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Highly sensitive interdigitated thermistor based on PEDOT:PSS for human body temperature monitoring

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Abstract

This work introduces a wearable, highly sensitive human body temperature sensor. The proposed thermistor sensor employs a poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) as a temperature sensing layer and interdigitated electrodes (IDEs) from Silver nanoparticles deposited on Polyimide (PI) and Epson glossy paper substrates. The IDEs were patterned using inkjet printer Drop-on-demand PiXDRO LP50. The PEDOT:PSS layer was added by drop casting technique. The sensitivity of fabricated sensors was tested for different IDE number of fingers to investigate their response to the temperature range of 28–50 °C. The sensors performed linearly in the tested temperature range. Repeatability has been verified for five temperature measurement cycles. The achieved sensitivities are −1.462% /°C and −3.202%/°C for Epson paper and PI substrates, respectively. The sensor bendability results highlight the capability of the proposed sensor to be utilized for the wearable human body temperature reading.

1. Introduction

Human body temperature monitoring is crucial due to its importance in detecting human health. Abnormal body temperature might be a symptom of illness [1–3]. Consequently, it is vital to utilize real-time and accurate temperature sensors to detect the human body temperature [1, 2]. Traditionally, temperature measuring instruments have been used because of their high performance. However, they are expensive, difficult to carry, and unpractical because they cannot be attached to the patient's skin during movement [1]. Moreover, their hard nature makes them incompatible with being used in new-borns [2]. On the other hand, developing wearable, flexible, portable, and Real-time temperature sensors are required to overcome these limitations [2, 4]. Wearable sensors offer conformability without irritating the patient's natural motion [3]. There are different types of temperature sensors. Resistance temperature detectors (RTDs) and thermistors are the most commonly studied and used. Both sensors rely on the change of the electrical resistance with temperature [3] and are perfect for batch production because they are simple to manufacture and have reduced costs [5]. Thermistors offer high sensitivity and faster response to temperature variations when compared to RTDs [6]. Thermistors are either positive temperature coefficient materials or negative temperature coefficient (NTC materials) [3, 6]. In contrast, RTD sensors are utilized in many applications which require high linearity [3], simple fabrication steps, and ease of mass production [7].

Different printing technologies have been considered for fabricating flexible temperature sensors [6]. Printing has effectively replaced traditional manufacturing techniques such as photolithography [8]. Photolithography has many disadvantages such as multiple device manufacturing procedures [6, 8], high-cost equipment especially the masks [8], and environmental unfriendly material waste [6, 8]. Instead, printing technologies offer speed and accurate deposition of a wide range of functional materials [8]. Printing methods differ from conventional manufacturing techniques because of the reduced material waste by controlled material deposition on demand at specified locations. As printing is done in a single step as against the numerous steps involved in clean room processes that use several procedures for patterning structures, the amount of resources wasted is reduced [5]. Among all printing technologies, inkjet printing is preferred because it eliminates the need for expensive masks, resulting in a cost-effective fabrication technique [8]. Additionally, inkjet printing is a precise and rapid technology [1] used to print micro and nanomaterials in different designs and patterns [8]. It also has a high printing resolution of 2880 dpi to obtain a continuous structure [4]. The material selection is the critical parameter for fabricating a highly sensitive temperature sensor [5, 6]. The thermistor design is based on an Electrode and a temperature sensing layer on top of it. The electrode patterning is usually done using metal nanoparticles [1, 6]. Silver nanoparticles (AgNPs)-based ink is preferable because it has the highest electrical conductivity [3]. In addition, silver has relatively acceptable costs compared to other metal nanoparticles [8]. The sensing layer directly affects the sensor's response to temperature and thus controls the sensor's sensitivity [1]. Therefore, it should be highly conductive, low cost, and have excellent performance with temperature [1]. Polymers are commonly used as temperature sensing layers. Among these polymers, Poly (3,4-ethylene dioxythiophene)-poly (styrene sulfonate) (PEDOT: PSS) features good mechanical flexibility [1], high conductivity [1, 4], easy processing [5], low cost [1], and environmental friendly [3] making it a perfect choice for temperature sensing [1, 6]. The strong mechanical properties of PEDOT-PSS make it a great choice for wearable applications because it maintains a strong bond with substrates even when bent at extremely small deflection angles [5]. To achieve flexible sensors, highly flexible substrates should be utilized. Paper substrate has been used for printed electronics because of its low cost, flexibility, and environmental safety [4]. The main drawbacks of paper are that it cannot withstand heating to high temperatures [6], and its low moisture resistance [4]. Although some temperature applications might not require a high operating temperature, most metal nanoparticle inks require thermal annealing to remove the protecting agents and achieve a higher conductive structure [4, 8]. This might prohibit the utilization of paper substrates in wearable electronics. Hence, polymer substrates have been considered to overcome these limitations. Polyimide (PI) commercially named Kapton [6] is the perfect solution for flexible temperature sensors. PI exhibits high resistance against heat and solvents [1, 4, 9], no electrical conductivity [1], high flexibility [4, 9] as well as solid adhesion to metal coatings [3]. It should be considered that the materials should not pose any health or medical risks because they are directly attached to the human skin [5].

Various measurements and characterizations should be considered when evaluating the human body temperature sensor. The most critical parameter is the temperature coefficient of resistance (TCR). It represents the rate of relative resistance change under static conditions to the corresponding temperature change [1, 3]. As the sensor's sensitivity is the slope of this curve, TCR equals sensitivity if the relationship is linear [1, 7]. The higher the TCR value, the higher the ability of the sensor to capture relatively small temperature changes [3]. The sensitivity of the sensor (TCR) is defined using equation (1) [1, 3, 7, 10, 11]:

$$\boldsymbol{TCR} = \alpha = \left(\frac{\boldsymbol{R}1 - \boldsymbol{R_o}}{\boldsymbol{R_o}\,(\boldsymbol{T}_1 - \boldsymbol{T_o})}\right) \tag{1}$$

where $R1$ is the material's resistance at temperature $T1$, Ro is the initial resistance at room temperature To.

The response and recovery time are other essential performance parameters. The response time is defined as the time required to move from the initial resistance at room temperature to 90% of the peak response resistance [1, 12]. In contrast, the recovery time is the time required to move from the peak response resistance to 10% over the initial resistance at room temperature [12]. These parameters indicate the ability of the sensor to rapidly respond to the temperature change whenever it is exposed to human skin. Other critical sensor parameters are repeatability and durability. Repeatability measures the response fluctuations when the same sensor is measured multiple times in the same temperature range and under the same working conditions [1]. The ideal sensor shall pose minimum fluctuations and consistently perform different temperature cyclic tests. Durability means the ability of the sensor to provide stable readings for a long time under the same environmental conditions [1]. It is also demanding to have high linearity in the sensor response. The linearity is the degree of deviation between the actual readings and the points forming the fitting curve usually expressed as a percentage [1]. The human temperature sensor should have a high sensitivity, fast response time, good durability, repeatability, and long-time stability to ensure real-time and long-term useful measures [1, 7, 13]. Moreover, the human-body sensor should operate well in a temperature range from 25 to 40 °C [5, 7]. Nevertheless, the sensor owes to have flexibility, lightweight, and bendability [7] to be attached to the human body without causing any discomfort or irritation.

Wearable and flexible temperature sensors have been explored extensively by researchers. Wang *et al* [12]. Developed a temperature sensor based on PEDOT:PSS for enhancing humidity stability by adding the crosslinker of (3-glycidyloxypropyl)trimethoxysilane (GOPS) combined with fluorinated polymer passivation (CYTOP). The sensor exhibits a high-TCR (TCR=−0.77%/°C) at a wide temperature range from 25 °C to 50 °C. Liu *et al* [13] reported a skin-attachable flexible temperature sensor on PI substrate, which incorporated polyethyleneimine (PEI) and reduced graphene oxide (rGO) as the adhesive and temperature sensing material for measuring temperatures from 25 to 45 °C with a sensitivity of 1.30%/°C. Maslik *et al* [14] presented inkjet—printed temperature sensor composed of silver conductive electrode pads and PEDOT:PSS sensing layer printed on a paper substrate. The sensor was evaluated in the range of 22 °C to −10 °C and TCR was measured to be −0.03%/°C. Rivadeneyra *et al* [15] proposed a full inkjet-printed PEDOT:PSS that is electrically contacted by an interdigitated electrode (IDE) on PET substrate. The sensor was tested in the temperature range of 20–70 °C. The sensitivity achieved was −0.8%/°C. Zhang and Cui [16] developed a wearable temperature sensor by printing PEDOT: PSS on a PI substrate. The sensor was capable of distinguishing the temperature change of 0.1 °C. The sensor has excellent bending properties that can be used for flexible and wearable applications. The results confirm the applicability of using PEDOT:PSS for producing a variety of temperature sensors because of its high sensing performance. Ali *et al* [17] fabricated a human body temperature sensor comprised of silver interdigital electrodes and a carbon black sensing layer and achieved a sensitivity of 0.375%/°C at a temperature range of 28–50 °C. Soni *et al* [18] fabricated a skin conformable flexible temperature sensor. The contact electrodes were silver printed using a shadow mask on PI substrate. The temperature-sensitive layer is made of GO/PEDOT:PSS. The sensor's response was observed over a temperature range from room temperature (25 °C) to 100 °C. The sensitivity was 1.09%/°C. Ozioko *et al* [19] utilized CNT/PEDOT:PSS polymer composite on PVC substrate using a simple drop-casting technique. The sensor showed a sensitivity of 0.64%/°C for temperatures varying from 20 °C to 80 °C. Jehn *et al* [20] presented CNT/PDMS-based temperature and strain sensor deposited on a PI substrate. The TCR was investigated upon varying the temperature in the range between 30 °C to 80 °C. The sensor exhibited −0.076%/°C in the tested temperature range. Kuzubasoglu *et al* [21] inkjet printed multi-walled carbon nanotube (MWCNT) based wearable temperature sensor on taffeta fabric. Prepared CNT-based ink was deposited on the substrate using a commercial desktop inkjet printer. The performance of the produced temperature sensor was evaluated in the temperatures range of room temperature to 50 °C. The obtained TCR was −1.04%/°C. An inkjet-printed CNT/PEDOT:PSS composite ink onto the adhesive polyamide-based taffeta fabric was introduced by the previous group [22]. The sensor exhibited a NTC behavior and sensitivity of −0.31%/°C for temperatures varying from room temperature to 50 °C. Gamil *et al* [23] constructed a temperature sensor based on graphene nanoplatelets (GNPs) using drop-casting on a PET substrate with an electrode made of platinum. The behavior of the sensor was examined by subjecting it to a temperature range from room temperature to 150 °C. The sensor had excellent linearity and its TCR was 0.14%/ °C. Another RTD temperature sensor made from Nickel on a flexible PI substrate using the screen-printing process was developed by Turkani *et al* [24]. The capability of the nickel sensor to respond to temperatures varying from −60 °C to 180 °C was investigated. The results demonstrated good linearity and TCR of 0.44%/°C. The latest group also fabricated a nickel-based RTD sensor but on a flexible ceramic platform [25]. The sensitivity was tested in temperatures varying from 25 °C to 200 °C and reached a value of 0.3%/°C. Thiyagarajan *et al* [26] fabricated an indium tin oxide (ITO) based temperature sensor with silver electrodes prepared using the screen-printing technique. The response of the sensor against varying temperatures between 30 °C to 50 °C was characterized. The calculated TCR value was −1.0877%/°C.

Herein, we present a highly sensitive wearable temperature sensor developed on both PI and Epson glossy paper. We employed inkjet printing for patterning the AgNPs as IDE structures, followed by drop-casting of PEDOT:PSS as the temperature sensing layer. The sensitivity of the fabricated sensors was studied for different electrode fingers and with respect to different substrates. The PEDOT:PSS-based sensors showed a NTC as well as linear resistance behavior at temperature range from 28 to 50 °C. The sensor was further exposed to a hot cup showing reliability with response and recovery time of 10 and 22 s, respectively. The sensor was also characterized in terms of flexibility, repeatability, and reproducibility. The paper is divided as follows: the materials and fabrication methods are given in section 2. This section covers all the information about the materials, fabrication process, and characterization setup. Followed by the results in section 3 which describes the results related to all the characterizations implemented on the sensors. Finally, the key outcomes and conclusion are summarized in section 4.

2. Materials and methods

2.1. Materials and substrates

AgNP conductive ink, specially designed for printed electronics, was purchased from NovaCentrix (PN: Metalon® JS-A102A) and used to produce IDE. The required viscosity and surface tension for inkjet printing is 10–12 cPs [5, 17, 27] and 28–30 dynes cm^{-1} [4, 28], respectively. The AgNPs ink from Novacentrix is specially developed for inkjet printing since it has a viscosity of 8–12 cPs and a surface tension of 19–30 dynes cm^{-1} [29]. A highly conductive aqueous solution of poly (3,4-ethylenedioxythiophene) doped with poly (styrene-sulfonic acid) (PEDOT:PSS, PH 1000) with a resistivity of 0.0012 Ω.cm is purchased from Ossila, UK [30], and filtered with (0.45 m Teflon filter) before use as temperature sensing layer and mixed with 5% DMSO purchased from Sigma Aldrich. All materials were used as received from the suppliers without any further synthesis or purification except the filtration. The filtration step is necessary to remove any large particles and hence avoid nozzle clogging. In this work, two flexible substrates were used to deposit the sensor onto them. A flexible Kapton® 200HPP-ST sheet (50 μm thick) from DuPont™ (Wilmington, Delaware, USA) was used as the first substrate. The Premium Glossy photo paper (Paper weight: 255 g m^{-2}, Thickness:255 μm) from (Epson, Japan) is the second substrate utilized in our work. The substrates are cleaned adequately with an IPA (Isopropanol), rinsed with DI water, and dried before printing.

2.2. Fabrication and characterization

The sensor design consists of IDE and PEDOT:PSS layer used as a temperature sensing layer. Two temperature sensor designs were studied in this work. We implemented eight and four electrode fingers in our sensor design and accordingly denoted 8 F and 4 F sensors, respectively, with 0.5 mm spacing and 0.2 mm finger width. Both designs are presented in figure 1.

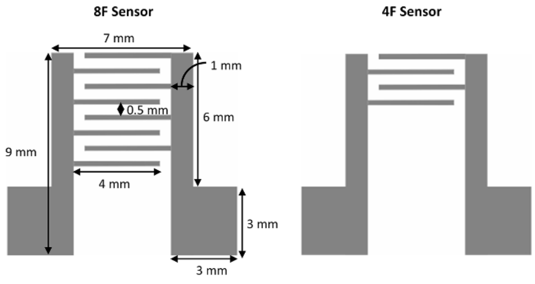
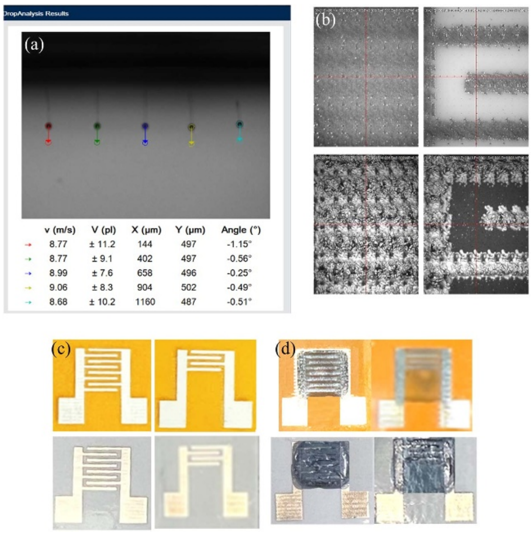


Figure 1. Two IDE designs: 8 F and 4 F temperature sensor.



	v (m/s)	V (pl)	X (μm)	Y (μm)	Angle (°)
→	8.77	± 11.2	144	497	-1.15°
→	8.77	± 9.1	402	497	-0.56°
→	8.99	± 7.6	658	496	-0.25°
→	9.06	± 8.3	904	502	-0.49°
→	8.68	± 10.2	1160	487	-0.51°

Figure 2. (a) Snapshot is taken from HMI tool for the speed of AgNP droplets jetted from the nozzles. (b) Snapshot taken from the print-view camera showing the interdigitated electrode on Epson paper (top view) and PI substrates (bottom view). (c) Photograph of printed IDE thermistors with different dimensions on both PI and paper substrates (d) with PEDOT:PSS drop-casted layer.

The inkjet printer PiXDRO LP50 with Dimatix DMC11610 cartridges (10 pL drop volume and 20 μm nozzle diameter) was used for the AgNP ink deposition as IDEs. The printing parameters were adjusted to platen temperature 50 °C, jetting frequency 1 kHz, and 16 active nozzles. The other parameters which depend on the ink properties were adjusted based on the outcomes of several printing trials with the ink such as jetting waveform, drop velocity (8.8 mm s^{-1}), and time of flight as shown in figure 2(a). To increase the electrical conductivity, two printing cycles were executed to increase the thickness of the Ag conductive Ink. The thermal curing of the printed silver electrode was done following the printing process at 140 °C for 10 min as recommended by the ink supplier. After this step, a highly conductive and continuous structure was obtained. Usually, the nanoparticle-printed inks require post-print treatment known as thermal sintering to remove the solvents from the ink [3, 4]. The sintering improves the conductivity and morphology of the printed ink [4]. To achieve this, the substrate must have thermal stability to high temperatures needed during the sintering process. The properties of the substrate such as the inks' dimensions, colour, and adhesion should not change at very high sintering temperatures [4]. The electrodes' fingers are uniformly deposited and there are not any short circuits between them as seen in figure 2(c). A closer and clearer image has been taken using the print-view camera in figure 2(b) and the snapshots confirm line continuity and homogenous printing. The PEDOT:PSS sensing layer is then drop-casted on top of the IDEs and annealed at 120 °C for 20 min. The fabricated sensor after drop-casting of PEDOT:PSS is shown in figure 2(d).

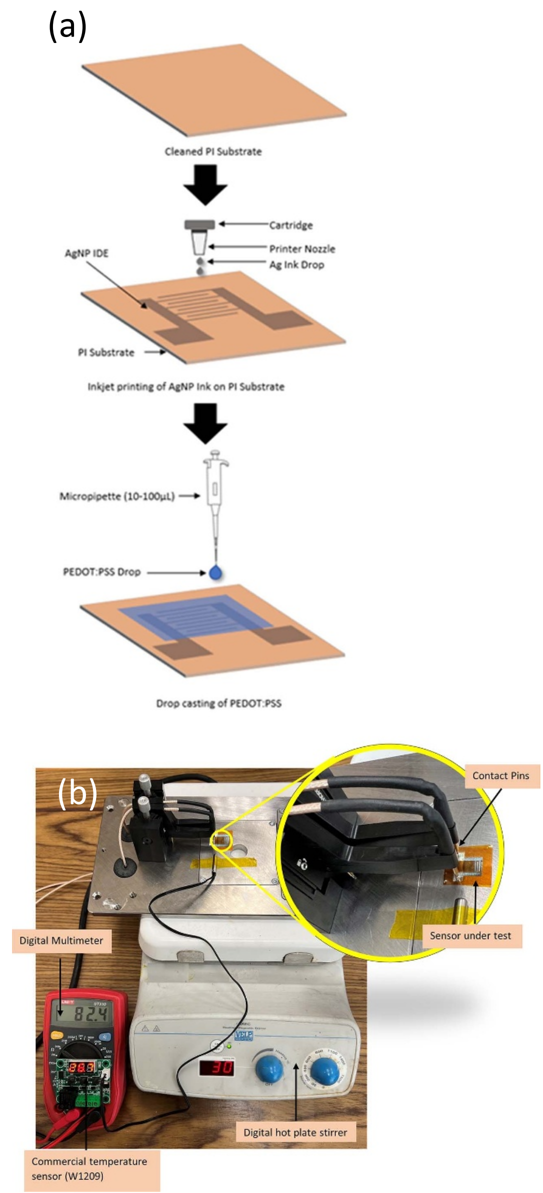


Figure 3. (a) Details of the fabrication process of interdigitated thermistor sensor (b) Resistance measurement Setup.

The fabrication process of the sensor is illustrated in figure 3(a). The sensor performance is characterized from room temperature up to 50 °C at ambient conditions covering the human body temperature range using a digital hot plate (Velp Scientifica™ AREC) and a Digital Multimeter to measure the resistance of the sensors. A commercial temperature sensor (W1209) is fixed to the hot plate surface to indicate the accurate temperature of the plate surface ash visualized in figure 3(b).

3. Results and discussion

3.1. Temperature measurement

The main purpose of fabricating these sensors is to monitor the human body temperature. As a result, the temperature range of interest is limited to 28–50 °C. The resistance variation of the IDE sensors was measured as a function of temperature in this range. The resistance- temperature relationship curve represents the sensor's linearity, and the slope of the curve is the sensitivity. Figures 4(a)–(d) the 8 F and 4 F IDEs sensors' response to temperature after linear fitting on both Epson paper and PI substrates. Two samples were fabricated from each sensor type following the same fabrication procedures and under the same environmental conditions. The measurement cycle is repeated five times for each sample and the error bar of the results is included the figure. It can be depicted from the figure that the sensors exhibit a linear relationship with the temperature in the range of 28–50 °C and that the resistance decreases with the temperature increase, indicating a NTC as expected according to the other studies done on PEDOT:PSS [4]. The creation of thermal electron–hole pairs is the primary source of semiconductive behavior, which results in a reduction in resistance at increasing temperatures [3]. The Sensitivities of the sensors printed on Epson paper are −1.462% /°C and −1.302% /°C for 8 F and 4 F, respectively. These results are associated with the sensitivity independent of the sensor's dimension change and only rely upon the conductivity of the sensing layer used. Similarly, the 8 F on PI had a sensitivity of −3.202% /°C and the 4 F showed a sensitivity of −3.099% /°C. The results verify that PI-based sensors had the best sensitivities compared to the Epson paper. In fact, paper substrate suffers from high surface roughness and porosity which cause disconnection and ununiform printed conductive structure, thus decreasing the sensor's conductivity [4]. Additionally, the graphs disclose that the samples fabricated following the same design exhibit equal TCR values. The obtained TCR values of all the fabricated sensors are summarized in table 1. It can be concluded that the sensors are eligible to be used for human body temperature detection applications because of their high sensitivity. However, the PI-based sensors are more desirable because of their better sensitivity.

3.2. Flexibility and bendability

The application of the proposed flexible/wearable sensors is to be attached to the human body, so the bendability of the sensor was characterized to investigate the maximum bending limit. This limit can be defined by finding the bending diameter that causes a sudden big change in the resistance value usually one that cannot be recovered. The characterization was done by compression bending of the sensor with a known diameter by attaching it to a digital vernier caliper as shown in figure 5(a). The sensor exhibits a slight resistance fluctuation during bending that is approximately proportional to the applied compressive stress and recovers upon release. When a

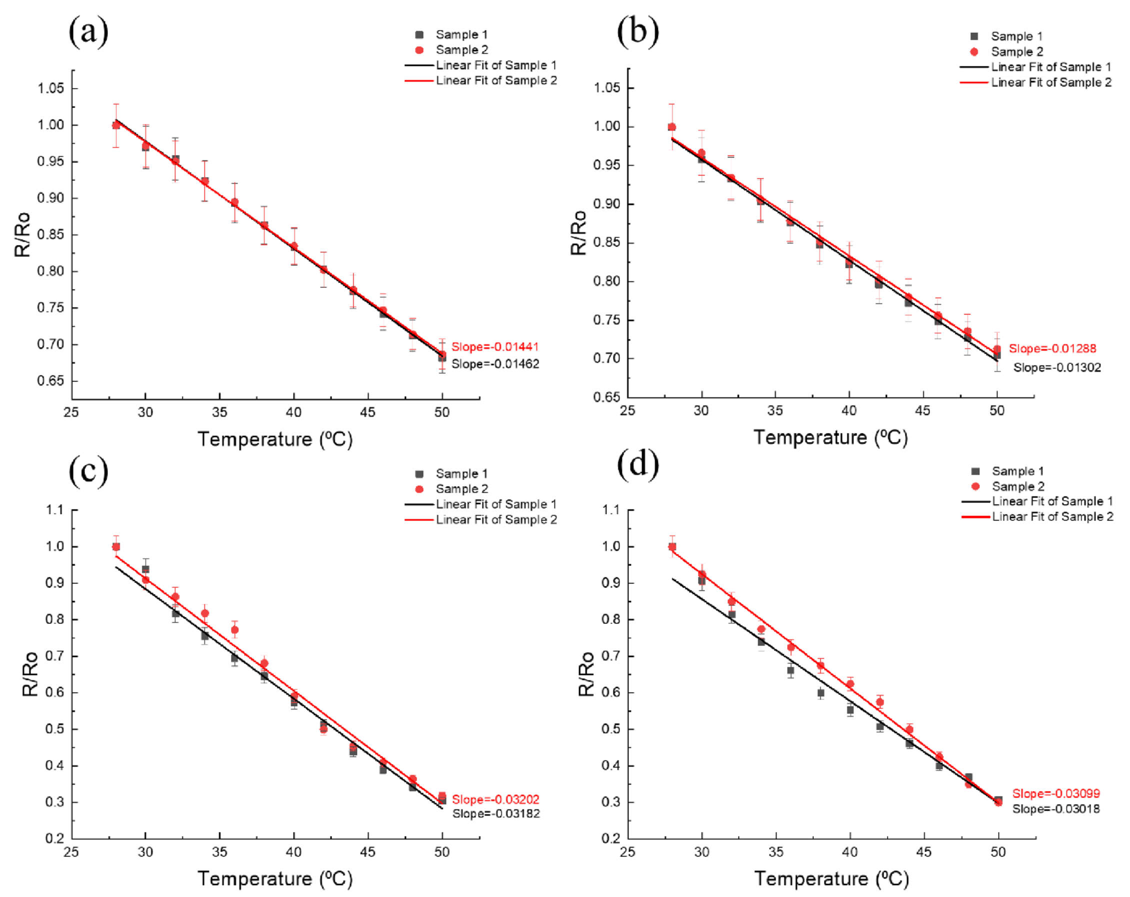


Figure 4. Response of the sensors to temperature change in the range of 28 °C–50 °C. (a) 8 F-Epson paper sensor response (b) 4 F-Epson paper sensor (c) 8 F-PI sensor response (d) 4 F-PI sensor response.

Table 1. TCR value of all fabricated sensors.

Sensor type	Temperature range	TCR
Sensor 8 F- Epson Paper	*28–50 °C*	*−1.462% /°C*
Sensor 4 F- Epson Paper	*28–50 °C*	*−1.302%/°C*
Sensor 8 F- PI	*28–50 °C*	*−3.202%/°C*
Sensor 4 F- PI	*28–50 °C*	*−3.099%/°C*

sensor reaches its bending limit, it will exhibit an abrupt, highly unrecoverable change in resistance due to fracture. Figures 5(b) and (c) present the bendability of both Epson paper and PI-based sensors. The Epson paper sensor had nearly the same resistance for all bending diameters less than 6.5 mm. After that, the resistance dramatically decreased indicating that the sensor exceeded its bending limit. On the other hand, the PI showed excellent bendability and flexibility as there was no significant change in the resistance values even when bending it to 1 mm. It can be deduced that both sensors can be utilized in wearable applications within the limits of their bending diameter.

3.3. Application demonstration

The applicability of the IDEs sensors to detect human skin temperature is checked. To achieve this, a highly conductive silver epoxy made of two parts (A&B) was used to connect the sensor's terminals to copper wires. The two materials were dispended of equal amounts and mixed well. The conductive epoxy was cured at 80 °C for 1 h as advised in the material datasheet [31] to achieve a strong mechanical and high conductive connection. The sensor is then attached conformably to a coffee cup with hot water. A commercial Temperature sensor is fixed to the cup also to indicate the exact temperature of the cup surface as shown in figure 6(a). The sensor successfully detected the temperature change once the hot water was added. The sensor responded to the temperature change with a resistance decrease from 1 MΩ to 0.6 MΩ which corresponds to 32 °C. The sensor's response and recovery time were also measured. The sensor exhibited a very short response time of 10 s as shown in figure 6(b). Noting that the experiment's initial environmental temperature was ≈19 °C which is a large temperature difference. When removed from the hot cup, the sensor took 22 s to return to its initial resistance. Likewise, the experiment is repeated Epson paper sensor with an initial resistance of 1.39 MΩ at 19 °C and dropped to 1.12 MΩ when exposed to the temperature of the hot cup 32 °C. The response and recovery time of the Epson paper sensor are higher than

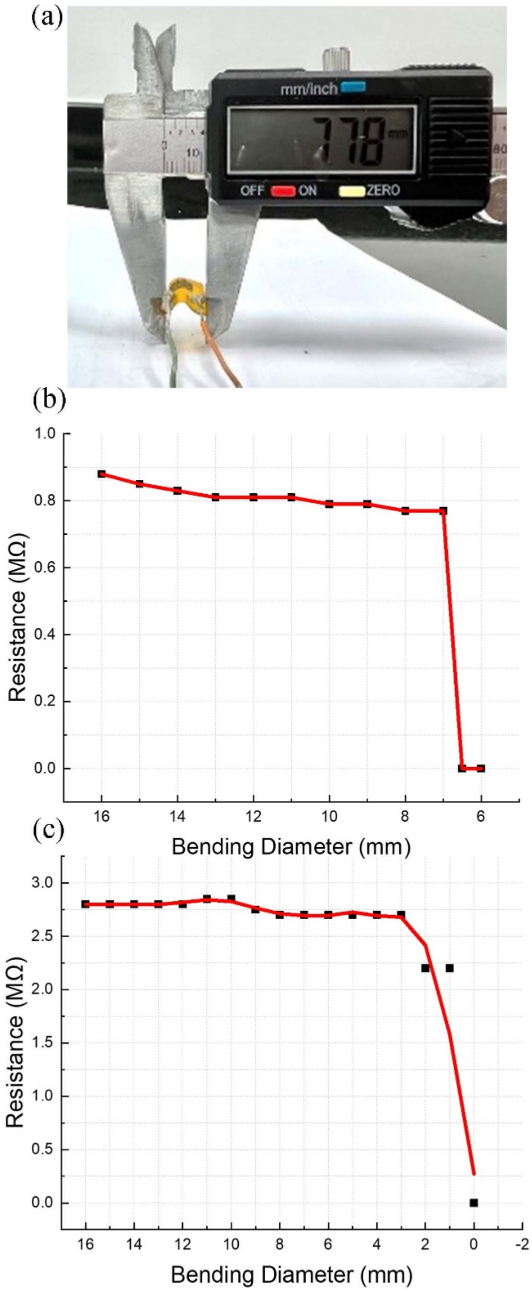


Figure 5. The resistance variation of the IDE sensors under different bending diameters. (a) The senor under flexibility test (b) effect of bending the Epson paper-based sensor, (c) effect of bending the PI-based sensor.

the PI sensor of 30 s and 41 s, respectively as presented in figure 6(c). These results are expected due to the thickness of Epson paper is almost five times bigger than the PI thickness. The results demonstrate the qualification of the sensor to be used in human skin temperature monitoring and any other relevant application.

3.4. Reproducibility

Reproducibility is the ability to fabricate multiple devices following the same procedures and using the same materials to get the same response. Five sensors are fabricated from the 8 F-PI sensor and 8 F-Epson sensor to investigate the reproducibility metric. Figure 7 shows the relative resistance-temperature curves of all the sensors. The graphs indicate that all sensors with the same substrate exhibit a similar sensing performance. The 8 F-Epson paper sensors showed a slight absolute TCR difference of 0.129%/°C. Correspondingly, the difference in TCR values of the 8 F-PI sensors was 0.243%/°C. The results reveal that the design is recommended for reproduction.

Table 2 lists different temperature sensors fabricated using different materials and geometries and characterized at different temperature ranges. As

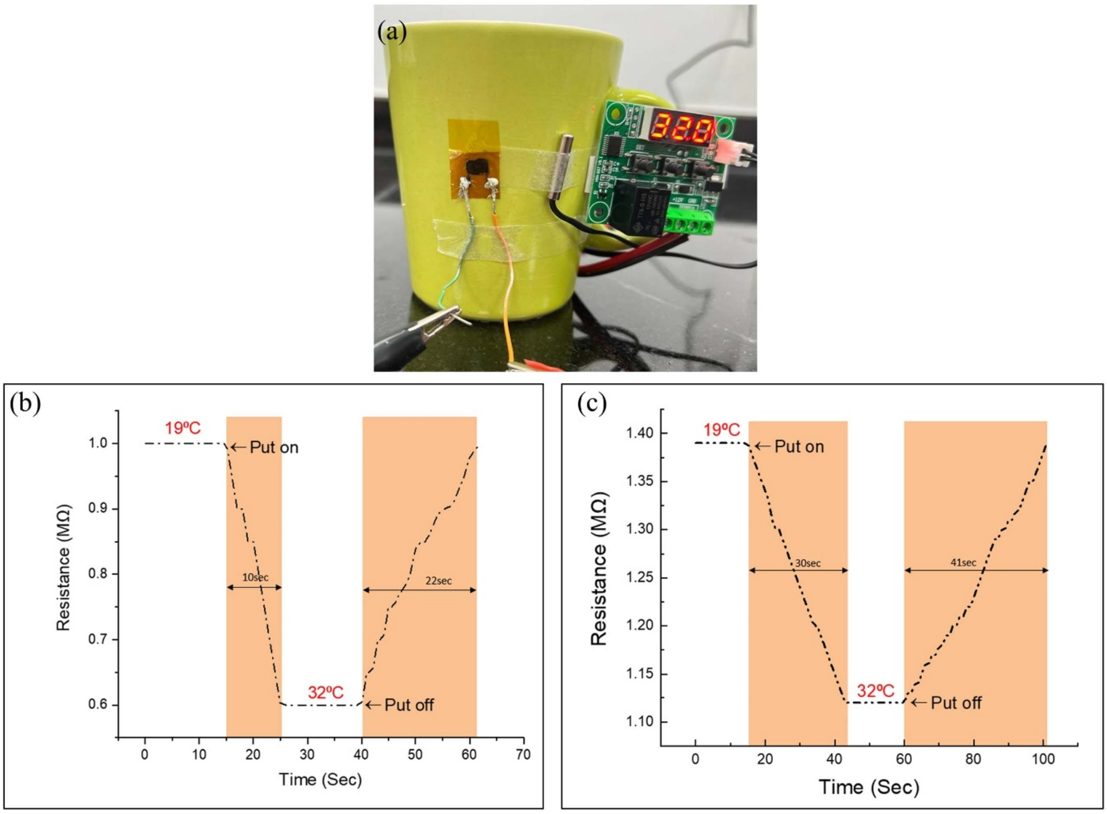


Figure 6. (a) Sensor response when attaching the sensor to the hot cup (b) response and recovery time of PI -based temperature sensor (b) response and recovery time of Epson paper -based temperature sensor.

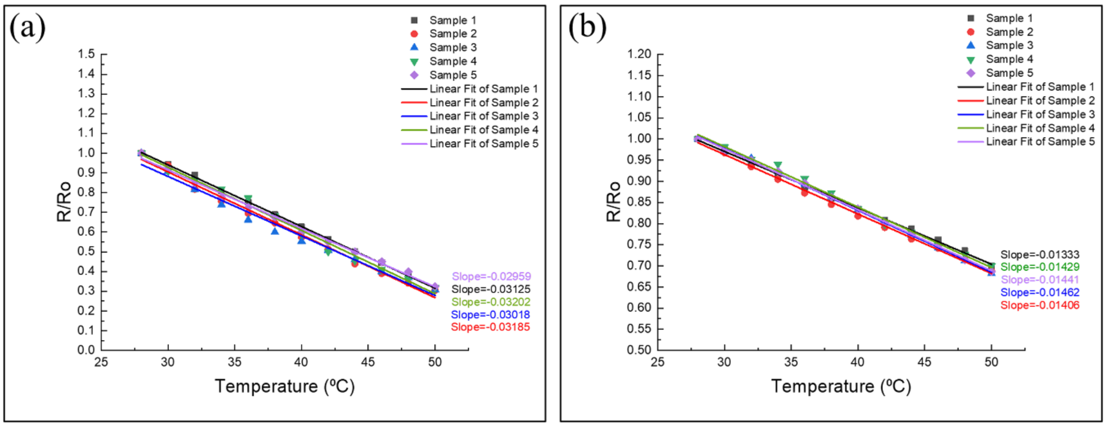


Figure 7. Relative resistance vs temperature of five printed temperature sensors. (a) Five 8 F sensors on PI substrate. (b) Five 8 F sensors on Epson paper substrate.

indicated in the table, the presented temperature sensor shows a higher sensitivity performance compared to other works reported in the literature. The proposed sensor is further compared to our previous works [32, 33]. The achieved high sensitivity in this work is because the used PEDOT:PSS has a very high conductivity (Resistivity <0.0012 Ω cm) [30]. The thermal sensing capabilities of PEDOT:PSS is caused by its microstructure. The PEDOT-PSS nanocrystal, where PSS surrounds the core and PEDOT remains in the grain's center, creates the core–shell structure. The insulating PSS component of the material has the greatest impact on the bulk resistivity of the PEDOT-PSS layer. At increasing temperatures, effective boundary size decreases as a result of smaller particle barriers, which affects the overall electrical resistance. At lower temperatures, the electrons lack the thermal energy to cross these limits, increasing the electrical resistance [5]. Our presented sensor has also been tested to be applied for body temperature monitoring. Both sensors on Epson paper and PI substrates exhibited excellent flexibility, good response and

Table 2. TCR value of all fabricated sensors.

Sensing material	Electrode's material	Substrate	Temperature range	Sensitivity (%/°C)	References
PEDOT:PSS	Ag	PEN	25–50 °C	−0.77	[12]
rGO	AU	Polyimide	25–45 °C	−1.30	[13]
PEDOT:PSS	Ag	Epson photo paper	22 to −10 °C	−0.03	[14]
PEDOT:PSS	Ag	PET	20–70 °C	−0.8	[15]
Carbon black	Ag	Polyimide	28–50 °C	+0.375	[17]
GO/PEDOT:PSS	Ag	Polyimide	25–100 °C	−1.09	[18]
CNT/PEDOT: PSS	Au	PVC	20–80 °C	+0.64	[19]
CNT/PDMS	Ag	Polyimide	30–80 °C	−0.076	[20]
MWCNT	—	Taffeta fabric	25–50 °C	−1.04	[21]
CNT/PEDOT: PSS	—	Taffeta fabric	25–50 °C	−0.31	[22]
GNPs	Platinum	PET	25–150 °C	+0.14	[23]
Nickel	—	Polyimide	−60–180 °C	+0.44	[24]
Nickel	—	Ceramic	25–200 °C	+0.3	[25]
ITO	Ag	PET	30–50 °C	−1.0877	[26]
PEDOT:PSS	Ag	Polyimide	28–90 °C	+0.113	[32]
PEDOT:PSS	Ag	Polyimide	28–50 °C	−3.202	This work

recovery time, and reproducibility which meets the requirements of real-time and comfortable human temperature detection.

4. Conclusion

In this work, we fabricated a wearable human body temperature sensor through inkjet printing silver IDEs and drop-casting PEDOT:PSS sensitive layer. Two designs have been made to investigate varying the number of fingers on the sensor sensitivity performance. Furthermore, both Epson glossy paper and PI were utilized as sensor's substrates. The PI-based sensor gave the highest temperature sensitivity of −3.202%/°C. While varying the number of fingers did not indicate any sensitivity enhancement. The sensor possessed high linearity and repeatability in the tested.

temperature range of 28–50 °C. The excellent flexibility and reproducibility of the sensor were demonstrated, which are strongly required for human body temperature detection. The Application was performed through the use of a hot cup to examine its performance. The sensor exhibited stable performance with response and recovery time of 10 s and 22 s, respectively, for a 13 °C step. The sensor presented a great potential in temperature detection applications, especially for the human body. As for the future, we intend to integrate the printed flexible temperature sensor with pressure/strain, humidity to enhance the utilization of the sensor in the healthcare applications.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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