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Low-Cost Inkjet Printed Resistive Temperature Sensors-How Good Are These Sensors?

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Abstract- The aim of the study investigates the different temperature behaviour of a printed resistive temperature sensor by measuring the corresponding resistance of the sensor with varying temperature profile. The fabrication of the printed resistive temperature sensor is done in conjunction with a low-cost inkjet printer and silver nanomaterial ink making the sensor very cost efficient and cheap. The printed temperature sensors were fabricated with varying sensor dimensions to study the impact of the sensitivity/measurement stability of the sensor and also to study the impact of bending to the respective sensor performance by geometrical design changes. The results point out to the fact of the variable sensitivity with varying sensor profile and active surface area (silver surface) associated with the sensor. The study also indicated the impact of the geometrical design on the sensor parameters for unwanted bending.

Keywords- *Low-Cost Printed Temperature Sensor, Low-Cost Printer, Printed Sensor, Temperature, Resistance, Printed Electronics, Resistive Sensor*

I. Introduction

Over the recent decades the interest over the low –cost printed electronics has been emerging as the one for the most researched topic around the globe. The flexibility of the printed circuitry and the possibility of digital manufacturing have added the pace of the growth of the printed electronics sector. Printed Electronics have made big leaps in the past decades to co-exist with the conventional silicon based electronics components and device manufacturing sector, especially in the area of the sensors. The current trends in the internet of things and automation process have pushed this growth especially in the field of printed sensors. The passive electronic components & device fabrication techniques through inkjet and comparable printing technologies such as screen printing have been demonstrated in the literature [1], [2], [3] & [4]. Conventionally the cost associated with the printed electronics is high ,this is due to the high cost of the production machinery & pre/post treatment (sintering) of the circuitry produced by the combination of flexible substrate and the nanoparticle ink (silver, carbon and graphene). In current study, reduction of the cost associated with fabrication of the sensor using the off the shelves low-cost inkjet printer in conjunction with silver nanoparticle ink [6] is proposed. The studies of electrical and mechanical stability of such a low-cost printer and the corresponding ink have been already demonstrated in the literature [7], [8], [9] [10], [11] & [12]. The reduction in the sintering temperature (pre/post) of the printed inks (conductive inks such as silver, carbon & graphene) on the flexible substrate and the controlled printing patterns precisely according varying drops size are the major roadblocks of printed electronics. The development of the water based inks enabling the sintering of the produced electronics circuity in the room temperature [6] have added pace to the extensive implementation of the printed electronics in various field like sensing technology. The subject of study investigates the influences of the sensor geometry, bending and impact of varying temperature of printed temperature sensor fabricated using low-cost printer in conjunction with silver nanoparticle ink. The study about sensitivity of these printed temperature sensors are also made for varying sensor geometries. The study is based on the assumption that there exists a relation between the measured resistances to the corresponding variance in the temperature profile [5]. The limitation of the study includes the ink [6] which has a continuous operational temperature of 70 °C. The detailed performance attributes of this ink [6] is not possible due to this limitation.

The nucleus of the study investigates the impacts of factors such as the bending and sensor geometry of printed temperature sensor inducing changes in its electrical characteristics. The impact of these factors on the stability & sensitivity of the temperature sensor is also studied in detail. This study details the degree of impact of these factors (sintering, sensor geometry and measurement stability/sensitivity) of the printed temperature sensor over the temperature range of 20 °C – 100°C.

The Figure 1 illustrates the different parameter affecting the functionality of the printed temperature sensor which we have formulated based on the previous studies [10], [11], [12]. The varying sensor geometry also induces a change in the sensor active surface area (silver surface) which also can be taken as variable factor in this study. The other constant influencing factor for the experiment includes the impact from the selection of the ink and the amount of ink [6] for each sensor design. The selection of the specific printer and the applied technology (piezoelectric) can be taken as constant. Based on the above assumptions following hypothesis are proposed for the study.

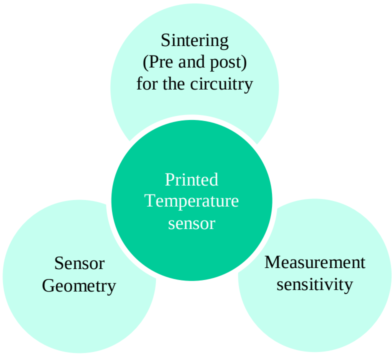

Figure 1. Variable factors impacting the performance of a printed temperature sensor

H1: If change in sensor geometry is made for the printed sensor, then there is change in the stability/sensitivity of the sensor (measured by the corresponding resistance over a temperature profile) is visible. The change in sensitivity is a linear function of change in sensor geometry.

H2: If the printed temperature sensor is induced to bending of the whole area in the nominal temperature profile (20 °C) then there is significant impact of the sensitivity of the sensor (measured by the corresponding resistance).

II. METHOD

As mentioned in previous studies [7], [8], [9] [10], [11], [12] & [13] the following materials and methods were used to test the hypotheses.

(a) Printer: All switches were printed with the low-cost printer from Brother (Typ: MFC-J6710DW); (b) Sensor Design / Geometry: The sensor was created by using Microsoft Word 2013. (c) Four different types of sensor design (Type A-D) depicted in the Figure 2-5 were adopted to check the dependency of the sensor geometry to the behaviour of the printed temperature resistive sensor. The sensitivity of the each type of the printed resistive sensors was studied to understand the geometrical influence on the printed resistive sensors.

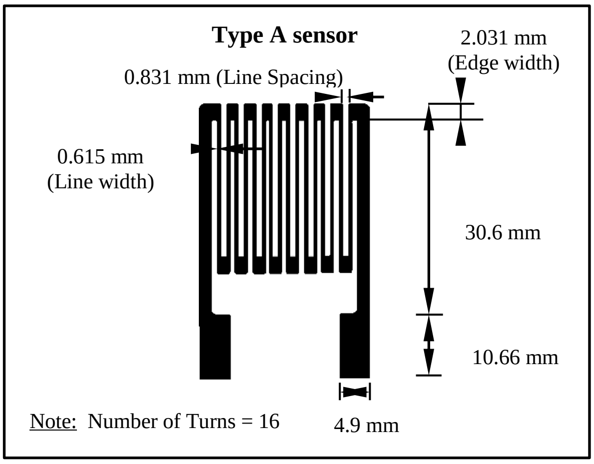

Figure 2. Design of the Type A printed resistive temperature sensor

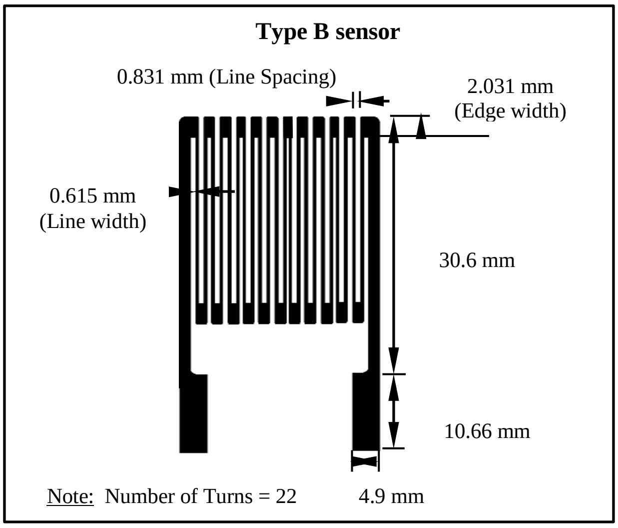

Figure 3. Design of the Type B printed resistive temperature sensor

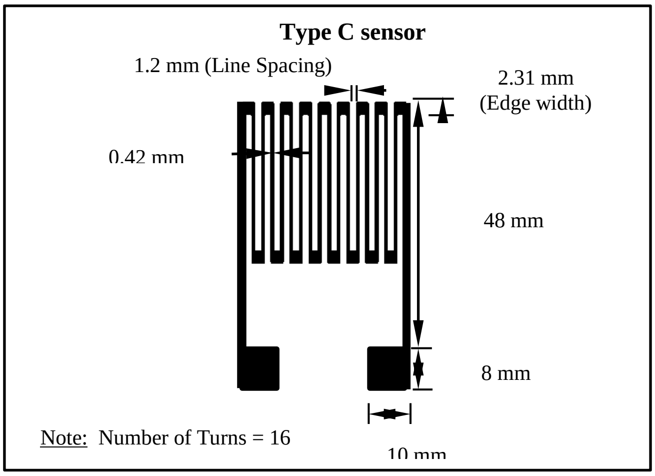

Figure 4. Design of the Type C printed resistive temperature sensor

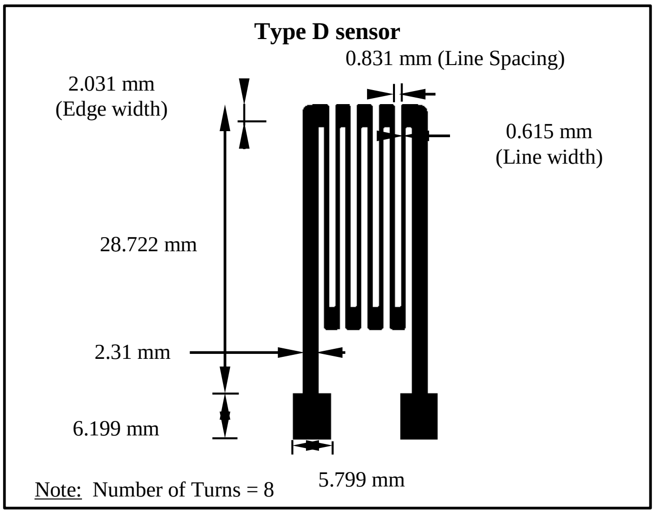

Figure 5. Design of the Type D printed resistive temperature sensor

(d) Layer Substrate: Novele™ was used as substrate from NovaCentrix. AgIC Printing System; (e) Ink: For printing were used the AgIC Circuit Printer Cartridge Set with a critical temperature range over 70°C (maximum continuous temperature); (f) Printout: All printed layers were not pre-treated or post-treated; (g) Test parameter: Electrical resistance Ω, temperature °C and geometry; (h) Measurement devices: Digital Multimeter (PeakTech), Digital 4 Channel Thermometer (Voltcraft Plus), Heating furenace (Memmert); (i) Test environment with Climate Chamber: An installation of the company Vötsch type VC³4018 (Link: http://www.v-it.com/de), with varying temperature profile from -6°C to 50°C & humidity of 40% throughout the cycle of test.

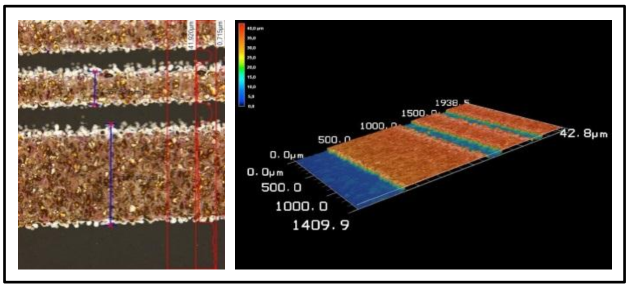

Figure 6. 3D-laser-scanning microscope-recording for Type D sensor

The study to simulate the unwanted influences from the factors like bending on the measurement stability and sensitivity of the printed sensor and for these following experimental procedures were selected:

A. Behaviour of the sensor to varying temperature profile:

The printed resistive temperature sensors with different geometrical design are subjected to the study for their attributes for varying temperature profile was performed. The Four varying geometrical designs (Type A-D) were fabricated and subjected to varying temperature profile from 20°C-100°C in a in the heating furnace. The varying temperature profile induces change in resistance associated with the printed sensors which are used to calculate sensitivity of the sensors. Three samples from each type of sensor (Type A- D) were subjected to the test experiments. These sensor were fabricated using AgIC ink [6] which has a maximum continuous temperature of 70°C were subjected for the study. The total duration of the each experiment was approximately around 20 minutes. This was the time required by the heat furnace to raise the temperature profile from 20 °C to 100 °C.

B. Bending:

The unwanted bending of the fabricated printed resistive sensors on a flexible substrate is studied in this phase of the experiment. The printed resistive sensors are subjected to bending in real time scenario (up to 45 ° in acute stages) after the first experimental analysis (Behaviour of the sensor to varying temperature profile). The studies of bending of these sensors are critical due to their respective application area demanding higher flexibility of substrate. The initial resistance and varying resistance corresponding to the bending profile (45°) were recorded for sensor for varying sensor geometry (Type A-D).

III. RESULTS

The following results were determined from the experimental procedure for the factors influencing like temperature, sensor geometry and bending.

A. Behaviour of the sensor to varying temperature profile:

All three samples fabricated with varying sensor geometry (Type A-D) could be used to study the impact of the temperature on the sensor performance. The series of experimental analysis for the all sensor (Type A-D) showed a linear relationship for the temperature range of 20°C–70°C. This is in accordance to the art mentioned in the literature [5]. All sensors had reaction (indicated by arrow in the Figure 7) point in the range of 70°C-85°C with resistance value not increasing any further with the increasing temperature profile. This reaction point in the behaviour of the printed temperature sensor could be linked to the properties of the ink used for the fabrication process [6] having a maximum continuous temperature of 70°C.

The experimental analysis of the printed temperature resistive Type A sensor is depicted in the Figure 7. The resistance associated with the varying temperature profile (20°C -100°C) was recorded. Throughout the experiment there was a linear relationship between the resistance and the varying temperature profile in the range of 20°C-80°C in the experiment 1&2. Between the 80°C–90°C there was a reaction (indicated by arrow in the Figure 7) point in the experiment with the resistance not increasing to the increase in the temperature profile. The reaction point (indicated by arrow in the Figure 7) for the printed resistive temperature sensor could be limited by the ink [6] used for the manufacturing which as a maximum continuous temperature of 70°C. The experiments 1&2 (sample 1&2 of Type A) indicated a polynomial behaviour for the temperature greater than the 80°C. The experiment 3 (sample 3 from Type A) didn't show this reaction point as for the previous samples. The reason could be the heat furnace was already in the higher temperature when the test was conducted, since they were tested in the same heating furnace after the experiment 1&2. The calculation of the sensitivity of this type sensor was 1.41566*10-3 ◦C−1 in average for all the experimental procedure. This was comparable to the sensitivity of 2.19*10-3 ◦C−1 mentioned in the art in the literature [5].

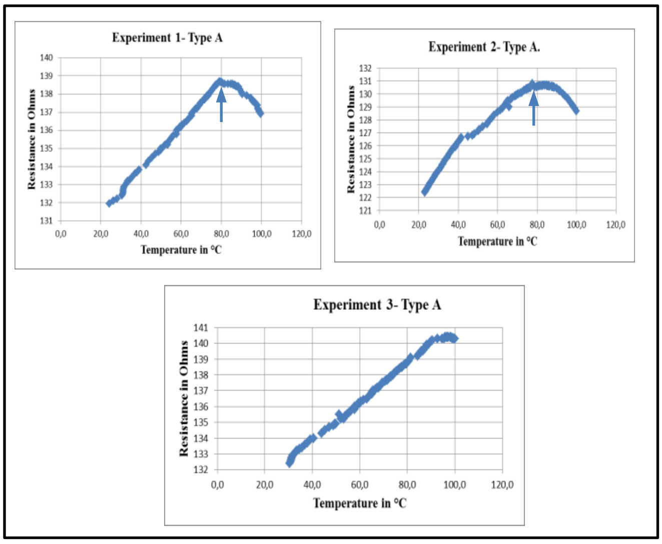

Figure 7. Functional relationship between resistance and temperature for varying temperature profile for Type A sensor

The experimental results for the sensor Type B showed the similar pattern that to that of the sensor Type A. There was a linear relationship between the resistances associated with the printed resistive temperature sensor to that of varying temperature profile. When compared to the geometrical design of Type B to Type A, the former have more number of turn (22) compared to the Type A sensor which has 16 turns. The basic principle for this type of design adoption was to increase the area of the sensing. The increase in the sensing area (more silver structure) also induced an increase of the resistance by 32 %. This increase in the sensing area was made to study the impact of the geometry on the sensitivity associated with the sensor. Experimental data recorded during the experiment (4-6) indicates the similar behaviour of the sensor to varying temperature (20°C–100°C) that of the sensor Type A with a reaction point (where the resistance is not increasing with the increasing with increase in the temperature profile indicated by arrow in the Figure 8) was observed in the temperature range of 80°C–90°C. There was a linear relationship for the resistance and temperature for varying temperature profile from 20°C–80°C. There exist a polynomial relationship for the resistance and temperature for the higher temperature (80°C) for the sensor as mentioned in the art in the literature [12]. The calculation of the sensitivity of this type sensor (Type B) was 1.10678*10-3 °C−1 in average for all the experimental procedure. The average sensitivity in terms of Ω °C−1 was 0.1994. There is change of 13.13 % in terms of the sensitivity of the Type B when compared to the Type A sensor. This increase in the sensitivity can be correlated to the increase in the sensing area of the Type B sensors.

The design considerations of the sensor Type C was to decrease the line width of the sensor to 0.42 mm from 0.615 mm when compared to that of Type A&B sensors. This decrease in the line width of the sensor was to study the impact of the measurement sensitivity of the sensor to varying geometrical profile. The experimental analysis pointed to the fact that the sensitivity of the Type C sensor was 1.978122 * 10-3 ◦C−1 in average over the all experimental setup. The average of the sensitivity expressed in 0.2103 Ω ◦C−1 which is 17.64 % higher compared to the sensor Type A and 5.183 % higher than the Type B sensor. Throughout the experiment the three samples (from Type C) had a linear relationship between the resistance and temperature of 20°C–70°C and polynomial relationship for the temperature higher than 80°C similar to that of the Type A and Type B sensors.

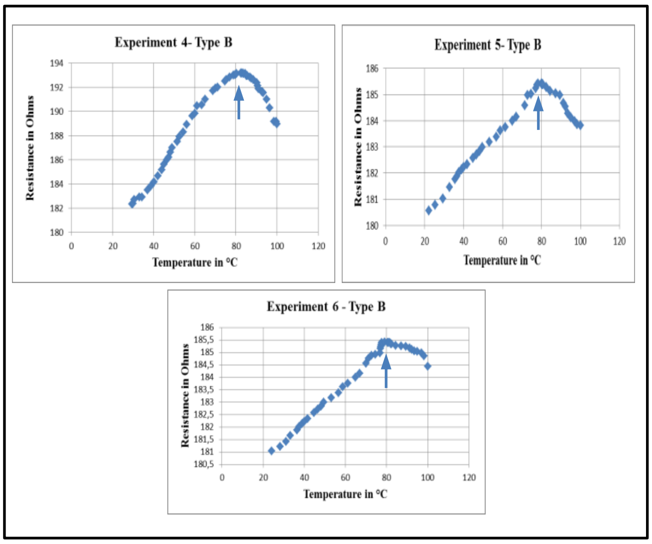

Figure 8. Functional relationship between resistance and temperature for varying temperature profile for Type B sensor.

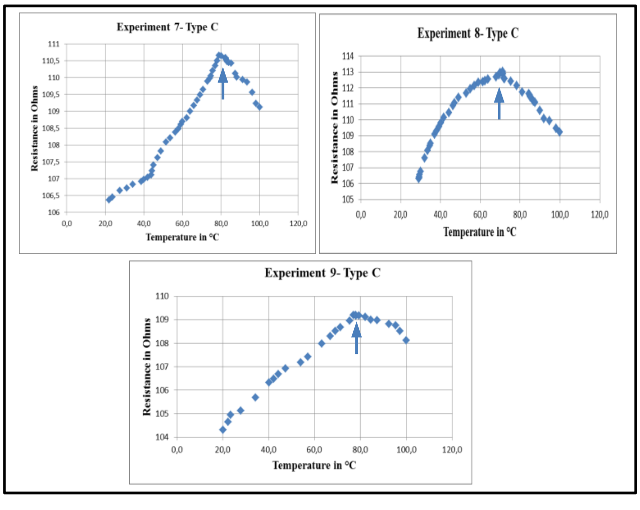

Figure 9. Functional relationship between resistance and temperature for varying temperature profile for Type C sensor.

The design of the Type D is similar to that of Type A & B with the line width of the sensor being (0.615 mm) constant. The number of turns of Type D sensor was reduced to 8 when compared to 16 of Type A and 22 for Type B. The design methodology was adopted to study the impact on the behaviour of the sensor to reduced sensing area with reduced number of turn. The experimental results indicate that there was no significance change in the behaviour of the sensing ability of the Type D sensor. The experimental data pointed to linear relations between the resistance and the temperature for the temperature range of 20°C-80°C and polynomial relationship for temperature higher than 80°C. The experimental analysis also pointed to a decrease in the average sensitivity of 1.146580*10^{-3} ◦C−1. The average sensitivity for sensor Type D expressed was 0.0507 Ω ◦C−1 which is 70% lesser to that of Type A sensor and 74.5 % lesser than that of Type B sensor.

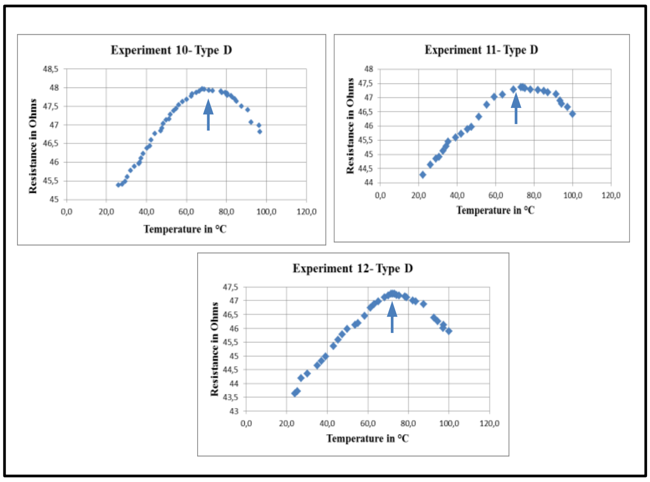

Figure 10. Functional relationship between resistance and temperature for varying temperature profile for Type D sensor.

B. Calculation of the sensitivity of the printed resistive sensor

The sensitivity of all temperature sensors was calculated to compare the impact of the geometrical designs of different type of sensors. The resistance measured to the corresponding varying temperature can be can be expressed as [13]

In the equation (1) T represents the temperature in °C and R0 represents the resistance corresponding to T=0°C.

$$R(T) = R_0(1) + AT + BT^2 + CT^3 \quad (1)$$

The equation (1) for small changes in the temperature ΔT around the temperature T can be rewritten as follows [5]

$$R(T + \Delta T) = R(T)(1 + \propto_T \ \Delta T) \quad (2)$$

Equation (2) can be simplified as

$$\propto_T = \frac{1}{R(T)} \ \frac{\Delta R}{\Delta T} \quad (3)$$

In the equation (2) $\propto_T$ is the sensitivity of the printed resistive sensor in units of °C-1. The $\propto_T$ can also be described as the temperature co-efficient of the printed sensor.

From the experimental procedure 1-9 the average sensitivity of the printed resistive sensor is calculated. The influence of the varying geometry to the sensitivity is studied to find the right geometrical combination of the sensor design.

TABLE I. SENSITIVITY ASSOCIATED WITH DIFFERENT SENSOR DESIGNS.

Sensors	Nominal resistance	Average Sensitivity (Ω ◦C^{-1})	Average Sensitivity (◦C^{-1})
Type A	122.41	0.1732	1.41566*10 -3
Type B	180.23	0.1994	1.10678*10 -3
Type C	106,32	0.2103	1.978122*10 -3
Type D	44.28	0.0507	1.146580 * 10 -3

To summarize the reduction in the sensing area/active area of the sensor surface (silver surface) reduces the sensitivity and stability of the sensor measurement. The behaviour of all sensors was identical to varying temperature profile, but the sensitivity associated with each sensor was highly correlated to the geometrical designs.

C. Bending: With posttreatment of the sensors

The printed resistive sensors were subjected to a bending test after performing test for varying temperature profile. This was carried out to simulate the unwanted bending of the sensor in the real world application and also to study the flexibility of the printed sensors.

The data recorded for the bending test of the Type A sensor is depicted in Table II. The experimental analysis of the Type A sensor indicated a change of up to 2% of resistance associated with the samples (3 samples) from the initial resistance measured after the varying temperature profile test. This is due to the densification of the silver nanoparticles during the previous experiments with the varying temperature profile. The total duration of 20 minutes in the heat furnace with temperature raising from 20 °C–100 °C was acting like sintering process enabling the sensors to reduce the resistance associated with it. Bending of 45° induced an average change 0.892 % of resistance associated with the Type A sensor.

TABLE II. RESISTANCE CHANGE ASSOCIATED WITH INFLUENCING FACTOR BENDING FOR SENSOR TYPE A

Sensor Type A	Initial resistance without contacts in Ohms	Resistance (with contacts) in Ohms before bending at 20 ° C	Resistance in Ohms after bending at 20 °C	% change in resistance
Experiment 13	126,97	128.52	127.36	0,8945
Experiment 14	118,26	119.83	118.80	0,8586
Experiment 15	127.68	128.69	127.50	0,9226

The data recorded for the bending test of the Type B is depicted in Table III. Similar to the results of Type A sensor, the experiments indicates a change of resistance of 1,244 % in average corresponding to the bending of the active surface area. The temperature treatment effect due to the previous set of experiment (4-6) have induced a sintering effect in the sensors and the reduction of resistance up to 2.8% of the previous value was visible. This phenomenon is similar to the Type A sensor.

TABLE III. RESISTANCE CHANGE ASSOCIATED WITH INFLUENCING FACTOR BENDING FOR SENSOR TYPE B

Sensor Type B	Initial resistance without contacts in Ohms	Resistance (with contacts) in Ohms before bending at 20 °C	Resistance in Ohms after bending at 20 °C	% change in resistance
Experiment17	176.17	177.23	177.16	0.0976
Experiment 18	177.87	179.15	175.65	1.9520
Experiment 19	178.05	180.05	177.02	1.6847

The results of the bending test for the Type C printed resistive sensor is depicted in the Table IV. The average change in the resistance due to the bending of the active surface of the sensor was 1.41 % when compared to the resistance value before bending in nominal temperature. This is higher than that of Type A sensor. This is due to the reduced line width of the sensor (0.42 mm) being more sensitive to the bending of the surface. The previous experimental procedure of varying temperature profile has induced a change of up to 3.4 % change in resistance when compared to the original resistance.

TABLE IV. RESISTANCE CHANGE ASSOCIATED WITH INFLUENCING FACTOR BENDING FOR SENSOR TYPE C

Sensor Type C	Initial resistance without contacts in Ohms	Resistance (with contacts) in Ohms before bending at 20 °C	Resistance in Ohms after bending at 20 °C	% change in resistance
Experiment 20	103.28	105.55	105.29	0.2403
Experiment 21	100.69	102.62	100.854	1.7183
Experiment 22	101.12	102.97	100.646	2.2552

The experimental analysis of the Type D sensor for the simulation of the bending after the test of varying temperature profile is depicted in the Table V. Throughout the experiment the average change in the resistance induced by the unwanted bending of 45° was 1, 1 % when compared to the original initial resistance. This type of sensor showed the less impact of the bending effect. This is due to the smaller geometrical dimensions and also this type of sensors had lesser number of turns (low active area for sensing).

TABLE V. RESISTANCE CHANGE ASSOCIATED WITH INFLUENCING FACTOR BENDING FOR SENSOR TYPE D

Sensor Type D	Initial resistance without contacts in Ohms	Resistance (with contacts) in Ohms before bending at 20 °C	Resistance in Ohms after bending at 20 °C	% change in resistance
Experiment 23	46,12	47,21	46,66	1.1650
Experiment 24	46,32	48,51	48,08	0.8864
Experiment 25	46,07	47,09	46,5	1.2529

To summarize the unwanted bending of the active surface area of the all the type of sensor (Type A-D) induced impact on the sensor electrical behaviour. The induced change was proportional to the sensor geometry and the active surface area. The change in the resistance for Type B and Type C was among the highest which had the highest active surface area (silver surface) to detect the impacts due to unwanted bending.

IV. DISCUSSION

A. *Hypothesis Testing*

Hypothesis H1: The hypothesis H1 can be confirmed with the experiments 1-12. The experimental results indicated that Type B sensor had the highest sensitivity is 0.1994 Ω $◦C^{-1}$which is highest among the sensors. This is due to that fact that the sensor Type B had the highest active sensor surface area (silver area) and the highest number of the turns (22). This high active surface enables the sensing of the varying temperature for this type of sensors. The Type D sensor with same line width (0.615 mm) and lesser number of turns (8) having a sensitivity of 0.0507 Ω ° C -1. The calculation of the sensitivity of this type sensor was $1.41566*10^{-3}$ °C -1 in average for all the experimental procedure. This was comparable to the sensitivity of 2.19 $*10^{-3}$ °C -1 mentioned in the art in the literature [5].

Hypothesis H2: The hypothesis H2 can confirmed with the experiments 13-25. There is significant change in the resistance and hence the sensitivity associated with the sensor types (Type A-D) with unwanted bending. The sensor Type B had the change of resistance of 1.24 % in average when unwanted bending of more than 45° was induced. The sensor Type C had the highest change in resistance induced due to the bending with 1,404 % followed by the sensor Type B. The change in resistance induced by bending in the Type D sensor was 1,101 % in average. The highest change due to bending was visible in the Type B and Type C sensor indicating the influence of the geometrical design impacting the electrical behaviour of the sensor. These two types of sensors had the highest active surface area (silver surface). The sensitivity to bending is higher in these types of sensor, since bending effect was well disturbed all to the surface area causing the change.

B. *Implications and Limitations*

From the experimental analysis following implications can be derived (a) the geometry of the printed temperature sensor plays a crucial role determining the sensitivity and stability of the printed resistive sensor. It also plays huge role in determining the influence of the variance of its electrical for the bending of the sensor. (b): The print quality is also another area that needs to investigate. This can be visualized by the difference in the initial resistance of samples of same type. This can be demonstrated with sample 1 of Type A sensor having resistance of 131.96 Ω when compared to sample 2 having 122.41 Ω in the nominal temperature. (c): The sensitivity of the all the sensor (Type A-D) after the reaction point is (resistance not increasing with increase in the temperature profile indicated by arrow in the Figure 7-10) is lesser when compared to the same in the temperature range of 20 °C- 80 °C. The limitation of this study includes the use of the silver nanoparticle ink from AgIc [6] having a continuous temperature of 70 °C which is possible factor behind the reaction point (with resistance value not increasing any further with the increasing temperature profile indicated by arrow in the Figure 7-10) in the sensor behaviour. The other limitation of the study includes the different time profile required by the heat furnace to cool down/heat up leading to measurement inaccuracies.

V. CONCLUSION

In summary a fabrication of low-cost printed resistive temperature sensor is possible with the low-cost circuit printers in conjunction with nanoparticle inks. The so fabricated sensors (Type A-D) showed a linear relationship between the resistance and the varying temperature in the range of 20 °C – 80 °C). The sensitivity and the stability of this kind of sensor can be improved if a professional printer is used for the fabrication process and also by the use of dedicated sintering methodology. The protection of the active area of these sensors (silver surface) with protection layer (encapsulation) resisting the environmental factors like humidity and the improvement of the print quality can be imparted as the future work.

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