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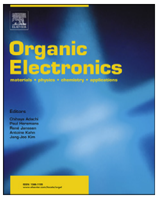

Up-scaling of the manufacturing of all-inkjet-printed organic thin-film transistors: Device performance and manufacturing yield of transistor arrays

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A B S T R A C T

All-inkjet-printed thin-film transistors (TFTs) have been demonstrated in literature using mainly laboratory inkjet equipment, simple one-channel layout and only a low number of manufactured TFT devices. We report on the development and the up-scaling of the manufacturing of all-inkjet-printed TFT arrays using industrial inkjet equipment. The manufacturing of the TFTs was carried out in ambient condition without the need for cleanroom environments or inert atmospheres and at a maximum temperature of 150 °C enabling the use of flexible polymer films as substrate. Arrays of 924 TFTs were manufactured on an area of about DIN A4 (297 × 420 mm^2). This allows the consideration of statistics, e.g. to determine the process yield as a function of device design and layout. We present process yields for all-inkjet-printed TFTs up to 82% demonstrating the potential of the developed all-inkjet-printing process.

1. Introduction

Printing of thin-film transistors (TFTs) is one of the major research topics in the area of printed electronics since many years [1]. One of the reasons is that transistors are basic components for integrated circuits and switches and thus the basis for most of the electronics and especially consumer electronics available nowadays. They are considered as most important electronic device and the key enabler of the digital revolution [2]. The idea of the manufacturing of transistors by means of printing technologies has been attracting many researchers during the last decades [1]. Printing technologies are considered as promising alternative to conventional lithography for the manufacturing due to their characteristics such as high-throughput, large area and low-cost production. Among the different printing technologies, inkjet printing as method with the highest degree of digitization dominates the research activities on printed TFTs [3,4]. There are numerous publications about inkjet-printed TFTs using different materials, different architectures and different inkjet technology platforms. However, in most of the publications only some of the layers are deposited by inkjet printing while others such as the dielectric and/or the semiconductor are spin-coated or electrode layers are evaporated [5–21]. Therefore, the reported device performance and yield is not intrinsic to an all-inkjet-printing technology platform.

In contrast, the number of publications about all-inkjet-printed TFTs is very low [22–34]. Most of the researchers of all-inkjet-printed transistors use the bottom gate bottom contact (BGBC) architecture and similar materials as we for the different layers.

Although all-inkjet-printed TFTs have been demonstrated, the viability of the inkjet printing process for the manufacturing of printed electronics and in detail of TFTs was considered to be unclear and is still under discussion [3,35]. Several reasons were identified, among others (i) pixelation issues due to the drop-by-drop approach, (ii) complex drying phenomena, (iii) drop placement accuracy and (iv) yield concerns when doing up-scaling to

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allow higher printing speed. While many researchers have studied pixelation and drying, the issue of drop placement accuracy and especially of yield remains poorly addressed. Pixelation issues in inkjet printing and corresponding effects of drying or post-processing were discussed among others by Diaz et al. [36], Soltman et al. [37], Ramon et al. [38] and Hammerschmidt et al. [39,40]. The study of drying dynamics of inkjet-printed droplets and their morphology on solid surfaces has attracted many researchers [41–45]. The improvement of drop placement accuracy is an important task for the printhead manufacturer. Drop placement accuracies less than 5 μm across the printhead were already reported in 2010 by Reinhold et al. [46] using Xaar piezoelectric inkjet printheads. The drop placement accuracy depends on many parameters such as jet-to-jet variation, nozzle straightness, nozzle and surface wetting, ink formulation, drop velocity and of course mainly on the distance between nozzle and substrate [47]. The lower the distance, the higher the accuracy. In general, 2 mm–3 mm stand-off distance is used for piezoelectric and thermal inkjet printing in the area of graphic printing [48]. However, usually paper is applied as a substrate in graphic industry, which is very rough on its surface compared to the plastic films mostly employed in printed electronics. Therefore, the nozzle-to-substrate distance can be decreased remarkably in printed electronics to 1 mm or even less. This will increase the drop placement accuracy.

The typical linear throughput of inkjet printing is about 1 m/s. Nowadays, a print speed up to 3 m/s for drop-on-demand inkjet printing is possible [49]. Of course, the print speed is still lower compared to competing conventional printing processes but can be considered as fast enough for the industrial manufacturing of TFTs. Usually, also not the print speed is the limiting factor for the manufacturing speed but the post-processing, e.g. drying and sintering of the deposited layers [50].

The concerns about yield when doing up-scaling in inkjet printing is probably the most important issue to be discussed. Up-scaling in inkjet printing is done by increasing the number of nozzles either (i) by using a printhead providing more nozzles, e.g. due to the nozzle arrangement in multiple lines or (ii) by forming arrays of multiple printheads. However, the larger the number of nozzles the more challenging the reliability issue of the process [49]. Finally, this reliability or in other terms the process yield will define if inkjet printing is a viable manufacturing process on industrial scale for printed electronics and specifically TFTs. Up-scaling and reliability of the inkjet printing process for TFT has been rarely addressed in literature. Abbel et al. [51] demonstrate an up-scaling strategy for the inkjet deposition of silver lines starting from small-scale laboratory equipment up to pre-industrial scale equipment. Kim et al. [25] indicate the manufacturing yield of the all-inkjet-printed TFTs with a simple one-channel layout as about 75% for 160 TFTs deposited on 20 × 20 mm^2. The deposition was done with a single inkjet nozzle system. We have demonstrated recently the up-scaling of all-inkjet-printed capacitors and all-inkjet-printed TFTs [33]. Yields up to 70% were obtained for the all-inkjet-printed TFTs. For the first time, industrial inkjet printheads were used next to laboratory printheads for the manufacturing along with a complex interdigitated source and drain (S-D) electrode design [33]. In this respect, state-of-the-art of inkjet-printed TFTs is still the manufacturing of only a few TFTs with a very simple layout on small areas using less than 16 nozzles as shown in Fig. 1A and C. This does not allow the consideration of process yield or any detailed statistical evaluation of the transistor characteristics. Our contribution demonstrates the successful up-scaling of the manufacturing of all-inkjet-printed TFTs on flexible polymer substrates. The developed manufacturing platform process allows the deposition of 924 TFTs on a single DIN A4 polymer film as depicted in Fig. 1B and C. All the deposition processes were carried out in ambient conditions. Statistical analysis of the TFTs allows the determination of the process yields for relevant layers as a function of TFT design.

2. Materials and methods

2.1. Substrate and inks

A 125 μm thick PEN film (DuPont Teijin Q65FA) of the size of DIN A4 (297 × 420 mm^2) with a one-side adhesion promoting chemical treatment was employed as flexible substrate for the printed TFTs. A commercially available silver nanoparticle ink purchased from Sun Chemical (SunTronic SunJet Silver EMD5603) was used for the deposition of the gate and S-D electrodes. The ink was filtered with a 0.45 μm syringe polytetrafluoroethylene (PTFE) filter, ultrasonically treated for 20 min and finally degassed before printing at 180 mbar for 10 min. Cross-linked poly-4-vinylphenol (cPVP, PVP ordered from Sigma Aldrich, Mw about 25000) was applied as dielectric material. PVP was dissolved in 10 mL propylene glycol monomethyl ether acetate (PGMEA) at room temperature supported by magnetic stirring for 3 h. Poly(melamine-co-formaldehyde) methylated (PMFM, from Aldrich, Mn about 432, 84 wt% in 1-butanol) was added as a crosslinking agent by stirring for 2 h. The ratio of PVP to PMFM was 5:1. Before printing, the dielectric ink was filtered with a 0.2 μm syringe filter. The ink formulation FS0096 provided by Flexink (Flexink Ltd., UK) was employed as organic semiconductor (OSC). It was special designed for the inkjet printing process consisting of an amorphous, conjugated and aromatic ordered p-type polymer dissolved in mesitylene.

2.2. Inkjet printing

The deposition of the different ink formulations were carried out with a Dimatix Materials Printer 2831 (DMP2831, Fujifilm Dimatix, USA) and a Dimatix Materials Printer 3000 (DMP3000, Fujifilm Dimatix, USA). The DMP2831 was used only for the deposition of the OSC ink formulation FS0096. The DMP 2831 was equipped with a laboratory cartridge printhead with 10 pL nominal drop volume. The printhead has 16 nozzles each with a diameter of about 21.5 μm. 4–16 nozzles were selected for printing at a frequency of 5 kHz. All other layers were deposited with the DMP3000 equipped with a Fujifilm Dimatix SE3 printhead. The SE3 has 128 nozzles arranged in a single line with a nozzle diameter of 42 μm. The nominal drop volume is 35 pL. The SE3 printhead is designed for high throughput printing of organic electronics according to industrial inkjet standards. Up to 105 nozzles were selected for the printing process at a frequency of 5 kHz. The clear distance between the nozzles and the substrate was maintained at 1 mm during printing. All samples were printed in ambient conditions. To control the layer formation, the substrate was heated for the deposition of silver ink to about 50 °C, for the dielectric ink to about 30 °C and for the OSC to about 35 °C up to 60 °C. Post-processing of the deposited thin-films was done in oven. The deposited silver ink was dried and sintered at 135 °C for 30 min. The dielectric films were dried inside a fume cupboard at room temperature for 20 min. Afterwards, the curing and crosslinking was performed at 150 °C for 40 min under low vacuum. The OSC film was dried at 100 °C for 20 min in oven. Storage of the samples was done in dark and low vacuum. All processing and characterization steps were carried out in ambient conditions.