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All Inkjet-Printed Temperature Sensors Based on PEDOT:PSS

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ABSTRACT This paper develops a simple, cost-effective, fully Inkjet-printed flexible temperature sensor with easy fabrication steps using PiXDRO LP50 inkjet printer. The thermistor sensor employed a Poly(3,4-ethylenedioxythiophene)-poly(styrene sulfonate) (PEDOT: PSS) as a temperature-sensitive layer with silver nanoparticles (AgNps) as a contact electrode. The sensor performance was evaluated on different dimensions and types of substrates. Epson Glossy paper with 255 μm thickness and Polyimide (Kapton HN) with 50 μm thickness were used over temperatures ranging from room temperature up to 50 °C and 90 °C for paper and Kapton substrates, respectively. The sensor developed over Glossy paper showed the best sensitivity of -1.67 %/°C in the chosen temperature range while the sensor showed $+0.113$%/°C on PI substrate.

INDEX TERMS AgNP, inkjet printer, PEDOT:PSS, temperature sensor, thermistor.

I. INTRODUCTION

Monitoring body temperature is a vital parameter that gives insight into human health conditions and reflects physiological activities [1]. Conventional Temperature sensing usually involves rigid temperature detectors, such as thermometers. The main drawback of this approach is the inability to combine with curved surfaces including human bodies or animals [2]. In addition, it is not ideal for children because thermometers cannot be positioned easily under the arm as desired [2]. Moreover, Rigid temperature detectors cause discomfort when contacted with uneven surfaces. As a result, it is crucial to have a flexible and wearable temperature sensor that can directly contact the human body. Flexible sensors offer mechanical robustness, biocompatibility, multifunctionality, comfort and enable next-generation wearable technologies [1]. Hence, rapid advances in the development and enhancement of flexible temperature sensors have emerged to replace the conventional sensors on a rigid substrate and provide a suitable solution for wearable applications [3]. There are various types of temperature sensors—resistive temperature detectors (RTDs) and Thermistors [4]. In RTDs, the temperature variation causes a change in the resistance of conductor material [1], [5], [6]. In contrast, the thermistors utilize the electric conductivity changes of a sensing material against temperature variation [7]. The main advantages of RTD temperature sensors are Low cost, good linearity, and a simple fabrication process [1], [6]. However, RTD's sensitivity is comparably low and has a slow response time. On the other hand, the thermistors are favorable due to their properties: highly accurate temperature measurements with great sensitivity, fast response, wide sensing range, and low cost [7], [8]. Thermistors have two types: the negative temperature coefficient (NTC) Thermistor and positive temperature coefficient (PTC). The resistance decreases with temperature in the NTC, while the resistance increases with resistance in PTC [1], [9].

The temperature coefficient of resistance (TCR), which represents the sensor's sensitivity, is the most studied parameter for all temperature sensors [6], [8]. As the TCR value increases, the sensor is susceptible to slight temperature variations [10]. The TCR is driven from Equation 1 [1], [5], [6], [8], [10].

$$\boldsymbol{TCR} = \boldsymbol{\alpha} = \left(\frac{\boldsymbol{R1} - \boldsymbol{R_o}}{\boldsymbol{R_o}(\boldsymbol{T_1} - \boldsymbol{T_o})}\right) \quad (1)$$

where, $\boldsymbol{R_0}$ is the initial resistance of the tested sample at a temperature $\boldsymbol{T_o}[°\boldsymbol{C}]$, and $\boldsymbol{R_1}$ is the resistance of the thermistor at absolute temperature $\boldsymbol{T_1}[°\boldsymbol{C}]$. The most common technologies utilized to fabricate flexible and wearable sensors are

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Photolithography and printing [11]. Photolithography manufactures reproducible, high-performance devices. However, unfortunately, the attractive attributes of these techniques come at a high financial cost because of the need for clean-room facilities, massive material wastage, and high fabrication cost [11], [12]. Thus, there is a need for inexpensive printing techniques with significantly lower fabrication costs and higher producibility to be affordable and easy to use. Inkjet printing has overcome the need for a stencil mask or clean-room lithography [13]. It offers accurate and continuous deposition of micro and nanomaterials into various substrates at ambient conditions [14]. Additionally, inkjet provides simple, variable print patterns with high resolution and low material consumption and cost reduction [11], [14].

Nowadays, printed thermistor temperature sensors grabbed the attention of massive researchers. In [15], Sahatiya *et al.* have developed a wearable temperature sensor and infrared (IR) photodetector on flexible polyimide (PI) substrate. Solar exfoliated reduced graphene oxide (SrGO) and graphene flakes were used as the sensing materials. Sensor performance is measured from 35 °C to 45 °C and exhibited −0.413 %/°C when using graphene flake and -0.74 %°C^{-1} for SrGO. Vuorinen *et al.* fabricated a temperature sensor dedicated to human body temperature measurements [16]. The sensor was evaluated in the human body temperature range from 34 °C to 44 °C, and the sensitivity was evaluated as 0.047 % /°C.

Maslik *et al.* in [17] fabricated an inkjet-printed temperature sensor consisting of Silver conductive Electrode pads and PEDOT:PSS printed on photo paper Epson Glossy, 225 g/m2 (PP) and reached a sensitivity of −0.03% /°C in 22°C to −10°C temperature range. Hsiao *et al.* [7] used inkjet printing technology to print NiO sensing layer between two parallel silver electrodes. The sensor was measured at 15°C - 80°C temperature variation and showed a good temperature sensitivity. Another sensor was introduced by Soni *et al.* [12], who utilized conductive silver as contact electrodes. At the same time, the (GO/PEDOT:PSS) composite was used to obtain the temperature-sensitive layer. The sensor was deposited on PVC substrate. The result of the sensor showed a sensitivity of −0.8 %/°C in the 25°C to 100°C temperature range [6]. Afterward, the latest researcher fabricated another sensor using the same materials on PI substrate instead of PVC [18]. The results showed that the sensitivity was increased to −1.09% /°C in the same temperature range. These results ensure that the substrates have a massive impact on the sensor performance. In [19], Ozioko *et al.* fabricated a temperature sensor with PEDOT: PSS and carbon nanotube (CNT) as a temperature sensing layer and AU contact electrodes. They achieved a sensitivity of 0.64%°/°C in the 20°C to 80°C temperature range. Nuthalapati *et al.* [3] fabricated rGO-Pd nanocomposite sensors array on flexible Kapton substrate and obtained −0.203 %/°C temperature sensitivity from −40.15°C to 99.85 °C temperature range. Kuzubasoglu *et al.* [10] used the inkjet printing technique to print conductive patterns using temperature-sensitive (MWCNT) ink on the fabric surface for high-precision reading in temperature sensing applications. The sensitivity of the sensor was evaluated in the temperature varying from room temperature to 50 °C and reached −1.04%/°C Sensitivity. The latest researcher also developed a temperature sensor based on specially formulated carbon nanotube (CNT) and (PEDOT:PSS) which are deposited onto the adhesive polyamide-based taffeta fabric [20]. The sensor exhibits a sensitivity of −0.31 % /°C in temperatures varying from room temperature to 50 °C.

This work introduces a full inkjet flexible, highly sensitive, and Low-cost thermistor temperature sensor that can be attached to the human body for continuous monitoring of body temperature. The proposed thermistor sensor was fabricated on two different flexible substrates at room temperature following easy fabrication steps. The proposed sensor composes of silver nanoparticles Electrodes and PEDOT:PSS as the sensing material. The proposed sensor was characterized and showed high sensitivity and linear resistance behavior for both substrates over the tested temperature ranges. The paper is organized as follows: Section II discusses the experimental procedures including the materials used to fabricate the sensors, the fabrication process in detail- starting from the synthesis, printing to the thermal curing- and the characterization setup we utilized to evaluate the performance of printed temperature sensors in the range of 28–50°C and 28–90°C on paper and Kapton, respectively. In the following section, we present and discuss the results and analyze the effect of different substrates and dimensions. Finally, we conclude our work and advise the future work.

II. EXPERIMENTAL PROCEDURES

A. MATERIALS

PEDOT:PSS conductive Inkjet Ink (Product No. 739316), from Sigma-Aldrich Chemical Company, was used as a temperature sensing layer in the thermistor sensor. To print the contact electrodes, a silver nanoparticle (AgNP) was purchased from Novacentrix (Product no. Metalon® JS-A102A). Both Inks were used without any further processing or synthesis. Materials with a viscosity of 10-12 cPs [14], surface tension 28-30 dynes/cm, and sub-micron particle size are ideal for inkjet printers [21]. Two types of substrates were utilized to fabricate the temperature sensor. The first substrate was Premium Glossy photo paper (Paperweight: 255 g/m2, Thickness:255μm) from (Epson, Japan). The second one was Kapton® HPP-ST (50 μm thick) from DuPont^{TM} (Wilmington, Delaware, USA).

B. SUBSTRATE AND INK PREPRATION

The Substrates were first cut into small pieces. For Epson photo paper, no pre-treatment is necessary. In fact, treating it with water or any solvent will change the property of the photo paper. The PI (Kapton) substrates were cleaned by immersing them in an IPA (Isopropanol) for five minutes. Then, they were sonicated for ten minutes in the sonication bath. Finally, the cleaned PI thin films were rinsed with deionized water and dried on a hot plate. After cleaning, the substrates were stored in a box to protect them from dust until the Inkjet deposition step. The AgNP Ink was first sonicated for 10 minutes to avoid nozzle clogging. Then, it was extracted and filtered using hydrophilic filter to get rid of any large particles. Finally, it was placed on the magnetic stirrer with a hot plate for 30 mins with a temperature of 80°C and stirring of 300 rpm. Similarly, the same steps were followed to prepare the PEDOT: PSS Ink with a temperature of 50°C and stirring of 350 rpm.

C. TEMPERATURE SENSORS FABRICATION

An Inkjet printer Drop-on-demand (DoD) PiXDRO LP50 with Dimatix DM/°C1610 cartridges (10 pL drop sizes and 20 μm Diameter) was used to print the sensing and electrode materials onto the substrates. The Temperature sensor design consists of two conductive electrodes and a thin PEDOT:PSS used as a temperature sensing layer. Two different designs with different dimensions were fabricated to investigate the effect of the dimension on the sensor sensitivity. The first temperature sensor (TS1) has two electrode pads with sizes 2×2 mm and 5 mm gap. In comparison, the second one (TS2) is a larger sensor with a pads size of 3×2 mm and a 6 mm gap. The PEDOT: PSS layer is printed between the two electrodes at 1×8 mm and 2×9 mm, respectively, as clearly indicated in Fig 1.a. The structure of the temperature sensor on either PI or paper substrates is shown in Fig 1.b.

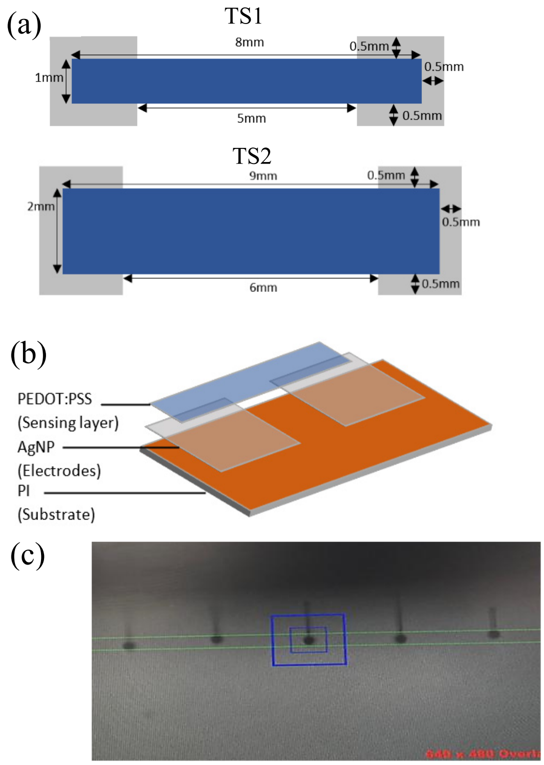

FIGURE 1. **a) Two thermistor dimensions implemented in this study TS1 and TS2 b) The structure of the thermistor printed either on paper or PI substrates c) Snapshot is taken from HMI tool for the droplets jetted from the nozzles.**

Before printing, the printhead was cleaned using an ultra-sonicator to ensure that no nozzles were blocked. The inkjet printing parameters were optimized to achieve a consistent droplet formation and homogenous printing. First, the inkjet printer plate temperature was set carefully to achieve good ink adhesion without causing any damage to the substrate. The optimum printing temperature for the Glossy paper substrate was 25°C which is room temperature. Experimentally, the substrate edges start to be bent for temperatures greater than room temperature. For Kapton substrate, the optimum printing temperature was 60°C to achieve better Ink adhesion. But increasing plate temperature beyond 50°C will speed up the evaporation of solvent from the nozzles and can cause deformation in the printed pattern. The jetting frequency was set to 1000 Hz, the number of Active nozzles was 16, and the resolution was 2000 dpi resulting in good printing continuity and resolution. The time of flight (TOF) was carefully studied and considered using the drop view in LP50 Human Machine Interface (HMI) tool. Time of flight controls the drop placement accuracy and increases the legibility of printed patterns. Moreover, it ensures synchronization jetting from all nozzles, as shown in Fig.1.c.

A single layer of AgNP is printed and cured at 140°C for 10 mins to form a highly conductive and continuous contact electrode. Then, three printing cycles were executed to produce a continuous PEDOT:PSS sensing layer followed by curing at 120°C for 10 mins as shown in fig.2.a. A photograph of the printed sensors on Epson paper and PI substrates

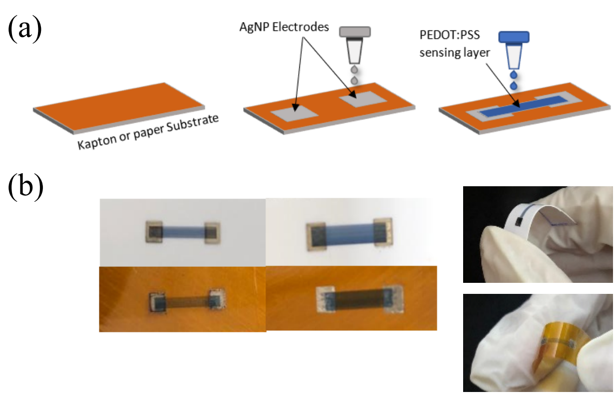

FIGURE 2. **a) Fabrication process of thermistor sensor based on Inkjet technology. b) Photograph of printed thermistors with different dimensions on both Kapton and paper substrates.**

are shown in fig.2.b. Figure 3 is a snapshot taken from the Printview camera showing the printed layers for both AgNP and PEDOT:PSS.

D. CHARACTERIZATION SETUP

The temperature sensors' response was characterized based on two-wire resistance measurement. A resistance measurement setup is prepared to record the resistance's variation with the temperature. The setup consists of a digital hot plate (Velp Scientifica^{TM} AREC) and Digital Multimeter

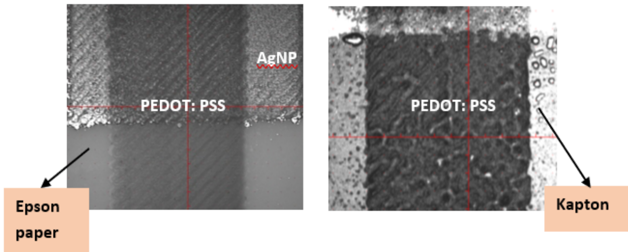

FIGURE 3. **Printview camera showing the printed layers.**

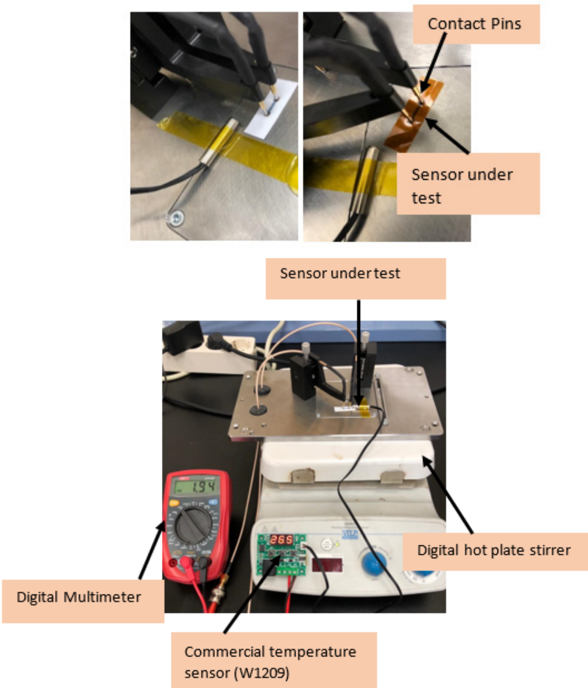

FIGURE 4. **Photographs show the contact pin on both PI and paper substrates and the experimental setup.**

connected to the sensor through contact pins. A Commercial temperature sensor (W1209) is fixed to the hot plate surface to calibrate the temperature and display the exact substrate temperature. The sensitivity measurement for the temperature sensors was carried out by gradually increasing the temperature by 2°C from room temperature to 50°C and 90°C for paper and PI substrates, respectively. The experimental setup used during measurements is shown in Fig 4.

E. PRINTED PATTERN CHARACTERIZATION

The contact electrodes have been investigated via a Scanning Electron Microscope (SEM). Fig. 5 shows the micrographs of the Ag electrode. The figure confirms that the average particle size is 30-50 nm, as indicated in the datasheet [22]. Also, the Ag nanoparticles are well bonded with each other resulting in good electric conductivity.

III. RESULTS AND DISCUSSION

The temperature sensors were measured over the temperature range of 28–50 °C and 28–90 °C for paper and Kapton

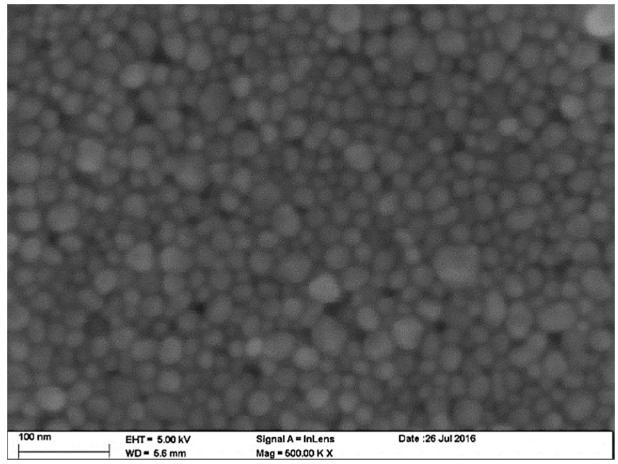

FIGURE 5. **SEM image of the silver contact electrode.**

substrates, respectively. Two samples were printed from each sensor TS1 and TS2, with the same design procedures and environmental conditions. Fig. 6 represents the Linear fit calibration curve of the Relative resistance change of the sensors against temperature. The TS1 and TS2 on paper substrate exhibit an NTC response where the resistance decrease as the temperature increases. On the other hand, the results of TS1 and TS2 on PI substrate show PTC response due to the influence of changing the substrate. The results show that the samples made with the same design exhibit equal TCR values. Furthermore, all the sensors had very good linearity in the tested temperature ranges as shown in Fig. 6. In addition, Fig. 6.a and 6.b includes the response of two different dimensions (TS1 and TS2) printed on Epson paper substrate. Likewise, Fig. 6.c and 6.d includes the response (TS1 and TS2) printed on PI substrate. As can be deduced from the figures, varying the sensor dimension doesn't contribute to the sensitivity enhancement. In addition, a minimum difference is observed between TS1 and TS2 in terms of sensitivity. On the other hand, varying the substrate affects the sensor response. Furthermore, the standard deviation of the mean is depicted in these measurements using the error bars indicating the probable range for the true mean that is represented by each data point.

The sensitivity and TCR values were obtained from equation (1) and are summarized in Table 1. It can be concluded that TS1 on photo paper Epson Glossy substrate gives the highest temperature sensitivity (−1.67%/°C) among all fabricated sensors and good linearity. This is possibly due to the content of the paper coating because of its strong influence on the resistivity of Ag nano-particle inks [17]. While the sensor exhibited lower sensitivity when fabricated on PI substrate.

The reproducibility of the printed sensors has also been characterized based on the Resistance -Temperature curves of five devices fabricated following the same procedures and exposed to the same environmental condition. As shown in Fig. 7, all these sensors exhibited a similar Sensitivity

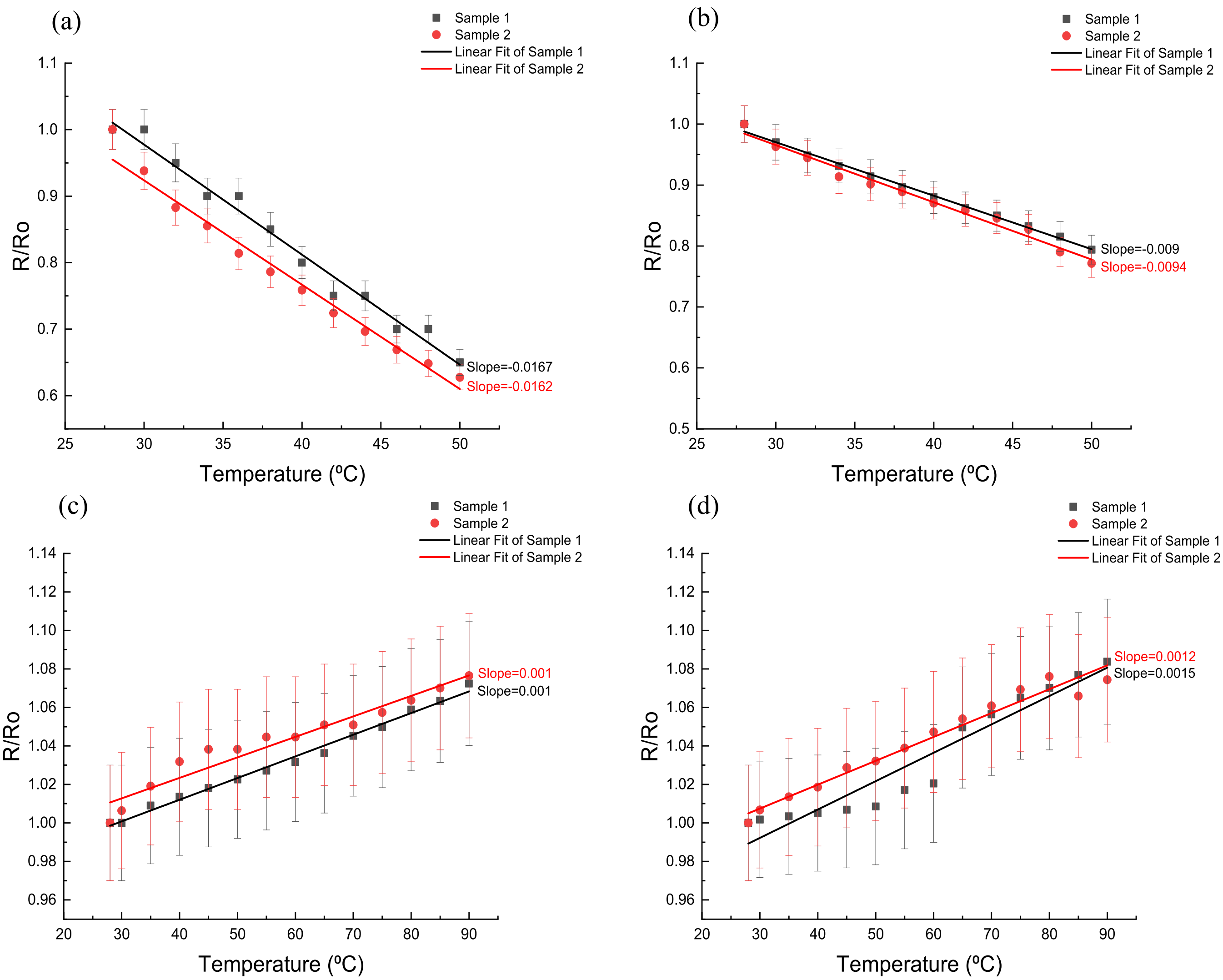

FIGURE 6. **Response of the sensors to temperature change. a) TS1 paper sensor response in range of 28–50 °C. b) TS2 paper sensor response in range of 28–50 °C. c) TS1 Kapton sensor response in range of 28–90 °C. d) TS2 Kapton sensor response in range of 28-90 °C.**

TABLE 1. **TCR value of all tested sensors.**

Sensor Type	Temperature range	TCR
Sensor TS1 on Paper	*28–50 ºC*	*-1.67 % /ºC*
Sensor TS2 on Paper	*28–50 ºC*	*-0.94%/ºC*
Sensor TS1 on Kapton	*28–90 ºC*	*+0.113%/ºC*
Sensor TS2 on Kapton	*28–90 ºC*	*+0.15 %/ºC*

performance with a slight change in TCR of 0.27 %/°C on Epson paper (Fig.7.a) and 0.01%/°C on PI (Fig.7.b), which indicated the good reproducibility of our printed sensors. These results confirm the reliability of PI, which had minimum TCR change among all the fabricated sensors when compared to the Epson paper. Furthermore, the prepared sensor was measured for 30 days to investigate its durability. Measurements show a slight sensitivity decrease of 0.2%/°C. The sensor exhibits high durability for temperature sensing between 28 and 50 °C.

Possible side effects on human beings should be avoided. As a prophylactic measure, the AgNP is kept away from human skin, and only the PI (which is chemically inert) has direct contact with the human body, causing no side effects. This contributes that the sensor fully satisfies the requirements of real-time and long-term temperature monitoring. Despite that the proposed sensor on PI substrate didn't have the best performance in terms of sensitivity, it offers flexibility, lightweight, and excellent reliability. Also, it was proven it has good reproducibility and is feasible to upgrade to mass production. Additionally, PI substrate has high-temperature sustainability and conformability, making it a suitable choice for Temperature sensing applications [14]. This makes the PI-based sensor promising to be used in human body temperature monitoring.

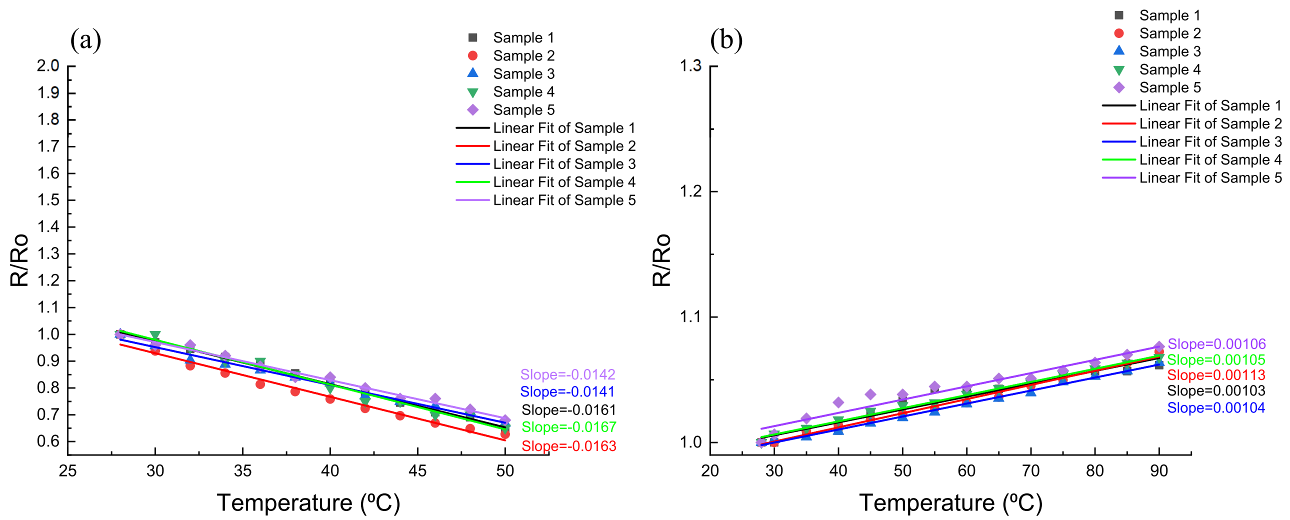

FIGURE 7. Relative resistance change with respect to temperature of 5 printed temperature sensors fabricated on the same environmental conditions. a) Five TS1 sensors on Epson paper substrate. b) Five TS1 sensors on PI substrate.

TABLE 2. Performance comparison for the temperature sensors.

Sensing material	Electrode's material	Substrate	Temperature range	Sensitivity (%/ºC)	Ref
SrGO	*CU*	*Polyimide (PI)*	*35-45ºC*	*−0.74*	*[15]*
PEDOT:PSS	*AgNP*	*Photo paper Epson Glossy*	*-20-10ºC*	*-0.03*	*[17]*
GO/PEDOT: PSS	*Ag*	*PVC*	*25-100ºC*	*-0.8*	*[12]*
GO/PEDOT: PSS	*Ag*	*Polyimide (PI)*	*25-100ºC*	*1.09*	*[18]*
CNT/PEDOT: PSS	*AU*	*PVC*	*20-80ºC*	*0.64*	*[19]*
MWCNT	-	*Taffeta fabric*	*25-50ºC*	*-1.04*	*[10]*
CNT/PEDOT: PSS	-	*polyamide -based taffeta fabric*	*25-50ºC*	*-0.31*	*[22]*
PEDOT:PSS	*AgNP*	*Polyimide (PI)*	*28-90ºC*	*0.113*	*This work*
PEDOT:PSS	*AgNP*	*Photo paper Epson Glossy*	*28-50ºC*	*-1.67*	*This work*

On the contrary, printed sensors on the paper substrate are ideal because it is cost-effective, environmentally friendly, and recyclable. The Unit cost of the Epson paper-based sensor was about 6.6478 Cents, while the PI-based was 17.8621 Cents. Consequently, utilizing the paper is advantageous and suitable for fabricating disposable low-cost Temperature sensors. In comparison, 50 μm PI foil has better conformability and wearability. Also, PI has a highly hydrophobic surface giving it stability against humidity and body sweat.

Table 2 shows a comparison between the fabricated temperature sensor with other sensors reported in the literature. This comparison shows that the proposed sensor on Glossy paper substrate provides better sensitivity than the previously fabricated sensors. It exhibits a high sensitivity and stable readings at a temperature range from 28 to 50°C. These results indicate that the proposed sensor can be used in wearable human body temperature reading.

IV. CONCLUSION

In this work, fully Inkjet temperature sensors were fabricated on two different substrates. The sensor consisted of silver conductive electrodes and a PEDOT:PSS sensitive layer deposited on 50μm thick Kapton substrate and Glossy photo paper. The sensors were characterized for resistance change against temperature. The achieved sensitivities for TS1 and TS2 on the paper substrate were (−1.67%/°C) and (−0.94%/°C), respectively, for a temperature range of 28–50 °C. The results were investigated for sensors on Kapton substrate, which showed (0.113%/°C) and (0.149%/°C) for TS1 and TS2, respectively, in the range of 28–90 °C. The Photo paper substrate was found to give the highest temperature sensitivity. Both sensors showed potential to be utilized for human body temperature monitoring. The advantages of the present approach include an easy, cost-effective fabrication process. Future work includes enhancing the temperature sensor performance.

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