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Fast-switching all-printed organic electrochemical transistors

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ABSTRACT

Symmetric and fast (∼5 ms) on-to-off and off-to-on drain current switching characteristics have been obtained in screen printed organic electrochemical transistors (OECTs) including PEDOT:PSS (poly(3,4-ethylenedioxythiophene) doped with poly(styrene sulfonic acid)) as the active transistor channel material. Improvement of the drain current switching characteristics is made possible by including a carbon conductor layer on top of PEDOT:PSS at the drain electrode that is in direct contact with both the channel and the electrolyte of the OECT. This carbon conductor layer suppresses the effects from a reduction front that is generated in these PEDOT:PSS-based OECTs. In the off-state of these devices this reduction front slowly migrate laterally into the PEDOT:PSS drain electrode, which make off-to-on switching slow. The OECT including carbon electrodes was manufactured using only standard printing process steps and may pave the way for fully integrated organic electronic systems that operate at low voltages for applications such as logic circuits, sensors and active matrix addressed displays.

1. Introduction

Major efforts have been invested to create a reliable platform consisting of organic field-effect transistors (OFETs) [1]. Along with this device development activity an impressive number of different organic semiconductors have been synthesized, of which the material properties have been improved with respect to solubility, processability and field-effect mobility [2,3]. However, to make OFETs a successful technology in distributed electronic applications, it is important that the operation voltages are kept low, preferably around 1 V or so; the OFETs are typically operated at voltages on the order of tens of Volts. High permittivity materials and ultra-thin film insulator films for the gate insulator have extensively been explored to achieve low-voltage operation in OFETs [4]. Device operation below 1 V in easily printed and robust OFET architectures has therefore been difficult to achieve. However, thin film organic transistors gated via a solid or gelled electrolyte layer have proven to be a promising robust alternative to achieve low driving voltages. There are two kinds of electrolyte-gated organic thin film transistors; electrolyte-gated organic field-effect transistors (EGOFETs) [5–7] and organic electrochemical transistors (OECTs) [8–12]. These two transistor types are not only governed by different switching mechanisms but they also exhibit differences in device characteristics and opportunities regarding device manufacturing. EGOFETs are typically manufactured by traditional photo lithography processing since small feature sizes are required to obtain good or at least proper transistor characteristics, while low voltage operation in OECTs can be achieved without using any very narrow and critical dimensions. This gives that OECT device structures are typically more robust and thus also easier to include and integrate into printed electronic systems. To print electronics onto labels and foils surface roughness, flexibility and non-planarity are obvious

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features that certainly is a challenge for thin film electronics. Hence, conventional printing techniques can be utilized in the manufacturing process of OECTs [13]. Another advantage of the OECT devices in comparison to OFETs is that this transistor type can deliver high on-current because an open transistor channel conducts charges through the entire bulk of the channel. Conversely, in the (EG)OFETs field-effect gating provide charge accumulation only along a thin sheet of the semiconducting layer. Printable or printed OECTs have been realized and reported previously for various applications, such as logic circuits [14], sensors [15,16] and active matrix addressed displays [17,18]. They typically suffer from non-symmetric switching characteristics, i.e. the on-to-off switching time is much shorter than the off-to-on switching time. Such switching characteristics are of course not desired since it would cause major problems related to slow updating, or even erroneous operation, in different printed electronic systems and applications. Here, novel architectures for printed OECTs are reported aiming at improving the switching time of OECTs and to achieve symmetric on-to-off and off-to-on switching.

2. Materials and methods

PEDOT:PSS, *Clevios SV3* purchased from Heraeus, which serves as the electrochemically active transistor channel, is patterned by screen printing on top of a flexible plastic substrate, for example the transparent polyethylene terephthalate (PET) foil *Polifoil Bias* purchased from Policrom Screen, and dried at 120 °C for 5 min. Carbon, *7102* conducting screen printing paste from DuPont, is typically patterned, for example by screen printing, as the source and drain electrodes on top of the PEDOT:PSS transistor channel. The carbon paste is dried at 120 °C for 5 min. An electrolyte is then deposited, by stencil printing, where the stencil is created by a screen printed lacquer layer in which an opening defines the area of the electrolyte pattern. The lacquer material, *Tactile varnish* purchased from Sericol, is cured by exposure to UV light. The compounds of the electrolyte layer, containing sodium poly(styrene sulfonate) (PSSNa, MW ~70,000), D-sorbitol and glycerol that were purchased from Alfa Aesar, Sigma–Aldrich and Merck, respectively, were mixed into an aqueous solution according to the weight ratio of PSSNa/D-sorbitol/glycerol/deionized water = 40/10/10/40 wt.%. The deposited electrolyte layer, which was solidified by careful evaporation of water at 50 °C for 45 s, ensures the ionic connection between the transistor channel and the gate electrode; the latter consists of PEDOT:PSS coated on PET, Orgacon EL-350 purchased from AGFA Gevaert, and is laminated on top of the electrolyte to complete the vertically stacked transistor device.

All measurements are performed in controlled environment at a temperature of ~20 °C and at a relative humidity of ~40%RH. The transistor sweeps were performed by using a HP/Agilent 4155 B semiconductor parameter analyzer and the transistor switching time measurements were performed by using two Keithley 2400 sourcemeter units. Graphical interfaces programmed in LabView (National Instruments) were used to control the measurements and to simplify data storage.

3. Results and discussion

The OECT, here reported, includes the poly(3,4-ethylenedioxythiophene) (PEDOT) as the active material in the transistor channel. The polymeric anion poly(styrene sulfonic acid) (PSS) ensures charge neutrality of the chemically oxidized PEDOT, such that the electrically conducting polymer PEDOT:PSS system is formed, see Fig. 1. An OECT device can be configured in either a lateral or vertical architecture; the main requirement though is that the transistor channel and the gate electrode are connected via an electrolyte that provides the ions required for the two electrochemical half-reactions necessary for the OECT device operation. Fig. 1 illustrates both a lateral and a vertical OECT structure, in which the source and drain electrodes, the transistor channel and the gate electrode all are based on PEDOT:PSS. A layer of electrolyte represents the ionic connection between the transistor channel and the gate electrode. The lateral transistor structure enables manufacturing using only two printing steps in which all the PEDOT:PSS layers are formed adjacent to each other in the same plane. The vertical structure is preferably realized simply by depositing or applying the gate electrode on top of an electrolyte, either by additive printing or by lamination. The vertical OECT design is typically advantageous in printed and relatively more densely integrated electronic systems since its structure is more compact. The lateral OECT architecture is more commonly

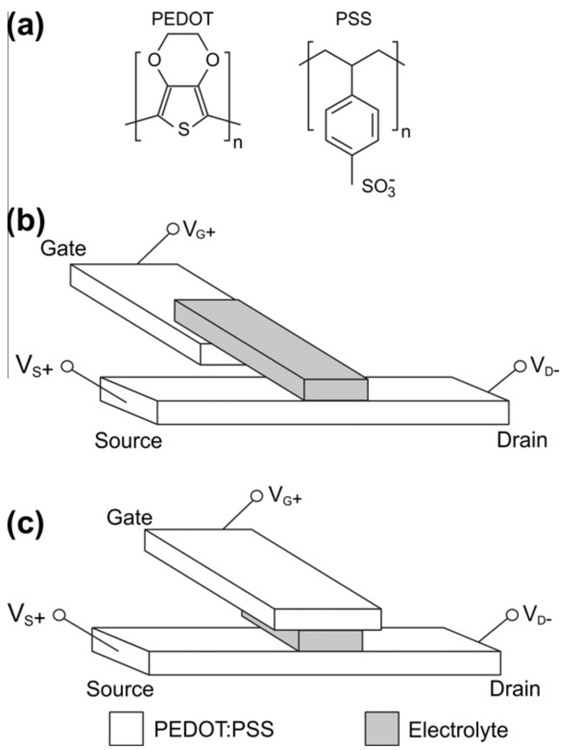

Fig. 1. (a) The chemical structures of poly(3,4-ethylenedioxythiophene) and poly(styrene sulfonate), that together form the electrically conducting polymer PEDOT:PSS, is shown to the left. (b) Sketch showing the architecture of a lateral OECT. (c) Sketch showing the architecture of a vertical OECT.