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All-printed low-voltage organic transistors

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ABSTRACT

All-printed low-voltage organic transistors were manufactured on a plastic substrate and measured in normal room atmosphere. All electrodes were ink-jet printed, while the homogeneous semiconductor and insulator layers were subsequently applied by the reverse gravure coating technique. No destructive effects from the rough plastic substrate or the printed silver source and drain electrodes were observed. Changes in the transistor characteristics after 48 days of ageing in room atmosphere were mainly attributed to a reduced conductivity of the polymer gate electrode.

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1. Introduction

Roll-to-roll manufacturing may enable large-area fabrication of organic electronic devices at low cost. Conducting, semiconducting and insulating materials in solutions and dispersions provide a possibility of roll-to-roll fabrication with traditional printing and coating techniques. Ink-jet (IJ) printing has recently been studied as a method for printing organic electronics [1–4], but also other printing methods have been used [5–8]. Organic transistors require both patterned structures and thin homogeneous layers. While the source and drain (S/D) electrodes need to be printed with high lateral resolution, the thickness and homogeneity are much more important for the semiconductor and insulator layers. Consequently, a combination of printing and coating techniques may provide better manufacturing methods than a single printing technique.

Spin coating is very often used for applying the semiconductor and insulator layers [1,4–6,8]. It is, however, mainly a laboratory scale method and has the disadvantages of low throughput, roll-to-roll incompatibility and

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that most of the material ends up as waste. Reverse gravure (RG) coating, on the other hand, is a roll-to-roll technique suitable for mass fabrication. This method produces thin homogeneous multi-layers over large areas for a wide range of ink viscosities [9,10].

Recently, we presented a low-voltage hygroscopic insulator field effect transistor (HIFET) printed and coated on a pre-patterned plastic substrate in air [10]. While traditional organic FETs usually operate at high voltages and require very smooth substrates for achieving high yield in the fabrication, the HIFET operates at low-voltage [11,12] and is rather insensitive to the roughness of the substrate [13] due to the operation principle [14] and the large thickness of the insulator. This ion modulated transistor is an excellent candidate for low-cost roll-to-roll manufacturing and can e.g. be used in humidity sensing applications [15] and when high switching speed is not necessary.

In this work we present a five-step process for fabricating all-printed HIFETs on plastic substrates completely by means of mass fabrication methods in room atmosphere. The RG coating technique was used to apply the semiconductor and insulator layers, while the electrodes were IJ printed. The transistors have been fabricated completely by roll-to-roll compatible printing and coating methods that are used in the printing industry.

2. Experimental

The HIFET geometry and process steps (Step 1–5) are shown in Fig. 1a. The substrate, a 50 µm thick Mylar® A film from DuPont Teijin Films, was washed with distilled water, acetone and isopropanol before printing. The IJ printer was a drop-on-demand Dimatix™ Materials Printer (DMP-2800) and the cartridge (DMC-11610) consisted of 16 nozzles with effective diameters of 21.5 µm. In Step 1, transistor S/D electrodes were fabricated by IJ printing a silver nanoparticle dispersion from Cabot with a drop spacing of 30 µm. The finger width (see Fig. 1b) of the electrodes was 200 µm, the channel width (W) was 1.5 mm and the channel length (L) was about 40 µm. A sheet resistance of 1–2 Ω/□ was achieved after sintering the electrodes at 120 °C on a hotplate for 20 min.

A low viscosity (~1 mPa s) semiconductor solution was obtained by dissolving 1.0 wt.% regioregular poly(3-hexylthiophene) (P3HT) from Plextronics in toluene and p-xylene (1:1). The solvent mixture was used to combine a lower evaporation rate (p-xylene) with a higher solubility (toluene). The insulator solution consisted of 10 wt.% of poly(4-vinyl phenol) (PVP) from ChemFirst/DuPont mixed with isopropanol. The viscosity was measured to about 10 mPa s by a Bohlin VOR rheometer. The P3HT- and PVP-layers were subsequently RG coated (Step 2 and Step 3) with a tabletop Mini-Labo™ test coater at a web speed (v_{web}) of 1.6 m/min and a roll speed (v_{roll}) of 0.6 m/min. A 20 mm diameter metal gravure roll with continuous trihelical grooves, 4.7 lines/mm, was used.

For IJ printing the gate electrode, the print head was optically aligned to print on the transistor channel area. As gate electrode material the conductive polymer poly(3,4-ethylene dioxythiophene) and poly(styrene sulfonate) (PEDOT:PSS) was used. In Step 4, a layer of the low-conductive Baytron P (Jet PE FL from H.C. Starck) was first IJ printed. This PEDOT:PSS water dispersion had a solid content of 1.49 wt.%, a viscosity of 8.5 mPa s and a conductivity of 1.4 mS/cm [16]. The non-crosslinked PVP was protected by this layer, when the more conductive, but ethanol containing, Baytron P (Jet HC) was IJ printed in Step 5. The ink had a solid content of 0.7 wt.%, a viscosity of 12 mPas and a conductivity of 74 S/cm [16].

All electrical characterizations of the HIFET were done in air in darkness at a relative humidity of 31–33% using an Agilent 4142B parameter analyzer and the conductivity measurements were done in a two probe configuration. The HIFET was stored in ambient air and in darkness between the measurements. The thickness of P3HT- and PVP-layers was determined from the absorption spectra and the surfaces were imaged with an atomic force microscope (AFM) (Park Scientific). The work function of evaporated silver on a Mylar® A substrate was measured in air as a function of time with the Kelvin probe technique. To determine the chemical composition of the IJ printed silver electrodes and to evaluate the P3HT coating on the electrodes, X-ray photoelectron spectroscopy (XPS) (Physical Electronics) was used.

3. Results and discussion

The characteristics of an all-printed HIFET measured two and 48 days after fabrication are shown in Fig. 2. The transistor switches between on- and off-state with a ratio

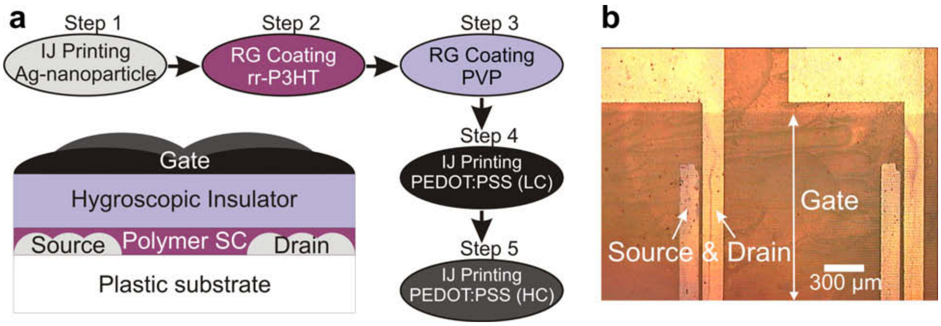

Fig. 1. (a) A five-step process flow for the fabrication of all-printed low-voltage organic transistors and a schematic image of a cross section of the transistor. Semiconductor is denoted as SC, while low- and high-conductive is denoted as LC and HC and (b) An optical microscope top-view picture of two all-printed devices.

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