DOI 10.5162/sensor2015/D4.1

Inkjet and Aerosol Jet® Printed Sensors on 2D and 3D Substrates

B. Polzinger[1], J. Keck[1], V. Matic[1], W. Eberhardt[1], H. Kück[1,2]
[1] Hahn-Schickard-Gesellschaft – Institut für Mikroaufbautechnik (HSG-IMAT), Allmandring 9B, 70569 Stuttgart
[2] Institut für Mikrointegration (IFM), Universität Stuttgart, Allmandring 9B, 70569 Stuttgart
keck@hsg-imat.de

Abstract:
Digital non-contact-printing technologies e.g. inkjet or Aerosol Jet® are becoming more and more interesting for the manufacturing of electronic components due to their benefits such as easy variation of printing layouts, short process chains without masks, large variety of usable substrates and inks - frequently based on nanomaterials - and a certain 3D capability. In this paper printed sensors for e.g. temperature, strain, intrusion, humidity, or magnetic fields fabricated by inkjet or Aerosol Jet® technology and characterization results are described.

Key words: Digital printing, inkjet, Aerosol Jet®, printed sensors, 3D substrates

Introduction

Printing technologies, especially screen printing, are widely used for the manufacturing of electronic components. Nowadays digital non-contact-printing technologies such as inkjet or Aerosol Jet® are gaining more and more importance for printing of electronic components on flexible foils [1-3]. They enable high productivity due to short process chains and are resource and environmentally friendly [4,5]. Jetting technologies also have the potential to enable direct printing of conductive structures, sensors, and passive devices onto injection molded 3D polymer packages [6,7]. With regard to the Internet of Things printed sensors are a particular promising application field. In this paper some examples of printed sensors are described which were fabricated by inkjet or Aerosol Jet® printing of nano metal and/or polymer inks on 2D and 3D polymer substrates.

Capacitive humidity and touch sensors

Capacitive humidity and touch sensors were fabricated based on printed differential interdigital capacitors (IDC) made of inkjet printed nano silver ink and an inkjet or Aerosol Jet® printed sensitive polymer layer (Figs. 1 and 2). Injection molded Polybutylenterephthalate (PBT) was used as substrate. EMD 5714 silver ink with 40 wt.% Ag from Sun Chemical Corporation Ltd. was used to print IDCs and conductor paths. The printed silver structures were annealed for 1h at 200°C. [8,9]

For the *humidity sensor* one IDC was covered with a humidity sensitive layer, whereas the second IDC remains uncovered acting as a reference capacitor. Two different printable materials were tested as sensing layers: Inkjet printed UV curing insulator EMD 6200 (Sun Chemical Corporation Ltd.) and polyimide Matrimid 9725 (Huntsman Corporation) printed with Aerosol Jet®. Reproducible results and low hysteresis were obtained. The mean values of the differential capacitive signal between an IDC coated with the printable polyimide Matrimid 9725 and an uncoated IDC depending on relative humidity and temperature is shown in Fig. 3. The standard deviation for every investigated relative humidity (RH) level for both humidity sensitive layers is very small and in the range between 1-2% of the mean value. The differential capacitive signal is clearly a function of the relative humidity and the temperature. The sensor sensitivity is increased at higher temperatures. The maximal signal shift of approx. 0.035 pF can be detected for the levels between 30 to 80% RH at 25°C, and approx. 0.045 pF at 85°C. The error caused by hysteresis of the sensor is defined as the quotient of maximal signal deviation and maximal signal shift. At 25°C no significant hysteresis occurs, whereas at 85°C a hysteresis error of 0.002 pF is observed.

Both IDCs for the *touch sensor* were covered with an UV curing insulator (EMD 6200) to protect the printed silver layer. Fig. 4 shows the signal sequence of two 10x10 mm^2 large IDCs on a PBT substrate when touching the sensor with a finger for about 2 s per touch. Due to the evaluation electronics the change in the capacity of one IDC (left one) is positive and for the other IDC is negative (right one). The sensor shows a very fast response time. The signal remains stable over the whole excitation time. The amplitude of the signal is about 0.4 pF. Thus the applied sensor design is able to improve sensitivity and to reduce drift effects caused by temperature changes or moisture absorption of the substrate.

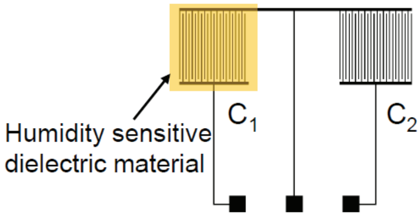

Fig. 1. Scheme of printed capacitive humidity sensor for differential measurement ($IDC_1 = IDC_2$) [8]

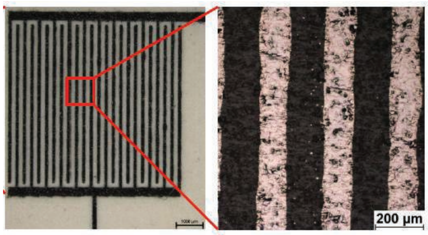

Fig. 2. Detail of capacitive humidity sensor from inkjet printed silver ink and Aerosol Jet® printed dielectric coating on polymer substrate [8]

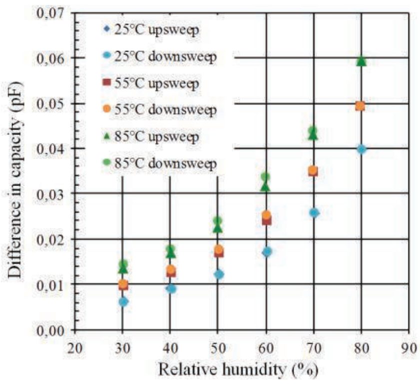

Fig. 3. Differential capacitive signal between IDC with printed polyimide and uncoated IDC during cyclic exposure to relative humidity levels (RH) between 30% and 80% at different temperatures [8]

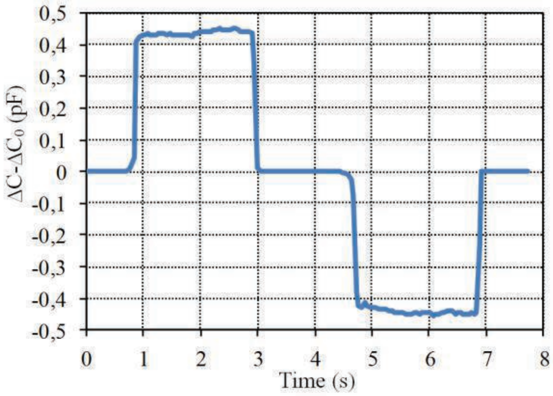

Fig. 4. Signal sequence of printed touch sensor on PBT substrate, IDC area 10x10 mm^2. Touch period ~ 2s. [8]

Magnetic field sensors

Magnetic field sensors based on toroidal core coils were fabricated using Aerosol Jet® technology to print the coil windings from nano silver or copper ink. After annealing the first printed lower part of the coil windings (1h/180°C for silver ink, UV light for copper ink) electroless copper plating is applied in order to reinforce the printed structures. A magneto-sensitive ferrite core is then deposited by means of a dispensing process (Figs. 5 and 6). Finally the printing and plating steps are repeated to complete the coil windings. [10,11]

The fine line printing capability of the Aerosol Jet® technology allows for higher winding numbers (up to 39 in our experiments) than it is possible with conventional non-printing fabrication processes. The coil windings have a line width of about 70 µm and a layer thickness of 5 - 10 µm after electroless plating. Typical electric resistances of the coils are between 3 and 20 Ω depending on the number of windings.

Fig. 7 illustrates the behavior of printed coils at different magnetic field strengths compared to non-printed coils. Due to their linear characteristics in the measured range up to 15 kA/m, the printed coils are suitable as analog position sensors. A demonstrator of such a magnetic field sensor was fabricated (Fig. 8). On the demonstrator the oscillator circuit controls the brightness of the LED which varies with the distance between the printed coil and the magnetic field.

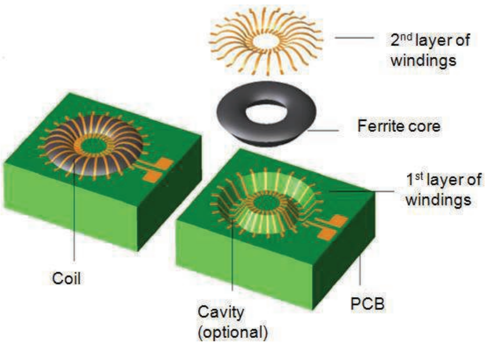

Fig. 5. Scheme of printed core coil [10]

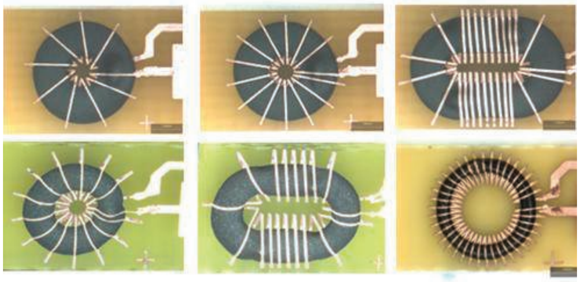

Fig. 6. Toroidal core coils with Aerosol Jet® printed windings from nano Ag or Cu ink and dispensed ferrite core on PCB substrate [10]

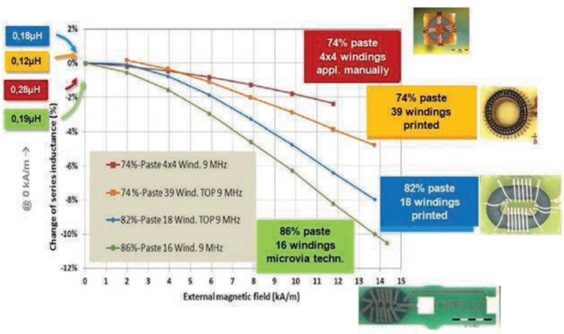

Fig. 7. Change of series inductance with external magnetic field of printed and non-printed toroidal core coils [10]

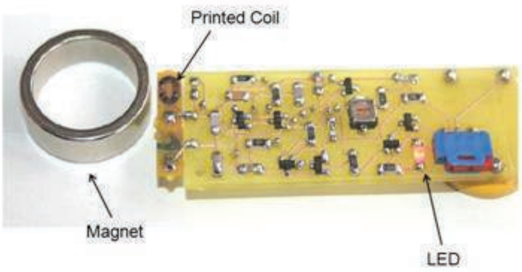

Fig. 8. Demonstrator of a magnetic field sensor based on a printed core coil [10]

Other printed sensors

Further sensor types based on nano silver ink were printed on various 2D and 3D polymer substrates such as temperature sensors (Figs. 9-10), strain gauges (Fig. 11) or intrusion sensors (Fig. 12). In each case the printed silver ink was annealed for 1 hour at 180-200°C. [7,12]

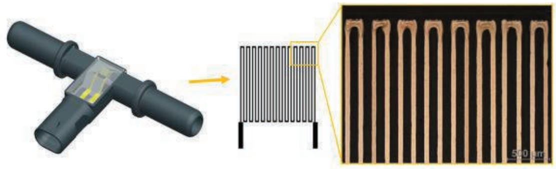

Fig. 9. Inkjet printed resistive temperature sensor on injection molded fluidic device [13]

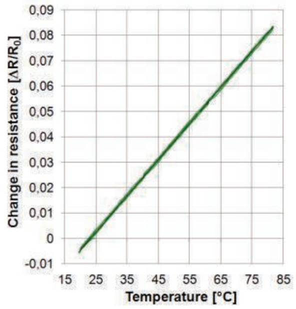

Fig. 10. Temperature characteristic of inkjet printed resistive temperature sensor [13]

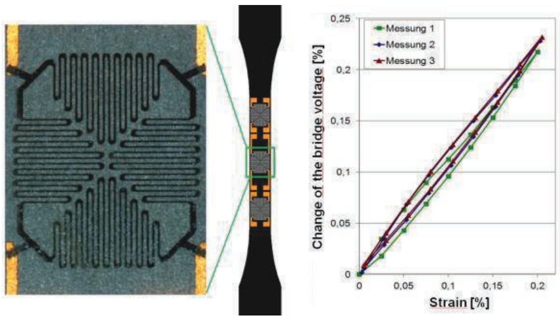

Fig. 11. Aerosol Jet® printed strain gauges in a Wheatstone bridge configuration on LCP substrate with characteristic curve upon strain [14]

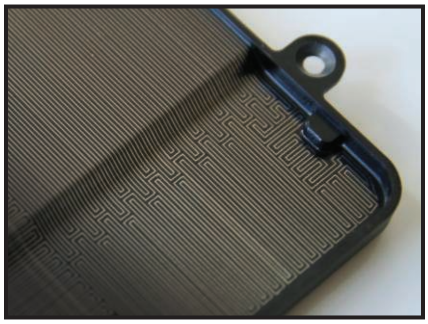

Fig. 12. Inkjet printed intrusion sensor structures on injection molded PBT substrate [15]

The printed *temperature sensor* (Fig. 9) shows a very good linear correlation between resistance and temperature. The temperature coefficient is about $2*10^{-3}$ K^{-1} (Fig. 10).

For the printed *strain gauge* typical k-factors of ca. 2 were found. There is only a slight hysteresis observed in the strain measurement probably due to the viscoelastic properties of the substrate injection molded from Liquid Crystal Polymer (LCP) (Fig. 11).

An *intrusion sensor* is commonly used to protect safety-relevant devices such as e.g. bank card readers. The sensor structure consists of a closed meshed conductor loop. Any attempt of mechanical intrusion into the device e.g. for data theft will cause breakage of the conductor loop leading to a shutdown of the device. Currently the standard technique to fabricate such devices is the LPKF-LDS® process [16]. Digital printing technologies have a high cost saving potential due to the much shorter process chain compared to the LPKF-LDS® process. The inkjet printed sensor shown in Fig. 12 is realized by inkjet printing of four meanders with a length of 5 m each.

Conclusions

The examples of printed sensors given in this paper clearly demonstrate the large potential of jet printing technologies to enable low-cost fabrication of sensor structures on 2D and 3D polymer based substrates. Thus modern cost-efficient digital printing technologies have high potential for generating new electronic components.

Acknowledgements

The authors would like to acknowledge the support of AIF within the IGF research projects no. 17162N and 15663N. Furthermore, we would like to thank BMBF and VDI/VDE for support of the projects ORFUS, PRONTO-DRUSYM and SADINA.

References

[1] R. Das and P. Harrop, Printed, organic & flexible electronics forecast, players & opportunities 2012-2022 IDTechEx 2012.

[2] K. Cherenack, C. Zysset, T. Kinkeldei, N. Münzenrieder, G. Tröster, Woven electronic fibers with sensing and display functions for smart textiles, *Adv. Mater.* 5178-5182 22 (2010); doi:10.1002/adma.201002159

[3] M. Mäntysalo, L. Xie, F. Jonsson, Y. Feng and L.-R. Cabezas A. and Zheng, System integration of smart packages using printed electronics, *IEEE 62nd Electronic Components and Technology Conference (ECTC), San Diego*, 997-1002 (2012)

[4] M. Hedges, A. B. Marin, 3D Aerosol-Jet® Printing - Adding Electronics Functionality to RP/RM, *DDMC, 2012 Conference, 14-15.3.12, Berlin;* doi:10.1117/12.2009278

[5] M. Singh, H. Haverinen, P. Dhagat, G. Jabbour, On Inkjet Printing-Process and Its Applications, *Adv. Mater.* 673-685 22 (2010); doi:10.1002/adma.200901141

[6] V. Matic, J. Keck, A. Ilchmann, B. Polzinger, W. Eberhardt, H. Kück, Printing of Functional Silver Structures on Polymer based 3D-Packages, *10th 4M Conference, Vienna, Austria, 2012*

[7] B. Polzinger, V. Matic, L. Liedtke, J. Keck, D. Hera, W. Eberhardt, H. Kück, Jetting of functional structures on moulded 3D devices 6th *LOPEC Conference, Munich, Germany, 2014*

[8] V. Matic, L. Liedtke, T. Guenther, A. Buelau, A. Ilchmann, J. Keck, B. Polzinger, W. Eberhardt, H. Kueck, Inkjet printed differential mode touch and humidity sensors on injection molded polymer packages, *IEEE Sensors 2014*, 3.-5.2014, Valencia; doi: 10.1109/ICSENS.2014. 6985485

[9] IGF-Vorhaben 17162 N: Systemintegration von gedruckten Sensoren und Auswertelektronik auf dreidimensionalen thermoplastischen Substraten (ISAT)

[10] J. Keck, B. Polzinger, W. Eberhardt, H. Kück, M. Giousouf, A. Kießling, A. Schreivogel, J. Kostelnik: Printed Ferrite-Based Toroidal Core Coils as Magnetic Field Sensors, *Microsystems Technology in Germany* 2014, 42-43

[11] BMBF-Verbundprojekt „Organische Multifunktionssystem“ (ORFUS, Verbund Nr. V3POL112)

[12] B. Polzinger, V. Matic, J. Keck, W. Eberhardt, H. Kück: Printing of Circuits and Sensors on 3D-Devices, Workshop Innovative Anwendungen der MID-Technik, Stuttgart, 9th Oct. 2013

[13] BMBF-Verbundprojekt „Drucktechnik für Sensoren“ (Pronto-Drusym, Verbund-Nr. V4CLU011)

[14] IGF-Vorhaben Nr.15663N: „Dünnschichtwiderstände in Mikrodrucktechnik“

[15] BMBF-Verbundprojekt „Neue Sensorstrukturen und Aufbautechniken auf dreidimensionalen Trägern mittels Inkjet-Druck nanoskaliger Dispersionen“ (SADINA, Verbund-Nr. V4MNI301)

[16] J. Franke (Editor): Three-Dimensional Moulded Interconnect Devices (3D-MID): Materials, Manufacturing, Assembly and Applications for Injection Moulded Circuit Carriers, Carl Hanser Verlag, München, 2014; doi: 10.3139/9781569905524