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The design challenge in printing devices and circuits: Influence of the orientation of print patterns in inkjet-printed electronics

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ABSTRACT

We present a morphological and electrical analysis of inkjet-printed two-dimensional films of silver nanoparticle inks arranged at different orientation to the raster-scan-based printing process. Different parameters causing morphological and functional irregularities in the inkjet-deposited films as a function of their orientation to the printing process are introduced in detail and the relevance for the field of printed electronics is discussed. Researchers have demonstrated the manufacturing of various microelectronic devices using inkjet printing. Nearly all of the devices are based on simple rectilinear geometries. Usually, these geometries have a preferential orientation that is exactly (i) along the deposition process or exactly (ii) perpendicular to the deposition process. So far, it was assumed that the geometrical and functional characteristics are identically for the both cases. However, we show empirically that this is not the case and help to understand the conditions that lead to the differences.

1. Introduction

Inkjet printing technology is considered as a promising tool for the field of printed electronics [1–6]. Due to its digital direct-writing approach, no mask is required and the deposition of multiple materials can be performed on large areas and also on comparable high throughput. Significant research activities were dedicated towards the development of electronic devices among many others resistors [7], capacitors [8,9], antennas [7,10], diodes [11,12] and transistors [13,14]. The focus has been usually set on the performance of the devices and their improvement. Also manufacturing aspects such as up-scalability and process yield were considered [15]. The exploitation of inkjet printing for the manufacturing of printed electronics based on the liquid deposition approach initiated substantial scientific discussions about fluid dynamics during the printing process and during the evaporation of the solvent [16–19]. It was found, that the inkjet deposition of precisely defined, smooth, uniform and patterned layers at small as well as large size is a big challenge for printed electronics but also a crucial requirement for higher device performance and industrial application. Considerable research work has been done to study the layer formation and influencing parameters in inkjet printing by focusing on single droplets [19–25], lines [17,19,26–30] and rectangles [18,31–33]. Recently, we have shown a systematic study of single droplet morphologies as a function of ink formulation as well as substrate properties such as surface energy and temperature [20]. Soltman et al. studied in detail inkjet-printed line morphologies [19] as well as morphologies of rectangles [18]. Soltman et al. demonstrated the importance of process optimization to obtain smooth, narrow and straight line characteristics by tuning the distance between neighboring droplets and the drop ejection frequency or to obtain well-defined rectangular pattern shapes by a dedicated print layout development that includes an evaporative compensation. Diaz et al. [27] investigated the formation of intersections of printed lines and introduced concepts based on print layout variations to limit morphological irregularities at the intersections. Singh et al. [32] discussed the layer formation of inkjet-printed rectangles as a function of printing parameters, temperature of the substrate and substrate treatment. Also Teichler et al. [33] studied the film formation of inkjet-printed rectangles. However, the focus was set on the variation of the ink formulation.

Our contribution will extend the discussions of these research works about inkjet-printed deposit morphologies and the conditions leading to them. So far, the influence of print layout orientation was not considered in detail. In a recent publication [26], we have indicated differences in the morphology of printed lines

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depending on their orientation. Lines deposited in printing direction (with an orientation along the printing pass) were found to have significantly higher widths than lines deposited perpendicular to the printing direction. This finding is of important relevance for the field of inkjet-printed electronics, since usually all the devices and circuits have elements with different orientation angle to the printing process. Thus, one needs to know about the differences when designing the devices and an understanding of the influencing parameters is a necessity for the development of arbitrary patterns for printed electronics with multiple orientation angles.

Here, we will show in detail the influence of the print layout orientation on morphological and functional characteristics. The influence on morphological properties has been demonstrated many times before using model ink systems usually consisting of dissolved polymers. However, most important for printed electronics are the functional properties that define the final performance of the device or circuit. Therefore, we have employed exemplarily two commercially available silver nanoparticle inks allowing to investigate both morphological characteristics as well as electrical characteristics. We have chosen rectilinear shapes for our print layout as basic geometry for most of the microelectronic devices and circuits. By intention, our rectilinear print layout consists of relatively large feature sizes. To have a clear distinction to previous research works, our rectilinear line patterns are composed of thousands of droplets. We still term them as lines since they are also macroscopically lines, but they consist of multiple lines printed next to each other thus representing a two-dimensional film. That is why they are more close to the research works done about rectangles [18,31–33] than the works focusing on individual lines [17,19,28–30] that are usually termed as one-dimensional films. All of our print patterns are deposited in a line-by-line raster-scan process which is the inherent principle of inkjet printing [26]. Independent on the orientation of the pattern to be printed, the printing process will be performed in all cases in this line-by-line manner. This procedure indicates challenges, since the printing time for a pattern element of the same size will depend on its orientation angle to the printing process. In addition, digital prepress issues (e.g. pixelation at print pattern edges), well known from traditional graphic industries, will come into play when deviating from simple alignment angles [34]. Digital design corrections, e.g. based on automatic compensation rules, are required to obtain the desired shapes in the printed patterns [35]. In printed electronics, 1-bit images are mainly used as print layout files. Thus, the print pattern layout is defined by a grid of black and white pixels (px) in a defined resolution and each of the black pixels will result in a single droplet ejected from the printhead. The individual print dots are arranged in a grid and have usually the same center-to-center distance, the same size and the same shape.

2. Materials and methods

2.1. Substrate and inks

Standard float glasses with a thickness of 2 mm and an area size of 100 × 100 mm^2 were used as substrates. There was no special coating on the glass. The glasses were cleaned before printing with acetone and ethanol. First, acetone impregnated tissues were applied to wipe off dirt, dust and other debris from the glass surface. Second, an ultrasonic treatment of the glasses was performed in acetone and in ethanol each for 3 min. Finally, the substrate was dried in a flow of nitrogen for a few seconds.

Exemplarily, two commercially available silver nanoparticle inks were employed for the study: (i) Sun Chemical EMD5603 (SunTronic SunJet Silver EMD5603, abbreviated: SUN) and (ii) UT Dots UTDAgIJ1 (UT Dots silver nanoparticle ink, abbreviated: UTD). SUN is a well-known and well established ink formulation in the field of inkjet-printed electronics and has been used by many researchers, e.g. Refs. [36–41]. The solvent is mainly based on ethanol and ethylene glycol. Therefore, the nature of the ink is hydrophilic. The UTD ink is less common in the field of printed electronics and the solvent is based on hydrocarbons that have generally hydrophobic characteristics.

The contact angle of sessile silver ink droplets with a droplet volume of about 1.5 μL on the cleaned substrate was determined for both ink formulations using a drop shape analyzer (Krüss DSA 100, drop angle measured was performed 2 s after the deposition of the droplets). The contact angle describes the degree to which the silver inks spread upon contact with the substrate. The contact angle of the SUN ink on the glass substrate was approximately 44.9° ± 1.7° and the contact angle of the UTD ink 9.0° ± 1.8°. Fig. S1 in the Supporting Information depicts photographs of the sessile droplets of both of the inks.

2.2. Print pattern layout

A dedicated print pattern consisting of simple lines (two-dimensional films) of different orientation to the printing process with and without measurement pads was developed allowing to investigate the influence of the orientation of the lines on their morphological and electrical characteristics. The software Adobe Illustrator and Adobe Photoshop were employed for the design. Firstly, the required print patterns were designed in Adobe Illustrator, exported as grey-scale file with a resolution of 5080 dpi (dpi – dots per inch) and converted to a 1-bit bitmap file using Photoshop and a threshold of 50%. The resolution of 5080 dpi was chosen since it is the maximum print resolution of the employed inkjet printer. Secondly, a grid pattern consisting of single print dots with the resolution of 1270 dpi, 1016 dpi and 847 dpi was layed over the before prepared print pattern like a mesh. All the print dots of the grid pattern which were located directly on top of the firstly prepared print pattern were defined as final dots to be printed. All the other print dots were deleted. Further information is found in Fig. S2 in the Supporting Information. Thus, the final patterns were designed in three different print resolutions: 1270 dpi, 1016 dpi and 847 dpi. These three print resolutions define the center-to-center distance of the inkjet-printed droplets (usually termed as drop space or drop distance) and thus the deposited material per area. Therefore, 1270 dpi, 1016 dpi and 847 dpi represent a drop space of 20 μm, 25 μm and 30 μm, respectively. The print pattern and a scheme of the different drop spaces is shown in Fig. 1. The print pattern is indicated in black and descriptions to the patterns are provided in blue colour. The print origin is marked with ¤. In x-direction (indicated with the solid blue arrow), the deposition of the droplets takes place unidirectional by transferring the printhead over the substrate. In y-direction (indicated with the dotted blue arrow), the substrate is positioned relative to the printhead aiming to address the next line without depositing any droplets. Then, the deposition process starts again unidirectional in x-direction. Thus, the deposition process is performed line-by-line in x-direction. 500 μm was set as digital width for the designed lines and they have a length of about 10 mm. The overall print pattern size is about 40 × 40 mm^2. The size of the contact pads is 2 × 2 mm^2. Four of the print pattern layouts were inkjet-printed on one glass substrate.

2.3. Inkjet printing and post-processing

The deposition of the SUN and the UTD inks was carried out