Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 96 (2020) 115–120

www.elsevier.com/locate/procedia

CIRPe 2020 – 8th CIRP Global Web Conference – Flexible Mass Customisation

Printed Electronics (PE) As An enabling Technology To Realize Flexible Mass Customized Smart Applications

Jarne Machiels [a,c,d]*, Akash Verma[b]*, Raf Appeltans[e], Mieke Buntinx[d], Eleonora Ferraris [b,]**, Wim Deferme [a,c]***

[a]Hasselt University, Institute for Materials Research (IMO), Functional Materials Engineering, Wetenschapspark 1, 3590 Diepenbeek, Belgium
[b]Advanced Manufacturing Lab, MAPS, KU Leuven, J. D. Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium
[c]IMEC vzw, Division IMOMEC, Wetenschapspark 1, 3590 Diepenbeek, Belgium
[d]Hasselt University, Institute for Materials Research (IMO-IMOMEC), Packaging Technology Center, Wetenschapspark 27, 3590 Diepenbeek, Belgium
[e]IMEC vzw, Kapeldreef 75, 3001, Leuven, Belgium

** Eleonora Ferraris, Tel.: + 32)15 31 69 44; fax: +32 15 31 74 53. *Email address:* eleonora.ferraris@kuleuven.be
*** Wim Deferme, Tel.: +32 1126 88 74; fax: +32 11 26 88 99. *Email address:* wim.deferme@uhasselt.be

Abstract

Printed Electronics (PE) involves additive deposition of functional materials on a substrate via printing processes to realize electronic circuits, interconnects, electrical components or devices. This methodology is opposite to the conventional microelectronics industry which is based on subtractive manufacturing techniques (e.g. etching). Some of the advantages of PE over conventional electronics are low prototyping costs, short time to market, less processing steps, etc. One of the features is the ability to manufacture flexible and customized products and devices. The applications of Printed Electronics apply to different sectors of industry like electronics, packaging, bio-medical, automotive, communication, etc. In this work, we present Aerosol Jet® Printing (AJ®P) and Screen Printing as two techniques for the realization of flexible and mass customized PE devices. Whereas the use of AJ®P is focused on rapid prototyping, Screen Printing allows to upscale for mass production. The two technologies are here implemented to realise conductive antennas on paper substrates, potentially to integrate into a delivery parcel box for the development of "smart packaging". This antenna design is based on the 13.56 MHz working frequency, which lies in the frequency spectrum of HF RFID/NFC applications. The print quality, electrical resistance and the basic functional characterization (working frequency) of these paper-based antennas are here investigated and reported.

Keywords: Printed Electronics; Screen Printing; Aerosol Jet® Printing; Customized printed antenna

1. Introduction

Printed Electronics (PE) is a production technological area which allows to deposit different types of materials on a wide range of substrates by various printing techniques. The purpose is to manufacture state-of-the-art electronic devices. It is not only restricted to printing and electronics, but it is a multi-disciplinary domain, an amalgamation of material science, physics, chemistry, wireless communication, reliability engineering, fractural mechanics, and many more [1]. It is one of the most emerging technologies rising up these days [2]. According to the IDTechEx report in 2019, the market value of the whole industry will be more than 30 Billion US $ by 2020 and expected to increase in the upcoming decade. The requirements of PE are a substrate, an ink, a printing technique and a sintering process in the end to create a fully printed device (Fig. 1). PE techniques are broadly divided in two categories, i.e. mask-based and mask-less printing. Some of the examples of mask-based are Screen Printing (SP), flexographic printing, gravure printing, etc. [1].

They require a stencil, a mask or a screen to deposit and transfer the ink onto a substrate in a desired pattern. Aerosol Jet® Printing (AJ®P) and inkjet printing, instead, are examples of mask-less techniques. They are also known as direct–writing techniques because indeed they do not require a mask or a stencil to print the desired pattern. These printing techniques are based on a digital platform which transforms a digital image

10.1016/j.procir.2020.01.062

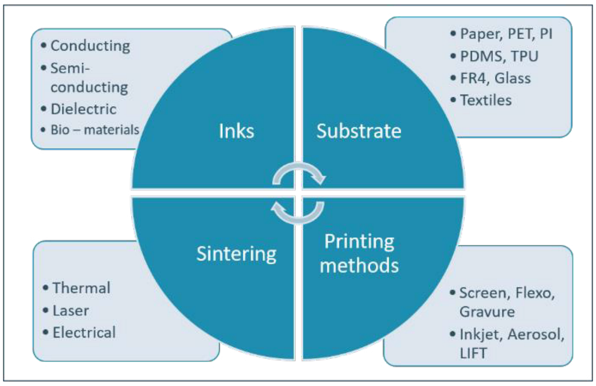


Fig. 1: Inks, substrate, printing technique and sintering are the building blocks of printed electronics (PE)

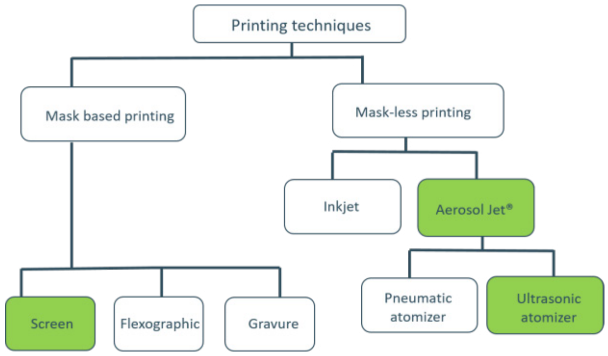


Fig. 2: Printing technologies are essentially divided in mask based and mask less techniques. This work applies screen and jet based techniques to realise flexible mass customised smart applications.

or a computer-aided design into a print pattern [1,3].

Some of the printing techniques are compiled in Fig. 2. In this work, AJ®P and Screen Printing are investigated to manufacture a printed antenna on a flexible (paper) substrate, as basic electronics element to develop smart customized devices, such as smart/luxury paper based packages, smart textiles, flexible screens. This work in particular introduced the combined added value of the two techniques in the development of flexible customized smart applications, where the AJ®P technique is used as prototyping process while screen printing as technology towards mass customization. Details of these techniques are presented in the following section 1.1.

1.1. Aerosol Jet® Printing and Screen Printing

Aerosol Jet® Printing (AJ®P) is a non–contact, direct writing printing technique which allows to print a wide range of functional materials on many different substrates in any designed manner [4,5]. In this printing technique, an “ink” is aerosolized into an aerosol of ink droplets which typically have a diameter of 1-5 µm [6]. The generation of aerosol is done by an ultrasonic atomizer or pneumatic atomizer. In this work, an ultrasonic atomizer has been used for the generation of the aerosol. This aerosol is entrained in the nitrogen gas and transferred to the deposition head. In the deposition head, a sheath gas is introduced which aerodynamically focuses the aerosol for the printing at the substrate beneath the tip by flowing in the co–axial direction [7,8]. Such type of processes allows to print feature sizes of 10 µm till several millimeters and thicknesses of 100 nm to tens of microns [7]. Because of the two different atomizing techniques, (AJ®P) allows to print inks with broad viscosities (1-1000 cP) and materials, like metals (Ag, Cu, Au, etc.), conductive polymers (PEDOT:PSS, PANI), carbon based resistive materials, dielectrics, bio–materials (gelatin, collagen [9]), etc. Furthermore, because of the adjustable stand–off distance, i.e. the distance between the nozzle and the substrate, it allows printing directly on 3D/free formed surfaces [5,10]. There are many different factors in AJ®P which affect the line width (µm), printing quality and the resultant electrical resistance (Ω) of the printed line. Some of the factors are the atomizer gas flow (sccm), the sheath gas flow (sccm), the focusing ratio (sheath gas flow/atomizer gas flow), the plate temperature (°C), the number of printing passes/layers (#), the printing speed (mm/sec), the sintering time (mins), the sintering temperature (°C), the nozzle diameter (⌀), the stand–off distance (mm)…etc. [8, 11].

Screen printing (SP) is a direct contact printing technique transferring ink onto a substrate (e.g. paper, glass, plastics, fabrics, etc.) by using a mesh screen with apertures. The open meshes result in the appropriate stencil or printing image while the impermeable coating of the surrounding area blocks the ink deposition [12]. This printing technique uses high viscous (100-100000 mPa.s), thixotropic (shear thinning) inks resulting in a rectangular cross-sectional morphology of the printed pattern [13]. A broad range of functional materials can be deposited, such as metal inks (Ag, Cu, etc.), polymeric inks (e.g. PEDOT:PSS), carbon-based inks, dielectrics… When applying an ink onto a substrate, the squeegee (rubber blade) is moved across the screen, thereby filling the mesh openings with ink. In this forward movement, the screen is momentarily forced to the substrate and the ink is deposited by capillary forces. The blade finally scrapes the ink excess to its initial position and the printing process can be repeated several times to print multiple layers. The maximum printing resolution is tens of microns and the layer thickness of one pass ranges from a few µm to 100 µm, depending on the screen’s mesh size. The main SP parameters include the screen dimensions (e.g. mesh size, mesh thickness…), the printing speed, the squeegee pressure and - hardness, as well as the snap-off distance [14]. In addition, rotary SP can significantly increase the printing speed (> 100 m/min) using a stationary positioned squeegee placed inside a cylindrical screen that rotates at the same rate as the web. This SP method is suitable for large-scale production because of its reliability, but on the other hand it is more expensive and challenging to set up [15].

Aerosol Jet® Printing is used extensively as a tool for Rapid Prototyping and customization in many different sectors of industries whereas Screen Printing is especially implemented for mass customization and production. Both techniques are well known but their output yield is still inferior when compared to the conventional electronics production techniques. AJ®P is successfully applied in 3D printing of 5G antennas for cell phone communication whereas SP is extensively used for batteries, screens and lighting applications. [16,17]. Section 1.2 discusses advantages and limitations of PE against conventional electronics production technologies, while section 1.3 refers to the applications of PE.

1.2. Conventional Electronics Vs. Printed Electronics technologies

Printed Electronics (PE) is a relatively recent technology as compared to conventional electronics manufacturing steps, like photolithography, etching, wire bonding, IC packing, etc.

Still PE offers many advantages, such as low processing and manufacturing cost when dealing with prototyping, product development and small series production. Manufacturing is also more flexible with respect to design, materials and integration opportunities. Also, it does not need cleanroom facilities, unlike lithographic processes. The conventional electronics industry is especially unable to produce devices with a form factor – i.e. to fabricate electronic devices which can bend, flex or even stretch and that are integrated in a shapeless substrate (as flexible foil, paper, textile…).

On the other hand, PE also offers a number of limitations. The resolution of the printed tracks is still way lower than the conventional electronics. As an example, the best resolution that AJ®P can provide is 10 µm whereas the current EUV (extreme ultraviolet) lithography step can provide a resolution around 20 nm. Even though processes like roll–to–roll can increase the production yield in printed electronics significantly, mass production along with the high accuracy is yet not par level with conventional production techniques. Other limitations of PE over conventional electronics are reliability, durability, down-scaling performance and high-end quality [1,18].

1.3. Applications of Printed Electronics

Printed Electronics has a diverse range of applications: pressure, humidity, temperature, chemical, etc. printed sensors, antennas, thin–film transistors, photovoltaics, active and passive components, interconnects, batteries, etc. [3,18,19,20]. The application of PE is also extended towards Neural and Tissue Engineering [21].

Printing of radio frequency identification (RFID) antennas shows promising opportunities in the field of flexible mass customized applications, for example wireless interaction with packages during transportation. In [22], Xu *et al.* have printed an RFID antenna with working frequency of 13.56 MHz using AJ®P and an extra step of electroplating. The electroplating step is an additional step which was implemented on the printed tracks to reduce their printed track resistances. Yuxiao *et al.* have printed an 24 GHz antenna on a 3D printed substrate [23]. In contrast to AJ®P, the domain of screen printed antennas have already been frequently investigated in the recent period by a number of researchers. Shin *et al.* report the use of SP for the development of UHF RFID dipole antennas on PET substrate [24].The work of Fernández-Salmerón *et al.* presents a UHF dipole antenna, directly screen printed on a cardboard package [25]. Janeczek *et al.* instead investigate screen printing to deposit HF RFID antennas on flexible magnetic sheets and polymeric foils [26]. According to the research of A. Pereira *et al.*, the potential of SP to develop near-field communication (NFC) tags on coated paper substrates has also been demonstrated [27].

However, this particular study of printed antenna layouts in the frequency spectrum of HF RFID/NFC applications on paper substrates is rather limited. In addition, the combined use of AJ®P for prototyping and SP for small serial production of customized smart applications has been just little investigated, especially when coming to the use of AJ®P technique. In this paper, this particular application is studied in details. Antenna printing is here taking as an example of PE application. The working frequency, bandwidth and type of an antenna can indeed easily be customized by changing layout, dimensions, and electrical requirements, etc. which is easier for PE rather than for conventional methods.

2. Materials and Methods

2.1. Inks and substrates

The key topic of this study is to investigate antenna printing via Aerosol Jet® Printing and SP by using conductive silver inks on fiber-based printing substrates. Hereby, p_e:smart paper type 2 (Felix Schoeller, Germany) and Algro Baress (Sappi, Southern Africa) were studied. P_e:smart paper type 2 is a white opaque paper-based substrate with hydrophilic nanoporous surface coating, which is specifically made for printed electronics. As reference material, the Melinex series ST 506 transparent PET foil (thickness: 175 µm) from DuPont Teijin Foils and FR4 were used for Aerosol Jet® Printing. In this study, the substrates were not pre-treated.

For the Aerosol Jet® Printing, conductive silver nanoparticle (AgNPs) ink 'JS-A221AE' from Novacentrix, Inc, USA was selected and investigated to print antennas. The ink has a sheet resistance of ~24 mΩ/sq/20µm. The viscosity of the ink lies in the range of 20 cP with the average particle size of 35 nm as mentioned in the datasheet of the manufacturer.

For SP, two conductive nano silver inks were selected: 'Orgacon SI-P2000' from Agfa-Gevaert (Belgium) and 'Loctite ECI 1011' from Henkel (Germany). Both inks are highly conductive with a sheet resistance below 5 mΩ/sq/25µm.

2.2. Printing strategies and equipment

An OPTOMEC AJ300 printer (ultrasonic atomizer) with a nozzle diameter of 300 µm was applied to investigate printing of RFID antennas on paper substrates. Nitrogen was used as the carrier gas. The printed samples were cured for 120 minutes at 120°C in a thermal oven. The atomizer and sheath gas flows were optimized for good continuous printing lines with minimal overspray. Printing speed was in the range of 5 – 7 mm/sec. This is crucial for controlling the deposition of the ink, wetting of the ink on different mentioned substrates and to avoid short circuits in the printed antenna. The printing was performed at room temperature, with 50% relative humidity.

An ISIMAT 1000 PE semi-automatic screen printer with screen mesh: 140 T/cm x 31 µm PET fiber was applied to deposit 4 different antenna designs by SP. As a post-printing step, the ink was cured for 10 min at 150°C in a ventilated box oven. For the set of multilayer prints, the prints were just dried using nitrogen gas for 30 s before printing the next layer.

2.3. Antenna design

RFID is a two-way data transferring method of automatic identification and data capture, consisting of a reader device and a transponder or tag. This tag – with a unique ID – exists of a (printed) antenna to receive/send radio signals and a microchip (for data storage). In this study, passive high frequency antennas are developed resulting in a read range of approximately a few centimetres [28].

The investigated antenna designs are square-shaped, post-it sized loop antennas, each with their own specific number of tracks and track width. These passive HF RFID antennas resonate at 13.56 MHz base carrier frequency and should function with indium gallium zinc oxide thin-film transistor (IGZO TFT) microchips, both designed and developed by Imec (Leuven, Belgium). The main electrical characteristics include the series resistance [Ω], inductance [µH] and RFID functionality by extracting the tags' code with a reader device Fig. 3 shows four different loop antenna designs which are studied in this work.

Because of the very limited literature on AJ®P printed antennas on paper, this printing concept was firstly validated by printing a common design of 2.4 GHz antenna (WLAN applications), and its Standing Wave Ratio (SWR) was compared to the theoretical etched antenna; later on, the AJ®P strategy to prototype 13.56 MHz antenna on flexible (paper) substrates for smart packages was fine-tuned and prototypes were realized on various substrates. Sheet resistance of the AJ®P printed pattern was measured by a four-point probe device by Ossila Ltd, UK. The microscopic images were taken by a Hirox KH8700 optical microscope. Standing Wave Ratio (SWR) was measured by ENA series (E5061B), Network Analyzer from Agilent Technologies. Successively, the antenna layouts of Fig. 3 were screen printed on p_e:smart paper type 2 by using the Orgacon and Loctite nano silver inks. For each ink-paper-design combination, 25 different antennas were deposited for a total of 200 antennas, as show case of the ability of screen printing to scale-up customised smart devices to (small) serial production. The screen printed antenna's layouts were electrically characterized on RFID functionality with the thin-film microchip by extracting the tag's code.

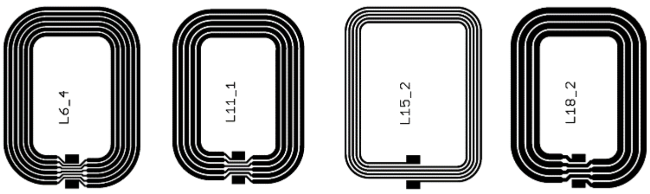


Fig. 3: Designs of high frequency RFID loop antennas with number of turns ranging from 4 to 6 turns, variable linewidth from 500 µm to 1600 µm and interspace ranging from 400 to 500 µm. The total size is in the range of 40 mm x 50 mm. Lx labels are the specific label investigated.

3. Results and discussion

3.1. Aerosol Jet® Printed Antennas

Comparison with etched antennas: Fig. 4 shows the Standing Wave Ratio (SWR) of a 2.4 GHz (working frequency (f_c)) antenna by AJ®P with Metalon® 'JS-A221AE'. The SWR (Standing Wave Ratio) was measured with a Network

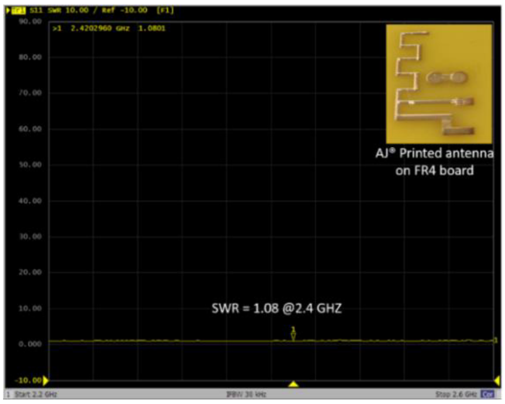


Fig. 4: Standing Wave Ratio (SWR) of a 2.4 GHz Aerosol Jet® Printed antenna on a FR4 board for the sake of comparison with conventionally etched antenna (i.e. on rigid substrates). A SWR of 1:1 means exact impedance matching and no loss in the transmission line.

Analyzer. In an ideal case, SWR of 1:1 means exact impedance matching and no loss in the transmission line. In our case, SWR is 1.08. This portrays the close match of the impedance of the load and the impedance of the transmission line carrying the RF signal between AJ®P and conventionally etched antenna design. This infer that the AJ®P can be enabling tool for the fabrication of any antenna layout.

3.1.1. Electrical characterization of printed tracks on different substrates

Fig. 5 shows the variation of sheet resistance vs the number of AJ® printed layers for various rigid and flexible substrates, including paper. The investigation is necessary to fine tune the AJ®P strategy to prototype printed antennas for customised applications on flexible (paper based) substrates, as luxury, smart packages, e.g. enabling to identify the content status. It can be seen that the sheet resistances decrease significantly until layer 4 and then starts to saturate relatively. This decrease of the resistance is due to the increase in the thickness of the printed tracks. All the substrates follow a similar trend, for exception of PET foils, as comparison, thefirst layer provides relatively high sheet resistance (576 ± 0.675 mΩ/sq) values as compared to the other substrates but starting from 2 layers, the sheet resistance values are in the same range as the other antennas. The reason for higher resistance value of the first layer of the Ag ink on the PET foil could be the first layer is not conductive enough due to less amount of material deposited and chemical interaction of ink-substrate.

3.1.2. Prototyping of Antennas on different substrates.

Fig. 6 shows the digital images of the printed tracks of the printed antennas (L6 design) on different types of substrates, including paper. The print quality is good, without overspray, fully dense and continuous. This also reveals the ability of AJ®P to print on a different class of substrates. Successful printing was done on FR4, PET and two different paper substrates.

FR4 was chosen as positive reference against conventional etching process. The rest of the substrates, two different types of papers and PET, are intrinsically flexible substrates which provide the flexibility and bendability to the printed prototypes of the antennas. These prototypes were not characterized but they showcase the potential of AJ®P to be a successful technology for Rapid Prototyping of flexible devices.

The series resistances of the antennas printed on Algro Baress, PET, p_e:smart paper type 2 and FR4 are 21 Ω, 51 Ω, 65 Ω, 49 Ω, respectively. All the antennas except p_e:smart paper type 2 were printed with 4 layers. A number of limitations, in case of AJ® Printing of the HF RFID, were also identified:

- Long printing time (~ 2 hrs for an antenna design)
- Low sintering temperature preferred for paper substrates
- Problems in adhesion and wetting with p_e:smart paper type 2

Electrical series resistance meet the requirements for the functional antenna and good quality printing has been observed.

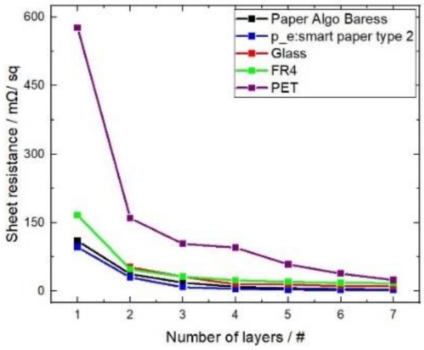


Fig. 5: Sheet resistance vs n.# of Aerosol Jet® Printed layers with silver ink JS-221AE on different substrates.

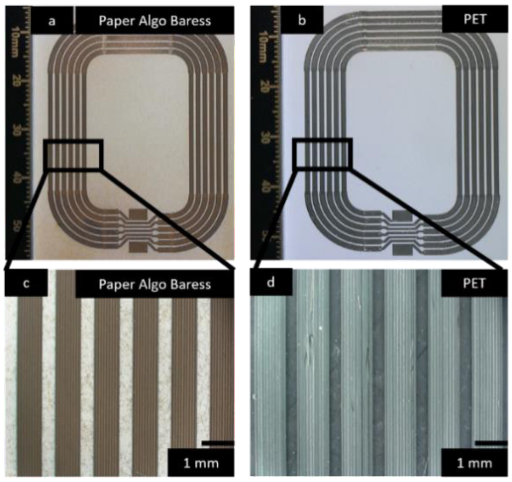
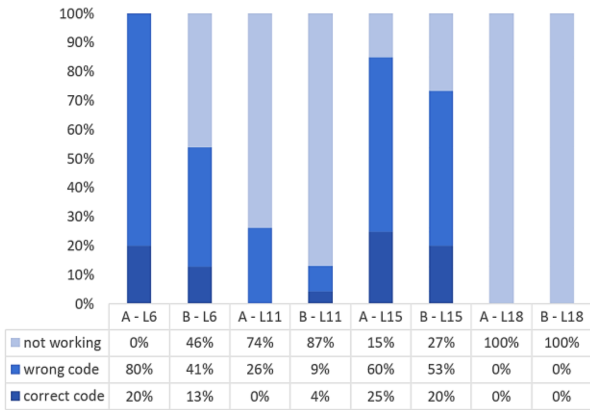


Fig. 6: Digital images of AJ® Printed L6 design antenna tracks on (a) Algro Baress (b) PET (c) printed tracks of antenna on Algro Baress 2 (d) printed tracks of antenna on PET

3.2. Screen Printed Antennas

Fig.7 shows the performance obtained for the screen printed antennas, in function of the particular design, ink and substrates used. As shown, due to the diversity in ink composition, track width, loop design and loop distance, the correct RFID functioning alters significantly for each ink-paper-design combination (Fig. 7).



	A - L6	B - L6	A - L11	B - L11	A - L15	B - L15	A - L18	B - L18
not working	0%	46%	74%	87%	15%	27%	100%	100%
wrong code	80%	41%	26%	9%	60%	53%	0%	0%
correct code	20%	13%	0%	4%	25%	20%	0%	0%

Fig. 7: RFID functioning of printed antennas on p_e:smart paper type 2 (A: 'Orgacon SI-P2000' and B: 'Loctite ECI 1011'

The L18 design did not generate functional antennas, i.e. no-communication occurred between the thin-film microchip and the reader device. The high track width of this design results in too low values of series resistance (19,3 ± 0,2 Ω) to pass the RFID functioning. In general, the L11 design does also not result in functional antennas while the other designs (L6 and L15) correspond moderately to the working range of the microchip's bandwidth. The entire selection of L6 antennas printed with 'Orgacon SI-P2000' ink transmits any code from the microchip to the reader device. This ink-paper-design combination looks most promising for printed HF RFID antennas and for that reason, the L6 antenna design is selected for further investigation.

As second step of the printed antenna development, the standard label material Algro Baress was investigated regarding printability of functional HF RFID antennas. Hereby, both conductive nano silver inks were screen printed 10 times referring the L6 antenna design. Based on the RFID functioning test, the series resistance and the inductance measurements, the antennas printed with 'Orgacon SI-P2000' ink showed unfavorable results: 90% of the antennas were not functional. The inductance of the non-working antennas was 2,13 ± 0,17 µH resulting in too high values of the antennas' quality parameter Q (Eq. 1)

$$Q = R/(2\ \pi f L) \quad (1)$$

with R is the series resistance [Ω], f is the frequency [Hz] and L is the inductance [H]. Too low Q values indicate weak energy transfer and other limitations that prevent data from being filtered. In contrast, too high Q values (as observed) indicate that a big amount of energy is being captured by the antenna and for that reason, the antenna functions as a filter for the requested data. Nevertheless, one tags' code of this ink-paper combination could be correctly extracted with the reader device; the antenna's inductance and series resistance were 2,92 µH and 48,3 Ω, respectively.

In contrast to 'Orgacon SI-P2000', the deposition of 'Loctite ECI 1011' ink onto the Algro Baress substrate led to 100% of functional L6 antennas. The inductance and series resistance were 2,98 ± 0,01 µH and 23,4 ± 1,2 Ω, respectively. According to Eq. 1, the antennas has a Q factor of 0,09 resulting in complete functionality with the thin-film microchip. Hence, the combination of 'Loctite ECI 1011', Algro Baress substrate and L6 antenna design is concluded to be successful for SP passive HF RFID antennas on paper substrates. Hereby, the antenna's inductance value should be approximately 3,00 ± 0,10 μH to meet the requirements of RFID functioning with the used IGZO-TFT microchip. The electrical resistance and inductance of this combination meets the requirements for the 100% functioning of the multiple printed antennas with the microchip. It showcases the SP can be effective tool for producing reliable customized antennas.

4. Conclusions:

In the context of AJ®P, different rigid and flexible substrates were investigated with test designs. By using those parameters, design L6 was printed on four different substrates. This showcased the potential of AJ®P as a rapid prototyping method whereas SP is more favourable for end product for flexible mass customized applications.

Flexible HF RFID antennas designs were printed by SP on fiber-based paper substrates and characterized successfully. This antenna is chosen as a single printed element out of numerous applications of PE. Different inks, substrates and designs were investigated to find out the optimal ink-paper-design combination (Loctite ECI 1011, Algro Baress, L6 design) for SP on the basis of printability, performance and antenna functionality. The functionality of this HF RFID antenna can be used in the "smart-packaging" applications of numerous products.

The successful prototyping by AJ®P of fully printed customized antenna and SP of functional antenna infers that these printing methods can be used as production method in the value chain. This implies that Printed Electronics can be an enabling technology for the development and manufacturing of flexible mass customized electronics applications and devices.

Acknowledgments

The authors would like to express gratitude to the Agentschap 'Innoveren & Ondernemen'. Apart from that, sincere thanks to all the partners of the project PAPERONICS especially Fetra vzw. This study is part of the CORNET project 'PAPERONICS: Low cost multisensory paper & packaging applications' (2019-2020). It is funded by Flanders Innovation & Entrepreneurship (VLAIO), Belgium (HBC.2018.0225) and AiF - German Federation of Industrial Research Associations, Germany. This work is also part of the TETRA 3D ElektroPrint -3D printen van vrije vorm elektrische/elektronische toepasssingen -HBC.2016.0067, also funded by VLAIO. Lastly, Jurre de Weerdt and Marc Scheirs are acknowledged for their expertise in 2.4 GHz antenna measurements.

References

[1] Suganuma K. Introduction to printed electronics. SpringerBriefs in electrical and computer engineering; 2014.
[2] Wu W. Inorganic nanomaterials for printed electronics: a review. Nanoscale. 2017; 9 (22):7342–7372.
[3] Kessler F. B, Khan S, Lorenzelli L, Dahiya R. Technologies for Printing Sensors and Electronics Over Large Flexible Substrates : A Review Technologies for Printing Sensors and Electronics over Large Flexible Substrates : A Review. IEEE Sens. J 2015; 15:3164–3185.
[4] J. M. Hoey, Lutfurakhmanov A, Schulz D. L, Akhatov I.S. A Review on Aerosol-Based Direct-Write and Its Applications for Microelectronics. J. Nanotechnol 2012 (2012):1–22
[5] Wilkinson N.J, Smith M.A.A, Kay R. W, Harris R. A. A review of aerosol jet printing—a non-traditional hybrid process for micro-manufacturing, Int. J. Adv. Manuf. Technol. 2019;105:4599-4619.
[6] Secor E. B. Principles of aerosol jet printing. Flex. Print. Electron 2018;3(3):035002
[7] Smith M, Choi Y.S, Boughey C, Kar-Narayan S. Controlling and assessing the quality of aerosol jet printed features for large area and flexible electronics. Flex. Print. Electron. 2017; 2(1):015004
[8] Mahajan A, Frisbie C.D, Francis L.F. Optimization of Aerosol Jet Printing for high-resolution, high-aspect ratio silver lines, ACS Appl. Mater. Interfaces 2013: 5(11): 4856–4864.
[9] R. Gibney, S. Matthyssen, J. Patterson, E. Ferraris, and N. Zakaria, "The human cornea as a model tissue for additive biomanufacturing: a review," Procedia CIRP 2017;65:56–63.
[10]Hedges M, Marin A.B. 3D Aerosol jet printing-Adding electronics functionality to RP/RM;2012.pp. 14-15.
[11]W.Verheecke et al. Optimizing aerosol jet printing of silver interconnects on polyimide film for embedded electronics applications. Eighth International DAAAM Baltic Conference Industrial Engineering.;2012 pp.19-21.
[12]Cruz S. M. F, Rocha L. A, Viana J. C.Printing technologies on flexible substrates for printed electronics. Flexible Electronics. IntechOpen; 2018.
[13]Ding J. et al. Preparing of highly conductive patterns on flexible substrates by screen printing of silver nanoparticles with different size distribution. Nanoscale Res. Lett.2016;11(1):1-8
[14] Fasolt B. et al. Effect of screen printing parameters on sensor and actuator performance of dielectric elastomer (DE) membranes. Sensors and Actuators A: Physical. 2017;265:10-19.
[15]Roth B, Søndergaard R, Krebs F. Roll-to-roll printing and coating techniques for manufacturing large-area flexible organic. Handb. Flex. Org. Electron. Mater. Manuf. Appl. 2014:171–192
[16]Yang W. et al. A Breathable and Screen-Printed Pressure Sensor Based on Nanofiber Membranes for Electronic Skins. Adv. Mater. Technol.2018;3(2) :1700241
[17]Cao R. et al. Screen-Printed Washable Electronic Textiles as Self-Powered Touch/Gesture Tribo-Sensors for Intelligent Human–Machine Interaction. ACS Nano 2018; 12 (6): 5190-5196
[18]Cui Z. Applications and future prospects of printed electronics. Printed Electronics: Materials, Technologies and Applications, Wiley Online Library, 2016, pp. 316–338.
[19]Nagels S. Silicone devices: A scalable DIY approach for fabricating self-contained multi-layered soft circuits using microfluidics. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, 2018, pp. 1–13.
[20]F. Molina-Lopez et al. Inkjet-printed stretchable and low voltage synaptic transistor array. Nat. Commun 2019;10 (1):1-10
[21]Seiti M, Ginestra P, Ferraro R.M , Ceretti E, Ferraris E. Nebulized jet-based printing of bio-electrical scaffolds for neural tissue engineering: a feasibility study. Biofabrication 2020;12(2):25024
[22]Xu B. et al. Aerosol jet printing on radio frequency identification tag applications. Key Eng. Mater 2013; 562 (565): 1417-1421
[23]He Y,et al. Aerosol Jet printed 24 GHz end-fire quasi-Yagi-Uda antenna on a 3-D printed cavity substrate. Int. Work. Antenna Technol. Small Antennas, Innov. Struct. Appl. iWAT 2017, pp. 179–182.
[24]Shin D.-Y, Lee Y, Kim C.H. Performance characterization of screen printed radio frequency identification antennas with silver nanopaste. Thin Solid Films 2009;517 (21):6112-6118
[25]Fernández-Salmerón J, at al. Passive UHF RFID tag with multiple sensing capabilities. Sensors 2015; 15(10): 26769–26782
[26] Janeczek K, Arazna A, Salski B, Lipiec K, Jakubowska M. Printed HF antennas for RFID on-metal transponders. Circuit World, 2016.
[27]Pereira A. et al. Near-field communication tag development on a paper substrate—application to cold chain monitoring.Flex. Print. Electron. 2018;3 (1):14003.
[28]A. Perrin and M. Souques, Electromagnetic fields, environment and health. Springer Science & Business Media, 2013.