Analysis of the mobility of printed organic p-channel transistors depending on the transistor geometry and orientation

D Spiehl\textsuperscript{1,*}, S Pankalla\textsuperscript{2}, M Glesner\textsuperscript{2}, and E Doersam\textsuperscript{1}

\textsuperscript{1} Technische Universität Darmstadt, Institute of Printing Science and Technology, Magdalenenstrasse 2, 64289 Darmstadt, Germany

\textsuperscript{2} Technische Universität Darmstadt, Microelectronic Systems Research Group, Merckstrasse 25, 64283 Darmstadt, Germany

E-Mail: spiehl@idd.tu-darmstadt.de

Abstract. The organic thin film transistor (OTFT) is an elementary part of most organic electronic products. A cost efficient and fast way to produce these circuits is by the use of mass printing techniques like flexography or gravure printing. A huge amount of OTFTs is produced via flexography and via spin-coating as a reference. The morphology of the printed layers and the electrical performance of the produced OTFTs are investigated. Based on these investigations, the dependence of the mobility on the transistor's source/drain geometry is analysed and explained. Analysed geometry parameters are the transistors channel length, channel width and its orientation compared to printing direction.

1. Introduction

Research in the field of printed organic electronics is developing rapidly. Besides organic light-emitting diodes (OLEDs) and organic photovoltaics (OPVs) the third huge topic is about organic thin film transistors (OTFTs). These are part of e-papers, smart packaging, flexible displays and radio frequency identification tags (RFIDs) [1]. The OTFT is an elementary part of most of these applications, especially if several OTFTs are connected to circuits.

A cost efficient and fast way to produce these circuits is by the use of mass printing technologies like flexography or gravure printing. Simulations of circuits consisting of printed OTFTs minimize production costs but must include electrical parameter variations in order to verify the reliability of the circuits. Thus, a huge amount of OTFTs is printed and the performance and variations of the process for OTFTs is investigated by electrical measurements [2] and morphological investigations. Based on these investigations, the dependence of the mobility on the transistor’s source/drain geometry is analysed and explained.

2. Materials and production

The OTFTs were built by the use of mass printing techniques for the semiconductor and gate layer; other layers were produced with conventional laboratory techniques. The chosen way to build the OTFTs was a top gate and bottom contact architecture. Figure 1 shows a photograph of a substrate with transistors and the production work flow.
The substrate is a Teonex Q65FA PEN film from DuPont Teijin Films. It has a thickness of 200 µm and a pre-treated side with a surface roughness of 0.6 nm, according to the manufacturer. A source/drain structure consisting of titanium as bonding agent and gold as electrode material was deposited onto the film by a photo-lithographical process. This structure was a layout of 83 transistors with different channel lengths \( L \) between 5 µm and 100 µm and with different channel widths \( W \) between 500 µm and 20707 µm [3]. There are several transistors with the same ratio of \( W/L \) but different \( W \) and \( L \). The transistors are ordered in different rows, columns and directions. Every transistor appears several times, so the homogeneity over the whole substrate can be examined.

![Figure 1. Photograph of a substrate with transistors (left) and production work flow (right)](image)

Before printing, the substrates were cleaned in an ultrasonic bath with isopropyl alcohol and were dried with clean dry air. Then a plasma treatment under argon atmosphere with a power of 300 W followed for two minutes. This leaded to a clean the surface and adjusted its surface tension for the first solution processed layer. Afterwards a self-assembled monolayer (SAM) was used to tune the work function of the golden electrodes to match the semiconductors HOMO-level.

The first printed layer was an organic p-channel polymer semiconductor that we printed by the use of flexography. One of the biggest challenges was the very low shear viscosity of the semiconductor fluid. The literature [4] lists a shear viscosity in the range of 50 mPas to 500 mPas for fluids printed via flexography, whereas here it was 1.7 mPas to 1.9 mPas - depending on the shear rate - for the solution of 1% polymers in the used solvent mesitylene. Viscosity was measured with a Thermo Scientific HAAKE MARS rheometer system. Printing was done with an IGT F1 printability tester at a printing speed of 1.5 m/s to gain a homogeneous layer. The dip volume of the anilox roller was chosen to be 12 ml/m\(^2\) to yield the wanted thickness of the dried semiconductor layer. The chosen printing plate was a photopolymer based printing plate. Printing plates made of elastomers like ethylene-propylene-diene-rubber instead of photopolymer based are advertised as resistive to the aggressive solvents used for organic electronics. But used the solvents, especially toluene for cleaning, even damage these materials and dissolve particles out of the printing plate [5]. So photopolymer based printing plates which are available in the needed format and short delivery times were used in this case. An alternative way to produce the semiconductor layer is via spin-coating. A rotation speed of 1500 rpms leaded to a thickness comparable to the printed layer.

After drying the semiconductor layer for 3 min at 100 °C on a hot plate, a gate-insulator was spin-coated onto the whole substrate and was also dried on a hot plate under equal conditions. The spin parameters were attached to gain the desired layer thickness of 1 µm.

At last a gate consisting of silver nanoparticles was printed onto the insulator. An anilox roller with a dip volume of 16 ml/m\(^2\) and a printing plate made of photopolymers was used. A printing speed of
1.0 m/s led to the best homogeneity of the gate. The silver was dried in a heating oven at 120 °C for 10 min.

No pre-treatments of the underlying layers were done prior to the processing of the gate-insulator and the gate.

3. Measurements
A set of samples with an ascending amount of layers was produced to measure the thickness and topography of each layer. Thickness measurements were done at edges prepared by scratching or wiping off the layers. Measurements were done with a sensofar Plµ Neox profilometer. The used profilometer provides confocal microscopy, white-light interferometry and phase-shift interferometry. The reliability of the measurements was ensured by using all methods provided and identifying the best method for each measuring task. The measured layer thicknesses of the semiconductor were 40 nm in case of spin-coating and 35 nm to 60 nm when printed. In both cases the surface roughness was about 5 nm. The measured thickness variations in the printed layer seem to be caused by swelling of the printing plate and dewetting of the semiconductor layer before drying. Figure 2 shows a confocal image of the thickness variations in the flexo-printed semiconductor layer with part of the source/drain structure beneath. The spin-coating of the gate-insulator was adjusted to result in a layer thickness of 1 µm. The printed gate had a thickness of 2 µm.

![Confocal image of a flexo-printed semiconductor layer with S/D beneath](image)

Output and transfer characteristics of 244 transistors with spin-coated semiconductor and 183 transistors with flexo-printed semiconductor were automatically measured according to a previously defined protocol [2]. This was done on a x-y-table using spring contact probes and a Keithley 2636A source-meter unit. Automatic evaluation of that immense data was realised by a VBA script within MSEXCEL [7], that determines the threshold voltage Vt and the mobility derived from the well-known simple MOS-Modell [6]. The calculated parameters are plotted arranged in rows and columns according to the substrate’s layout.

4. Results
Altogether, the mobility of transistors with a spin-coated semiconductor is comparable to the mobility of transistors with flexo-printed semiconductor (Figure 3). For the investigations, we only took transistors with a mobility µ of 1E-3 cm²/Vs or higher into account. Here it has to be announced that
the reachable mobility in the chosen top gate and bottom contact architecture is, according to the manufacturer of the semiconductor, $5 \times 10^{-2}$ cm$^2$/Vs when semiconductor and insulator are produced via spin-coating and the conducting layers are evaporated. The thickness variations of the printed semiconductor layer shown in Figure 2 have no negative influence on the mobility.

![Figure 3. Dependence of the mobility $\mu$ on the transistor channel width $W$ (left) and on the transistor channel length $L$ (right)]](image)

Overall we have seen same behaviour for transistors with both, spin-coated and flexo-printed semiconductor. Regarding to Figure 3 (left) the mobility decreases with greater $W$. The reason is an increasing number of defects and traps over the larger area within the channel. Transistors with a channel width $W$ of 3.8 mm and 20.707 mm drift a little of. This could be due to their round geometry [3], which leads to additional influences on the mobility. Figure 3 (right) shows the dependence of the mobility $\mu$ on the transistor channel length $L$. We previously showed that it is more probable that a transistor with the shown geometries works if its $L$ is greater than approx. 10 $\mu$m [7]. According to this, the mobility $\mu$ also increased with greater $L$. This can be addressed to the contact resistance that has major influence on the current for small channel lengths [8]. Thus, those two effects superimpose and transistors with small ratio of $W/L$ show higher mobility.

There is no clear dependence of the mobility on the orientation of the transistor channel relative to the printing direction (Figure 4). The mobility of transistors with flexo-printed semiconductor reaches its climax for uniaxial transistors. Uniaxial transistors were realised with circular, concentric source/drain structures [3]. But the value is within the error of measurement, so no prediction is possible. In addition to that, round transistors gained a higher mobility, as described on the previous page.
5. Conclusions
We showed the production of partly printed OTFTs with flexo-printed or spin-coated semiconductor layers, to be able to compare between these two, usually chosen production techniques. With a measurement routine we were able to compare performance parameters of more than four hundred transistors. This we have done for the transistors mobility depending on the production technique of the semiconductor layer, the transistor channel width W, the transistor channel length L and the transistor orientation compared to printing direction. We showed, that for our transistor design the mobility µ increases with decreasing channel width and the mobility increases with the channel length. The transistors orientation relative to the printing direction has no influence on the mobility.

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