Inkjet-Printed Interconnection of Unpackaged Die in Paper-Based Electronics

P. Bezuidenhout, S. Smith, K. Land and T-H. Joubert

This work details manufacturing processes developed to integrate an unpackaged silicon die onto a paper substrate, as part of constructing a hybrid inkjet-printed paper-based circuit. This integration between rigid components and flexible substrates is beneficial in low-cost applications and capitalises on the advantages of both the well-established integrated circuit technology and the emerging paper-based electronics platforms. A superglue incline at the chip edge formed a ramp for printing the silver interconnects between the paper-based circuit and the chip pads. Two printing protocols are compared, the first a single layer using 5 µm drop spacing, and the second using a 35 µm drop spacing for 3 layers. An unpackaged RFID tag die is successfully integrated and is presented as proof of concept.

Introduction: This paper describes the manufacturing process involved in the development of hybrid paper-based circuits, which includes the integration of an unpackaged silicon die onto a paper substrate using inkjet printing. This work contributes to the development of flexible, low-cost and disposable electronics with application possibilities in sectors such as smart packaging, health and environmental monitoring [1, 2].

Paper is ubiquitous, flexible, biodegradable, inexpensive, readily available, and used to manufacture various products such as envelopes, books, newspapers, and disposable dishware. Most paper types are 10% of the cost of plastic films, and even specialised printed electronic paper is in the region of 1% the price of silicon [2, 3].

Inkjet printing is a key enabling technology in printed electronics, supporting rapid prototyping of circuits which may offer a decrease in time to market, as well as production time [4]. It provides high repeatability, minimal material waste cost, and can be used on non-planar substrates [4]. It is a non-contact and maskless additive digital deposition method that diminishes substrate limitations, allowing printing on various substrates and topographies simultaneously. This is required for circuits and interconnects in the hybrid integrated circuit (IC) paper-based systems, which enable the development of solutions that take advantage of both well-established IC technology and the emerging paper-based electronic platform [1], [5]. Aspects of the proposed work have been investigated, such as using silver paste to connect an unpackaged die by moulding [1], and by using other printing techniques to implement direct die packaging methods [6]; however, no paper-based inkjet-printed solution was identified. This work addresses various current challenges in the field such as integrating flexible substrates with rigid components and unpackaged dies, as well as the conductive adhesion of different substrates [6, 7].

In previous work [5], passive components and various IC package types were integrated onto paper, in combination with superglue (Precision Superglue, Henkel Loctite, Germany) as an adhesive, and Polydimethylsiloxane (PDMS) as a coating agent. Here, an unpackaged die was connected to an inkjet-printed paper-based circuit using a Superglue ramp. This ramp both adhered the die to the paper, as well as provided an inclined printing plane for the interconnects. The real-time positional feedback properties offered in inkjet printing was used to triangulate an accurate position for each pad, and to evaluate the various printed interconnects. By combining the printing procedures described before in [5] with further developed methods, the printed interconnects were successfully manufactured. A functioning RFID tag circuit demonstrated an application using an unpackaged die on paper.

Materials and Methods: The Dimatix DMP 2831 drop-on-demand piezo inkjet printer (Fujifilm Dimatix, Santa Clara, USA) was used to print conductive features with NPS-JL nano-silver paste (Harima Chemicals Group Inc., Tokyo, Japan) onto a photo paper substrate (NB-RC-3GR120, Mitsubishi Imaging (MPM) Inc., Swedesboro, NJ USA). The Dimatix printer settings include a jetting voltage of 33 V, a nozzle temperature of 30˚C, and a platen temperature of 30˚C [5]**.** Thermal curing was completed at 80°C for 2 hours.

Measurement techniques: A lumped passive component model was used to perform track analysis. Contact and track resistances were measured using an impedance analyser (GW-Instek LCR-8110G, Taipei, Taiwan). Kelvin probing was selected in order to minimize measurement errors generated by lead and contact resistances. The RFID tag based on the design from the development kit (SL900A-DK-STQFN16, ams AG, Premstaetten, Austria) was scanned using an AS3993 FERMI Reader (AS3993-QF_DK_R Fermi reader, ams AG, Premstaetten, Austria) and displayed using reader 2.4.2 firmware.

Inkjet Printing Process: In preceding work the electronic and geometric track properties were investigated for various inkjet drop spacings and number of printed layers [5]. The optimal drop spacing for pre-packaged chip connections was found to be 5 µm for 1 printed layer, and 35 µm for 3 layers, respectively. For 5 µm drop spacing, a layer thickness of 128 µm and a track width twice that of the design value were observed, due to spreading of the large ink volume. This is advantageous for the pad connection, where a chip wire bond structure is imitated. For 35 µm drop spacing and 3 layers, a thickness of 13 µm and 7% planar spreading were observed. Therefore, a 3-layer printed line is appropriate for connecting the die to the paper substrate. Fig 1 is an illustration of the hybrid inkjet-printed paper-based RFID tag.

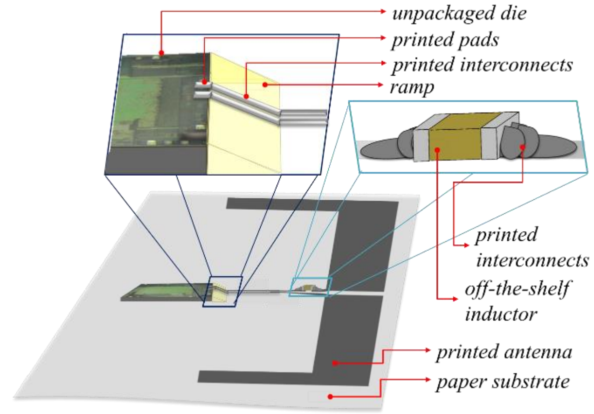


Fig. 1 *Unpackaged die in hybrid inkjet-printed RFID tag on paper.*

The IC pad dimension is approximately 70 µm on a side. The maximum width of the printed interconnect was selected to match the 70 µm. The first layout design contained a 35 µm by 35 µm block, printed in a single layer on top of the selected pad using 5 µm drop spacing. The second layout design consisted of a 70 µm x 3 mm line used to connect the pads to the paper substrate over the superglue ramp, using a 35 µm drop spacing for 3 layers. Each pad was individually aligned [5] before printing. The inductor interconnect was printed by first printing a single layer with 5 µm drop spacing on the printed connection pad, after that, the inductor was adhered using superglue, and lastly, a 35 µm drop spacing print of 3 layers was performed.

Ramp Development and Manufacturing: The average thickness of an inkjet-printed track is 5 - 15 µm [5], while a die thickness is typically 200 - 300 µm [1]. Therefore, non-planar printing requires that an interface ramp must have steps with height less than the track thickness. The effectiveness of the superglue was verified against two other adhesives in [7], and in this application Precision superglue was used to manufacture the interface ramp. In general, printed electronics on superglue also enables biocompatible applications such as wound monitoring [8]. The superglue was pre-treated at 120˚C for an hour, with 30 minutes of linear temperature ramp-up and ramp-down.

A die model was made from resin coated paper with similar dimensions as the silicon die (250 µm x 3 mm x 3 mm) for optimising the printed interconnects before implementing them on the unpackaged die. Before printing, the ramp is fabricated manually by applying superglue around the die edges, waiting approximately 5 minutes for the layer to dry, and then applying the next superglue layer. A microscope is used to observe the die on the paper substrate from the side to appraise the height of the ramp. After the correct height is obtained the interconnects may be printed, as shown in Fig. 2.

The Dimatix printer dispenses ink drops in a linear manner (horizontally) and then scans in the orthogonal direction (vertically). The attributes of horizontal and vertical connections in Fig. 2 may subsequently differ. Furthermore, the minimum printed feature size is dependent on the drop spreading due to the substrate properties. In Fig. 2, the topography of the silver ink on the superglue is different in comparison to that on the paper. This indicates that the superglue is more hydrophilic than paper, causing an increased line width and a reduced layer thickness, which will lead to higher resistivity.

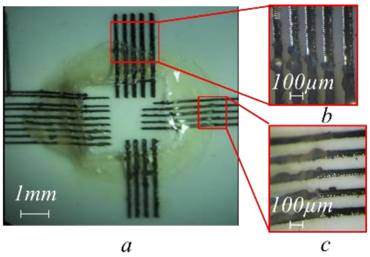


Fig. 2 *a. Printed interconnects to a paper die model. b. Vertical interconnects and c. horizontal interconnects.*

The model die results in Fig. 3 shows the resistance averaged (with standard deviation bars) over 10 experiments for tracks printed on paper and superglue, as well as the total interconnect resistance. The resistance of the track on the superglue is five times larger than that of a similarly sized track on paper. There is a total interconnect resistance of approximately 13.9 Ω, but for simple circuits this is adequate. The instrument calibration is performed on copper, and the probe-silver contact resistance is a large component of the total interconnect resistance, with an average value derived as 6.3 Ω.

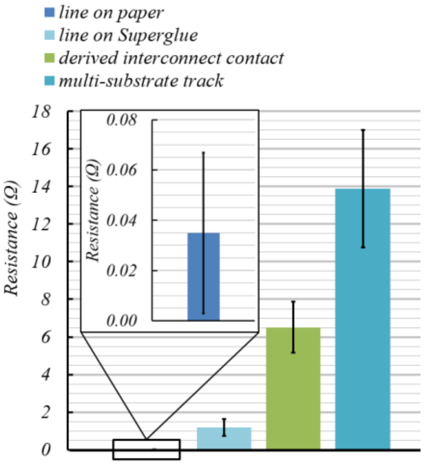
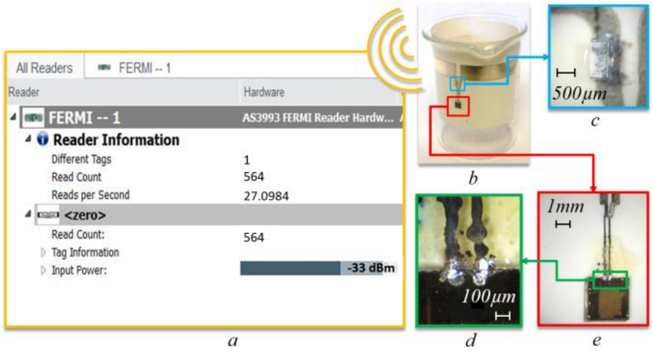


Fig. 3 *Resistance components of the printed model die interconnects.*



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All Readers    FERMI -- 1
Reader                          Hardware
FERMI -- 1                      AS3993 FERMI Reader Hardw...
  Reader Information
    Different Tags              1
    Read Count                  564
    Reads per Second            27.0984
  <zero>
    Read Count:                 564
    Tag Information
    Input Power:                -33 dBm
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Fig. 4 *a. RFID reader output, b. flexible paper-based inkjet-printed RFID tag with integrated unpackaged die inside a 50ml beaker, c. inkjet connected off-the-shelf inductor, d. inkjet-printed die to paper interconnects, and e. hybrid integrated die.*

Unpackaged IC implementation: Fig. 4 shows the functioning RFID tag with the unpackaged die integrated onto the paper substrate, along with a printed antenna and an off-the-shelf inductor. The RFID tag is placed inside a 50ml beaker with a circumference of 40 mm, to show the flexibility of the circuit. The RFID tag is shown in Fig. 4b was scanned at a distance of 100 mm, and the output in Fig. 4c was recorded using the AS3003 FERMI reader. At the Korean standard (917 - 920 MHz frequency), an input power of -33 dBm was used to read 564 values. This compares well with a development board RFID tag power of -31dBm, confirming that the unpackaged die integrated onto the paper using inkjet-printed interconnects was successfully implemented.

Conclusion: A hybrid inkjet-printed manufacturing process was developed to integrate an unpackaged IC onto a paper substrate. Various inkjet-printing manufacturing challenges in the electronic integration of different functional materials are addressed, although automated dispensing of the superglue ramp needs to be considered in future. Integrating an unpackaged die onto a biodegradable paper substrate with a digital process decreases the cost of the hybrid system while maintaining the excellent silicon performance. As a demonstrable proof-of-concept, a functional, flexible RFID tag was manufactured using the integration processes. This technology can contribute to a variety of active fields such as wearables, healthcare, environmental monitoring and smart packaging. Resistivity optimisation for tracks on superglue, and exploration of the printed track to die pad contact, will extend the range of applications where this integration method is useful.

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References

1. Mäntysalo, M., Xie, L., Jonsson, F., Feng, Y., Cabezas, A.L., Zheng, L-R.: 'System Integration of Smart Packages Using Printed Electronics', IEEE Electronic Components and Technology Conf., San Diego, CA, USA, May 2012, pp. 997-1002.
2. Grau, G., Kitsomboonloha, R., Swisher, S.L., Kang, H., Subramanian, V.: 'Printed Transistors on Paper: Towards Smart Consumer', *Advanced functional materials*, 2014, **24**, pp. 5067-5074, doi: 10.1002/adfm.201400129.
3. Steckl, A.J., 'Circuits on Cellulose', *IEEE Spectrum*, 2013, **50** (2), pp. 48 – 61, doi: 10.1109/MSPEC.2013.6420146. http://spectrum.ieee.org/semiconductors/materials/electronics-on-paper.
4. Andò, B., Baglio, S., Bulsara, A.R., Emery, T., Marletta, V., Pistorio, A.: 'Low-cost inkjet printing technology for the rapid prototyping of transducers', *MDPI Sensors*, 2017, **17** (4), pp. 1-11, doi: 10.3390/s17040748.
5. Bezuidenhout, P., Land, K., Joubert, T-H.: 'Integrating integrated circuit chips on paper substrates using ink-jet printed electronics', 17th Annual International Conf. the rapid product development association of South Africa, Vanderbijlpark, South-Africa, November 2016.
6. Marinov, V.R., Swenson, O., Atanasov, Y., Schneck, N.: 'Laser-assisted ultrathin bare die packaging: a route to a new class of microelectronic devices', SPIE Laser-based Micro- and Nanopackaging and Assembly VII, San Francisco, CA, USA, February 2013, pp. 1-19.
7. Das, R.: 'Printed, flexible and hybrid electronics: hot trends and market outlook', IDTechEx Report. 2017.
8. Jones, C.D., Ho, W., Samy, M., Boom, S., Lam, W.L.: 'Comparison of glues, sutures, and other commercially available methods of skin closure: A review of literature', *KEI Medical Research Archives*, **5** (7), July 2017, pp. 1-11.