Organic Electronics 15 (2014) 1096–1104

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Factors governing photo- and dark currents in lateral organic photo-detectors

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ARTICLE INFO

Article history:
Received 19 September 2013
Received in revised form 23 January 2014
Accepted 5 March 2014
Available online 17 March 2014

Keywords:
Lateral
Top-contact
OPD
Space charge limited conduction

ABSTRACT

We study the factors governing the dark and photo currents in lateral organic photodetectors (OPD). The dark current is found to be strongly limited by space charge limited conduction (SCLC) across a highly depleted gap and arises mostly from transient capacitive currents due to the charge accumulation in the organic layers near the contacts. Similarly, the photocurrent is found to be strongly limited by the collection of photogenerated carriers at the contacts, which limits the sensitivity of lateral OPDs. Furthermore, evidence of the contribution of some photons falling outside of the gap area are reported and have to be taken into account when one wants to conduct accurate external quantum efficiency estimates of lateral OPDs. Finally, it is found that the dark current is significantly increased after the device is exposed to light, likely to be due to the filling of charge traps by photogenerated carriers, while the photocurrent remains unchanged, leading to a decrease in the overall sensitivity of the device upon repeated exposure to light. The results shed the light on the performance limitations in lateral OPDs.

1. Introduction

Organic photodetectors (OPDs) have a high potential for use in future imaging and sensing systems, such as on flexible substrates [1]. There have been reports from several research groups of OPDs with encouraging performances [2–6]. These OPDs, in general, utilize a vertical device architecture where the photoactive organic semiconductor layers are sandwiched between top and bottom electrodes that provide electrical contact. More recently, an interest in utilizing a lateral device architecture, instead of the vertical one, has emerged. In this architecture, the two contacts are positioned on the two sides of the photoactive material with respect to the direction of the incoming signal, separated by a small gap of typically a few tens of micrometers. In lateral OPDs, applying an electrical bias from an external source across the electrodes creates an electrical "channel" across the gap and thus allows the collection of photogenerated carriers produced by the exposure of the semiconductor materials to illumination. Lateral OPDs are different from light-detecting organic thin-film transistors that normally operate on accumulation mode under gate bias [7]. This lateral architecture has been the focus of a number of recent studies [8–14] since it offers some advantages over the vertical one. These include that exciton generation and charge transport can be made to take place in separate layers, such as in bilayer heterojunction lateral OPDs and therefore independent optimization of both processes can be more easily achieved in them in comparison to vertical OPDs [8–10]. Moreover, the integration of lateral OPDs with conventional detectors read-out integrated circuits might be facilitated [14]. Furthermore, in lateral OPDs, the electrodes are not in the "optical path" of the signal and thus they are not required to be transparent. This makes the lateral architecture particularly advantageous

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http://dx.doi.org/10.1016/j.orgel.2014.03.002
1566-1199/

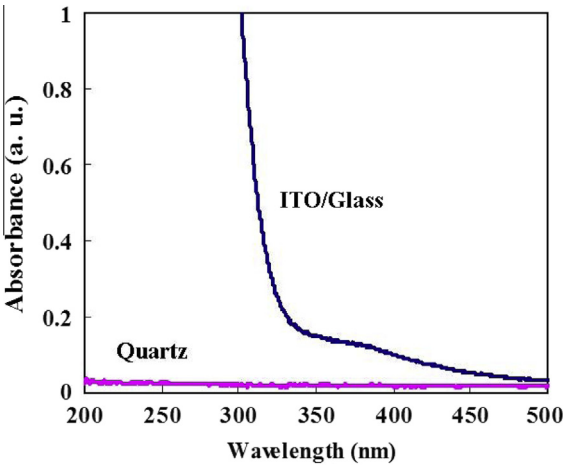

Fig. 1. Comparison of the absorbance spectra of pre-patterned ITO on glass substrate and quartz substrate.

for ultraviolet OPDs, since they can be directly fabricated on quartz substrate, almost not absorbent below 350 nm, in contrast to the commonly used indium tin oxide (ITO)-coated glass substrates that often lack sufficient transmission at these wavelengths, as shown in Fig. 1.

Despite this, little attention has been paid to the factors governing the photo-response and the charge transport behaviour in general in lateral OPDs. For example, as charge carriers travel much longer distances in these devices in comparison to their more conventional vertical counterparts (10's of microns versus 10's of nanometers, respectively), both the photocurrent and the dark-current (denoted by I_{ph} and I_d, respectively), and thus OPD sensitivity, can be expected to be influenced and limited by additional factors, such as space charge build-up across the gap, a factor that has not been addressed.

Moreover, it has been assumed in previous studies, but has never been verified, that the photocurrent arises from the dissociation of excitons created in the gap area only. Such a hypothesis could lead to a miscalculation of the device's external quantum efficiency (EQE) by omitting the contribution of some excitons generated outside of the gap area.

In this work, we use a bilayer heterojunction top-contact lateral OPD, fabricated through a simple shadow mask technique, to study the factors governing I_d and I_{ph}. The results shed light on some limitations of lateral OPDs.

2. Device fabrication and experimental procedure

In this study, we fabricate and test lateral OPDs utilizing N,N′-bis(naphthalen-1-yl)-N,N′-bis(phenyl)-benzidine (NPB) and tris(8-hydroxyquinolinato) aluminum (AlQ_3) as a light absorbing donor material and electron acceptor material, respectively. NPB has strong absorption at 350 nm, and the heterojunction at the NPB/AlQ_3 interface is known to be efficient in the dissociation of excitons formed in the NPB layer [15] and thus the materials system NPB/AlQ_3 can serve as good model compounds for materials typically used in UV OPDs. The molecular structures of NPB and AlQ_3, their Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) energy levels [15] are shown in Fig. 2(a). The absorption spectra of 30 nm-thick NPB and AlQ_3 are also shown from 300 nm to 450 nm.

The fabrication process we use to make top contact OPDs is depicted in Fig. 2(b) and can be divided in four basic steps: (i) deposition of the NPB and AlQ_3 layers; (ii) introduction of a silver wire with a diameter of 25 μm on top of the organics; (iii) deposition of silver, the wire serving as a shadow mask for the metal deposition; (iv) and removal of the wire and creation of a 25 μm-wide gap between the two electrodes. The width of the silver electrodes is 4 mm. All devices are fabricated by the deposition of the organic materials and metals at a rate of 1.0 Å/s using thermal evaporation at a base pressure of $\sim 5 \times 10^{-6}$ torr on cleaned quartz substrates. Fig. 2(c) shows a top-view micrograph of the gap area of a top-contact lateral OPD with a measured channel of around 24.4 μm.

Current–voltage (I–V) measurements are carried out using an Agilent 4155C semiconductor parameter analyser. Photo-measurements are performed under a 350 nm-radiation of 0.8 mW/cm^2 from a 200 W Hg–Xe white lamp equipped with Oriel-77200 monochromator, with the sample illuminated from the bottom (i.e. through the substrate). All tests are carried out with the sample kept in a dry nitrogen atmosphere.

3. Results and discussion

Fig. 3 shows the I–V characteristics, both in the dark and under UV illumination (0.8 mW/cm^2 at 350 nm), of a bilayer heterojunction lateral OPD, comprising a 50 nm thick NPB bottom layer and a 20 nm thick AlQ_3 top layer. The figure inset shows the same data, but presented as a function of the bias electric field, calculated by dividing the bias voltage with the gap size and assuming the electric field is uniform in the channel. This is provided here only to allow approximate comparisons with other published data. As, in principle, the electric field will not be uniform [16], we revert to the use of voltages rather than electric fields throughout the rest of this work in the interest of accuracy. As the figure shows, the device exhibits a good photoresponse, reflected in a substantially higher current flow under illumination versus that in the dark. For example, the I_{ph}/I_d ratio at 15 V bias is about 100 times. The detectivity $D^* = R/(2qJ_d)^{1/2}$ of this device is calculated to be 3.1×10^{10} cm Hz$^{1/2}$/W at 15 V (assuming the channel area is the only photoactive area), where R is the photocurrent response (A/W), q is the absolute value of the electron charge (C), and J_d is the dark current density (A/cm^2). I_{ph} arises from photo-generated carriers produced from excitons created in the thick NPB light-absorbing layer. A fraction of these excitons diffuses to the NPB/AlQ_3 interface where, due to the HOMO and LUMO offsets of NPB and AlQ_3, they get dissociated into "free" electrons and holes on AlQ_3 and NPB molecules, respectively, across the interface. The electrons are collected through the AlQ_3 acceptor layer, and drift across the gap under the effect of the