A disposable flexible humidity sensor directly printed on paper for medical applications

D Barmpakos¹², A Segkos², C Tsamis² and G Kaltsas¹

¹Department of Electronic Engineering, Technological Educational Institute of Athens, 28 Ag. Spyridonos Str., Egaleo, 12210, Athens, Greece
²Institute of Nanoscience and Nanotechnology (INN), National Centre for Scientific Research “Demokritos”, Patr. Gregoriou E & 27 Neapoleos Str., Aghia Paraskevi, 15341, Athens, Greece

e-mail: d.barmpakos@inn.demokritos.gr

Abstract. The present study demonstrates an inkjet – printed interdigitated electrode array on paper substrate and its evaluation as humidity sensor. Inkjet droplet formation analysis has been performed in order to achieve repeatable results regarding generated droplets, based on the driving pulses applied on the inkjet piezoelectric element. Droplet formation has been monitored using stroboscopic effect. Three different paper substrates, namely high glossy inkjet photo paper, glossy inkjet photo and matte inkjet photo paper have been evaluated to investigate compatibility with the ink. Relative humidity measurements have been carried out in a controlled environment. Material degradation, long term response and memory effect are some of the aspects which were studied within the frame of the present work. The proposed sensor provides the opportunity for novel biomedical applications given the flexible substrate nature and the low – cost, single – step fabrication approach.

1. Introduction

Flexible, printed electronics represent the future in electronic devices manufacturing; additive processing means less wasted materials which in turn drives to decreasing polluting waste and costs. For example, acidic etching wastes about 90% of copper [1], while advances in precise methods of additive processes such as inkjet printing lead to cost effective, bottom – up design and manufacturing. Thus, both scientific groups and the industry have been extensively investigating possibilities for micron – scaled, production ready approaches such as roll to roll production [2]; printed electronics are expected to hold a market share of $24.3bn by 2020 [3] with applications such as in medical assessment – assistance devices [4, 5] and humidity sensors printed on paper [6 – 8]. Paper – based sensors have a fistful of attractive features: paper is massively available, it has environmental – friendly properties and its flexibility provides a wider variety of installation capabilities.

In this work, inkjet droplet formation was analysed prior to silver nanoparticle ink – paper substrate compatibility tests. Interdigitated electrode arrays were printed and evaluated as a relative humidity sensor on paper. Evaluation of the sensor performance as well as long term stability experiments were performed.
2. Experimental Process

2.1. Inkjet printing
A piezoelectric drop-on-demand inkjet printer (Thetametrisis FR-DEPOSIT), with Microdrop MD-K-140 nozzle (diameter: 70 μm), was utilized for all printing sessions. Droplet formation was monitored by strobe synchronization with a XIMEA MQ013MG – E2 camera. The system allows for multi parametric (pulse voltage, duration, time delay etc.) droplet adjustment. An example of the resulting droplets is presented in figure 1. Silver nanoparticle ink NSBSIJ–MU01 from Mitsubishi Paper Mills (Ag solid content: 10 – 20 wt%, average particle size: 20 nm, viscosity: < 10 cps) was chosen because of its compatibility with the printing system and for its chemical sintering capability. Chemical sintering, in contrast to other sintering methods such as thermal, photonic and microwave sintering, allows for good electrical conductivity without requiring additional steps in manufacturing [9].

![Figure 1](image_url)

**Figure 1.** Resulting droplets from a driving pulse of 63 V with a duration of 12 μs; time difference between the snapshots is 20 μs. Scale line in lower right corner is 70 μm.

2.2. Ink–substrate interface
Mitsubishi Paper Mills provides dedicated, pre-coated substrates with the sintering agent for the activation of the chemical sintering process, but it was shown that other commercially available inkjet photo glossy papers can initiate the process in a similar manner [10]. Therefore, an inkjet photo glossy paper with basis weight 210 g/m² and thickness 241.3 μm was chosen for the development of the sensors. Average printed droplet diameter was 80 μm ± 5μm. Both high glossy inkjet paper and matte paper were rejected for further development since the results were not considered satisfactory for the specific application. High glossy paper (basis weight 280 g/m², thickness 292.1 μm) helped in well-defined patterns, but poor adhesion and drying were observed, while matte inkjet paper’s (basis weight 125 g/m², thickness 139.7 μm) roughness caused major issues in continuous line formation.

2.3. Characterization
Resistivity was measured to be $\rho_{\text{paper}} = 18.075 \times 10^{-7}$ Ωm, which is of same magnitude as similar presented work in literature [11]. It has to be noted that all lines are single – printed with respect to rapid time – to – prototype and minimal utilized consumption approach, conductivity is expected to further increase by printing successive layers of ink.

Scanning Electron Microscopy analysis with a JEOL JSM 7401F reveals that the coalesce of sintered nanoparticles resulted in relatively uniform silver lines, although in some cases line discontinuities or cracks were detected, possibly due to the small amount of ink used.

2.4. Interdigitated electrode array
Each array includes 6 fingers, with a finger width of 500 μm and a gap of 500 μm; the physical sensor is presented in figure 2. The dimensions were chosen for optimal relationship between electrical conductivity and device dimensions. The maximum printer resolution for the particular set of materials is 150 μm. Electrodes were printed in room conditions (23°C, 41%rH) and after optical inspection, validation of isolation between the fingers was performed with a prober using an HP 4140B pA Meter -
DC voltage source. A double staircase voltage waveform was applied (-10 V to 10 V DC with 100 mV step size) and no short – circuit was detected.

3. Evaluation in humidity sensing
Relative humidity measurements were carried out in a sealed teflon cavity with controlled humidity. This was achieved by controlling a Brooks Instruments mass flow controller connected via RS232 to LabVIEW, and different humidity alternations were performed by adjusting the mixture of dry air and air from a bubbler fed into the cavity (figure 3). A voltage of 10 V was applied to the electrode pads and current was measured with a Keithley 2400 source meter in order to extract the electrical resistance; the source meter was connected to LabVIEW via GPIB. All of the procedures were incorporated into a control – measurement custom script, where the user controlled both the mass flow controller and the measurement instrument. Relative humidity in the measurement chamber was monitored via a Hanna HI 9565 hydrometer.

3.1. Response to humidity
In order to evaluate the sensor’s response to different relative humidity values, as well as sensor recovery, a relative humidity sweep from 20% to 90% was performed. In each step, the sensor was exposed to humid air for 30 minutes and for dry air for 15 minutes. Figure 4 presents the results; it is evident that the sensor is free of memory effect, meaning that independently of humidity percentage, resistance measurements when the sensor is exposed to dry air is similar.  

3.2. Long – term stability
In order to assess the performance of the proposed sensor with regard to long term stability, systematic measurements for 120 days were performed. Prior to measurements, the sensor was heated in an oven in 40°C for 30 minutes in order to dissipate any humidity inside the substrate and electrodes and was exposed to dry air for 10 minutes, followed by exposure to 40% rH for 60 minutes and back to 0% rH. By analysing the resistance – relative humidity results, a linear fitting model (R² = 0.9952) can be extracted when working with logarithmic Y scale (figure 5). A stable behaviour is observed 75 days after printing the sensor, as presented in figure 6.
Figure 5. A linear model accurately describes the relationship between humidity and electrical resistance.

Figure 6. Material degradation causes an increase in electrical resistance for 75 days.

4. Conclusions
A relative humidity sensor on paper was developed and evaluated in the range of 20 – 90%rH. Sensor characterization highlights its ability to retain the same zero humidity background level value without the need of external active elements, eliminating memory effect on the 0%rH signal baseline. The developed sensor was characterized with respect to long – term behaviour, and sensor’s response was fully stabilized approximately 4 months after fabrication. The developed sensors can easily be adopted for medical applications, where low-cost solutions are required; body moisture detectors on patients could be easily implemented utilizing the proposed technology. Moreover, the linear dependence of the material degradation process can be exploited as low-cost electronic timestamps of products in controlled environments (e.g. surgery rooms).

References
[1] Cui Z 2016 Printed electronics: Materials, Technologies and Applications (John Wiley & Sons Singapore) Crossref
[2] Abbel R, Teunissen P, Rubingh E, van Lammeren T, Cauchois R, Everaars M, Valeton J, van de Geijn S and Groen P 2014 Transl. Mater. Res. 1 015002 Crossref
[3] Das R and Harrop P 2013 Printed, Organic & Flexible Electronics: Forecasts, Players & Opportunities 2013–2023 (IDTechEx)
[4] Poon C, Zheng Y, Luo N, Ding X and Zhang Y 2014 Wearable Sensors (Elsevier) pp 543–562
[5] Lin P and Feng Y 2012 Adv. Mater. 24.1 34–51 Crossref
[6] Quddious A, Yang S, Khan M M, Tahir F A, Shamim A, Salama K N and Cheema H M 2016 Sens. 16.12 2073 Crossref
[7] Sauer S and Fischer W J 2016 Procedia Eng. 168 489–492 Crossref
[8] Yuan Y, Zhang Y, Liu R, Liu J, Li Z and Liu X 2016 RSC Adv. 6 47498–47508 Crossref
[9] Grouchko M, Kamysnysh A, Mihailescu C F, Anghel D F and Magdassi S 2011 ACS nano 5.4 3354–3359 Crossref
[10] Kawahara Y, Hodges S, Cook B S, Zhang C and Abowd G D 2013 Proc. ACM Int. Conf. on Pervasive and Ubiquitous Computing ACM p 201 Crossref
[11] Ando B and Baglio S 2013 IEEE Sens. J. 13.12 4874–4879 Crossref