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Performance improvement of $IF(CN_2)_2$ meta based N-channel OTFTs and their integration into a stable CMOS inverter

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ABSTRACT

In this work we report the fabrication of N channel transistors based on $IF(CN_2)_2$ meta molecule. The effect of $IF(CN_2)_2$ meta evaporation parameters on corresponding TFTs performances, is evaluated and highlighted here. Since the effect of deposition conditions for this molecule type has not been reported yet, here we report an improvement about 20 times of field effect mobility when deposited at substrate temperature of 80 °C and deposition rate of 0.7 Å/s, and then annealed at low temperature. Reached mobility of 2.2×10^{-3} $cm^2/V{\cdot}s$, is comparable to reported μ_{FE} of single crystal indenofluorene TFTs. The optimum mobility in these evaporation conditions was explained by the best compromise between the grain size and packing density of films. Fabricated $IF(CN_2)_2$ meta based devices are combined to 6,13-Bis(triisopropylsilylethynyl)pentacene devices and then integrated into a CMOS inverter logic circuit. The inverter's VTC shows large output voltage swing. Electrical stability of the performed inverter was also evaluated and the inverter shows a correct electrical stability, after 3 h of non-stop operation and the peak to peak magnitude corresponding to V_{OUT} decreases only by 2.6%.

1. Introduction

Organic electronic has attracted some interest due to the potential advantages that it offers such as low temperature processing, flexibility, printability, affordable production cost and the ease to perform devices compared to classical electronics [1–5]. During the last decades many applications were successfully achieved using the fundamental circuit element, organic TFT, and these applications include gas sensing [6,7], AMOLED display addressing [8] and logic gate circuits such as CMOS [9,10] or CMOS-like inverters [11]. For low power consumption systems, logic Complementary MOS circuits are preferred. These require the use of both P and N channel transistors. A great deal of progress was made with P channel transistors. Indeed mobility from 1 to 5 $cm^2/V{\cdot}s$ has already been reported for evaporated molecules [12]. Until now performing N channel transistors with interesting mobility and stability has been a real challenge. Because of poor electronic transport in their active layers, N channel transistors commonly present low field effect mobility and electrical stability. This constitutes a serious obstacle to achieving CMOS circuits.

Regarding the mobility, a closer look at the molecule design highlighted the effect of molecule's geometry on its electrical properties. In fact a variety of studies on N channel materials reported the effect of the molecule geometry on its electrical properties [13,14]. It has been demonstrated that planar geometry of molecules, such as Thiophene-Naphthalene molecules [14], promotes the π-π stacking of molecular orbitals. On the other hand a strong π stacking leads to an improvement in the electronic hopping over the system, and thus the mobility can be increased [15]. Another approach to enhance the field effect mobility consists of improving the elaboration conditions of the active layer. In case of evaporated molecules, it is obvious that deposition parameters such as temperature deposition or deposition rates have an impact on the film growth [14,16–20], which is directly correlated with the electronic transport. In fact, large grain structure and packing grain density lead to a high field effect mobility.

In this work the molecule used for the active layer is an indenofluorene derivative ($IF(CN_2)_2$-meta). This molecule is characterized by a planar geometry and deep LUMO energy level. Some studies on indenofluorene derivatives reported N channel transistors with a saturated mobility of 3×10^{-3} $cm^2/V{\cdot}s$ for crystal OFETs

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[21], while 0.16 $cm^2/V{\cdot}s$ is reached for an active layer deposited using the epitaxial method [22]. However no application of these transistors as an element of CMOS logic gate circuit was demonstrated.

Herein we report the integration of evaporated $IF(CN_2)_2$-meta-based OTFTs devices, in CMOS inverter circuits and their electrical stability. Several papers focused on N channel transistors with high mobility, in which organic circuits were performed. However these transistors are lacking electrical stability when integrated into circuits. In this paper we start by an optimization study on the N channel transistor which deals with the effects of deposition parameters of $IF(CN_2)_2$-meta molecule and post annealing treatment, on OTFT's field effect mobility. Once N channel devices are optimized, they are combined to Tips-Pentacene-based devices, and used to perform an organic CMOS inverter, possessing good time stability under voltage polarization.

2. Materials and methods

Bottom gate bottom contact transistors are performed on previously cleaned glass substrate, with acetone and ethanol-alcohol rinsing. To define the gate contact, 150 nm evaporated aluminum layer is followed by a photolithography step. SU-8 photoresist is spin coated at 320 nm and used as agate dielectric in order to avoid leakage current and to make a smooth interface with the active layer. Source and drain contacts are defined using photolithography on 60 nm evaporated gold. Finally SU-8 is etched on vias zones. The last step consists of thermal evaporation of 8 nm of IF $(CN_2)_2$ meta molecule, under high vacuum with controlled conditions ($p = 3.10^{-7}$ mbar, $T_{sub} = 30$ °C and $d_r = 0.4$ Å/s).

As announced above, $IF(CN_2)_2$ meta molecule (Fig. 1) is characterized by a planar geometry and deep LUMO energy level, measured at −3.81 eV. This deep LUMO level resulted from the introduction of (CN_2) electro-attractive groups. Note that this molecule's band gap is 2.1 eV and large enough to avoid minority carrier injections from the source/drain metal which may contribute to an increase in the OFF drain source current. More information about $IF(CN_2)_2$ meta synthesis and chemical characterization can be found in a previous paper [23].

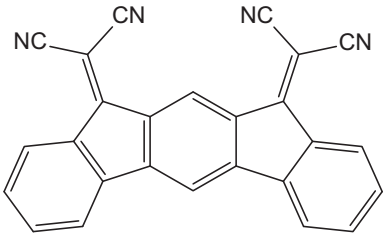

Fig. 1. Chemical structure of $IF(CN_2)_2$ meta molecule.

3. Results and discussions

Devices were stored and characterized under nitrogen ambient. All electrical characterizations were performed using Keithley 2636A. Transfer characteristics I_D-V_{GS} were plotted at room temperature. All the measurements were carried out in the same conditions, and the gate-source voltage V_{GS} varied from −15 V to 60 V with a 1 V step, at constant drain-source voltage V_{DS} (+10 V). In these conditions of polarization the transfer curve in linear regime can be plotted. Output characteristics I_D-V_{DS} were plotted while V_{DS} varied from 0 to 70 V with 2 V step and V_{GS} varied from 0 to 60 V with 10 V step.

Transfer and output characteristics of W/L = 1000 µm/10 µm transistors are given in Fig. 2. Organic transistors performed at $T_{sub} = 30$ °C with a fixed deposition rate $d_r = 0.4$ Å/s show field effect behavior. Negligible OFF current about 10 pA is observed at $V_{GS} = -15$ V, confirming a low injection of minority carriers into the active layer owing to the $IF(CN_2)_2$ meta molecule's large band gap. The good insulating property of SU-8 insulator is confirmed with a low leakage current I_G limited at 10 pA at $V_{GS} = 60$ V.

Linear field effect mobilities are calculated using MOSFET equations in a linear regime ($V_{DS} \ll V_{GS} - V_{TH}$) Eq. (1).

$$I_D = \frac{W}{L}\mu_{FE}C_{ins}(V_{GS} - V_{th})V_{DS} \tag{1}$$

where W and L are the width and length of the channel, μ_{FE} is the field effect mobility, C_{ins} is the gate insulator capacitance per area unit here $C_{ins} = 7.6$ nF/cm^2, V_{TH} is the threshold voltage and V_{DS} is applied source drain voltage. Field effect mobility is calculated from transconductance g_m given by the following:

$$g_m = \left\{\frac{\partial I_{DS}}{\partial V_{GS}}\right\}_{V_{DS}=cte} = \mu_{FE}\frac{WC_{ins}V_{DS}}{L} \tag{2}$$

The calculated field effect mobility was found to be $\mu_{FE} = (1.5 \pm 0.2) \times 10^{-4}$ cm^2/V·s, and this value is average on devices possessing W/L = 1000 µm/10 µm. This transistor length was selected to represent the present device performances, in order to avoid any access resistance effect.

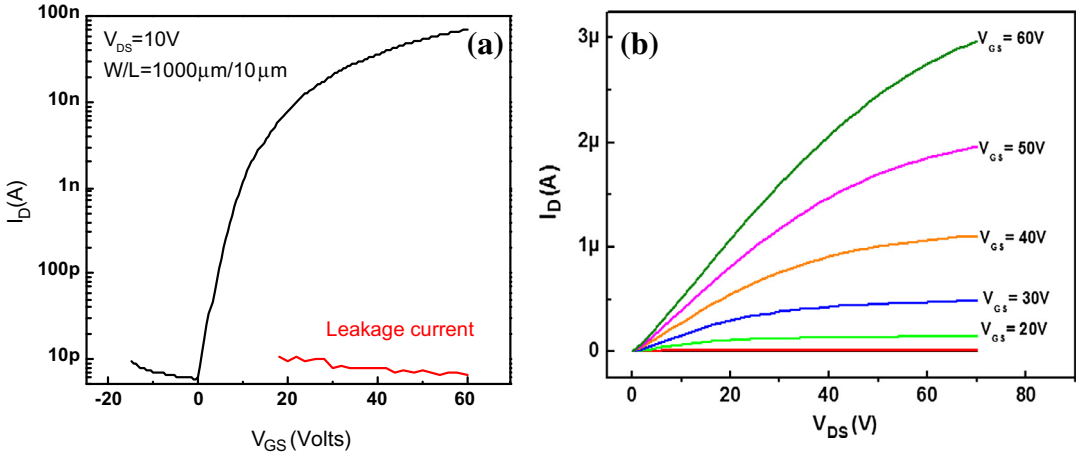

Fig. 2. (a) Transfer characteristic at VDS = 10 V and (b) output characteristic of $IF(CN_2)_2$ meta based OTFT.