Printed Temperature Sensor based on Graphene Oxide/PEDOT:PSS

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I. Summary And Motivation

Temperature is an important physical parameter which need to be monitored for various applications ranging from health monitoring to robotics [1, 2]. In humans, accurate measurement of the variations in the skin temperature is utilized for investigation of homeostasis, physical activities, cardiovascular health and several other health diagnostics methods [1-5]. For robotics, the integrated temperature sensing can help in distinguishing the hot and cold objects. Among a variety of temperature sensors (e.g. thermocouple, mercury thermometer etc.) the resistive method based temperature detection is widely used due to its rapid response, stability and accuracy [4, 6]. Various materials (e.g. semiconductors, metals, metal oxides and ceramics etc.) have been used to develop the temperature sensors [7-10]. However, owing to the complex processing steps along with the lack of flexibility, many times it is difficult to integrate these sensors on surfaces that can confirm to curvy body parts of a robot or prosthetic limb. In this context, printing technologies with simplified processing steps are aimed to provide low cost route for flexible/bendable sensors [11-14].

Here, we present a simple, cost effective and one step route for the fabrication of printed temperature sensors on flexible substrates. We have utilized conductive silver (Ag) paste as the contact electrodes, while the graphene oxide/poly(3,4-ethylenedioxythiophene): poly (styr-enesulfonate) (GO/PEDOT:PSS) composite was employed as to obtain the temperature sensitive layer. Owing to excellent adhesion and electrical performances with the flexible polyvinyl chloride (PVC), the Ag paste is an excellent conductive material for presented material [11]. The biocompatibility, insulating nature and presence of functional groups in GO also allow the strong functionalization of conducting and temperature dependent PEDOT:PSS [15, 16]. The correlation of microstructural changes in PEDOT:PSS with the physical and electrical properties is discussed in detail [16]. The effect of variation in temperature from room temperature (RT) to 100 ºC was systematically investigated by measuring the variation in resistance across the sensing GO/PEDOT:PSS layer. The fabricated temperature sensor demonstrates ~ 57% decrement in resistance along with a sensitivity of 7 Ω/ºC (0.8 % per ºC) at 100 ºC from RT.

II. Advances over Previous Works

Temperature sensing is an extensively explored research area and a wide variety of fabrication methods and materials have been reported for the fabrication of temperature sensors [3, 4, 6-8]. Common techniques used for the fabrication of temperature sensor involves photo-lithography processes followed by vacuum deposition of materials and etching, which leads to large amount material wastage and thus increases the fabrication cost [17]. Most of the times, the complex processing and higher temperature requirements are not suitable with flexible substrates [11-14, 17]. In this context, utilizing printing process is advantageous and suitable for the fabrication of flexible and wearable devices and systems over large areas at reduced cost [11-14]. As compared with the literature, the

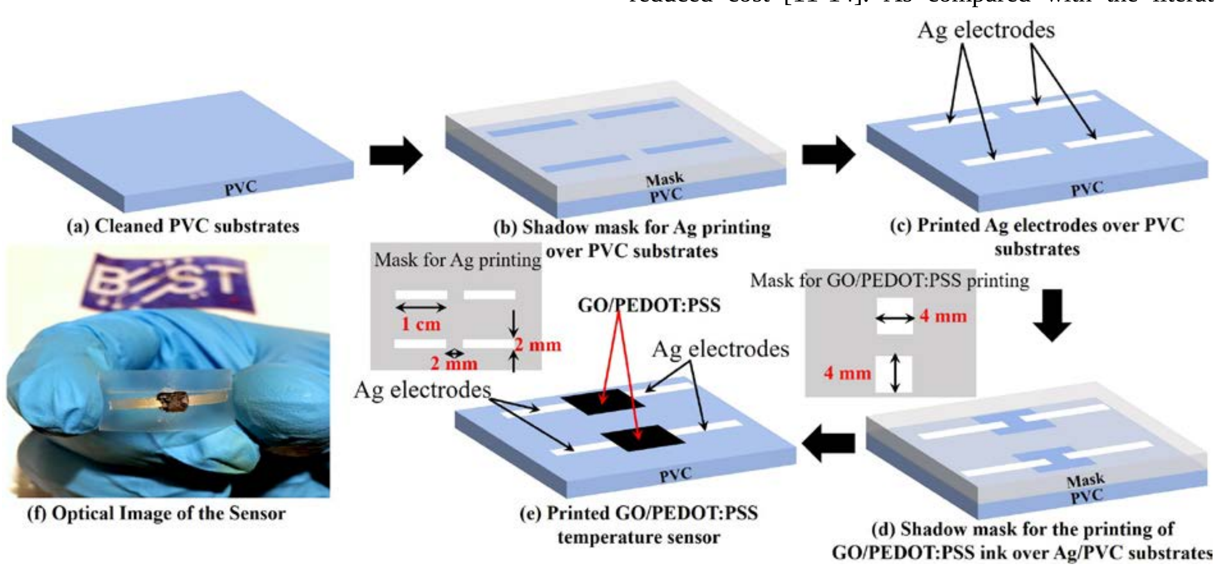

Fig. 1: (a) – (e) The process flow for fabrication of printed GO/PEDOT:PSS based temperature sensor; (f) Image of fabricated temperature sensor.

sensitivity of the sensor in the present study is considerably higher (> 25 %) with the previous reports in the literature and summarized in Table I [3, 18, 19]. The enhanced sensitivity evidently reveal the potential of the sensor for large area wearable electronics applications.

TABLE I. PERFORMANCE COMPARISON FOR FLEXIBLE TEMPERATURE SENSORS

Sensitive Material	*Temp. Range (ºC)*	*% Sensitivity (ºC^{-1})*	*Ref.*
Reduced GO	30 – 100	0.6	[3]
Carbon Nanotube	21 – 80	0.25	[18]
Silver	20 – 60	0.2	[19]
GO/PEDOT:PSS	RT – 100	0.8	**This Work**

III. RESULTS AND METHODOLOGY

A. Materials: The Ag conductive ink (186-3600) and PEDOT:PSS was purchased from RS components and Merck, UK respectively.

B. Fabrication: The steps followed for the fabrication of printed GO/PEDOT:PSS temperature sensor are illustrated in Fig.1. The PVC substrates (1.5 cm × 1.5 cm) were cleaned by ultrasonication in methanol, IPA, de-ionized water (resistivity 15 MΩm) for 5 minutes each, followed by N_2 dry and dehydration bake on a hot plate at 100ºC for 10 min. The Ag conductive ink was printed on the desired location on the PVC substrates with the help of a shadow mask (Fig. 1(b)) followed by drying at 50 ºC for 5 min (Fig. 1(c)). The dimension of each Ag electrodes were 1cm in length and 2 mm in width, with the separation of 2 mm. The GO powder was synthesized using modified Hummers method, as described in [15, 20]. The GO powder at a concentration of 1 mg/ml was dispersed in DI water under mild sonication. Finally the GO dispersion and PEDOT:PSS in the ratio 1:1 was mixed under constant stirring at 700 rpm. Afterwards, the GO/PEDOT:PSS ink was printed over the Ag/PVC using a shadow mask of dimension 4 mm × 4mm, as shown in Fig. 1(d) and (e). The optical image of the fabricated temperature sensor is shown in Fig. 1 (f).

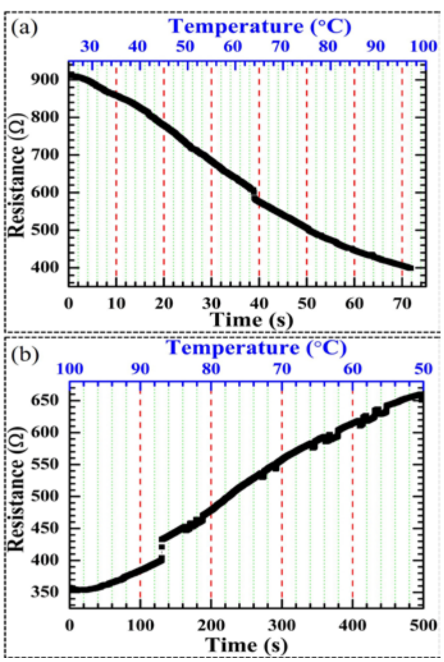

Fig. 2: (a) Influence of temperature from RT to 100 ºC on variation in resistance of printed GO/PEDOT:PSS sensor; (b) Response and recovery time of GO/PEDOT:PSS temperature from 100 ºC to 50 ºC.

C. Characterization: The change in the resistance of the sensor as a function of temperature was measured using a LabView controlled Agilent 34461A series multimeter. The temperature of the hot plate was calibrated using a high precision IR thermometer (FLUKE 62 MAX). During the measurement the temperature of the hotplate was raised from RT to 100 ºC. Fig. 2(a) shows the variation in resistance for the fabricated sensor over temperature and time. Initially, at RT, the resistance of the sensor was ~ 910 Ω (from Fig. 2(a)). On further increasing the temperature to around 35 ºC, the resistance was measured to be around 850 Ω corresponding to ~ 6.5 % change. On further increasing the temperature to 45 ºC, the equivalent resistance change was ~ 15 %. The temperature of the human skin varies depending on the ambient, location, and possible infections caused due to fever [2, 5]. For human health monitoring (such as homeostasis, physical and cardiovascular activities) the temperature range of 30 - 45 ºC is most important [2, 5]. Hence, the printed GO/PEDOT:PSS based sensor could be utilized for the human health monitoring applications. In addition, to check the feasibility of the sensor in hot environment, the temperature was further increased up to ~100 ºC, at which the resistance of the sensor decreased rapidly and approached to ~400 Ω, signifying ~57% decrement. The fabricated sensor exhibited a sensitivity of ~ 7Ω/ºC. Thus the printed sensors can be attached to a robotic hand to distinguish between hot and cold objects. Fig. 2(b) shows the response and recovery time of the sensor when temperature was decreased back from 100 ºC to 50 ºC. It can be seen from Fig. 2(b) that the sensor follows the same pattern in reverse direction.

IV. CONCLUSIONS

To summarize, printed temperature sensor using silver paste and GO/PEDOT:PSS as conductive electrodes and sensitive layer, respectively is presented in this paper. With resistance change of ~ 57% and sensitivity of 7Ω/ºC (0.8 % per ºC) for temperature varying from RT to 100 ºC, the sensor showed potential to be utilized for human health monitoring and prosthetic arms. The advantages of the present approach include facile, cost-effective, scalable fabrication and compatibility with e-skin. Future work will be directed towards the large area fabrication of the printed sensors and investigating the effects of compressive and tensile bending cycles.

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