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Strain induced graphite/PDMS sensors for biomedical applications

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ABSTRACT

This paper presents the design, fabrication and implementation of novel graphite/PDMS sensors for biomedical applications. The fabrication involves 3-D printed molds which were developed using acrylonitrile thermoplastic polymer as the filament. Graphite and PDMS were used to develop the electrodes and substrate of the sensor patches respectively. The electrodes were patterned in an interdigitated manner with the casting of graphite powder on the 3-D printed molds. The operating principle of the sensor patches is described along with the COMSOL simulation result which depicts the electric field density distribution between the two groups of electrode fingers of opposite polarity under an applied stress. The characterization and experimentation of sensor patches were done by analyzing the changes in their complex conductivities at different operating conditions. The highest bending radius of curvature achieved by the developed sensor patches is 6 mm. The sensor patches were then employed for strain-sensing purposes by attaching them on different parts of the body like finger, elbow, neck and knee. Strain sensing was successfully done based on the bending of the different joints on which the sensor patches were attached. The promising results shown by the sensor patches increase the chances of utilizing them in future in the biomedical world.

1. Introduction

The intervention of sensor applications in the real world has led to a huge impact on improving the quality of life. Nowadays, the usage of sensor and actuators is involved in every sector in some way to increase the efficiency of operation in terms of time and money. Not only in the environmental [1,2] and industrial [3–5] world, the biomedical world [6] have been a major sector where, starting from the physiological parameters of a person, different chronic diseases [7] are being monitored and diagnosed by the use of sensors. Around two decades back, semi-conductive sensors became commercialized in the market [8], but their potential applications were restricted by their size and cost. With time, researchers have been able to improve the quality of the existing sensors in terms of cost and the technique used for fabrication, input power, and working efficiency. Even though the miniaturization of the sensor sizes with microelectromechanical systems (MEMS) helped to achieve the above-mentioned attributes to some extent, there were certain distinct disadvantages related to them, encouraging of sensors with flexible materials [9] to be fabricated and implemented.

Along with the advantages of MEMS-based sensors, flexible sensors [10] have better electrical, mechanical and thermal properties than their counterpart rigid materials. The technique and raw materials used to develop a particular type of sensor depends largely on its application. Some of the common techniques used to develop flexible sensors are photolithography [11], screen printing [12], laser cutting [13]. But still these increase the overall cost of fabrication along with the requirement of expertise to fabricate them. One of the better ways to fabricate sensors with flexible substrates has been the use of 3-D printing where the initial mold can be printed with specified dimensions at very low cost, followed by their use to develop the patches. Another big advantage of using 3-D printing for fabrication purposes is the use of thermoplastic polymers to develop the templates. The high tensile strength, easy bendability, recyclability and high performance in terms of fatigue properties compared to metals [14] makes the thermoplastic polymers [15] cheaper and a favorable choice for 3-D printing purposes. This paper presents the use of the 3-D printing technique to develop molds, which was used as the template to develop the sensors by the casting method. The use of small quantities for fabrication, easy fabrication technique and possibility of generating flexible devices are some of the reasons for choosing the casting method.

The raw materials processed to develop the sensor patches depend on the cost, properties and availability of the materials. Some of the common materials used to develop the substrate

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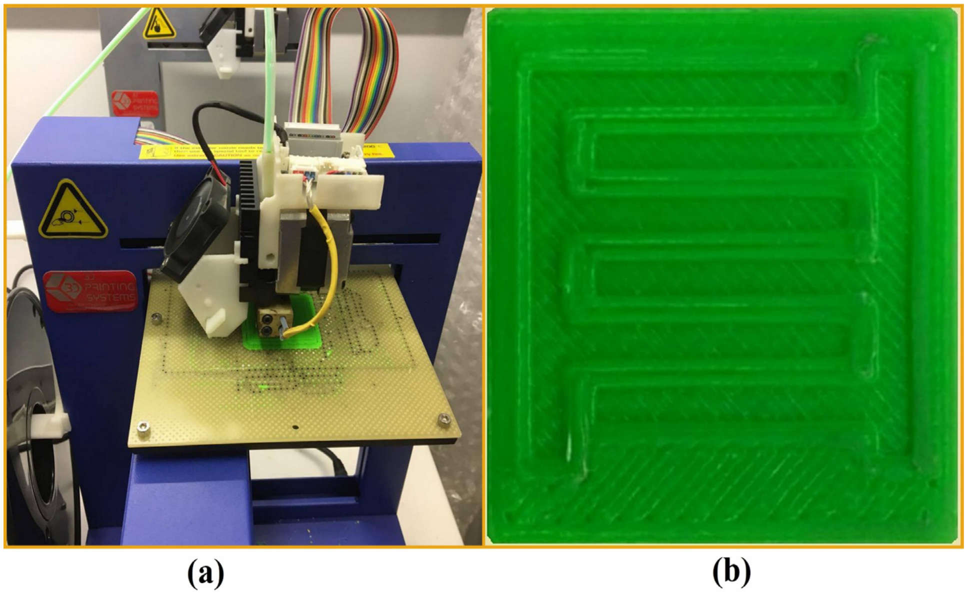

Fig. 1. The 3-D printing systems (a) were used to develop the molds (b) using the Acrylonitrile Butadiene Styrene as the printing filament. The height of the trenches on the mold was adjusted to 500 microns.

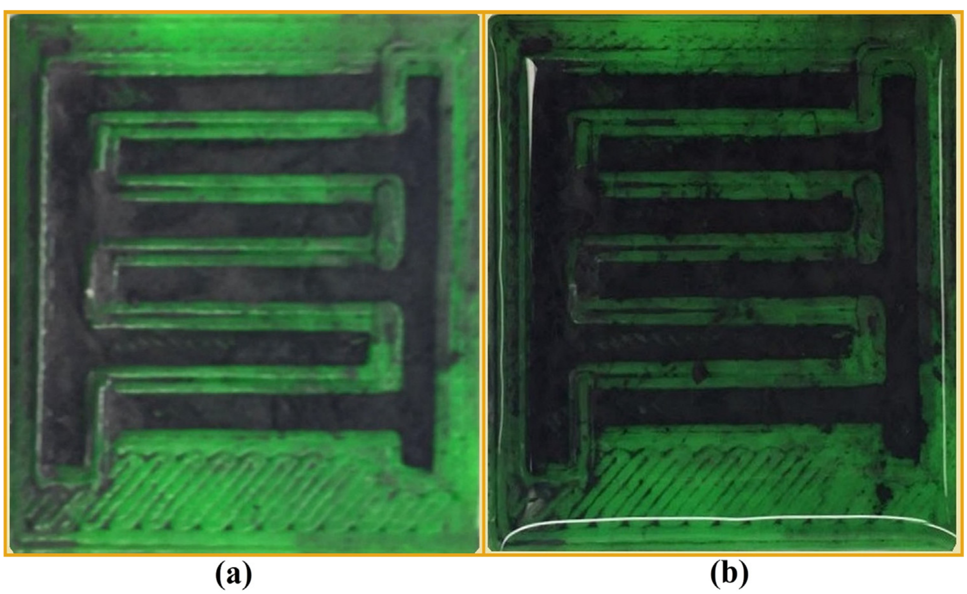

Fig. 2. Graphite powder was cast on the 3-D printed mold (a), followed by the casting of PDMS (b) on top of it. These two layers defined the electrodes and substrate of the sensor patches.

of the sensors are polydimethylsiloxane (PDMS) [16], polyethylene terephthalate (PET) [17], Polyimide (PI) [18], polyethylene naphthalate (PEN) [19] and Poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS) [20]. The differences between these polymers are based on their type, elastic nature, chemical properties and ability to form cross-linking with other materials. Some of the advantages of using PDMS over the other mentioned polymers are its low cost, high tensile strength, hydrophobicity and ability to form excellent interfacial bonding with added fillers [21]. Similar to the substrate materials, there are different conductive elements like gold [22], silver [23], Carbon Nanotubes (CNTs) [24], and carbon allotropes [25,26] to develop the electrodes of the sensor patches. Some of the allotropes of carbon used for fabrication purposes are graphite [27] and graphene [28]. Some of the advantages of graphite lie in its high compressive strength, high electrical and thermal conductivity and corrosion resistance. But the biggest advantage of graphite is its biocompatibility [29], which makes it a popular choice to develop devices for biomedical applications. This paper presents the utilization of PDMS and graphite powder to develop flexible sensor patches that were utilized for strain-sensing applications.

The utilization of sensors has held a pivotal role in the field of biomedical applications [30] for quite some time. Sensors developed with different materials have been characterized and implemented for various biomedical applications. There are some commercial pressure bending sensors that could be used as strain and pressure sensors as shown in Table 1 that are available commercially in the market. These types of sensors do provide a varied application in the field of biomedical applications, the fabrication cost, size of the sensors and the complexity in the nature of the sensors increases their overall prices. Strain sensing has been one of the popular choices of application where flexible electronics have been