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Aerosol jet printed top grids for organic optoelectronic devices

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ABSTRACT

Aerosol jet deposited metallic grids are very promising as transparent electrodes for large area organic solar cells and organic light emitting diodes. However, the homogeneity and the printing speed remain a challenge. We report homogeneous and rapidly printed metallic lines based on a complex-based metal–organic silver ink using a processing temperature of 140 °C. We show that inhomogeneities, which are present in printed structures at increased printing speeds and mainly caused by drying effects, can be improved by adding high boiling point solvents. We demonstrate solution processed highly conductive and transparent hybrid electrodes on inverted organic solar cells comprising digitally printed top silver grids.

1. Introduction

Printable organic electronic devices, such as organic photovoltaics (OPV) [1–4], have become an intensive field of research in the last decade due to their mechanical flexibility, light weight, and potential low fabrication cost. However, not only the material properties, but also the role of the deposition techniques is relevant for the device performance. For example, the control of layer-specific thicknesses and homogeneities are crucial aspects in the fabrication of optoelectronic devices, and are a current topic in the field of printed electronics [5–7]. Deposition techniques like inkjet and aerosol jet provide enormous potential for functional printing and have been investigated intensively in the past years [8–10]. These digital contact-free printing techniques implemented in sheet-to-sheet (S2S) inline systems are suitable for the mid-size production of personalized optoelectronic devices, or small series of integrated circuits on flexible or stiff substrates [11]. Moreover, the advantages of digital S2S production are for example, the negligible time needed to modify the system for a different device design or architecture. In contrast to roll-to-roll techniques not all production processes (e.g. drying, sintering, etc.) need to take place in the same time frame.

Much research has been done in the field of transparent and solution-processable electrodes for OPV devices, such as the application of randomly aligned silver nanowires in combination with highly conductive and transparent polymers [12–14]. Recently, the aerosol jet technique has gained a lot of interest due to its high accuracy and contact-free material deposition [15]. The working principle of an aerosol jet is presented in Supplementary Fig. 1. This technique allows a deposition of a large variety of functional inks, e.g. nanoparticle, or

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polymer inks [16,17] with a broad viscosity range from 0.5 cP to 1000 cP. In addition, it can yield highly accurate structures with a feature size down to 10 μm, as well as homogeneous layers in the cm^2 regime, which meets the requirements of electronic multilayered devices. This digital printing technique can also be used as a fast and cost-efficient experimental design optimization tool for feature size dependent circuit design, system integration, or current-collecting grids for optoelectronic devices such as OPVs.

The main focus of this work is placed on the optimization of digital aerosol jet printed current-collecting grids for transparent electrodes towards its application in large area organic optoelectronic devices, i.e. solar cells and light emitting diodes. The hybrid electrodes are based on highly conductive PEDOT:PSS (poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate)) and a metal–organic (MO) silver ink. The influence of printing speed and its corresponding increase in surface-to-volume ratio of the printed lines on the resulting film morphology have been investigated. Furthermore, high boiling point co-solvents have been used to optimize the ink formulation towards an improved printing outcome when printing at higher printing speeds. The printing results were characterized by atomic force microscopy (AFM), and by white light interferometric microscopy. Finally, transparency and sheet resistance of printed grids were investigated and solution processed inverted organic bulk heterojunction (BHJ) solar cells with poly-3-hexyl thiophene (P3HT), and phenyl-C61-butyric acid methyl ester (PCBM) as the active material on ITO/ZnO covered glass substrates with hybrid electrodes as top anode have been demonstrated.

2. Experimental section

The silver ink used in this work is a metal–organic (MO) complex ink (PR-010, InkTec®). The ink contains <40 wt.% silver complex compound, <58 wt.% ethanol, and <2% 2-Amino-1-butanol [18]. For a proper atomization, the ink was diluted with ethanol in a volume ratio of 1:1. This ink was chosen because of its low annealing temperature (140 °C) and high printing resolution with an ultrasonic atomization system. The annealing needs to take place when the deposited ink is wet. Already dried MO complex ink turns brownish and is not getting conductive anymore during further annealing steps. For this reason, in the following, high boiling point co-solvents were used to slow down the film drying process.

The inverted solar cells were fabricated on structured pre-cleaned ITO covered glass substrates. The ITO with a ZnO layer prepared from a precursor as described in Ref. [19] was used as the cathode in our inverted stack. P3HT:PCBM was used as the active material. P3HT (MaDriX) and PC60BM (Solenne) were dissolved separately in 1,4-Dichlorobenzene (40 g/L) and blended afterwards in a ratio of 1:0.9. The solution was then spun in nitrogen atmosphere resulting in a thickness of 180 nm.

The top anode consisted of a well investigated material composition with conductive PEDOT:PSS and an aerosol printed current collecting grid [20]. A defined area of PEDOT:PSS (Clevios™ PH1000, Heraeus Precious Metals) solution with 5 vol.% dimethyl sulfoxide (DMSO) was achieved using a pre-structured heat release tape on top of the active material. The spin coated film was dried at 140 °C for 15 min in nitrogen atmosphere resulting in a 100 nm thick layer. Following this procedure a specific

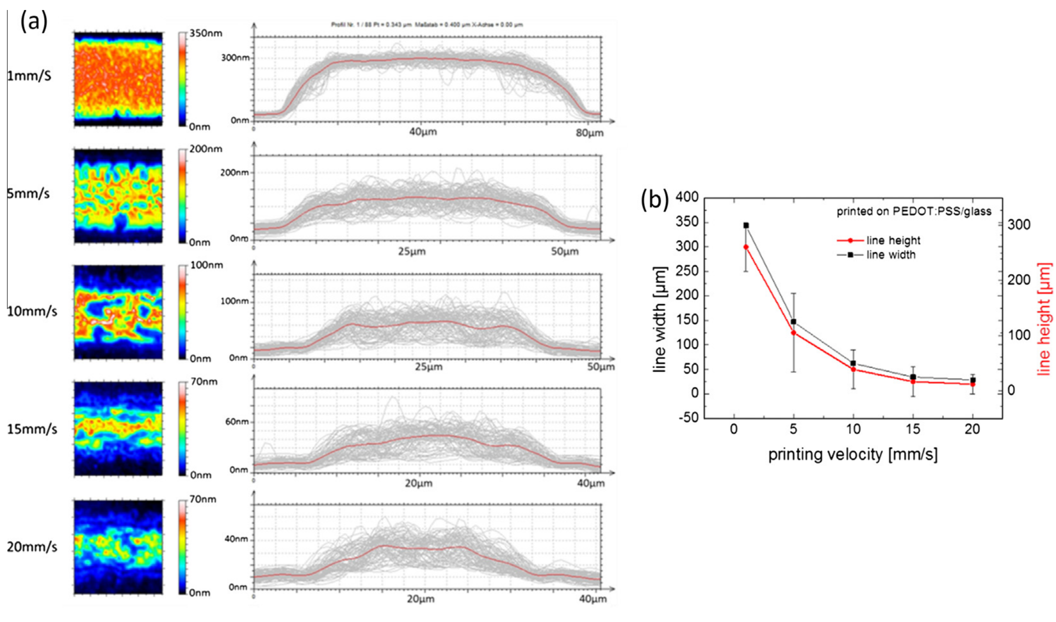

Fig. 1. (a) Interferometry images and cross-sections of silver lines printed on PEDOT:PSS with 1, 5, 10, 15, 20 mm/s printing speed. (b) Corresponding average line width and height with error bars.