© Applied Science Innovations Pvt. Ltd., India Carbon – Sci. Tech. 10/2(2018)1-11

Carbon – Science and Technology

ISSN 0974 – 0546

http://www.applied-science-innovations.com

RESEARCH ARTICLE Received: 28/3/2018, Accepted: 6/6/2018

Inkjet printed temperature sensor and its quality characteristics

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Abstract: The subject of the study investigates the fabrication and measurement accuracy of resistive temperature fabricated using low-cost inkjet printer. For this study a low-cost commercially available inkjet printer was used in conjunction with a high-quality nanoparticle ink for the fabrication process. Electrical conductive silver nanoparticle ink from AgIC with a sheet resistance of 200 mΩ/sq was used in the fabrication process. The selection of the ink was based on the fact that no additional sintering process was needed for curing. The temperature sensors were fabricated without pre/post treatments to determine the influence of lack of pre/post treatment, influence of resulting bending due to lack of encapsulation and influence of environmental factors / aging on the temperature measurement accuracy. The result of the study indicates a linear relationship between the temperature and corresponding sensor resistance in the range of 20-80 °C. In the higher temperature ranges more than 80 °C, a polynomial relation between the temperature and corresponding resistance can be visualized. The results also indicates to the fact that lack of the print quality outshines all other negative influence (lack of encapsulation and environmental) as the major factor influencing the temperature measurement accuracy.

Keywords: Low-cost printer; printed temperature sensor; Low-cost printed electronics; temperature; resistance

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1. Introduction: Over the recent past decades interest in the printed electronics and fabrication methodologies including the low-cost inkjet printing have made big leaps to co-exist with conventional silicon based manufacturing systems. Fabrication of inkjet printed passive components and devices have been already demonstrated in the literature [1 - 4]. The low-cost inkjet printing methods being alternative to the conventional electronic parts have been demonstrated through the art in the literature [5 - 9]. The improvement of the electrical properties and the stability associated with the low-cost inkjet printing process are keys to bridge the gap between the conventional fabrication processes and the low cost inkjet printing technologies. The study about the improvement of the electrical & mechanical stability of such low-cost inkjet printed silver nanoparticles in combination with polymer inks were demonstrated in the literature [7 - 9]. Bringing down the pre and post treatment temperature on the printed flexible substrate (100 °C – 200 °C) can also be considered as a road block for the realization to production. The conductive /dielectric inks used to print (fabrication) also plays an important role to bring the low-cost inkjet printed electronics to main stream. The invention of inks with conductive nanoparticle and lesser curing temperature (room temperature) are currently available in the market [6] have made huge strides in commercialization of low-cost printed electronics. The subject of this study investigates the influences of the factors such as bending & printer quality on a low-cost inkjet printed resistive temperature sensor. Effect of quality of the printing and the impacts of the attributes from the ink used for the fabrication process is also subjected to the study. A relevant limitation of the study includes the ink itself which have larger impact on the temperature measurement profile. This can be considered as the critical problem which needs to be addressed in case of a temperature sensor. The functionality of the printed temperature sensors based on the assumption, that there is a significant relation between resistance (Ω) and temperature (°C): "change in resistance is observed upon varying the temperature" [5]. Such relations are linear in a range from 30°C to 42 °C as well as -10 °C to 140 °C [5]. Unfortunately, the use of inks sometimes are limited by maximum continuous temperature, e.g. AgIC Inc. limited their ink to 70 °C (see datasheet) [6]. With such a limitation of the conductive ink used for the fabrication, the temperature measurement in the range over 70°C in a non-permanent scenario is unknown.

The subject of the study investigates factors that are influencing the temperature measurement via measurement of corresponding resistance for varying temperature in the range of 20 °C to 100 °C for a printed low-cost sensor. The following factors were considered as relevant influencing variables with regard to the target value of resistance (Ω) for the purpose of indirect measurement of the temperature in ° C in the course of the investigation: (1) ink; (2) printer; (3) Printed surface; (4) amount of ink; (5) sensor geometry; (6) bending of the printed surface; (7) pre- and post-treatment; (8) Environmental factors (humidity and temperature change). With regard to the above mentioned influencing factors, this study is based on the following assumptions:

Table (1): Factors influencing the characteristics of printed temperature sensor

Sr. no.	**Factors influencing**	**Constant**	**Variable**	**Comments**
1	Ink	X		Constant, since the influencing variable is easily controllable
2	Printer	X		Constant, since the influencing variable is easily controllable
3	Surface area	X		Constant, since the influencing variable is easily controllable
4	Volume of ink	X		Constant, since the influencing variable is easily controllable
5	Sensor geometry	X		Constant, since the influencing variable is easily controllable
6	Bending		X	Variable, due to the fact that automatic / unwanted bending of the surface (e.g. Foils) could occur in the higher temperature range
7	Temperature pre & post treatment		X	Variable as higher temperature could automatically/ unintentionally cause unintentional compaction or partial destruction of the ink
8	Environmental factors		X	Variables, lifetime of the sensor (ageing) can induce automatically / unintentionally change in resistance.

Note: Summarization of the influencing factor from the literature review [1-10].

Thus from the eight variables, five variable are kept constant and the variables which deviate unintentionally in the reality are varied in the study to record the result. The influencing factors such as bending, temperature after treatment and environmental factors are taken into the consideration of interest for this study. From this the following hypotheses concerning the influence of these three factors on the temperature measurement in °C can be derived via resistance. Hypothesis H1 considers the unwanted self-bending of the surface, in this case a PET film on which the sensor is printed. As a result the sensor acts also as a strain sensor (added functionality) through an increased or decreased resistance depending on the curvature of bending that's inside or outside (bending). As mentioned in the previous studies [7 - 10], the maximum curvature of the film (PET substrate) can reach an angle greater than 45 ° in the higher temperature range, unless they are strongly fixed. Since a low –cost printed sensor without being strongly fixed is taken as the test piece for the study and the following hypothesis can be formulated in the temperature range of 20-100 °C:

H1: If the sensor surface experiences an unwanted bending of greater than 45 ° outwards due to influence of temperatures in the range of 20-100 °C, then there is a significant increase of the measured resistances Ω that is temperature measurement inaccuracy of greater than 10% takes place.

The Hypothesis H2 and H3 are concerned with the study of influence of the lack of temperature treatment for the densification of the ink on the flexible substrate films to the functional relationship between resistance (Ω) and temperature (°C). This is in line with the art mentioned in previous studies [7 - 10]. This includes the detailed study about the change in the functional relationship between resistance (Ω) and temperature (°C) due to the automatic/unintentional compression of the ink on the flexible substrate foil taking place at the higher temperature. Following hypotheses can be formulated in the temperature range of 20-100 ° C.

H2: If the ink is not densified on the surface via temperature after treatment, then there exist no linear relationship between resistance Ω and temperature °C described in the literature [5] for a temperature range of 20-100 °C.

H3: If the ink on the surface reaches the temperature of 100 °C for a short duration inducing a strong compression of the ink , then there exist a linear relationship between the resistance (Ω) and temperature (°C).

The hypothesis H4 clarifies the question of degree of influence of environmental factors measured in terms of humidity and temperature impacting the sensor functionality/capability. The following hypothesis describes the facts:

H4: If an untreated or after-treated printed temperature sensor is subjected to a temperature and humidity change from 85 °C at 85 % humidity to 10 °C at 45 % humidity for 60 days, then the temperature measurement accuracy decreases by 10 %. This change in measurement accuracy is observed in corresponding resistance measurement.

1. **Method:** As mentioned in previous studies [7 - 10] 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*. The following figure shows the design:
    c) Layer Substrate: Novele™ was used as substrate from NovaCentrix. AgIC Printing System;
    d) Ink: For printing conductive silver ink from AgIC Circuit Printer Cartridge Set with a critical temperature range over 70°C (maximum continuous temperature) were used. Electrical conductive silver nanoparticle ink from AgIC with a sheet resistance of 200 mΩ/sq. was used in the fabrication process [6] .The composition of the conductive silver ink consists of silver (15 % wt (Silver 0.1 mg/m3)), water and ethanol. The viscosity of the conductive silver ink is 2-3 [mPa*s] and the surface tension is 30 -35 [mN/m]. The selection of the ink was based on the fact that no additional sintering process is needed for curing, the ink can be cured with normal room temperature. The integration of the adopted silver ink to the printer selected was easier;
    e) Printout: All printed layers were not pre-treated or post-treated;
    f) Test parameter: Electrical resistance (Ω), temperature (°C) and geometry;
    g) Measurement devices: Digital Multimeter (PeakTech), Digital 4 Channel Thermometer (Voltcraft Plus), Heating furnace (Memmert); (i) Test environment with Climate Chamber: An installation of the company Vötsch type VC³4018 (Link: http://www.v-it.com/de), with following two test cycles was used: Cycle 1 with a temperature of 85 °C and a humidity of

85% as well as a duration of 48 hours and cycle 2 with a temperature of 10°C and a humidity of 40% as well as a duration of 24 hours. The total test time was approximately 60 days

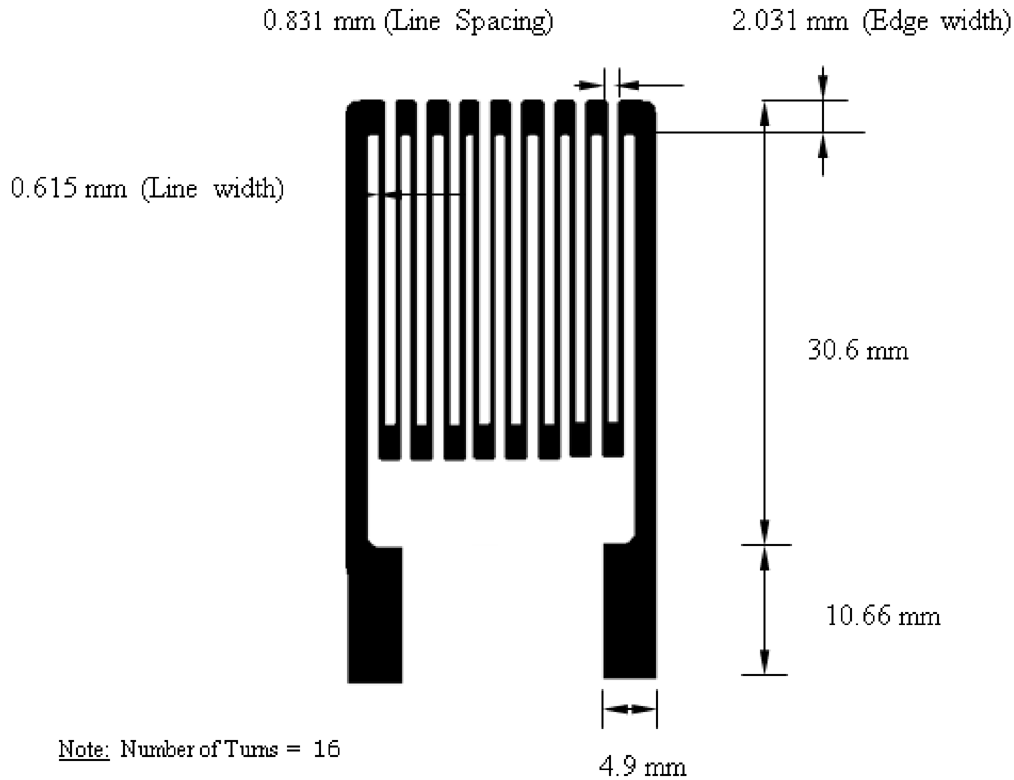

Figure (1): Design of the temperature sensor.

Figure (2): Fabricated inkjet printed resistive temperature sensor used for the experimental analysis.

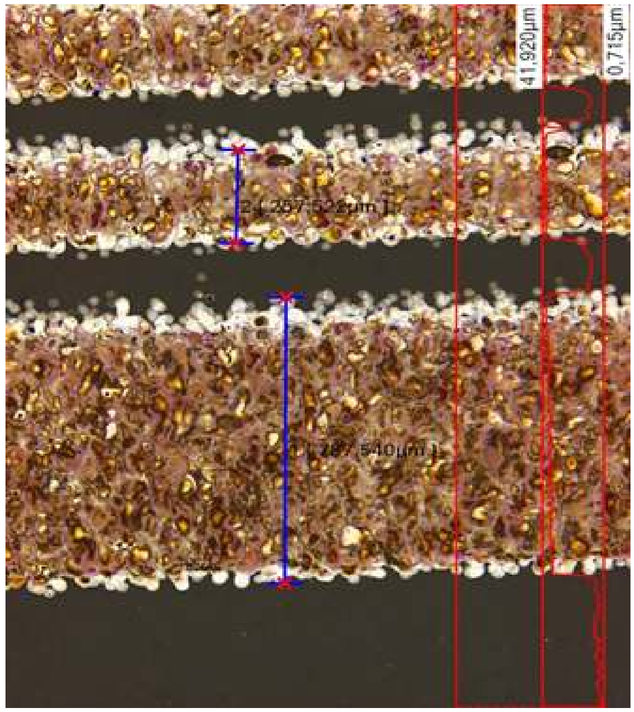

Figure (3): 3D-laser-scanning microscope-recording of the surface of inkjet printed resistive temperature sensor.

To investigate the unwanted influence of the factors like "temperature after treatment, bending and environmental factors" on the measurement accuracy of the printed temperature sensor, the following test procedures were selected:

2.1.Temperature after-treatment:

In this experimental procedure the impact from an unwanted temperature treatment is simulated to the printed sensor which leads to a compression effect of the ink on the substrate film, which in will turn lead to a reduction in resistance value. For this purpose the sensor printed by using the AgIC ink [6] were placed in the heating furnace at temperature of 20 °C and the temperature was gradually increased to 100 °C. Within this period total number of measuring points n= 20 were recorded. The number of repetitions (c) was set at c = 5, so that the total number of measurement points (N) is equal to N = n * c = 100 were recorded. Thereafter, the same printed sensor was cooled down again to 20 °C and again subjected to the above procedure, thus there were two temperature profiles from the printed temperature sensor could be compared.

2.2. Bending: In this experimental procedure the unwanted influences on the printed sensor caused by the bending of the PET film were studied. In this case the substrate film acts as a strain sensor, for this reason, based on preliminary tests in regard to the possible bending of the foil, it was assumed that there is an outward curved bending at 45 ° in the extreme case, which is expected to increase the resistance of the printed sensor. Thus the cumulative effect of temperature and bending would be visible in the measurement and inducing an increased resistance associated with the printed resistive temperature sensor. The flow of implementation of the investigation takes place in the form that, the already tested sensors from the temperature after-treatment are now subjected to the bending and measured again.

2.3. Ageing: To study the impact of the printed resistive temperature sensor to ageing process, the sensors were exposed in a climate chamber to 85 °C in an alternating stress at 85 % humidity (48 hours) and 10 °C at 40 % humidity (24 hours) for 60 days. After the ageing test the electrical properties of the printed sensor were measured. The tested samples were approximately 9 cm long printed circuit traces that represent the delicate, thin turns / turns of the original sensor. Their functionality was considered particularly irrelevant.

3. Results

The following results were determined for the individual influencing factors like "temperature after treatment, bending and environmental factors".

3.1. Temperature after treatment: Measurement Results from all the test series could be used. The survey of statistical features showed no particularities or deviations. The series of experiments from 1-5 showed linear relationship between the resistance and temperature for temperature range of 20 - 100 °C. As already shown in various literature investigations [5], almost a linear behavior between the temperature & resistance was demonstrated for subsections in the lower temperature ranges, as illustrated in the following figures:

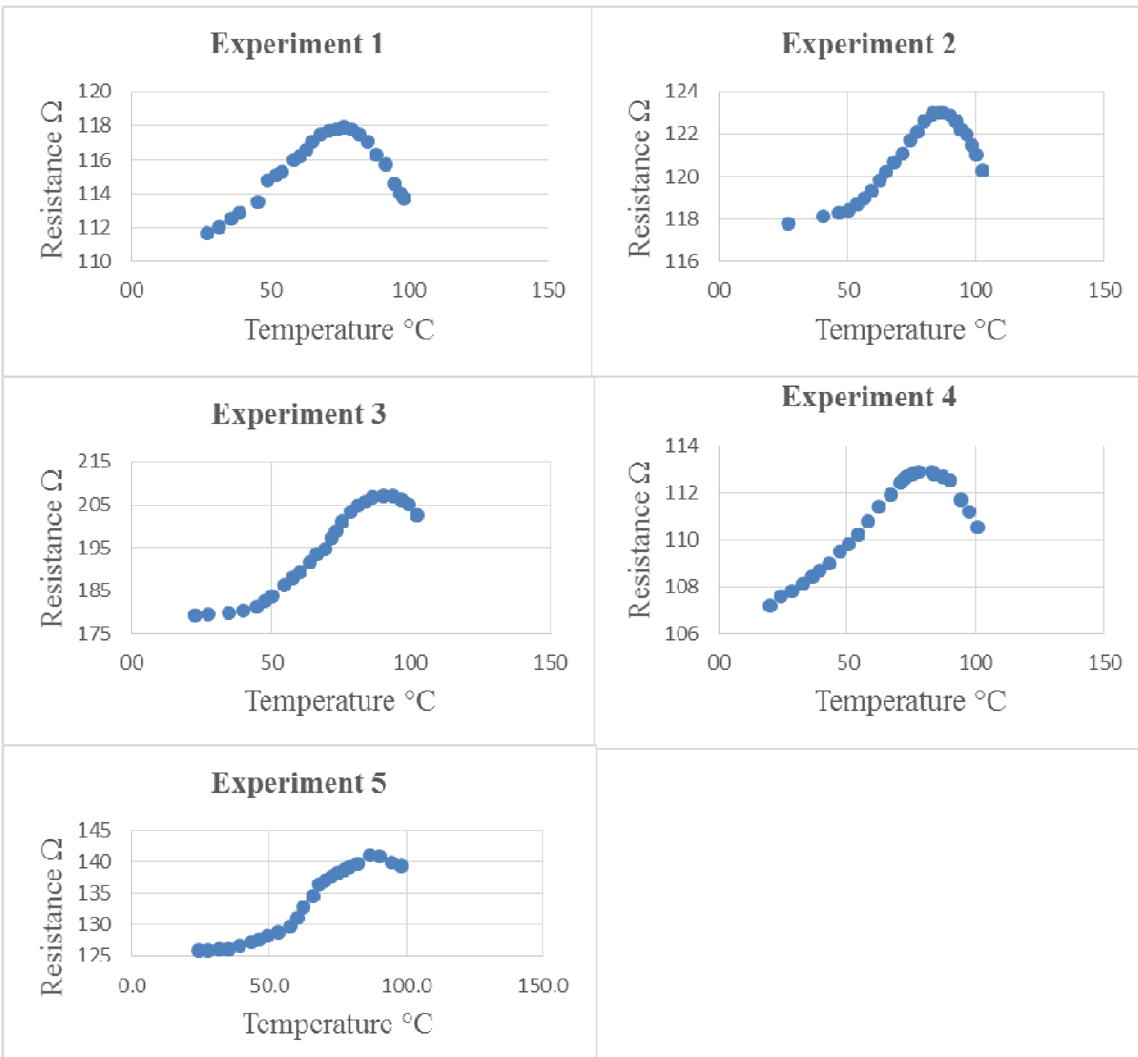

Figure (4): Functional relationship between resistance and temperature before temperature after treatment

Experiments 1 - 4 shows linear relationship between resistance and temperature for the temperature in the range 70-80 °C and for higher temperatures a non-linear behavior becomes visible. The behavior suggests a polynomial course for the temperature more than 80 °C for the printed sensors.

In all pictures a turning point (fall of resistance) is recognizable, which lies depending on the experiment between temperatures of 70 - 90 °C. In connection with the above mentioned results it was necessary to examine how the sensor behaved in a repeated measurement environment, i.e. to check whether there is a significant influence on the following measurement after the sensor have reached the temperature of 100 °C for one time for a short-time duration. For this purpose, in experiments 6 - 10, the same sensors after cooling to 20 °C were again subjected to the same measurement procedure as of Experiment 1-5. The consideration of the statistical features showed no special features/deviations, so that all measured values could be included in the investigation. The following results were now available in this regards.

The results of the test series consisting of experiments 6 -10 shows a nearly linear course for all experiments, which is in accordance with the literature [5]. It is also expected that the average resistances of experiments 6 - 10 were on average 6 % - 11 % lower compared to experiments 1 - 5 in the lower temperature range between 20 °C and 30 °C. For the upper temperature ranges, the difference tended to decrease further.

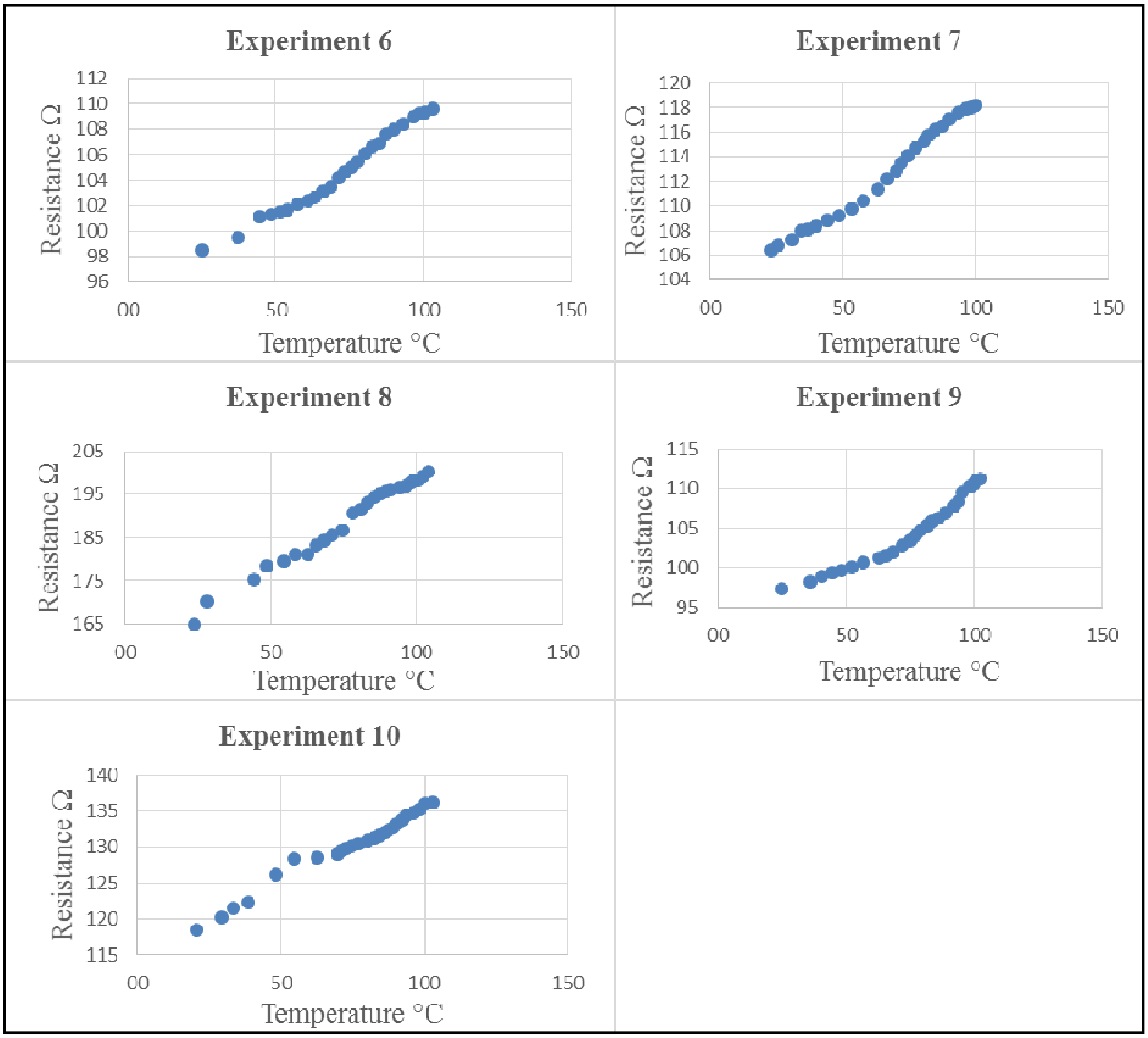

Figure (5): Functional relationship between resistance and temperature after temperature post- treatment.

3.2. Bending: In the next step, the influences of the bending on the printed resistive temperature sensor were examined. For this purpose, the test samples from the Experiments [6 -10] were used again. The bending 45 ° of the printed sensor induced an increased resistance 0.6 - 1.1 Ω in average at 20 °C output temperature were measured.

Table (2): Change in the resistance associated with influencing factor bending.

Experiment	Resistance value at 20 °C - Before bending in Ω	Resistance value at 20 °C - recorded during the bending in Ω	Change in resistance Ω
6	97.7	98.3	+ 0.6
7	106.1	106.8	+ 0.7
8	165.0	166.1	+ 1.1
9	97.4	98.3	+ 0.9
10	118.5	119.2	+ 0.7

It was not possible to repeat the bending tests in order to enlarge the sample, since a single bending have already resulted in partial / significant increases in the resistance value. In the perspective of the experiments the numbers of trials were very small, pointing to the necessity to continue the test with other test series which yielded the following results.

Table (3): Test results for the extended test series for influencing factor bending.

Experiment	Resistance value at 20 °C - Before bending in Ω	Resistance value at 20 °C - recorded during the bending in Ω	Change in resistance (Ω)
11	107.4	108.6	+ 1.2
12	110.5	111.4	+ 0.9
13	107.9	109.2	+ 1.3
14	112.8	114.4	+ 1.6
15	109.8	110.4	+ 0.6

Also in the second series of experiments, the resistances increases during the bending process leading to a permanent change the in resistance associated with the printed resistive temperature sensor after bending. This makes a repetition of the experiment impossible due to the permanent change in resistance. In total experimental points of $N = n * C = 5 * 2 = 10$ attempts, resistance due to outward bending is expected to increase in the range of +0.6 to +1.6 Ω. Finally the bending test was considered over the entire temperature range. For this purpose a new test series with experiment starting from 16-20 was carried out with newly fabricated sensors. These sensors taken for the new test series were not subjected to any temperature pre/post treatment. From the five experiments in the test series, three experiments were evaluated.

The experimental procedure to visualize the effect of bending with temperature started with initial temperature of 20 °C with expected change in resistance around + 0.6 Ω and + 1.6 Ω. Over the course of the experiments it can be noted that the corresponding functional relationship between resistance and temperature over the range of 20 °C to 100 °C temperature was not linear, but some area of the experimental data showed linear relationship between the resistance and temperature could be visualized. Conspicuous however was the fact that in this test series with resistance of the printed sensors were in the range 80 - 85 Ω ,which were generally well below the resistances of the previous test series(average resistance of the printed sensor from previous test series were greater than 100 Ω).

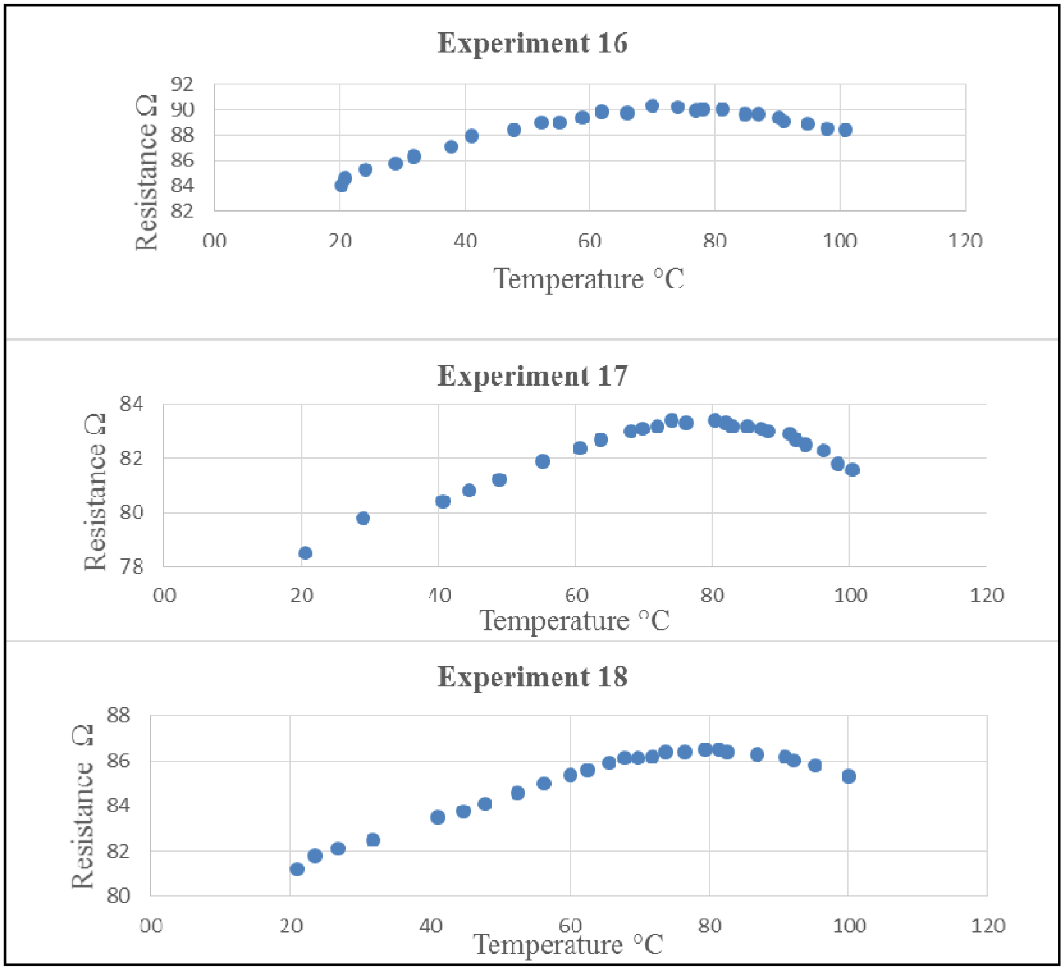

Figure (6): Functional relationship between resistance and temperature without temperature pre / post treatment with bending effect

3.3. Environmental factors / ageing effect: To test the impact of the environmental/ ageing factors on how the turns (geometry of the printed sensor) behave under the above mentioned influencing factors, a new test series was created. The experiment 20 - 25 was performed to evaluate the above mentioned influencing factor and yielded the following results mentioned in the Table (4). The experiments were carried out in the in the climate chamber from manufacturer Vötsch.

Table (4): Test results for the influencing factors Environmental/ ageing factor on the sensor.

Experiment number	Resistance value at 20 °C - before the climate chamber experiment in Ω	Resistance value at 20 °C - after the climate chamber experiment in Ω	Change in resistance in Ω (%)
20	16.11	13.89	- 2.2 (13.7%)
21	15.20	13.87	-1.3 (8.6%)
22	16.38	15.21	-1.2 (7.3%)
23	15.92	14.84	-1.1 (6.9%)
24	16.39	15.45	- 0.9 (5.5%)

The results indicates a decrease in resistances in the range of -0.9 Ω to -2.2 Ω, i.e. it can be assumed that heating up to 85 °C for the experiment has contributed to the compaction of the ink (curing of the ink) thereby reducing the resistance associated with the printed sensor. The resistance reduction has a maximum value of 13.7 %. The results suggest that the sensor as a whole could have reduced resistivity as part of the investigation.

4. Discussion

4.1. Hypothesis Testing:

Hypothesis H1: The question of the investigation was on the influence of unwanted bending on the flexible substrate film impacting the temperature measurement capability of a low- priced printed sensor. The results shows the increase in the resistance comparatively low in the range from +0.6 Ω to +1.6 Ω, assuming an output resistance of 100 Ω on average from the printed temperature sensor. So with a measurement error less than 10 %, Hypothesis H1 can be confirmed.

Hypothesis H2: Deals with the question of influence of an unwanted or unscheduled temperature after treatment on the functional relationship between resistance and temperature of a printed temperature sensor. The results indicate that for a temperature profile of 20 °C - 100 °C the relation between resistance associated with printed temperature sensor and increase in the temperature is not linear. These points to the fact that derivation of individual functions in this context is necessary to draw the correct conclusion about the temperature and corresponding resistance measured for the printed temperature sensor. In other words, the relationship between resistance and temperature is complex and eludes a simple interpretation. Thus hypothesis H2 is confirmed.

Hypothesis H3: The investigation deals with the question of whether a short one-time increase in temperature up to 100 °C is sufficient to densify the ink, so that there exist a linear functional relationship between resistance and temperature for the sensor after this effect. The results points to fact the increase in the temperature above the 100 °C is sufficient to achieve a necessary densification of the ink (curing of the ink), thus Hypothesis H3 is confirmed. This aspect is relevant since temperature sensor would give false results on a case-by-case basis, depending on whether a linear or non-linear functional relationship is assumed by the viewer.

Hypothesis H4: Study investigates the influence of environmental factors on the measuring accuracy of the temperature sensor. The results are in line with the assumption that the resistance of the non-pretreated pattern varies by more than 10 %, in the present case a maximum of 13.7 %. Thus the Hypothesis H4 is confirmed i.e. the environmental factors can influence the measurement accuracy of the temperature sensor in a range of more than 10 %.

4.2. Implications and Limitations

From the above results, the following implications can be derived. (a) Low-cost inkjet printed temperature sensors can be manufactured but, if left untreated presents a considerable difficulties in interpreting the values of a functional relationship (between resistance and temperature) may change as part of the temperature measurement (b) Measurement inaccuracies due to bending of the temperature sensor at elevated temperatures is a conditionally a relevant problem, since the measurement deviations are in the range of well below 5 %; (c) Environmental factors / ageing can influence the temperature measuring capability of the sensor to a relevant extent of more than 10%; (d) An important influencing factor, which was not actually the subject of the investigation is the considerable fluctuation of the print quality, which is visualized by different initial resistance values for the individual sensors. In the 20 experiments considered, the lowest value of resistance was 80 Ω and the maximum value was 180 Ω for the individual sensors. These fluctuations are much more influential in temperature measurement accuracy than all other factors combined, even though the average resistance of the sensor from the majority of experiments was between 90-110 Ω. The scope of future investigations should take into account that the sensor as a whole for subjecting a climatic chamber test and the effects of an inexpensive encapsulation of the tracks of the sensor should also be examined.

In summary a low-cost inkjet printed temperature sensors are still unsuitable for professional use, but the use of low-cost semi-professional printers and low-cost heat after treatment systems could make a significant contribution to improving measurement accuracy.

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