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WO_3-doped LiF as gate dielectric for p-channel vertical organic field effect transistor application

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ABSTRACT

We report low voltage operable p-channel vertical organic field effect transistors (VOFETs) using 5,5‴″-Dihexyl-2,2′:5′,2″:5″,2‴:5‴,2‴′:5‴′,2‴″-sexithiophene (DH6T) as organic semiconductor and tungsten trioxide (WO_3) doped lithium fluoride (LiF) nano-composite of various concentrations as high-k dielectric. Among the various doping concentrations of WO_3, the 5 wt% WO_3-doped LiF shows the best performance. The gate leakage was effectively reduced from 10^{-4} A/cm^2 order to 10^{-6} A/cm^2 by the addition of 5 wt% WO_3-doped LiF as compare to 0 wt% WO_3-doped LiF, resulted in higher drain current for this device. The best values of threshold voltage, mobility, on/off ratio, trans-conductance and sub-threshold slope for the devices made were estimated to be 0.85 V, 0.034 cm^2/Vs, 10^5, 60 µS and 0.32 V/decade respectively.

1. Introduction

Organic field effect transistors (OFETs) are promising devices for flexible organic devices such as flexible displays, flexible radio-frequency identification tags, and large area sensors [1–3]. However, the organic field-effect transistors have large operating voltage because of the low carrier mobility and long channel length [4]. Recently, low-voltage operation was realized by vertical organic field effect transistors (VOFETs) [5–7] with short channel length perpendicular to the substrate. The high driving current and low operating voltage can be achieved in VOFET by making very short channel, the thickness of the organic layer deposited between the two electrodes known as channel length of a few hundred nanometers for the device. Further lowering the operational voltage of VOFETs can be achieved by reducing the threshold voltage and the sub threshold swing. The parameters control of VOFETs device can be done by the gate dielectric and the charge accumulations at the dielectric–semiconductor interface [8]. Therefore, to achieve low operational voltages, high-capacitance, high dielectric constant gate insulators that form trap-free interfaces are essential [9–13]. However, a very thin dielectric layer is hard to be formed, and will cause large gate leakage current, and deteriorate the device functionality and reliability under electrical bias stress.

Many organic dielectrics including Benzocy-clobutene, Polyvinlyalcohol (PVA), Polyvinlyphenol, Poly(methylmethacrylate), Cynoethyl Pullulan, Polyimide, etc. have been used to fabricate OFETs. Polymers with hydroxyl groups (such as the poly(vinyl alcohol) (PVA) and poly(4-vinyl phenol) present pronounced hysteresis in transfer characteristics [14]. Lee et al. reported that the number of trapping sites at the semiconductor-dielectric interface increases with the increase of hydroxyl groups in polymer dielectric, which caused a large hysteresis [15]. To overcome this issue many high-k organic/inorganic, bilayer and hybrid dielectrics have been used to achieve low voltage operation in OFETs [16,17].

In this work, we have introduced inorganic-metal oxide nano-composite as gate dielectric for an ambipolar p-type VOFETs structure to overcome the high gate leakage problem. The aim is to improve the performance of organic devices by increasing the induced gate capacitance. Lithium Fluoride (LiF) has been widely used as gate dielectric for VOFETs, [6,7] hence we have chosen this as host material in our study. The high capacitance can be provided to device by LiF which has a dielectric constant (~9) and band gap (13.6 eV) [18]. In the doping content, tungsten trioxide (WO_3) have been chosen because in thin film form WO_3 shows various novel properties, which can be used for advanced microelectronic applications [19]. The dielectric and electrical studies of all these WO_3-doped LiF nano-composite thin films with various concentrations have been done in our previous work [20]. The device made up of 5 wt% WO_3-doped LiF among all the doping concentrations of WO_3 in LiF shows the best performance. The enhancement in the dielectric and electrical properties of LiF-WO_3 nano-composite, open up new ways for large applications in the field of organic

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semiconductor devices.

2. Experimental details

In this study, indium tin oxide coated glass substrates with sheet resistance of 20 Ω per square have been purchased from Vinkarola USA. Along with the pattering of the substrates, distilled water, Acetone, trichloroethylene and propan-2-ol solvents have been used consecutively 20 min each for cleaning the substrates using ultrasonic bath and dried in vacuum oven at 120 °C for 30 min. The annealed substrates were immediately loaded into a thermal evaporation coating unit by avoiding any exposure to ambient air for the fabrication of devices. Fabricated device structure was Indium tin oxide (ITO 120 nm)/ 5,5′′′′′-Dihexyl- 2,2′:5′,2′′:5′′,2′′′:5′′′,2′′′′:5′′′′,2′′′′′-sexithiophene (DH6T, 150 nm)/Al(20 nm)/ x wt% WO_3 doped LiF (120 nm)/Al (150 nm). All layers were deposited by thermal evaporation technique with the use of shadow mask under a base pressure of 5×10^{-4} Pa and the evaporation rates were 0.5–1 Å/s for the organic materials, 2–4 Å/s for gate electrode, and 1 Å/s for dielectric layer. A source electrode is deposited at the evaporation rate of 0.1–0.2 Å/s under the base pressure of 3×10^{-4} Pa. Active pixel area was 2 mm × 2 mm, where channel width is 2 mm and the channel length is 150 nm which is thickness of DH6T layer between two electrodes. For the capacitance measurement a metal insulator metal diode structure has been fabricated in which ITO has been taken as bottom electrode and Al has been taken as top electrode and WO_3-doped LiF thin film with different doping concentration has been sandwiched between these two electrodes. Thickness of each layer was measured by quartz crystal thickness monitor Model DTM-101 and examined by ellipsometry (Woollam 2000). Capacitance variation as a function of frequency was taken by ac impedance spectroscopy using Solatron 1260 impedance analyzer. The output and transfer characteristics were measured by semiconductor characterization system (Keitheley 4200). For the leakage current measurement Keithly 2400 source measure unit interfaced with a computer, have been used. Morphological characterization was performed by atomic force microscope (AFM; Solver P47-PRO SPM) in tapping mode. All measurements were carried out at room temperature and under ambient conditions.

3. Results and discussions

The fabricated device structure of VOFET is shown in Fig. 1a. The active cell, capacitive cell and metal insulator semiconductor (MIS) structure are the main component of the device structure. The active cell has the p type organic semiconductor of DH6T and capacitive cell consist x wt% WO_3-doped LiF dielectric material. Source electrode is the common electrode for both cells and it should be thin, rough and partially oxidized [5–7,21]. Fig. 1b–g shows the AFM images of gate dielectric with various doping concentration of WO_3 in LiF thin films grown at Si substrates. From the AFM images (Fig. 1b–e) it can be seen that the grain size of the WO_3 increase with increase of WO_3 in LiF up to 5%, whereas WO_3 gets transformed into bulk form and gets agglomerated with further increment (Fig. 1f–g) and this can be the possible reason behind the variation in capacitance and dielectric constant in the gate dielectric.

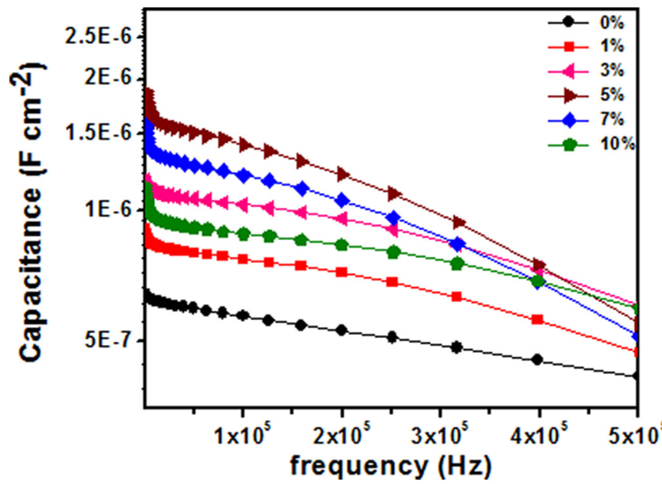

Fig. 2. Capacitance as a function of frequency using various concentration of WO_3 in LiF.

The capacitance properties of the WO_3-LiF nano-composite thin film with different doping concentration were evaluated by the fabrication of parallel plate capacitor devices where ITO and Al are considered as bottom and top electrode. Fig. 2 shows the capacitance variation as a function of frequency for this device structure. It can be seen from the figure that increasing of WO_3 content in LiF, effectively enhances the capacitance of WO_3-doped LiF dielectric for 5 wt% among all the doping concentrations. The dielectric constant has been calculated by using the following formula:

$$Ci = \frac{k\varepsilon_0 A}{d} \tag{1}$$

where C_i is the measured capacitance in Farad (F), ε_0 is the permittivity of free space (8.85×10^{-12} F/m), d is thickness of the dielectric film, k is dielectric constant of the dielectric materials and A is the area of the device. With the help of capacitance measured values and dielectric

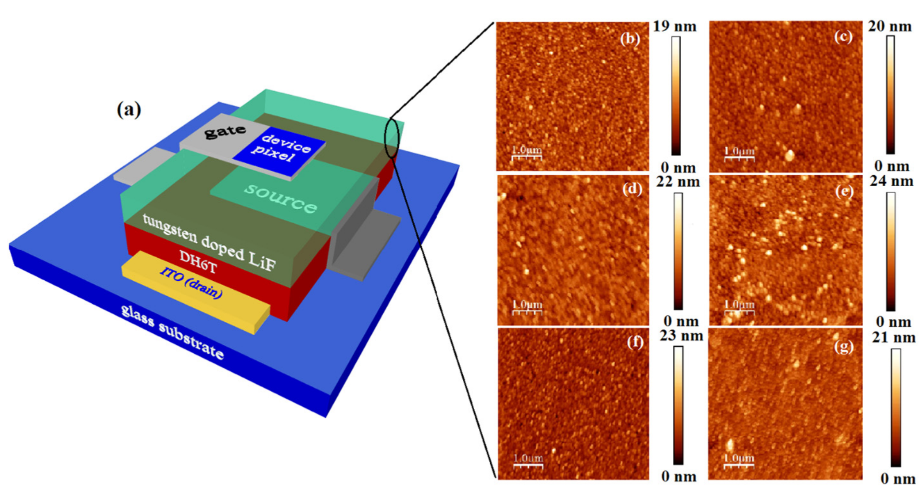

Fig. 1. (a) Device structure. AFM images of WO_3 doped LiF thin films at different concentrations of WO_3: (b) 0%, (c) 1%, (d) 3%, (e) 5%, (f) 7%, (g) 10%.