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Inkjet-Printed Human Body Temperature Sensor for Wearable Electronics

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ABSTRACT This paper presents an all-printed human body temperature sensor developed on a plastic substrate with high deformation characteristics. The sensors are developed on 50μm thick Kapton substrate with structural configuration of silver interdigital electrodes (IDEs) fabricated through inkjet material printer DMP 2850 and the sensing film based on carbon black deposited through doctor blade coating. Interdigital distance of the IDEs were optimized by evaluating sensors' performance against changing the fingers spacing within a close range of 0.1–1 mm. Good sensitivity i.e. 0.00375 °C^{-1} is achieved at a temperature range of 28 to 50 °C with response and recovery times of 4 and 8.5 sec, respectively. Robustness of the sensor was also evaluated for a period of 50 days and a negligible drift (1Ω) in the base resistance was recorded. The sensor exhibited bendability down to 5 mm and was also characterized for the chemical and electrical properties i.e. resistance variation, surface morphology and Raman shift analysis of the carbon black. This wearable sensor can potentially be applied on human body for continuous temperature monitoring as well as on the artificial skin for social and industrial robotic applications.

INDEX TERMS Temperature sensor, human body temperature, printed sensor, silver nanoparticles, inkjet printing.

I. INTRODUCTION

Recently, printed werable sensors for monitoring of vital biosignals, such as body temperature, respiration rate, blood pressure, glucose and electrophysiology have attracted tremendous interest in the biomedical research community [1]–[5]. These sensors are developed on biocompatible substrates and integrated conformably onto the target surfaces. In some cases these sensors are printed as electronic tattoos attached directly to the human skin or else integrated within textiles exhibiting higher deformation [6]–[8]. Among the various vital signs, human body temperature measurement is given special consideration, which is exploited as an early indicator for variety of diseases [9]. For long-term in-situ monitoring, the temperature sensors are desired to be flexible and stretchable enabling conformable integration onto the human skin [10]. Commercially available sensors are developed on planar substrates which are rigid and cannot be applied on non-planar surfaces for wearable sensing applications. On the other hand, the lower glass transition temperature (Tg) of polymeric substrates does not allow manufacturing of these sensors through conventional clean room processes. Therefore, the new emerging trend of printed electronics technology enables fabrication of electronic devices, circuits and systems on variety of substrates at ambient conditions [11]. A number of printing technologies have been reported recently for development of flexible electronics and sensors on polymaric substrates. The two major approaches i.e. contact and non-contact based are practiced for the development of printing system. In contact printing technique, the patterned inked surfaces are brought in physical contact with the target substrate [12]. The contact-based printing technologies includes gravure printing, flexographic printing, micro-contact printing, nano-imprint and screen printing. Whereas in the non-contact printing, solution is deposited through nozzles on the target substrate following a pre-programmed pattern. Non-contact printing techniques include, slot-die coating, aerosol, electrohydrodynamic and inkjet printing [13]–[15]. The non-contact printing techniques have received greater interest for flexible

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electronics manufacturing due to the attractive features such as simplicity, affordability, speed, adaptability to the fabrication process, reduced material wastage, high resolution of patterns and easy control by adjusting few printng parameters [11], [16]–[22]. Inkjet printing is the prominent contactless technique for fabrication of electronic devices on variety of substrates at ambient conditions and is very efficient in material usage. Inkjet printer can produce patterns repeatedly at resolution as high as $\sim 50\mu$m and film thicknesses of upto few nanometers [21]–[23]. For development of temperature sensors, variety of materials and geometries have been adopted such as resistive temperature sensor on paper substrate [23], silver meander pattern on plastic substrates [24] and graphite-polydimethylsiloxane composite [25], [26] etc. All these sensors have certain limitations, for instance temperature range, sensitivity and fabrication processes etc. Among the limitations of printed temperature sensors, drift in the resistance with passage of time is one of the serious issues [27]. In wearable electronics applications, sensors need to be stable and fabricated at room temperature over a variety of unconventional substrates such as plastic, paper and cloth [28]–[31].

In this paper, we propose a human body temperature sensor fabricated through inkjet material printer at room temperature in two steps deposition process. The proposed sensor consists of silver based interdigital electrode and carbon black film as sensing element, which are sensitive towards human body temperature. The proposed sensor has two terminals that provide change in resistance against temperature detection. The change in resistance is directly proportional to the change in temperature i.e. positive temperature coefficient (PTC). IDE fingers spacing were optimized for the high sensitivity (0.00375 $°C^{-1}$) and linear resistance behavior at temperature range from 28 to 50 °C is recorded. The sensor response is very linear on the human body temperature readings. The fabricated device was cured at appropriate temperature and characterized for the temperature sensing on human body as well as on a variable temperature hot plate. Morphological characterizations were carried out through scanning electronic microscopy (SEM) and optical microscope. In this paper, experimental procedure is given in section "Fabrication", experimental results are discussed in section "Discussion and verification", and "conclusion" is summarized in last section.

II. MATERIALS

A. FLEXIBLE SUBSTRATE

Substrates play an important role in wearable electronics especially, when fabricated through printing technologies. Substrates primarily limit the use of high glass transition (Tg) materials, besides the chemical inertness to the different constituent surfactants used in the printable solutions. Compatibility in terms of thermal, mechanical and chemical properties of all the materials is crucial in case of multilayered structures. A 50 μm Kapton substrate was chosen based on the processing requirements and compatibility with the printable solutions i.e. silver and carbon black. The distinguished properties of Kapton substrates are light weight, high temperature sustainability and conformability makes it suitable choices for wearable electronic and sensing applications.

B. ELECTRODE AND SENSING FILM MATERIALS

The interdigital electrodes (IDEs) were printed using silver (Ag) nanoparticle solution. Silver ink particularly developed for the inkjet printing DMP 2850 was purchased from Sigma Aldrich and used without any further processing/synthesis. Ag nanoparticles loading of ~40% in ethylene glycol at the viscosity i.e. ~10 cP required for the material inkjet systems. Carbon black for the sensing layer was also purchased from Sigma Aldrich and mixed in ethylene glycol at ~18 wt.%. The synthesized solution had a viscosity of ~22 cP, which is in suitable range for the screen printing.

III. EXPERIMENT

Prior to printing the sensors, substrate was properly cleaned following a standard preparation protocol. Plastic substrates usually require wet cleaning procedures and surface treatments that help in enhancing the print quality and adhesion between functional material and target substrate. Kapton substrate was cleaned with acetone followed by isopropanol and deionized water respectively. Substrate was treated by UV activation in plasma etcher for 5 min. Dimatix DMP 2850 inkjet printing system was used for patterning the electrodes and doctor blade for the temperature sensing film. Usually, materials with viscosity of 10-12 cP are favorable for the inkjet material printers to make micrometer sized droplets through nozzle in combination with piezoelectric actuators. Volume of the droplets is partially dependent on the average particle size, viscosity, surface tension, and vaporization points of the solvents. Process related control parameters that have a direct impact on the volume and speed of the droplets generation are the piezoelectric actuation controlled by pulsating waveforms, voltages, jetting frequencies, meniscus setpoint, and orifice size of the nozzle and the stand-off distance of printhead from the target substrate. IDEs were designed using commercially available ACE-3000 design tool. Dimensions of the sensing electrodes and inter-finger spacing were experimentally validated and the optimized designs were selected for the sensor fabrication. The designed file was converted into computer compatible i.e. *.bmp* and *.ptn* file format for the DMP-2850 inkjet printer. Silver ink was filled in the reservoir (3 ml) and 10 pL of 16 nozzles piezoelectric cartridge. Substrate was placed on the platen and desired pattern of the interdigital electrode was loaded along with setting various parameters of the printer such as platen temperature 35 °C, dripping frequency 1 kHz, standoff distance 100 μm and 16 number of nozzles. The printing parameters such as jetting waveform, drop velocity (7 mm/sec), and droplet spacing at 25 μm were selected in the Dimatix drop manager window. All these parameters were adjusted based on the experimental outcomes by using the Ag ink several trials.

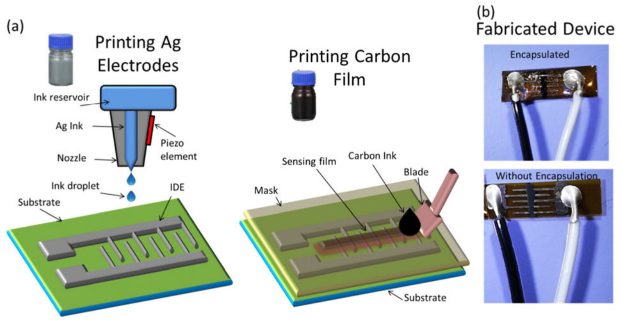

FIGURE 1. **(a) Fabrication of Ag electrodes and carbon sensing film. (b) Fabricated devices bottom without encapsulation and top encapsulated with silicon epoxy.**

Two printing cycles were executed to increase the layer thickness that enhances the electrical conductivity as well as the mechanical robustness and adhesion of the Ag patterns to the Kapton substrate. The printed structure was sintered in oven at 200 °C, for 1 hour as recommended by the ink supplier. The sample was then loaded in the doctor blade machine for the deposition of carbon black film on the IDE. Carbon ink was deposited with the help of mask pattern that covers the overlapped area of electrode fingers. The fabrication process of IDE and carbon film is shown in **Fig.1(a)**. The device was cured at 150 °C in a furnace after the deposition of carbon film. Copper wires were connected to the electrodes in order to make it accessible for the electrical characterization. Fabricated devices are shown in **Fig.1(b)** both encapsulated and without encapsulation. Encapsulation plays an important role in the device performance as Ag is prone to oxidation and carbon film is sensitive to humidity and gasses. After the encapsulation, the device was stable at electrical resistance vs temperature. Two-part silver based conductive epoxy (EPO-TEK) was mixed properly and applied at the connecting pads while contacting the connecting wires. A hotplate at 100 °C was used to partially cure the conductive epoxy while applying at the pads. A final heat treatment at 150 °C was used to complete the silver conductive epoxy curing establishing a mechanically strong and electrically conductive connection.

IV. RESULTS AND DISCUSSIONS

A. PHYSICAL AND CHEMICAL ANALYSIS

Quality of the printed films depends both on the physical and electrical characteristics of the films and patterns. In order to maintain a good quality of printing, fabrication processing parameters and substrate pretreatments need to be properly carried out i.e. substrate cleaning and optimized pattern width and thickness. IDE finger width 200 μm and gap between fingers 600 μm with high accuracy were printed repeatedly without any noticeable variations. By using DMP 2850, an accuracy of ± 5 μm was achieved by repeatedly printing the similar structures on Kapton substrates several times and the printed patterns remained in close proximities. In order to maintain a good conductivity especially for the Ag electrodes, two printing passes were performed. Electrodes and sensing film have been investigated by SEM. **Fig.2(a)** show the micrographs of the Ag electrode at scale of 10 μm confirming the proper deposition and sintering. Ag nanoparticles are properly bonded with each other resulting into enhanced electrical conductivity. **Fig.2(b)** shows micrograph of the Ag paste, which is used to establish connection for the measurement and readout purpose. **Fig.2(c)** show the SEM image of the carbon black film deposited on the Ag electrode. The micrograph confirms the proper deposition and sintering of the carbon black film. Raman spectrum of the carbon black is shown in **Fig.2(d).** It is composed of two peaks D-band and G-band, the first band range is from 1260 to 1320 cm^{-1}, the G-band peak ranging from 1560 to 1610 cm^{-1}. The D line appears from sp2 hybridized carbon structure. The physical properties of the carbon black film are strongly correlated with the ratio of D and G bands types of C–C bonding. Mainly ratio of the sp3/sp2 carbon phases depends on fabrication conditions where it can be changed in a range from pure diamond to pure graphite. G-band peak represents the nearby atoms which are moving in opposite directions but perpendicular to the plane of the carbon black sheet. D-band peak represents the atoms moving in radial directions in the plane of the carbon black sheet.

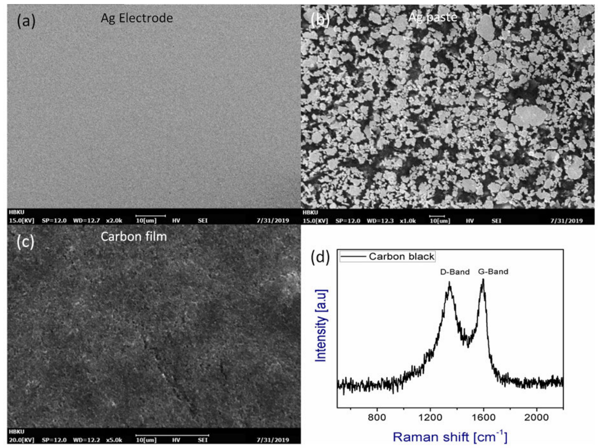

FIGURE 2. **(a) Ag electrode, (b) Ag paste for the interconnection wires, (c) carbon thin film and (d) Raman shift analysis of the carbon film.**

Fig.3(a) shows 3D Nano profiler analysis of the Ag electrode printed on Kapton substrate and the roughness analysis of the electrode. Printing cycles were kept at two in the experiment of Ag patterns in order to achieve the desired resistivity value at around 20 $\mu\Omega$-cm after sintering in the oven at 200 °C. Multiple numbers of printing passes is good for the conductivity of pattern if the finger spacing is wide enough to accommodate spreading of the ink on the substrate. In our case the spacing between the fingers is 600 μm. From the 3D image, the height of the electrode finger is almost 1 μm and thickness of 200 μm. The electrodes are formed properly with good aspect ratio to assure the desired conductivity. Roughness chart is given in the inset of Y-direction plot of **Fig.3(a)**. Carbon film was deposited on the Ag electrodes through doctor blade as shown in **Fig.3(b)** (roughness table is shown in the inset where *sq.* value is 1707 nm).

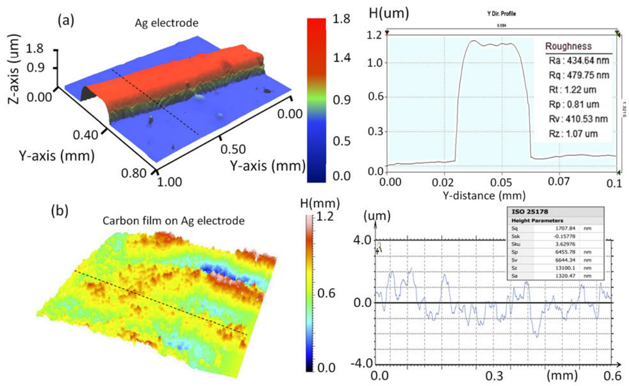

FIGURE 3. 3D Nano profile analysis (a) Ag electrode on Kapton substrate, (b) Carbon film deposited on Ag electrode.

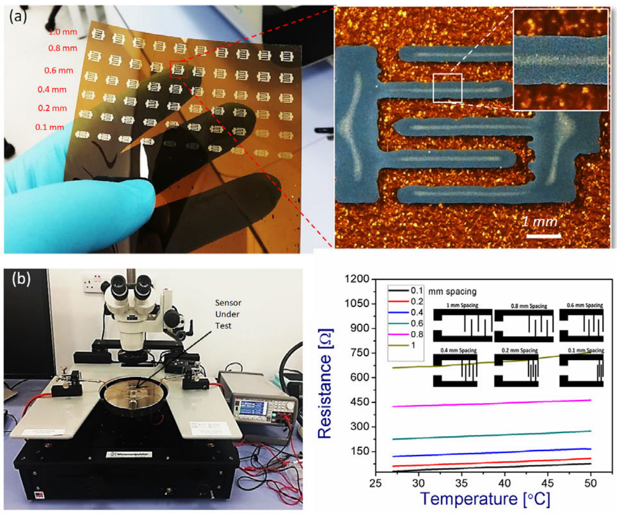

FIGURE 4. (a) 6 type of electrodes with different finger spacing 1.0mm to 0.1mm, (b) Electrical characterization of individual sensor for resistance variation against temperature change from 28 to 50°C.

B. ELECTRICAL CHARACTERIZATIONS

Temperature sensors were optimized by varying the finger spacing of the electrodes. Total of six different electrodes with finger spacing 1.0 mm down to 0.1 mm were fabricated on PI substrate as shown in **Fig.4(a),** the trace width was kept 200 μm to make sure the Ag conductivity. Inset of **Fig.4(a)** shows microscopic image of the electrode, it can be seen that the fingers of the electrode are properly deposited with uniform trace width throughout and there is no short circuit path between them. Carbon ink was deposited on the electrodes 1 mm wide and 1 $\sim$ 2 μm thick on all the electrodes. Electrical characterization was done with source meter in combination with a probe station as shown in **Fig.4(b)**. It was observed that all the sensors gave a resistance change against the temperature variation from 20 to 50°C but the base resistance was different for each type of sensor and it was expected because space between the fingers is directly proportional to the resistance of the carbon film.

Resistance temperature detector (RTD) is the contact-based temperature sensors that change its resistance along the change in temperature. This variation in resistance caused by temperature change is used to detect the temperature of measuring body. The advantages of RTD type temperature sensors are small size, high accuracy, short response time and simple architecture. The TCR can be calculated by the following equation (1), [24].

$$TCR = \frac{R_b - R_a}{R_a\,(\boldsymbol{\Delta} T)} \tag{1}$$

Here, $\Delta T = T_b - T_a$ is change in temperature of the sensor, T_a is initial temperature at 28 °C of the sensor, T_b is present temperature of the sensor, R_a is initial resistance of the sensor at 28 °C and R_b is current resistance at a particular temperature. The sensitivity of the temperature sensor is calculated by

$$S_{sens} = \frac{\boldsymbol{\Delta R}}{R_a} \tag{2}$$

Here, S_{sens} is sensitivity, $\Delta \boldsymbol{R} = \boldsymbol{R_b} - \boldsymbol{R_a}$. The variation in resistance with respect to temperature change was observed by using our proposed sensor for different sizes of patterns.

The sensor was analyzed for the temperature characteristics in order to measure the real time temperature of the human body. For this test temperature sensor was taped on the wrist and leads were connected to source meter for the resistance measurement as shown in the inset of **Fig.5(a)**. at human wrist temperature the sensor measured 445Ω. Sensor was tested for 10 endurance cycles each for 20 min to observe the stability of the sensor against human body temperature. The resistance deviation was recorded as ±1Ω (443 $\sim$ 445Ω) during the test as shown in **Fig.6(a).** The sensor showed a stable response although during the test wrist was not fixed which can cause resistance variation. Sensor was tested for the temperature span of 28 $\sim$ 50 °C to analyze the stability of the device against temperature variations. The sensor was placed on a variable temperature plate and leads of the sensor were connected to the source meter. Temperature of the sensor holding plate was increased by 1 °C and resistance was recorded as shown **Fig.5(b).** It was observed that the sensor's behavior is linear throughout the temperature range and repeatable. Although the targeted application of the proposed sensor is human body temperature measurement but it out performed for the temperature range from 28 to 50 °C which increase the applications area of the sensor such as robotic artificial skin. Sensitivity of the sensor was calculated from the measured data of the resistance against temperature by using Equation 2. **Fig.5(c)** shows sensitivity data of the sensor for the temperature range of 28 to 50 °C.

C. TESTING ON HUMAN BODY

In order to characterize the sensor on human body, **Fig.6(a)** shows temperature sensing test of the sensor by placing finger on the sensor. The sensor was encapsulated with silicone epoxy to avoid electrical contact between finger and sensor. The sensor was placed in such a position so that encapsulated side was facing down and finger was brought into contact from the substrate side covering the effective area of the sensor. Results show, when finger is placed on the sensor, due

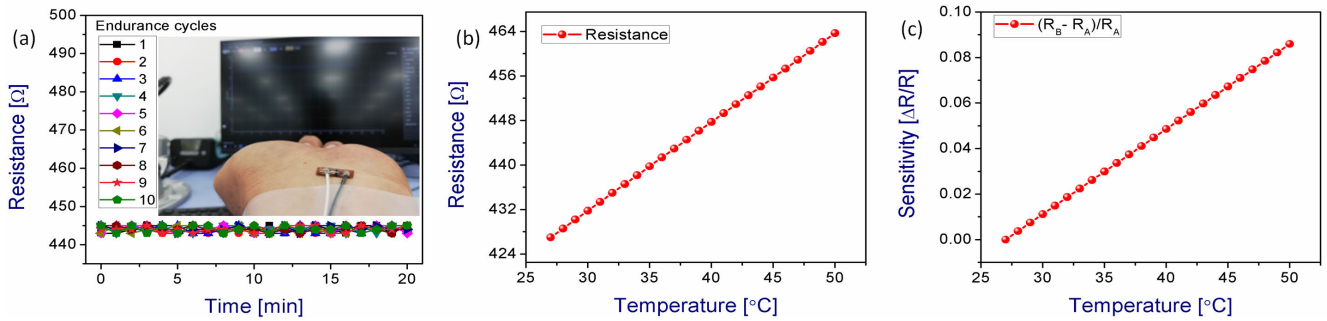

FIGURE 5. **(a) Sensor endurance test on human wrist, (b) Resistance reading of the temperature sensor ranging 28 to 50 °C, (c) Sensitivity analysis of the sensor.**

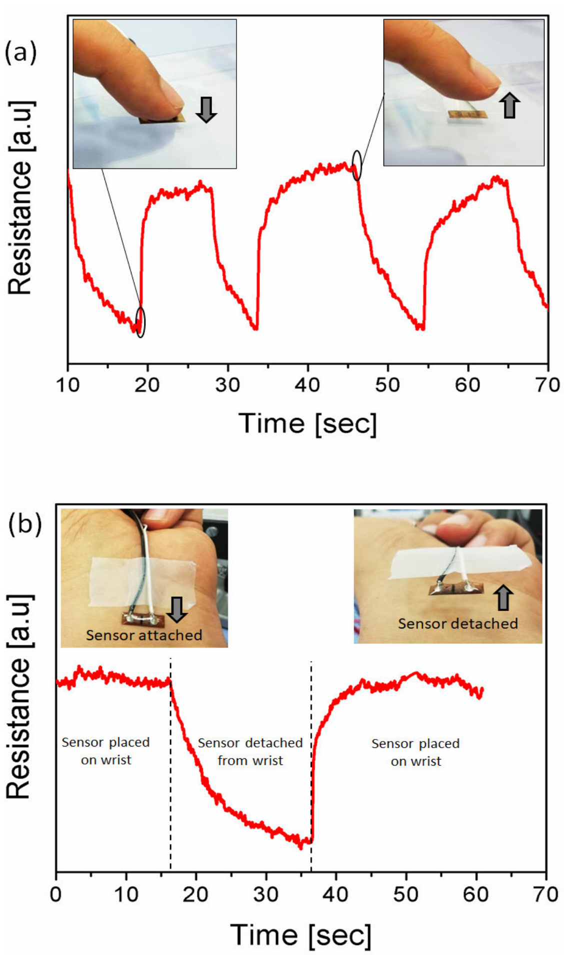

FIGURE 6. **(a) Temperature sensing by finger placing on the sensor, (b) Attaching detaching sensor on the wrist.**

to finger's temperature the resistance of the sensor increases and when the finger is not in the contact the resistance recovers to the initial values. Although a human finger is not suitable for the temperature reading, nonetheless the change in resistance is prominent because of the high sensitivity of the sensor. **Fig.6(b)** shows temperature sensing test on the human wrist. For this analysis, sensor was connected to the source meter through leads and was placed on the wrist with the help of plastic tape. It can be seen in the figure; initially

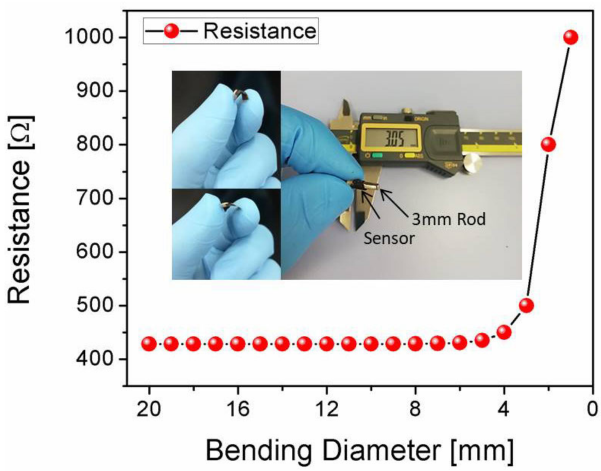

FIGURE 7. **Bending analysis of the proposed sensor.**

the sensor is attached on the wrist shows high resistance on the Y-axis. As the sensor is detached from the wrist its resistance decreases gradually. After the recovery time sensor is again attached on the wrist and resistance is increased. This resistance change is between the human body and room temperature, at the testing time room temperature was 24°C.

D. BENDABILITY ANALYSIS

Sensor was characterized for its bendability characteristics to find the maximum bending limit as the sensor is supposed to be utilized in the wearable electronics. For this characterization sensor was bent over the metallic rods of various diameters (20 mm down to 1mm). From 20 mm to 5mm the sensor did not show any change in the electrical resistance at 28°C temperature as shown in **Fig. 7**. The inset shows the sensor bending on a metallic rod measured with digital vernier caliper. Below the 5 mm bending diameter, the sensor resistance increased to 1000 Ω from initial resistance of 424 Ω, effectively due to the carbon film cracks. The sensor can be used within the limits of bending 5mm diameter.

E. RESPONSE ANALYSIS

Response and recovery time analysis of the sensor was carried out. Sensor was connected to source meter and placed on a

TABLE 1. Resistance reading of the sensor @ 38.5 °C over the time.

Days	1	10	20	30	40	50
Resistance (Ω) @38.5°C	44.45 4	445.60	445.62	445.66	445.60	445.65

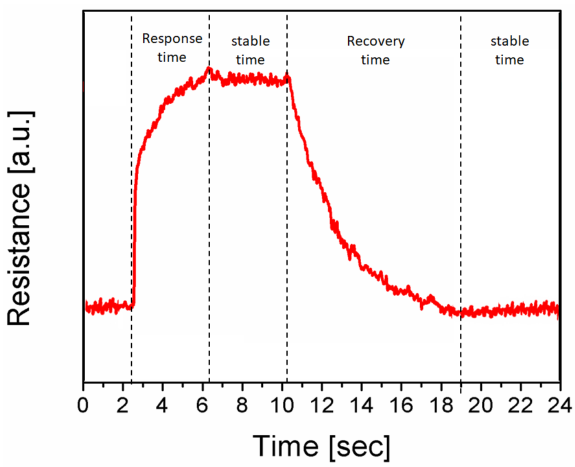

FIGURE 8. Response and recovery time analysis of the sensor.

TABLE 2. Performance comparison of the proposed sensor.

S.N	Temp. Range	Sensitivity	Type	Res/ Rec Time	Mat.	Ref.
1	0-100 °C	1.07m/°C	Resistive	-----	Ag	[24]
2	20-60 °C	2.2m/ °C	Resistive	-----	Ag	[29]
3	20-70 °C	4 mV/°C	Resistive	-----	CNTs	[30]
4	22-200 °C	3.3m/°C	Resistive	-----	CNTs	[3]
5	10- 120 °C	0.008/°C	Resistive	-----	QDs	[26]
6	0-120°C	80pF/°C	Capacitive	3/3.5	GO	[31]
7	28-50 °C	3.7m/°C	Resistive	4/8.5	Carbon	This work

human wrist in order to record the response time. Initially the sensors' resistance was low and afterward due to temperature the resistance, reached a high value and became stable. A delay of 4 sec was recorded as response time of the sensor as shown in **Fig.8.** Response time was recorded as 4 sec, it is the time of resistance transition from low to high (on the time scale from 2.2 to 6.2 sec). After the 4 sec interval, resistance of the sensor became stable which depicts the value of temperature. To analyze the recovery time, sensor was removed from the wrist and time was recorded for the resistance transition from high to low as shown in **Fig.8**. The recovery time was recorded as 8.5 sec approximately. Resistance reading of the sensor over the time was recorded for 50 days as shown in **Table 1**. It was found that encapsulated sensor exhibited stabile behavior over the span of 50 days where only 1.196 Ω drift was recorded between day 1 and day 50. This characterization of the time span assures that the proposed sensor is robust enough against time span to be used in the wearable electronics for temperature reading.

Table 2 shows a comparison of the proposed sensor with those reported in few of the reported related researches. All sensors listed in the table are temperature sensors with different temperature range, material, geometry and sensing type *i.e.* resistive or capacitive. In [31], the sensor is based on graphene oxide in combination with IDE where the capacitance changes against the temperature change and the sensitivity is 80pF/°C. This sensor shows good sensitivity and response/recovery time relatively, but it is based on capacitive detection which requires a readout circuit. In our proposed idea the sensor is resistive and does not require readout circuit but a resistor to form a voltage divider network and voltage against the sensor is read directly by the electronic system *i.e.* microcontroller or PC. Rest of the sensors provided in the table are resistive, but their performance is not better than the proposed sensor in terms of sensitivity and response recovery time. We believe the proposed sensor would be a good alternative for the wearable printed electronic system.

V. CONCLUSION

Human body temperature sensor fabricated through inkjet material printer DMP 2850 and doctor blade was presented. The sensor consisted of silver interdigital electrodes coated with carbon black thin sensing film on 50 μm Kapton substrate. The spacing (0.1 to 1 mm) between fingers of the IDE was optimized and sensitivity of 0.00375 °C^{-1} was achieved. The sensor exhibited linear and stable readings at temperature range from 28 to 50 °C with response and recovery time of 4 sec and 8.5 sec respectively for 50 days. The proposed sensor exhibited bendability down to 5mm diameter and was also tested on human body for temperature reading on the wrist and finger. Furthermore, senor was characterized for resistance change against temperature, surface morphology and chemical characteristics of the sensing film through Raman shift. The achieved results are impactful and show that the proposed sensor can be a good basis for the wearable human body temperature reading.

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