study was performed to determine the concentration of graphite used in the trenches of the mould to develop the electrodes. A trade-off was done between the electrical con-