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Solution-processed low-voltage organic phototransistors based on an anthradithiophene molecular solid

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ABSTRACT

Low-voltage organic phototransistors (OPTs) are attractive candidates for optoelectronic applications such as photodetectors and memory devices. Here we describe a solution-processed low-voltage organic phototransistor based on a triethylgermylethynyl-substituted anthradithiophene (diF-TEG ADT). Two kinds of dielectric materials were used: 80-nm-thick potassium alumina (PA) and 300-nm-thick thermally grown SiO_2. To investigate its application in a moist environment, the performance at different humidities was characterized. Results showed that the device was very stable in high humidity. A major change in drain current (I_{DS}) was observed when connecting or disconnecting the gate electrode to the device. This feature may motivate the application of diF-TEG ADT-based phototransistors as multistage photo-controlled memory devices.

1. Introduction

Organic field-effect transistors (OFETs) have attracted much attention due to their possible application in the fabrication of devices with large area, light weight, flexibility, and low cost. The performance of OFETs depends on various parameters, the main ones being charge carrier mobility (μ) and threshold voltage (V_T). In the last two decades, progress in organic semiconductors research has led especially to great increases in carrier mobility [1–4].

An interesting alternative application of OFET technology is the organic phototransistor (OPT). Its current can be modulated by both light and electric fields. Charge transport modulation, the ability to generate photo-induced charge, and mechanical flexibility are helpful for the application of OFETs to optoelectronic devices [5]. In addition to charge carrier mobility and threshold voltage, the key parameters for evaluating the performance of OPTs are photocurrent/dark-current ratio (P) and photoresponsivity (R),

$$P = \frac{I_{DS,illu} - I_{DS,dark}}{I_{DS,dark}}$$

$$R = \frac{I_{ph}}{P_{ill}} = \frac{I_{DS,illu} - I_{DS,dark}}{P_{in}A}$$

where $I_{DS,illu}$ and $I_{DS,dark}$ are the drain current under illumination and in the dark, A is the area of the active region of the transistor under illumination, and P_{in} is the illumination intensity. High photocurrent/dark-current ratio and photoresponsivity are desired for organic phototransistors. OPTs based on crystalline anthracene microplates [6] exhibited a relatively high photocurrent/dark-current ratio (>1.4 × 10^5, I = 1.4 μW/cm^2) and photoresponsivity (1.1 × 10^4 A/W). Kim et al. [7] Fabricated OPTs based on crystalline microribbons with a high photocurrent/dark-current ratio (1.2 × 10^6, I = 5.6 μW/cm^2). A large photoresponsivity of 1.2 × 10^4 A/W (30 μW/cm^2) was obtained from OPTs based on 6-methyl-anthra [2,3-b]benzo[d]thiophene crystalline microribbons [8]. To date, the best photoresponsivity for OPTs was (4.08 ± 1.65) × 10^5 A/W using single fibers from perylenebis (dicarboximide)s (PDI) [9].

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Linear acenes have attracted much attention in electrical applications due to their carrier mobilities and excellent intermolecular π-interactions. Pentacene is one of the original p-type organic semiconductors and is commercially available [10]. However, the costs associated with vacuum processes needed for pentacene-based thin films makes the application of pentacene as OPTs more expensive. In addition, the limited chemical stability and oxidation processes in air make pentacene less reliable. Functionalized pentacene organic semiconductors were reported to show a persistent photoconductivity effect [11], but this effect has yet to be observed in functionalized heterocyclic analogs. Difluoro-triethylgermylethynyl-substituted anthradithiophene (diF-TEG ADT) [1] (Fig. 1) is a new member of the linear acene family, kinetically protected and solubilized with triethylgermylethynyl groups in positions 6 and 13 of the ADT [12]. Moreover, the addition of two fluorine substituents not only enhanced the stability of the organic material but also emphasized the two-dimensional π-stacked arrangement. Therefore, we introduced diF-TEG ADT-based materials for fabrication of crystalline thin films due to their highly solubility and high degree of intermolecular interactions.

Low power consumption is of great importance for the application of optoelectronic devices, especially for phototransistor devices. The majority of reported organic devices operate at high voltages, typically from 10 to 100 V. However, most targeted applications of OPTs, such as portable and battery-powered photosensors or digital imagers preferably operate at lower voltages [13]. Low-voltage operated and low-power ambipolar OPTs based on pentacene/$PC_{61}BM$ heterostructures had been investigated and a self-assembled monolayer (octadecylphosphonic acid) was used as the gate dielectric. These transistors could operate below 3 V or −3 V [13]. However, the fabrication of pentacene again needs high vacuum deposition. A 7,7,8,8-tetracyanoquinodimethane (TCNQ)-based low-voltage OPT had also been reported [14]. It exhibited stable n-type characteristics with a photosensitivity >1 mA/W at an optical power of 5.98 mW/cm^2.

New dielectric materials are developed for inexpensive device fabrication process and the reduction of the operating voltage required for new flexible/printed electronics technologies [15]. There are two methods to reduce the operating voltage. One is to increase the mobility of the organic semiconductor, while another alternative is to develop high dielectric constant materials (high-*k* materials) as the gate-dielectric. However, not all high *k* materials are suitable for low-voltage operated gate-dielectrics. First, the dielectric layer should be amorphous rather than polycrystalline, because crystalline grain boundaries may lead to considerable leakage current. Second, the dielectric material should have sufficient band offset. A small band gap offset will also lead to leakage current because of charge injection. Third, the dielectric material should be thermally and chemically stable. Finally, the surface defects should be as few as possible [16].

The sol–gel-derived sodium alumina (SA)-type dielectric material was discovered by our group in 2009 [17]. It exhibited high dielectric constant and promising gate-dielectric performance. Moreover, the SA-FETs with both inorganic and organic semiconductors can be operated at low voltage (2 V). Yu et al. investigated the effect of different alkali metal ions (Li^+, Na^+, K^+) incorporated into alumina on the gate-dielectric behavior of solution processed oxide FETs. Compared to plain alumina, the ion-incorporated alumina metal–insulator–metal capacitors showed a possible electric double layer capacitor (EDLC) behavior. Also, ion-incorporated alumina showed a higher AC conductivity than plain alumina, which could

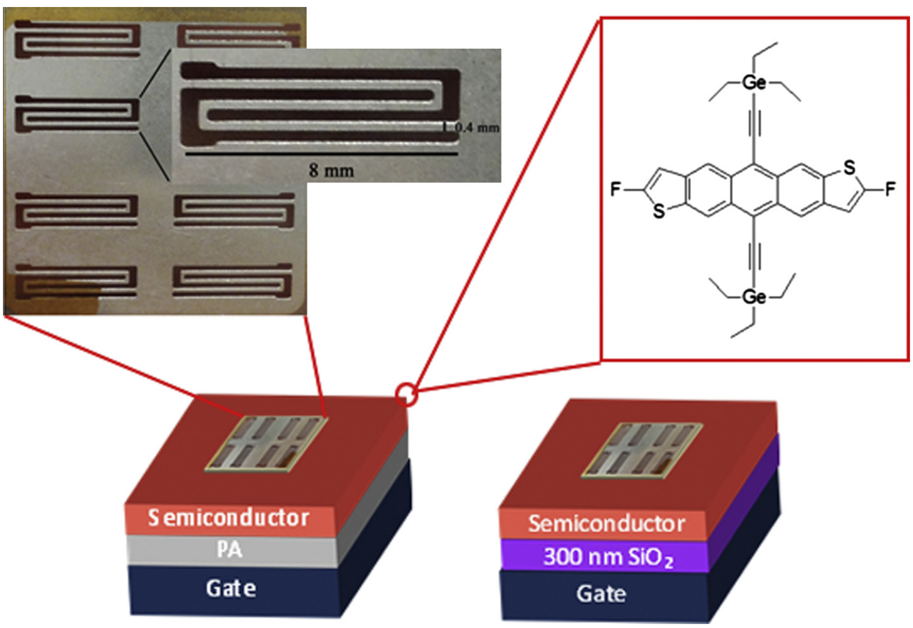

Fig. 1. Device architecture of OPTs with the interdigitated electrode mask used for fabricating device and the chemical structure of diF-TEG ADT.