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# Untreated Low Cost Inkjet Printed Temperature Sensors -Conditionally Suitable?

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## Abstract

The subject of the study investigates different temperature behaviour of a printed temperature sensors fabricated using a low-cost inkjet printer and silver nanomaterial ink. The aim of the investigation was to check whether an inexpensive printed temperature sensor without pre and post treatment can provide a reliable temperature data reading in the range of the temperatures from 20 ° C to 100 ° C. For this purpose test number of N = 200 experimental evaluations were carried out. The experimental results indicates a positive linear relationship between the resistance (Ω) and temperature (°C) for the temperature range of 20°C and 70°-80°C (sensor B) and 75-85°C (sensor A). The results also indicates a non-linear or negative linear correlation between resistance (Ω) and temperature (°C) for the temperature range of between 70°-80°C for sensor Type B and 75-85°C & 100°C for sensor Type A. There exist also a polynomial functional relationship between the resistance (Ω) and temperature (°C), when we consider measurement for the entire temperature range, which can be used for the prediction of the temperature data.

## INTRODUCTION

Low-cost inkjet-printed products became more and more relevant for industrial use. Significant progress can be seen in printing technology, pre- and after treatment and inks [1] [2] [3] [4]. Problems are reported with regard to lifetime [5] [6], e.g. cycle bending reliability [5]. As mentioned in previous articles the ink itself is a relevant factor in combination with low-cost printed electronics [7] [8] [9]. The quality of the ink influences the printout in a significant way: “The investigations have shown that it is possible to print useful, low-cost circuits by combining suitable inks (in this work silver and carbon ink), while printers with higher quality (compared to the Brother printer used) from the middle price segment are certainly to be preferred for semi-professional / professional applications” [7]. That means, it is a question of the right combination of different quality factors like ink, printer, geometry, pre & post treatment and others. The relevance of the inks was also highlighted by other researches: “When flexed, PEDOT:PSS remained conductive for a lower radius of curvature (10 mm) than silver. Among the printed patterns, the sinewave pattern was observed to be superior for flexible electronics applications“[6]. Stability against flexing is one quality aspect, environmental stability of conductive inks another aspect [10] [11], e.g. caused by the hygroscopic behavior or pH-value [12] or temperature [13] [14]. The limitation of an ink with regard to the temperature is a problem which needs to be considered in case of a temperature sensor. A printed temperature sensor based on the assumption, that there is relation between resistance (Ω) and temperature (°C): “…change in resistance is observed upon varying the temperature” [13]. The reported relation is, depending of the application, printer – professional or semi-professional - and ink, linear in a range from 30°C to 42°C or -10°C up to 140°C [13]. The use of different inks are also limited by maximum continuous temperature, e.g. the ink from AgIC Inc. is limited to 70°C (see datasheet) [15], which is maybe a limiting factor for temperature measurement of more than 70°C itself. The printing technology is – beside the treatment [16] [17] [18] [19] the other relevant aspect with influence the quality of the printed electronic. Depending on the quality, the price ranges for printers “… between 30.000 € for semi-professional up to more than 100.000 € for professional use” [7]. To sum up, there is still room for improvement in the area of investigation [20] [21] [22] [23].

Aim of the research is to figure out, whether it is possible to print a reliable, functioning cheap temperature sensor within a non-critical temperature range from 20 °C up to 70 °C - based on a combination of low-cost / non-professional printer and a high quality silver ink [15] with a maximum continuous temperature of 70°C. Based on these assumption the following hypotheses was formulated:

**H1:** If a high quality silver ink – limited to 70°C maximum continuous temperature – is used for printing a temperature sensor for measuring a fluctuating temperature range of 20°C up to 70°C with a low-cost / non-professional printer, than we will have a good positive linearity between resistance (Ω) and temperature (°C) in the observed range.

Furthermore should be investigated the critical temperature range from 70°C up to 100°C. The following hypotheses was formulated:

**H2:** If a high quality silver ink, limited to 70°C maximum continuous temperature is used for printing a temperature sensor for measuring a fluctuating temperature range of 70°C up to 100°C with a low-cost / non-professional printer, than we will have a good positive linearity between resistance (Ω) and temperature (°C) in the observed range.

The aspects of pre or post treatment are not taken into to the consideration, due to the fact that a cheap printed sensor is subject of this research (without pre and post treatment).

## METHOD

### Materials and Methods

As mentioned in previous studies [7] [8] [9] the following materials and methods were used to test the hypotheses.

(a) Printer: The switches were printed with the low-cost printer from Brother (Typ: MFC-J6710DW); (b) Sensor Design / Geometry: The first sensor (Type A) was created by using *Microsoft Word 2013*. The following figure shows the design:

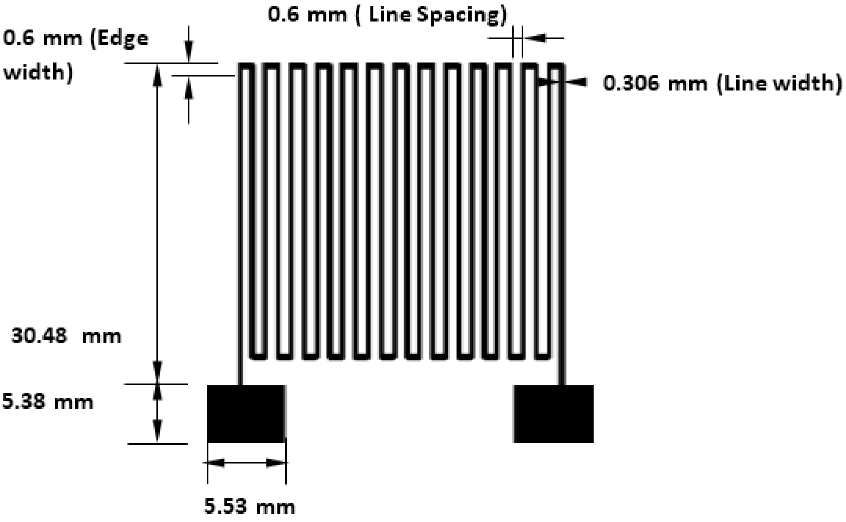


**Figure 1.** Design of the temperature sensor – Typ A

The second sensor (Type B) was created based on the assumption, that the design parameters may have also an influence of the quality of the temperature sensor:

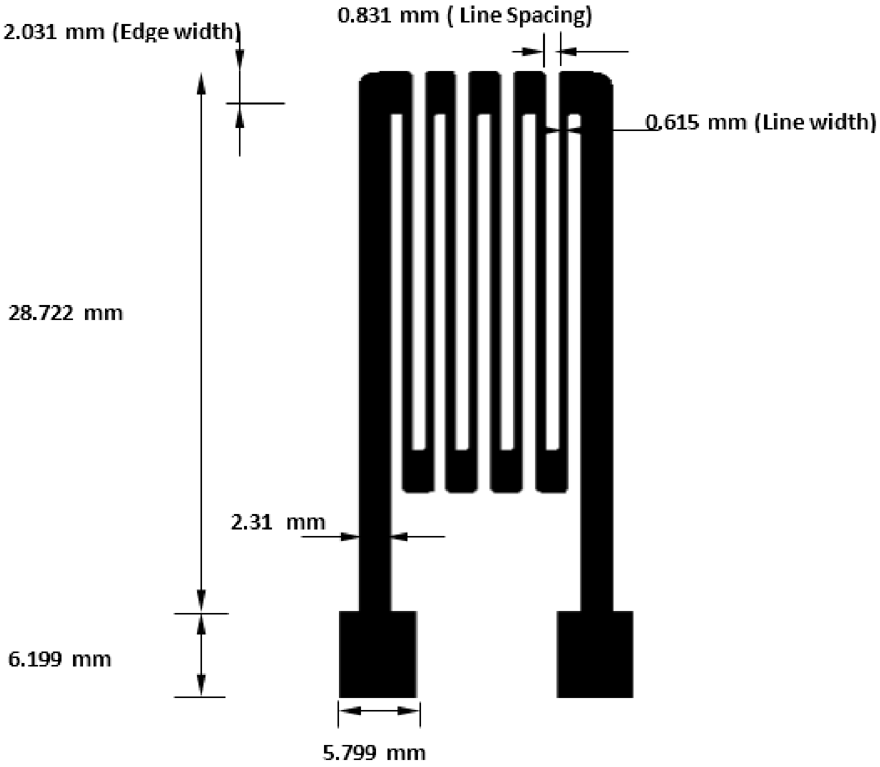


**Figure 2.** Design of the temperature sensor – Typ B

(c) Layer Substrate: *Novele™* was used as substrate from *NovaCentrix.* AgIC Printing System; (d) Ink: For the printing were used the AgIC Circuit Printer Cartridge Set with a critical temperature range over 70°C (maximum continuous temperature). In this set the silver ink has already been poured into a set of 3 *Brother LC71* (US) / *LC1240* (Europe) cartridges; (e) Printout: The printed layer was 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).

## Measurement Procedure

The aim of the study was to find a possible relation between the large target temperature and the resistance associated with the printed temperature sensor, taking into the account of the influences from nanomaterial ink, printer and design/ geometry.The initial measurement started with Type A and Type B sensors printed with the AgIC ink [15] being placed in the heating furnace at a temperature of 20 ° C. Then the temperature of the heating furnace was raised from 20 ° C to 100 ° C and within this time period, measurement points (n= 20) for the varying temperature and corresponding resistance of the both sensors (Type A and Type B) were collected. 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. So in total 100 experimental data were collected for sensor Type A and 100 experimental data were also collected for sensor Type B. Based on the recommendations of Dankoco et al (2016) [13], the sensitivity (temperature coefficient) was determined at 20.7 ° C. The sensitivity (temperature coefficient) was 0.81807 * 10-3 ° C-1 for the printed temperature sensor evaluated in this study in comparison to 2.19 * 10-3 ° C-1 from the study by Dankoco et al. (2016) [13]. The sensors were again tested for the functionality as per the art mentioned in the literature [13].

## RESULTS

The collected measurement data sets were checked for outliers and plausibility. The five datasets for the Type A sensor could be completely taken into account, i.e. N = 100 experimental points. For sensor Type B two datasets had to be removed due to problems in the measurement out of five data sets. So in total 60 (N = 60) experimental data points were available for the sensor Type B. The consideration of descriptive characteristics such as Mean, standard deviation and variance showed no abnormalities for the measurement data.

### Hypotheses H1 and H2 for Temperature Sensor Typ A

The investigation provided conformation of hypothesis H1 (20 ° C to 70 ° C) or hypothesis H2 (70 ° C to 100 ° C) with respect to the temperature sensor Type A. The corresponding results are depicted as below:

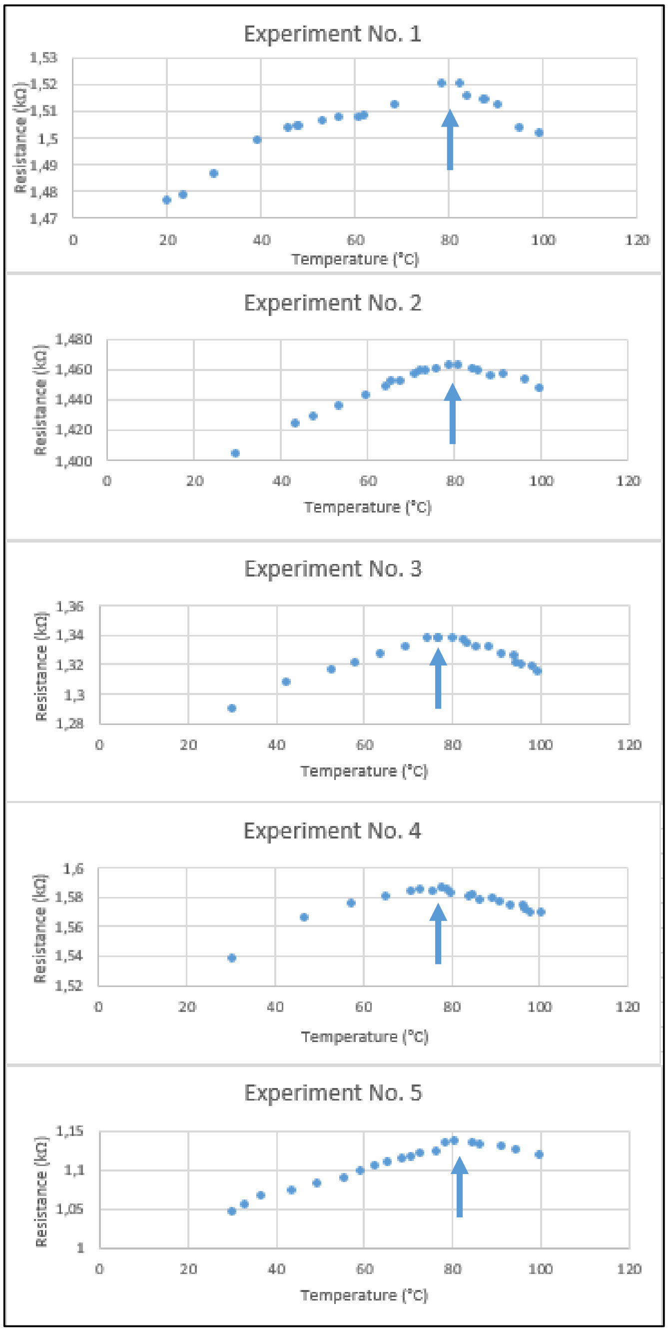
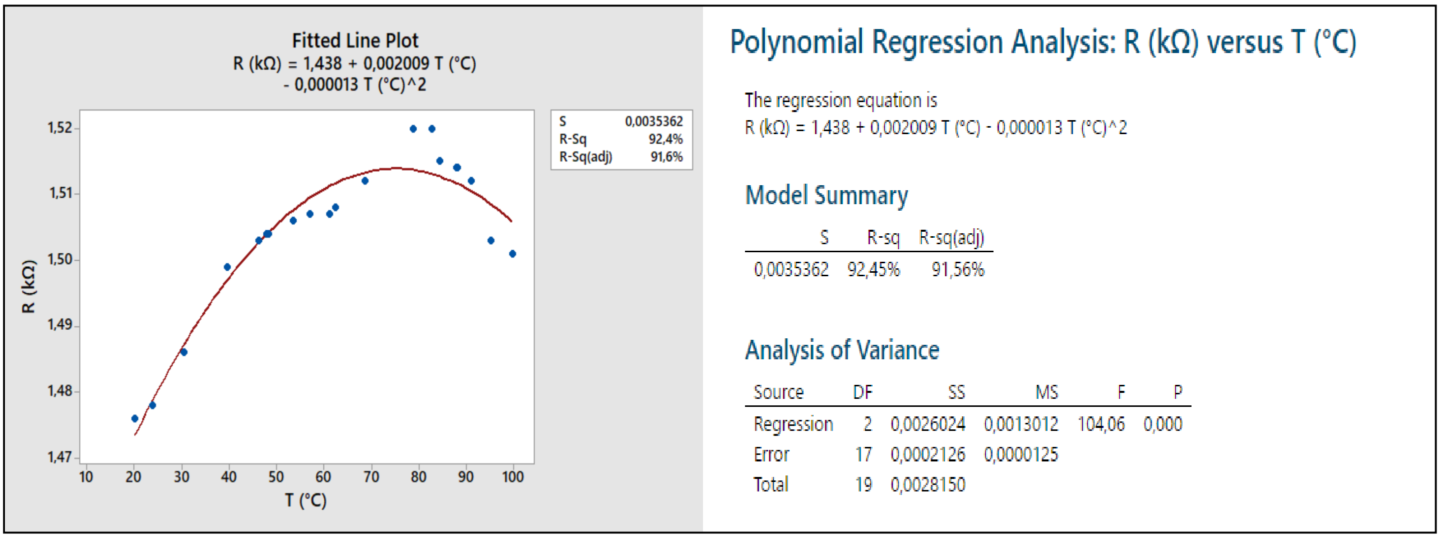


**Figure 3.** Results – Correlation between Temperature (°C) and Resistance (kΩ) – Typ A

Descriptive analysis from the Fig. 3. suggests that between 20 ° C and 75 till 85 ° C (indicted by arrow symbol in the Fig. 3), there exist a linear relationship between the temperature measured and the corresponding resistance of the printed temperature sensor. This is in accordance to the Hypothesis H1. Whereas the measurement points above 75 ° C especially between 85 ° C and 100 ° C, there exist no positive linear relationship between temperature (°C) measured and the corresponding resistance (Ω) of the printed temperature sensor. This indicates to a non-linear relationship between the temperature (°C) measured and the corresponding resistance (Ω) for these temperature ranges. In all experiments, it is still noticeable that at around 80 ° C temperature, a reaction (fall of resistance) is likely to occur that significantly alters the correlation between the measurements. The calculated correlation coefficients according to Bravis-Pearson can be found for the experiment number 1-5 at $r_1$ = 0.98 and $r_2$ = 99.86 and $r_3$ = 99.19 and $r_4$ = 0.98 and $r_5$ = 0.99. Thus to conclude from measurement data , that there is a strong positive linear correlation for all experiments at temperatures of 20 ° C to 75 ° C / 85 ° C. For the temperature range between 75 ° C / 85 ° C and 100 ° C, there exists negative linear correlation for all experimental data with values of r (regression coefficient) from -0.97 to -0.98.

Due to the course of the curve, an investigation was feasible for possible non-linear relationships. An investigation with the statistics software Minitab 18 yielded the following results:



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Polynomial Regression Analysis: R (kΩ) versus T (°C)

The regression equation is
R (kΩ) = 1,438 + 0,002009 T (°C) - 0,000013 T (°C)^2

Model Summary

        S    R-sq  R-sq(adj)
0,0035362  92,45%     91,56%

Analysis of Variance

Source      DF         SS         MS       F      P
Regression   2  0,0026024  0,0013012  104,06  0,000
Error       17  0,0002126  0,0000125
Total       19  0,0028150
```

**Figure 4.** Results – Polynomial Regression between Temperature (°C) and Resistance (kΩ) – Experiment No. 1 from Sensor Type A

**Table 1:** Polynomial Regression – Comparison

| Experiment | Regression Equation | R-sq(adj) | Regression p-Value |
|---|---|---|---|
| No. 1 | R (kΩ) = 1,438 + 0,002009 T (°C) - 0,000013 T (°C)^2 | 91,56% | p = 0,000 |
| No. 2 | R (kΩ) = 1,312 + 0,003527 T (°C) - 0,000021 T (°C)^2 | 95,01% | p = 0,000 |
| No. 3 | R (kΩ) = 1,190 + 0,003852 T (°C) - 0,000026 T (°C)^2 | 90,34% | p = 0,000 |
| No. 4 | R (kΩ) = 1,453 + 0,003471 T (°C) - 0,000023 T (°C)^2 | 98,59% | p = 0,000 |
| No. 5 | R (kΩ) = 0,942 + 0,003922 T (°C) - 0,000021 T (°C)^2 | 95,07% | p = 0,000 |

Note: Polynomial Regression between Temperature (°C) and Resistance (kΩ) – Experiment No. 1 from Sensor Type A

The results from the analytical statistics with respect to Experiment No. 1 using sensor Type A indicates that the total considered measured data could have a non-linear relationship. This can be sufficiently explained through function of polynomial type regression with R (kΩ) = 1.438 + 0.002009 T (° C) - 0.000013 T (° C) ^ 2. A comparative analysis of Experiment Number 2 - 5 gives the following results as depicted in Table 1. The results indicate that a polynomial regression model is present for all experiments. For the entire temperature range between of 20 ° C up to 100 ° C the experimental data shows high similarities with R-sq (adj) averaging more than 90 % indicating high explanation of the variance.

After cooling the samples they were again tested for their functionality by raising the temperature to 100 ° C. The measured resistance values for this secondary temperature profile did not show much significant deviation with respect to the initial value measured with the respective samples. A multiple repetition of the heating & cooling and recording the respective temperature & resistance of the samples were not performed.

### Hypotheses H1 and H2 for Temperature Sensor Type B

The investigation on the Type B temperature sensor with respect to the hypothesis H1 (20 ° C to 70 ° C) or hypothesis H2 (70 ° C to 100 ° C) yielded the following results

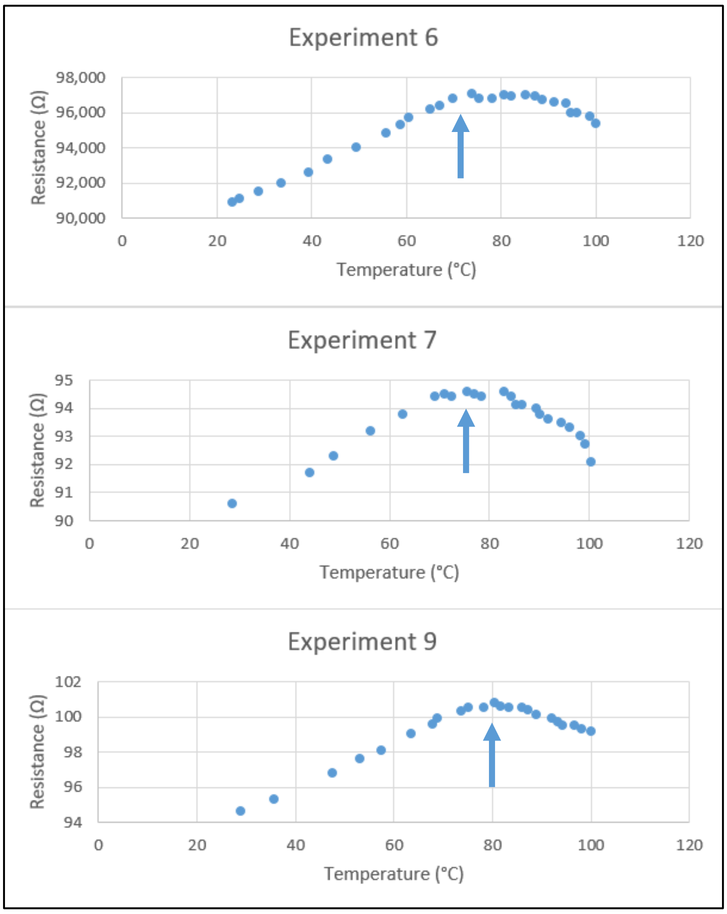
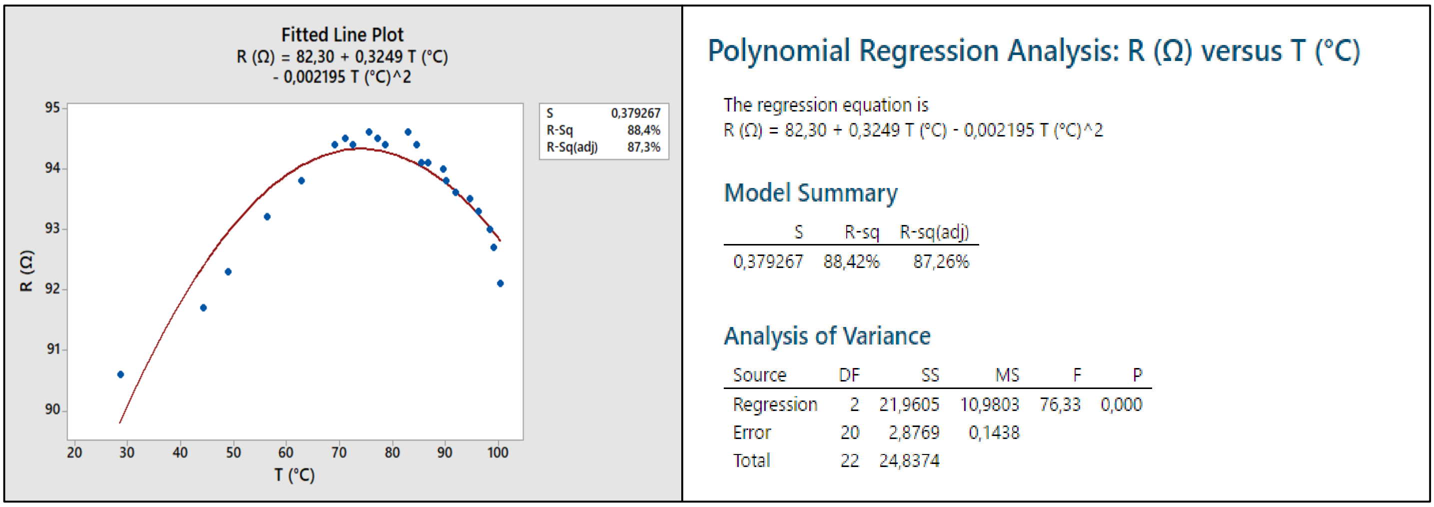


**Figure 5.** Results – Correlation between Temperature (°C) and Resistance (Ω) for sensor Type B

Three out of five trail experiments were considered for the printed sensor Type B. The descriptive analysis of the printed temperature sensor Type B yields comparable results that to that of printed sensor Type A with an exception for experiment 6 & 7 indicating a significant reaction taking place in temperature range of Between 70 ° C to 80 ° C (indicted by arrow symbol in the Fig. 5) for Type B sensor instead of temperature range 75 ° C and 85 ° C as compared for the Type A sensor. Due to the limited database and experimental data, a final assessment was not possible in this regards. The analytical analysis provided the following results for Type B sensor:



Polynomial Regression Analysis: R (Ω) versus T (°C)

The regression equation is
R (Ω) = 82,30 + 0,3249 T (°C) - 0,002195 T (°C)^2

Model Summary

| S | R-sq | R-sq(adj) |
|---|---|---|
| 0,379267 | 88,42% | 87,26% |

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 21,9605 | 10,9803 | 76,33 | 0,000 |
| Error | 20 | 2,8769 | 0,1438 | | |
| Total | 22 | 24,8374 | | | |

**Figure 6.** Results – Polynomial Regression between Temperature (°C) and Resistance (Ω) – Experiment No. 1 from Sensor Type B

The results of the analytical statics shows that printed temperature sensor Type B had a polynomial curve similar to that of Type A with R-sq (adj) of 87.26%. After cooling the samples from Type B ,they were again tested for their functionality by raising the temperature to 100 ° C similar to the experimental procedure done to the printed temperature sensor Type A.

## DISCUSSION

### Hypothesis Testing

**Hypothesis H1**, it can be confirmed that there exist a hypothetical linear relationship between the resistance (Ω) and temperature (° C) for the printed temperature sensor for the temperature range between 20 ° C and 75 ° C till 85 ° C. This is in accordance with the previous result mention in the literature [13].Furthermore it could be determined that the AgIc silver nanoparticle ink [15] used in accordance to manufacturer's instructions for the temperature profile more than 70 ° C , showed a significant change in the resistance behaviour. The fact that the measurement capability of the printed temperature sensors had no negative impact after a single cooling and reheating could also be determined. From the experimental data & analytical analysis, hypothesis H1 can be confirmed. Fabrication of powerful temperature sensor can be realized by combining the high-quality nanoparticle ink and low-cost printer can be demonstrated with this research. The geometry of the printed temperature sensors (Type A & Type B) had no significant impact on performance of the sensors.

**Hypothesis H2:** Linear relationship between temperature and resistance as mentioned in the literature , for example in Brinad et al. (2012) in Dankoco et al. [13] cannot confirmed, however a nonlinear or negative linear relationship in the form of a polynomial function was discovered for the temperature range from 70 ° C to 100 ° C for the fabricated printed temperature sensors. The examination of the temperature sensor Type A and Type B pointed to that fact turning point (reaction) exist for both sensors in the temperature range of 75 ° C - 85 ° C and 70 ° C - 80 ° C respectively , with resistance value not increasing any further with the falling temperature profile. Furthermore it could be also stated that the measuring capability of the temperature sensor were not adversely affected by the short-term exceeding of the critical temperature of above 70 ° C with the respect to the attributes of the ink [15] .

### Implication and Limitation

Based on the above results, conclusions can be drawn regarding the use of such temperature sensors: (1) Low-cost printed sensors can provide good measurement performance when used in conjunction with high quality inks and making the use of semi-professional / mid-range printers will significantly improve the performance profile; (2) A linear relationship existing between the resistance and temperature can be assumed for the sensor Type A and Type B for the temperature range of 20 ° C to 70 ° C / 75 ° C and these printed sensor can easily deliver interpretable result up to at least 70 ° C. A demanding conversion or special interpretation of the resistance and temperatures are not required for this range of operation; (3) Non-linear gradients are possible at temperatures greater than 70 ° C, whereby a polynomial function could be determined, which could be used for the prediction of the temperature profile with respect to the respective ink. A corresponding conversion / interpretation of the results are required; (4) For printed temperature sensors, the influence of ink in comparison to the printer, geometry, foil, pre- and post-treatment is of particular importance. Limitations of this investigation includes the lack of multiple repetitions of the measuring capability in short & long term for the temperature sensor when temperatures exceeds 70 ° C. Limitation also includes the lack of study of the impact of pre- and post-treatment of the printed sensor on their respective performances. In addition to the above facts the examination of the behaviour of the similar inks from different manufactures in same temperature profile can be included in the scope of future studies.

## CONCLUSION

A silver ink in conjunction with a low-cost printer on a PET film was used to produce a temperature sensor. The results shows that a low –cost inkjet printed temperature sensor without any additional pre or post treatment exhibits a positive linear relationship between temperature & resistance for the temperature range between 20 ° C and 70 ° C and also exhibits a non-linear or negative linear relationship for the temperature range from 70 ° C to 100 ° C. Considering the entire temperature range of the experiment from 20 - 100 ° C, a polynomial function could be derived for the investigated ink [15] which could be used for the prediction of the entire temperature range with appropriate calculation methodologies. The influence of pre/post-treatment of the printed sensors on the functional relationship between resistance and temperature requires to be investigated further in detail. From the above results, it can be concluded that untreated low-cost inkjet printed temperature sensors are of only limited suitability for temperature measurement.

## REFERENCES

[1] T. Furukawa, „Printing technology for electronics,“ in *Electronics Packaging (ICEP), 2016 International Conference* , Japan, 2016.

[2] C. Sekine, Y. Tsubata, T. Yamada, M. Kitano und S. Doi, „Recent progress of high performance polymer OLED and OPV materials for organic printed electronics,“ *Science And Technology Of Advanced Materials,* Nr. 15, pp. 1 - 16, 2014.

[3] Z. Cui, C. Zhou, S. Qiu, Z. Chen, J. Lin, J. Zhao, C. Ma und W. Su, Printed Electronics: Materials, Technologies and Applications, China: Wiley - Higher Education Press, 2016.

[4] A. Sridhar, T. Blaudeck und R. R. Baumann, Inkjet Printing as a Key Enabling Technology for Printed Electronics, Schweden: Material Matters, 2011, pp. 12-15.

[5] T. Happonen, J. Häkkinen und T. Fabritius, „Cyclic Bending Reliability of Silk Screen Printed Silver Traces on Plastic and Paper Substrates,“ *IEEE Transactions on Device and Materials Reliability,* Nr. 15, pp. 394-401, 15 July 2015.

[6] J. Vaithilingam, E. Saleh, C. Tuck, R. Wildman, I. Ashcroft, R. Hague und P. Dickens, „3D-inkjet Printing of Flexible and Strechable Electroncis,“ Additive Manufacturing and 3D Printing Research Group, Faculty of Engineering, University of Nottingham, Nottingham, 2015.

[7] L. Sommer, „A concept to optimized mechanical stability and resistance of low-cost inject-printed silver ink tracks by combination of different conductive inks,“ *Far East Journal of Electronics and Communications,* pp. 301-315, 2017.

[8] L. Sommer und D. Skopek, „Rapid Prototyping of Flexible Printed Circuits and Printed Membrane Switches,“ *Journal of Materials Science & Surface Engineering,* pp. 739-742, 2018.

[9] L. Sommer und C. Kessler, „Conductive Atomic Force Microscopy Analysis of Double Layer Inkjet Printed Electronic Structures (C-AFM),“ *International Journal of Science and Engineering Investigations,* 2017.

[10] D. C. Paine, H.-Y. Yeom und B. Yaglioglu, „Transparent Conducting Oxide Materials and Technology,“ in *Flexible Flat Panel Displays*, Chichester, John Wiley & Sons, 2005.

[11] A. Elschner, S. Kirchmeyer, W. Lövenich, U. Merker und K. Reuter, PEDOT: Principles and Applications of an Intrinsically Conductive Polymer, USA: Taylor & Francis, 2010.

[12] S. Chen , L. Song, Z. Tao, X. Shao, Y. Huang, Q. Cui und X. Guo, „Neutral-pH PEDOT:PSS as over-coating layer for stable silver nanowire flexible transparent conductive films,“ *Organic Electronics,* Nr. 15, pp. 3654 - 3659, Dezember 2014.

[13] M. Dankoco, G. Tesfay, M. Benevent und M. Bendahan, „Temperature sensor realized by inkjet printing process on flexible substrate,“ *Materials Science and Enginerring B,* pp. 1-5, 2016.

[14] V. Arnaud, L. Sydänheimo, M. M. Tentzeris und L. Ukkonen, „A Fully Inkejet-Printed Wireless and Cjipless Sensor for CO2 and Temerature Detection,“ *IEEE Sensors Journal,* pp. 89-99, 2015.

[15] A. Inc., AgIc Inc., 18 February 2018. [Online]. Available: https://agic.cc/en/. [Zugriff am 18 February 2018].

[16] Novacentrix, „http://www.novacentrix.com,“ Novaentrix, [Online]. Available: http://www.novacentrix.com/products/pulseforge/1200. [Zugriff am 26 November 2016].

[17] M. Burger, „www.meyerburger.com,“ Meyer Burger, 26 November 2016. [Online]. Available: http://www.meyerburger.com/en/products-systems/competences/inkjet-printing/photovoltaics/rd-equipment/pixdro-lp50/. [Zugriff am 26 November 2016].

[18] E. Sowade, H. Kang, K. Y. Mitre, O. J. Weiß, J. Weber und R. R. Baumann, „Roll-to-roll infrared (IR) drying and sintering of an inkjet-printed silver nanoparticle ink within 1 second,“ *Journal of Materials Chemistry C,* Nr. 3, pp. 11815 - 11826, 22 September 2015.

[19] S.-P. Chen, H.-L. Chiu, P.-H. Wang und Y.-C. Liao, „Inkjet Printed Conductive Tracks for Printed Electronics,“ *ECS J. Solid State Sci. Technol.,* Nr. 4, pp. 3026 - 3033, 6 February 2015.

[20] M. Park, J. Im, M. Shin, Y. Min, J. Park, H. Cho und S. Park, „Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres,“ *nature nanotechnology,* Nr. 7, pp. 803 - 809, 25 November 2012.

[21] W. Shen, X. Zhang, Q. Huang, Q. Xu und W. Song, „Preparation of solid silver nanoparticles for inkjet printed flexible electronics with high conductivity,“ *Nanoscale,* Nr. 6, pp. 1622 - 1628, 2014.

[22] Y. Zheng, Z. He, Y. Gao und J. Liu, „Direct Desktop Printed-Circuits-on-Paper Flexible Electronics,“ *Scientific Reports,* Nr. 3, pp. 1 - 7, 2013.

[23] D. McCoul, W. Hu, M. Gao, V. Mehta und Q. Pei, „Recent Advances in Stretchable and Transparent Electronic Materials,“ *Advanced Electronci Materials,* Nr. 2, pp. 1-51, 2016.

[24] AgIC, „https://shop.agic.cc/products/circuit-printer-cartridge-set,“ AgIC, 10 October 2016. [Online]. Available: https://shop.agic.cc/products/circuit-printer-cartridge-set. [Zugriff am 5 January 2016].

[25] C. M. Switch, „Cixi Membrane Switch Factory,“ Cixi Membrane Switch Factory, 10 Oktober 2016. [Online]. Available: http://www.cnjunma.com/polydome-membrane-switch.htm. [Zugriff am 10 Oktober 2016].

[26] Snaptron, „www.snaptron.com,“ Snaptron, 10 October 2016. [Online]. Available: http://www.snaptron.com/quality/. [Zugriff am 10 October 2016].

[27] Schäfer, *Testanlage,* Deutschland: Schäfer GmbH, 2016.