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A Disposable Inkjet-Printed Humidity and Temperature Sensor Fabricated on Paper †

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Abstract: In this work we present the development of a low-cost humidity and temperature sensing platform on paper by inkjet printing, using a commercial AgNPs conductive ink. The humidity sensing module was capable of measuring relative humidity in the range of 0–90%rH, exhibiting linear response with minimal memory effect when returning to 0%rH baseline signal while the temperature sensor performed linearly as well in the range of 25–75°C. Process repeatability has been verified by electrical and optical characterization. Mechanical bending results highlight the platform's capability to serve as an easy to install, flexible multi-parametric sensing platform.

Keywords: printed electronics; inkjet-printed sensors; paper sensor; humidity; temperature

1. Introduction

Paper as a device substrate is attractive due to its low cost and massive availability; paper-based electronics are being adopted in fields such as smart packaging and logistics monitoring, mainly because they can be developed by printing electrically functional inks with techniques available in mass production systems (e.g., packaging and labeling systems). The aforementioned fields will vastly benefit from integrating smart monitoring systems in the supply chain which report crucial measurements, because critical thresholds in humidity and temperature inevitably affect goods initial quality, which in turn leads to danger for the consumers and cost increases for the companies. Inkjet-printed metallic nanoparticle-based humidity sensors have been reported both on paper [1] and other flexible substrates such as polyimide and PET, while flexible temperature sensors have also been demonstrated on various substrates in recent publications [2]. By integrating these sensors on the same device, simultaneous measurements of temperature and humidity can be achieved.

In this work, we investigate the integration of a previously reported humidity sensor [3] with a temperature sensor on the same substrate for self-compensation using room temperature processing and for multi parametric sensing as well. Chemically sintered devices are fabricated using suitable ink at room conditions, which in contrast to thermal or other methods of sintering does not require additional manufacturing steps resulting in a reduction of the fabrication time and cost.

2. Materials and Methods

2.1. Inkjet Printing

A piezoelectric drop–on–demand inkjet printer (Thetametrisis FR-DEPOSIT), with Microdrop MD-K-140 nozzle (diameter: 70 um) was used for printing the sensors on inkjet photo glossy paper (basis weight 210 g/m$_2$, thickness 241.3 μm). Silver nanoparticle ink NSBSIJ-MU01, Mitsubishi Paper Mills (Ag solid content: 10–20 wt %, average particle size 20nm) was printed after filtered through a 5μm PET filter. Printer's hotplate and nozzle temperature were set to 25 °C. The inkjet piezoelectric driving pulse settings for repeatable, stable droplet generation were found to be 68V–12 μs (amplitude-duration). Droplet spacing was set to 68μm in both X and Y axes, resulting in satisfactory droplet overlapping; by increasing droplet spacing, droplets failed to form a continuous line while further decreasing droplet spacing resulted in bulge formation (Figure 1a–c).

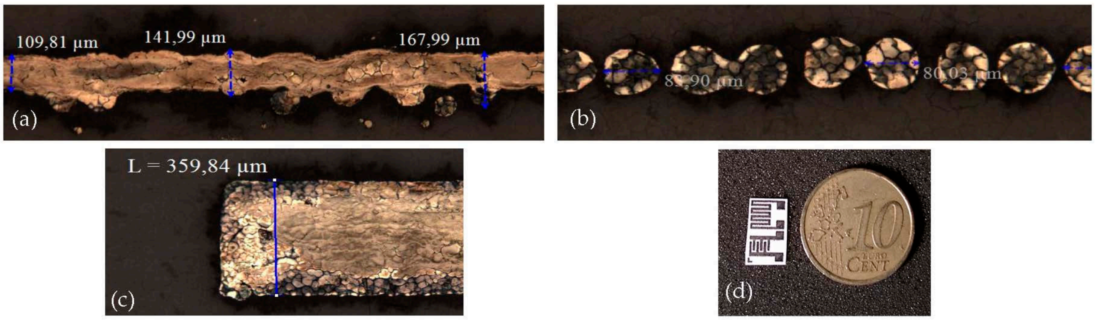

Figure 1. Droplet spacing: a line printed with (**a**) 40 um; (**b**) 70 um spacing; (**c**) five lines printed with 68 um droplet spacing; (**d**) photograph of the device with a 0.10 euro coin for scale. The optical microscope images were acquired with a dark filter.

The sensing platform consists of an interdigitated electrode array (6 fingers with equal width and gap of 180um) for humidity sensing and meander-shaped pattern for temperature sensing (Figure 1d). Paper's electrical resistivity is strongly depended on the absorbance of water vapors, therefore by exploiting this phenomenon, relative humidity levels can be extracted by measuring the electrical resistance between the IDEs. Regarding temperature measurements, it is known that metallic inks present a positive TCR [2], therefore measuring electrical resistance is adequate for sensing temperature levels as well; these two phenomena and the sole requirement of resistance measurement lead to a coupled platform which can provide information via simple electronic interfacing, eliminating more advanced circuitry required for capacitive measurements.

After printing, a sintering process is required in order for the silver nanoparticles to weld and form a uniform conductive path; in contrast to traditional sintering methods such as thermal, photonic, microwave and other, the utilized ink is capable of chemically sintering in room conditions [4].

2.2. Measurement Protocols

Humidity measurement setup is described in previous work [3]; in brief, the sensor is installed inside a sealed Teflon cavity, where a Brooks Instruments mass flow controller is utilized for adjusting a mixture of dry air and air from a bubbler fed inside the cavity. A Keithley 2400 source meter is used for applying a voltage of 10V to the electrodes and for measuring electrical current; Air flow and temperature from the mass flow controller as well as voltage-current measurements are monitored by LabVIEW. Relative humidity inside the chamber is monitored by a Hanna HI9565 hydrometer.

For temperature response evaluation, the platform was placed onto a hotplate where high resolution thermal images were obtained periodically by an infrared camera (FLIR A655SC). A Keithley 2000 multimeter was simultaneously logging resistance measurements from both humidity and temperature sensors; a custom LabVIEW program was utilized for controlling sampling frequency and monitoring data in real time.

In order to evaluate impact of different bending angles to the sensors resistance, a Mutitoyo 164 162 Digimatic micrometer head was utilized. The sensors' one side was clamped onto the head, with the other side of the sensor was mechanically fixed. Bending tests were performed by changing the travel length of the micrometer head.

3. Results & Discussion

3.1. Humidity Measurements

Response to relative humidity pulses in the range of 20–90% rH exhibited an adequate sensitivity, with a drop of approximately one order of magnitude per 20% rH and a steady baseline signal in 0% rH (Figure 2a); relationship between relative humidity and electrical resistance is presented in Figure 2b.

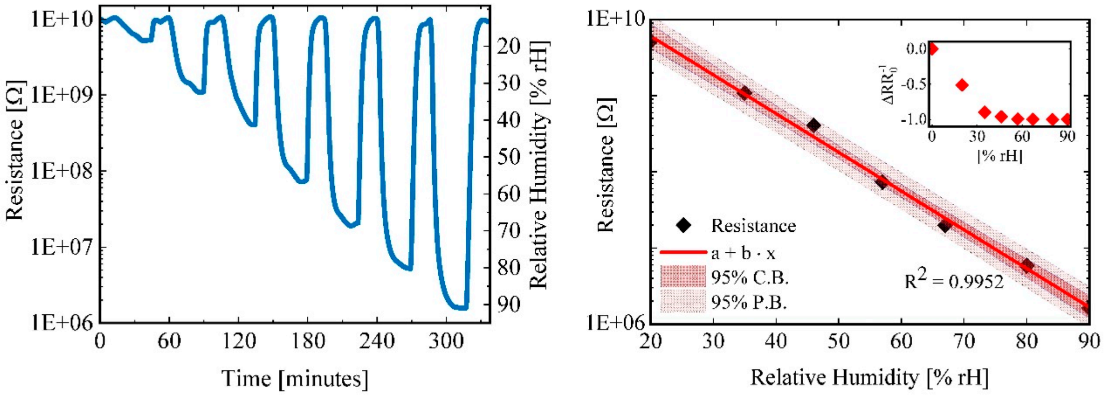

Figure 2. (**a**) Sensor response under different humidity pulses; (**b**) relative humidity-electrical resistance relationship. Y axis is logarithmic while the inset plot presents the percentage change of resistance for different humidity values.

3.2. Temperature Measurements

The sensing platform was evaluated in the temperature range of 25–75 °C; Figure 3a presents the normalized resistance variation as a function of temperature. The specific behavior indicates a TCR value of 9.0655×10^{-4} °C^{-1}. Sintering effect is evident in resistance values, where samples printed two weeks prior to measurements exhibit an overall lower resistance and higher sensitivity than freshly printed ones, as shown in Figure 3a.

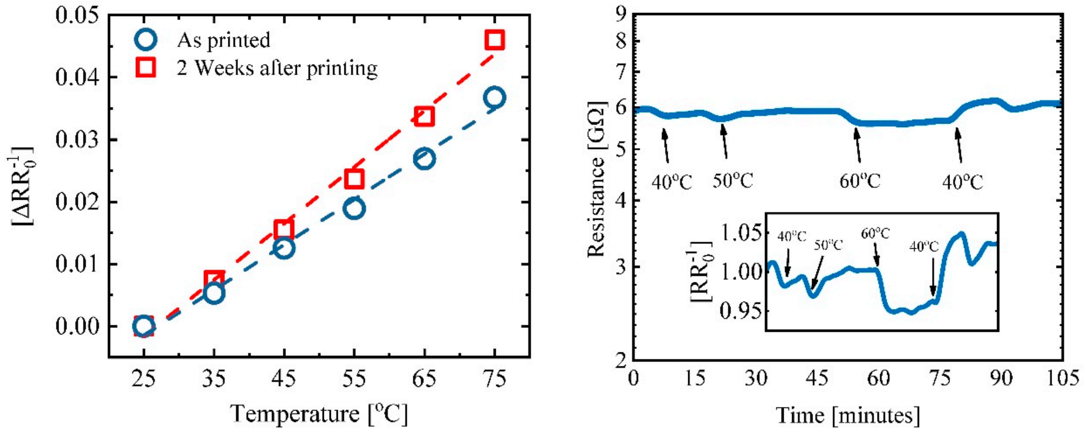

Figure 3. Temperature experiments: (**a**) Temperature response of freshly printed temperature sensor (blue) and 2 weeks after printing (red); (**b**) Resistance of humidity sensor under different temperatures. Inset plot: normalized response.

In parallel, the humidity sensor response was monitored during temperature measurements, in order to assess the effect of temperature in humidity sensing. Figure 3b presents the variations in resistance caused by different temperature levels. It was observed that temperature influence, although relatively low (as presented in Figure 3b, inset) has an impact in humidity sensor response.

3.3. Bending Effects on Sensor Resistance

For investigating the sensor flexibility which will allow installation in non-planar surfaces, bending experiments where conducted and the results are depicted in Figure 4. Variance in resistance is negligible for bending angles up to 45°; for larger bending angles, it was observed that inkjet-printed lines formed cracks and discontinuities leading to a permanent damage to the samples. Therefore, we can assume the device is practically immune to bending up to 45°.

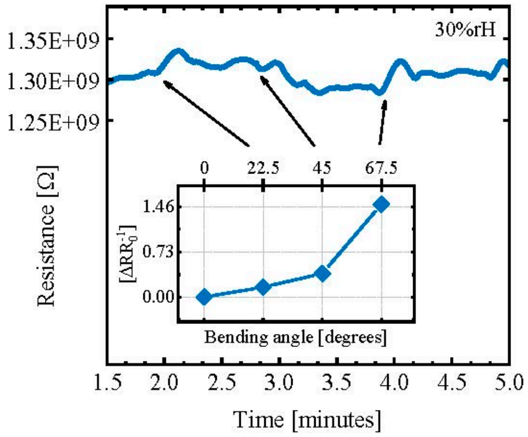

Figure 4. Resistance response under different bending angles. Inset plot presents percentage of resistance variation.

4. Conclusions

A sensing platform consisting of a humidity and a temperature sensor was developed on paper substrate using inkjet printing of commercial silver nanoparticle ink. The platform was evaluated for various humidity and temperature levels, alongside with influence of temperature in humidity sensor's response at constant humidity. Moreover, bending experiments suggest that the sensors can be integrated on packaging of goods for overall quality management without significant loss of performance even under high bending conditions.

Author Contributions: D.B. fabricated the devices and performed the characterization, A.S. contributed to device characterization, C.T. & G.K contributed to the design of the experiments and to the results assessment. All authors contributed to analysis of the results and paper preparation.

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Conflicts of Interest: The authors declare no conflict of interest.

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