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Induced characteristics of n- and p-channel OFETs by the choice of solvent for the dielectric layer towards the fabrication of an organic complementary circuit

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ABSTRACT

In this study, we proposed a facile and low-cost method to fabricate complementary circuits, by the careful selection of the solvent for the dielectric layer. We show that the dielectric solvent exerts a direct influence on performance of organic field-effect transistors (OFETs), but the difficulty rests in finding solvents whose orthogonality does not attack the semiconducting layer in a device of top-gate architecture. OFETs (p- and n-channel), in which such orthogonality was achieved, exhibited the best performance, most probably due to the lower roughness of the semiconductor/dielectric interface. The search for transistors that have similar characteristics (mobility, threshold voltages, I_{on}/I_{off}, etc.) afforded the manufacture and characterization of an organic complementary circuit whose gain was higher than 7. This study therefore shows that the correct choice of solvents, especially that of the dielectric layer, is very important for the development of organic electronic circuits.

1. Introduction

The growing development of organic thin film transistors (OTFTs) has been fostered by the fact that these devices can be easily manufactured by low-cost conventional printing methods [1], among other advantages. Although OTFTs are still far from being applied as high frequency devices, they have revealed to be strong candidates for many other technological niches as disposable devices, printable electronic cards, and flexible and large area electronics [2]. Plastic circuits for RFID tags, for example, is one application of OTFTs that has been currently explored [3], paving the way for the area of organic field-effect transistors (OFETs), which have been successfully applied as biological and chemical sensors [4,5]. The versatility of OFETs has also opened new fields such as memory circuits [6] and light-emitting devices [7]. Different from silicon-based technology, OFETs can be fabricated by solution deposition at room temperature equally on rigid or flexible substrates, having the advantage of low cost processing. Such requirements are of relevance for the majority of electronic device applications, as integrated and digital circuits [8]. In this sense, the challenge this technology now faces is the fabrication of inverter circuits, the most coveted being a complementary logic unity. The necessary and challenging requirement for an organic complementary logic circuit is to achieve a perfect marriage between *n*- and *p*-channel OFETs [9,10].

The vast majority of electronic polymers are *p*-type conductors [11,12], and only recently researchers are getting good results for *n*-type, result of the effort in synthesizing new structures [13]. Besides that, in the last years, it has been exhaustively discussed in the literature that the OFETs performance depends not only on the semiconductor properties, but also on the properties and compatibility of the dielectric material [14,15]. In particular, the value of the electronic mobility of the semiconductor channel can vary by the action of the dielectric material. Therefore, the physicochemical properties of the dielectric material and the roughness of the dielectric-semiconductor interface play an important role in the device's performance [16,17]. The choice of the solvents, either for the semiconductor solution or for the insulating material (dielectric layer), also influences the final properties of the OFETs [18,19]. The charge carrier mobility along the channel, for example, is one entity that depends on the semiconductor-dielectric interface, which is affected by the solvent characteristics used

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for the gate dielectrics [20]. Particular attention must be given for the case of top-gate OFETs, since a perfect orthogonality between the solvents for the dielectric and the semiconductor is required. That is, avoid the dissolution of the underlying film (semiconducting layer) during the deposition of the dielectric layer is a difficult task to be overcome. Top-gate architecture has the advantage of protecting the semiconducting active layer from the environment, acting as a self-encapsulation, and also provides low contact resistance [21]. It also makes easier the lithographic patterning processes, as well as the use of inkjet printing technique [22,23].

In order to build an organic complementary inverter, we present in this work a simple and low-cost method to enhance and tune the electrical performance of p- and *n*-channel OFETs. The material chosen for the dielectric layer was the poly(methyl methacrylate) (PMMA), while we used poly(3-hexylthiophene-2,5-diyl) (P3HT) as *p*-type semiconductor, and poly{[N,N'-bis (2-octyldodecyl)-1,4,5,8-naphthalenedicarboximide-2,6-diyl]-alt-5,5′-(2,2′-bithiophene)} (PNDI2OD-T2) as *n*-type. Some dielectric solvents as methyl-ethyl-ketone (MEK), n-butyl acetate (nBA) and dimethyl sulfoxide (DMSO) were selected to produce the dielectrics layers. The different properties of these solvents (boiling temperature, electric polarity, etc.) resulted different characteristics for the produced PMMA films, which induced changes in the performance of the manufactured top-gate OFETs. Finally, this study has demonstrated that similar p- and *n*-channel device performances can be obtained through the careful selection of the dielectric solvent, which allowed us to build an organic complementary circuit.

2. Experimental

2.1. Fabrication and characterization

Glass slides (25 × 25 mm), used as substrates, were cleaned obeying the following steps: *(i)* an ultrasonic bath with (KOH) and after with deionized water, *(ii)* acetone bath (heat until the boiling point) for 10 min, and (iii) isopropanol bath for 10 min. The gold source and drain electrodes (W/L = 20) were deposited by thermal evaporation on top of the glass substrate (L is the channel length and W the channel width). For the active layer, regioregular poly(3-hexylthiophene) (rr-P3HT,Sigma Aldrich) was used as p-type semiconductor and poly([*N*,*N*-9-bis(2-octyldodecyl)-naphthalene-1,4,5,8-bis(dicarboximide)-2,6-diyl]-alt-5,59-(2,29-bithiophene)) – P(NDI2OD-T2), from Polyera Corporation, as n-type semiconductor. Both polymers were dissolved in o-dichlorobenzene (o-DCB) to obtain solutions of 20 mg/mL. The active layers were deposited by spin-coating, keeping 2000 rpm for 2 min for the n-type semiconductor, and 500 rpm for 1 min plus 3000 rpm for 1 min for the p-type semiconductor. To remove residual solvent molecules and to improve the microcrystalline morphology, the rr-P3HT and P(NDI2OD-T2) films were annealed in vacuum at 160 °C for 15 min and 120° C for 1 h [24], respectively. Poly(methyl methacrylate) (PMMA, Sigma Aldrich, MW = 120 kD) was used as the dielectric layer. PMMA (70 mg/mL) was dissolved in methyl-ethyl-ketone (MEK), *n*-butylacetate (nBA) and dimethylsulfoxide (DMSO), and the solutions were filtered through a 0.45 μm PTFE filter before being deposited by spin-coating. In order to achieve PMMA films thickness around 800 nm, the PMMA/MEK solution was deposited at 1000 rpm for 30 s, while the PMMA/nBA and PMMA/DMSO solutions were deposited at 500 rpm for 30 s. The top-gate structured OFETs were completed by the deposition of the gate electrode by thermal evaporation using a metal shadow mask, resulting in a thin layer of silver of 70 nm in thickness. The complementary inverter was constructed using the p- and n-channel OFETs fabricated on two different substrates.

The electrical characteristics of the OFETs and the complementary inverters were performed inside a nitrogen filled glove-box using a semiconductor characterization system (*Keithley 4200-SCS*). The transistors parameters, as field-effect mobility (μ_{FET}), threshold voltage (V_T) and subthreshold swing (S) were obtained from the saturation regime ($|V_D| = 80V$) using the gradual channel approximation model [25]. The voltage gain and the noise margin of the inverters were calculated from the dV_{out}/dV_{in} and by the maximum product criteria (MPC) [26], respectively. The schematic device structure of the top-gate bottom-contacts OFETs, the molecular structures of the polymers and the solvents used in this study are shown in Fig. 1.

3. Results and discussion

As discussed above, the top-gate architecture requires a solvent for the dielectric that is orthogonal in relation to the

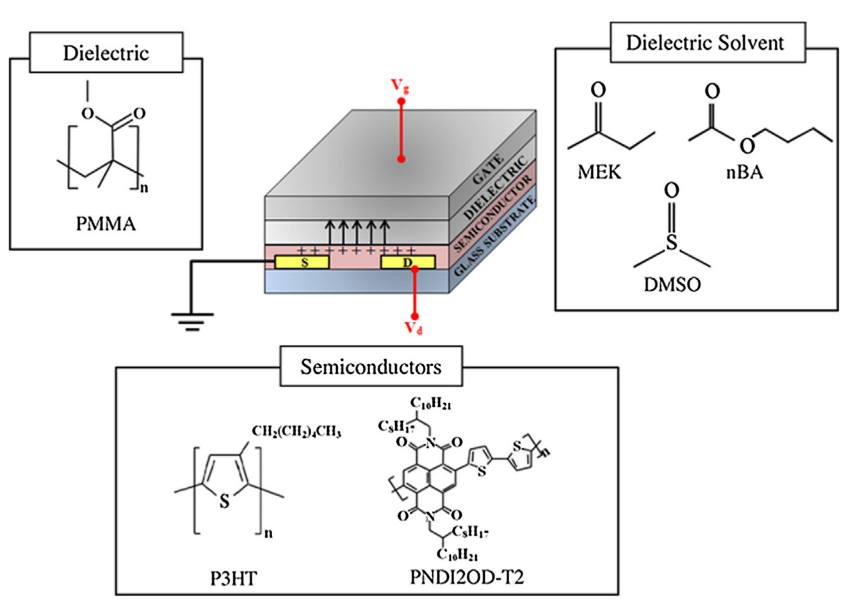

Fig. 1. Top-gate bottom-contacts OFET architecture. Molecular structures of the dielectric and semiconductor materials. Dielectric layer solvents used in this study.