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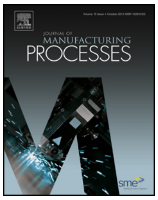

Design and fabrication of multilayer inkjet-printed passive components for printed electronics circuit development

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ABSTRACT

Printing electronic passive components suffers from the lack of a wide variety of appropriate materials for developing components with specific characteristics and for specific dimensions. This paper introduces a multilayer approach for the inkjet printing of resistors, inductors and capacitors. The materials and process steps for the manufacturing, the individual component characteristics and the equivalent circuit is provided for all passive devices. It is shown that the multilayer approach is a suitable strategy for manufacturing inkjet printed passive circuit elements with tailored characteristics for implementation into functional printed electronics devices.

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1. Introduction

Modern society is entering a novel technological paradigm based on the interconnections of objects in our surrounding environment – referred to as the Internet-of-Things (IoT) [1,2].

IoT consists of the connection of everyday objects by networks and databases, allowing the possibility to detect changes in the environment in which they are inserted, and the implementation of the corresponding response [3–6]. Thus, the distributed computing capability and the access to the large quantity of produced information [7] enables to act into the environment in a preventive or reactive way ensuring better quality of life, energy saving and security, among others.

Although strong benefits are expected from this new paradigm [8], the introduction of its full potential needs the development of new techniques and production methods [9]. In particular, this new concept implies the implementation of active areas (e.g. sensors and actuators) from very small to large scale, on flexible and/or irregular surfaces [10] and they will have to withstand the harsh and varying conditions of the surrounding environment.

As a consequence, a new concept for electronics able to keep up with new sensor and actuator systems is required, the development of flexible electronics being one of the most promising approaches.

There is an increasing interest to exploit graphic printing techniques for the manufacturing of flexible electronics. Printing technologies allow the deposition of functional materials not compatible with conventional electronic manufacturing processes [11] on large areas and on rigid as well as flexible or irregular surfaces.

There are several printing techniques that can be classified into contact printing and non-contact printing techniques [12]. In the case of contact printing, the substrate is in direct contact with intermediate forms where the ink is located before its transfer to the substrate and therefore there is a risk of contamination and damage of the substrate due to the contact. However, non-contact printing methods can transfer inks to substrate without any contamination and damage risk. Thus, they enable materials deposition on sensitive and irregular surfaces. Contact printing techniques such as flexography [13,14], gravure [15,16] and screen [15] printing are usually characterised by high processing speed and low-cost due to the possibility to implement it to a roll to roll (R2R) manufacturing process, which can be considered as indicator for mass production.

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Non-contact printing methods are e.g. inkjet [15], laser-induced forward transfer (LIFT) [17] and aerosol-jet [18–20] printing. They are typically based on the digital direct-writing approach without any need for physical masks to enable patterning. Therefore, pattern change is possible without associated costs making the process attractive for highly individualized products and/or products with short run length.

Inkjet printing is considered as one of the most promising techniques for non-contact and low-cost printed electronics production. It is applicable to large areas and is compatible with flexible or irregular substrates [15,21–23]. It represents an additive and non-contact process without the need of high temperatures [24], photolithography, high vacuum [24] or etching steps which typically occur in traditional micro fabrications techniques.

Examples of inkjet-printed devices include thin film transistors [25–27], organic memories [28], antennas and RFID tags [29,30], light-emitting devices [31,32], solar cells [33,34], electrical components [35] and sensors [22,36–38], among others. These examples show that inkjet-printed active devices cannot compete with the traditional semiconductor production in terms of integration, performance and cost [39]. On the other hand, they show potential advantages in for large area, flexible and stretchable applications.

In the field of passive devices, on the other hand, it is possible to fabricate competitive components by printing technologies. Further, they can represent advances in terms of device integration as passive devices are still the most voluminous parts of the current electronic circuits, even considering the surface-mounted-devices (SMD) solutions.

Despite the fact that current electronics is increasingly becoming digital, passive components are still essential for electronic development, particularly in the area of sensing. Most of the sensors still have an analogue response [22,37,38], as well as in the wireless communication area [40], where modulation and demodulation of the signal thought passive components is necessary.

According to the needs of electronic circuits, it is necessary to be able to fabricate components with specific functional characteristics appropriate to the circuit and the function to be performed, which is still a challenge for printed electronics. The fabrication of those components by printing technologies is only possible using materials with a broad range of functional characteristics (such as dielectric constant or electrical conductivity), or through process engineering to tailor the few materials that currently exist for printing to the component characteristics to be obtained.

The actual development in the printing of passive components has focused on the improvement of the performance per unit of area. This goal can be achieved in three ways: a) through the use of new printing technologies with higher resolution, higher repeatability and guarantee of thinner and uniform layers; b) the use of new inks with higher performance and stability and c) the use of new manufacturing strategies and methods using existing technologies and inks. In this way, and resembling the traditional passive components fabrication method evolution, the use of multilayer architectures can be considered a suitable solution both, for increasing the ratio of performance per unit area and to tailor the characteristics of passive components to accomplish with the specificity of circuit fabrication demands.

This work is focused on the introduction of the multilayer concept for inkjet-printed passive component fabrication, in particular, coils, capacitors and resistors, allowing the fabrication of complete circuits with fewer materials and therefore ensuring high reproducibility and success rate. Further, this methodology will allow to tailor the characteristics of the components for specific application needs.

All components have been fabricated entirely by inkjet printing, based on silver nanoparticle, polymeric conductive and dielectric inks, including full details of the fabrication process. Further, the performance of the structures is included as well as the modelling of the different components, allowing to modelling and design of more complex analogic circuits.

Thus, the present work introduces multilayer approach for the inkjet printing of resistors, inductors and capacitors and shows that it represents a suitable method for the fabrication of passive circuit elements with tailored characteristics for implementation into devices.

2. Experimental details

2.1. Equipment

Inkjet printing was performed using a Drop-on-Demand (DoD) Dimatix Material Printer (DMP) 3000 from Fujifilm Dimatix equipped with a DMC-11610 (propylene) cartridge and a print head with 16 nozzles. The print head ejects a nominal drop volume of 10 pL per nozzle. The nozzle-to-nozzle distance is 254 μm and the capacity of the ink cartridge is about 1.5 ml.

The DMP 3000's additive bottom-up fabrication process is capable of jetting a wide range of functional fluids after the definition of a large set of parameters such as waveform, voltage and drop ejection frequency, print head and substrate temperatures, in order to optimize the drop generation and formation according to the substrate, ink and patterns application.

The manufacturing process ends with the post-processing of the deposited ink e.g. a curing, drying and sintering process. The post-treatment for the inkjet-printed layers were carried out in a Nabertherm TR240 oven.

2.2. Materials

Heat stabilized Teonex Q65HA (Teijin DuPont films) poly (ethylene naphthalte) (PEN) films having 125 μm thickness were used as a flexible plastic substrates.

The PEN substrate is similar to poly(ethylene terephthalate) (PET) [41] substrates (typically used in these applications), except that PEN shows an excellent thermal stability, with a dimensional shrinkage of 0.1% at 150 °C for 30 min. It withstands temperatures up to 190 °C and has a surface treated face especially dedicated to printing applications. Further, it shows transparency in the visible range, which facilitates the printing and characterisation of the devices. The surface energy of the PEN substrate was measured with a Kruess Mobile Drop system. It was determined to ∼38 mN/m.

All the conductive layers were printed with UTDAgIJ1 [42] silver nanoparticle ink from UT DOTs Inc. which is a commercially available ink formulation.

It was necessary to optimize the deposition parameters for the print head to eject well-defined droplets resulting in well-defined patterns. The control signal applied to the piezo-electric print head is called as waveform which is a certain voltage over time. Fig. 1a shows the optimized jetting and non-jetting waveform for the UTDAgIJ1 silver ink and the ejected droplets with a drop-watcher camera. The non-jetting waveform is applied to the print head in the in idle mode avoiding the drying of the nozzle orifice due to a soft movement of the meniscus of the ink.

The maximum drop ejection voltage was 29 V and the drop ejection frequency was limited to 2 kHz for higher repeatability. It was also verified that the best results were obtained with 40 °C print head and 45 °C substrate temperatures. With these well-defined conditions, lines with 60 μm width were obtained. Finally, the nanoparticle silver ink was dried and sintered at a temperature of 150 °C for 30 min.

The dielectric layers were printed using a cross-linked poly (4-vinyl phenol) insulating material. The solvent was propylene

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