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Effect of UV irradiation on solution processed low voltage flexible organic field-effect transistors

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ABSTRACT

Effect of ultra-violet (UV) irradiation (λ_{peak} = 365 nm) on the electrical characteristics of solution processed flexible TIPS-pentacene organic field-effect transistors (OFETs) has been investigated. Pristine TIPS-pentacene OFETs demonstrated average field-effect mobility of 0.1 $cm^2 V^{-1} s^{-1}$, with near zero threshold voltage and current on-off ratio of ~10^4. On UV irradiation, OFETs displayed a joint photoconductive and photovoltaic effect due to photo-generated excitons. The maximum current modulation and photo-responsivity obtained from these OFETs were ~500 and ~43 mA/W respectively at an intensity of 1.8 mW/cm^2 while operating at a low voltage of −5 V. On increasing the irradiation time, a positive shift in the threshold voltage was observed. At larger values of irradiation time, a roll-off in maximum drain current and mobility values were observed, which was attributed to slight deterioration in crystallinity due to prolonged UV exposure, as confirmed from X-ray diffraction studies. Similar trend was observed for mobility and threshold voltage values, when gate bias during UV irradiation was increased. In addition, transistors exhibited a repeatable dynamic response to periodic pulses of UV irradiation.

1. Introduction

An extensive research advancement in the field of organic field-effect transistors (OFETs) has already lead to their successful integration in many applications such as flexible displays [1,2] radio frequency identification (RFID) tags [3], wearable devices [4], and various types of sensors including chemical sensors [5], bio-sensors [6], gas sensors [7], and pressure sensors [8]. Use of OFETs in various optoelectronic applications like photo-sensing [9–11], optical memory elements and photo-switches [12–14] has also been very widely explored due to photo-sensitive nature of organic semiconductors. However, majority of these reports along with a recent study by our group [15] deal with photo-sensitive properties of organic semiconductors in the visible range of electromagnetic spectrum. Effect of ultra-violet (UV) irradiation on organic semiconductors largely remains under-explored with very less reports available. Nonetheless, a detailed study of the effects of UV irradiation on organic semiconductors and corresponding devices is highly imperative for development of several low cost, low power and high performance civil and military applications including smoke and fire detection, missile warning, combustion monitoring and ozone sensing [16,17]. To the best knowledge of authors, for most of the organic semiconductors, which have been explored as UV detectors, corresponding devices are in the diode architecture and have been fabricated on

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rigid substrates [18–23]. However, a photo-OFET is always a better choice over a photo-diode due to simultaneous photo-detection and amplification along with higher sensitivity. Despite this fact, reports on UV sensitive photo-OFETs are unfortunately obscure and effect of UV irradiation on the performance of OFETs remain under-addressed. For this reason, it is highly essential to study the effect of UV irradiation on the electrical characteristics of OFETs.

In this study, we report the effect of UV irradiation on the electrical performance of low voltage, flexible, solution processed OFETs. Organic semiconductor TIPS-pentacene was selected for this study due to its high performance and air stability [24–26]. Pristine OFETs function at moderate operating voltage of −10 V and show a mobility of 0.11(±0.08) $cm^2 V^{-1} s^{-1}$ with current on-off ratio of ~10^4. UV irradiation was found to increase the off currents and threshold voltage (V_{TH}) in positive V_{GS} direction due to photo-generation of excitons. Photo-OFETs yielded a maximum drain current modulation (ratio of irradiated and dark currents) of ~500, a maximum photo-responsivity of ~43 mA/W for UV irradiation with an intensity of 1.8 mW/cm^2. A Higher exposure time under UV irradiation led to a positive shift in V_{TH} and reduction in the saturation current and mobility. This reduction was attributed to decrease in the degree of crystallinity of organic semiconductor due to prolonged UV exposure. On increasing the gate bias during irradiation, similar positive shift in V_{TH} and reduction in mobility was observed. In addition, these OFETs showed a repeatable switching response to periodic illumination pulses, signifying their capability to be used as UV switches.

2. Experiments

Flexible polyethylene terephthalate (PET) substrates (thickness: 127 μm) having a 130 nm thick layer of indium tin oxide (ITO) with surface resistivity of 60 Ω/sq, were used to fabricate bottom-gate top-contact OFETs. Procedures of substrate cleaning and deposition of bi-layer gate dielectric consisting of high-k HfO_2 and poly(4-vinylphenol) (PVP) on cleaned substrates were similar as described in our previous reports [15,27]. A 0.5 wt % solution of TIPS-pentacene solution was prepared in toluene by stirring for 3 h at 70 °C, which was cast on dielectric deposited substrates. Au source-drain contacts (200 nm thick) were deposited by thermal evaporation under a high vacuum of 10^{-6} Torr using metal shadow masks. The schematic of the device architecture and digital image of the fabricated devices are shown in Fig. 1(a) and (b). All processing and characterization steps were performed in dark and ambient conditions. Electrical characterizations of the devices were performed using Keithley 4200 SCS. Saturation regime field-effect mobility of the devices (μ_{sat}) and V_{TH} were calculated from transfer characteristics of the devices, as in our previous reports [27,28]. Capacitance density (C_i) of the HfO_2/PVP hybrid dielectric layer was found to be 24.46 ± 0.71 nF/cm^2 at 1 KHz.

To investigate the steady-state response of the devices to UV irradiation, a 2 terminal low power UV LED with a peak wavelength of 365 nm was used as a UV light source. This light source was adjusted to shine above the sample with maximum intensity of 1.8 mW/cm^2. The figures of merit of a photo-OFET, the current modulation or the ratio of current under irradiated and dark conditions current (P) and photo-responsivity (R) have been evaluated using following equations,

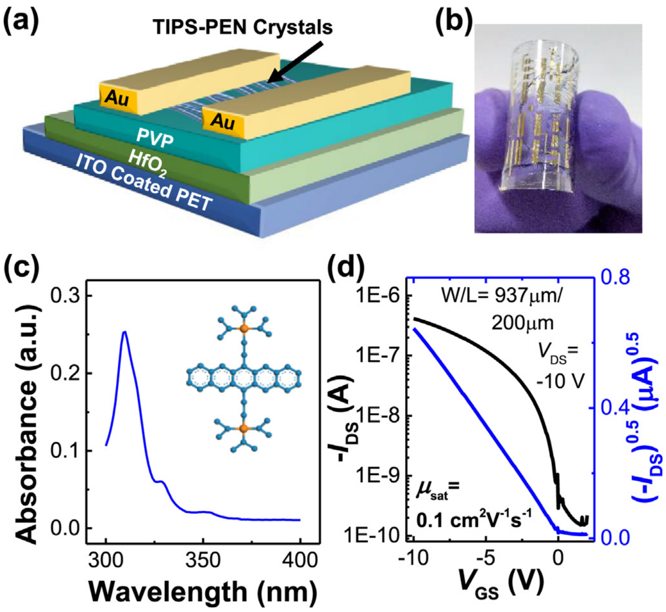

Fig. 1. (**a**) Device structure of a bottom-gate top-contact TIPS-pentacene OFET. (**b**) Digital image of fabricated flexible OFETs. (**c**) UV absorption spectrum of TIPS-pentacene. (**d**) Transfer characteristics of a representative TIPS-pentacene OFET.

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