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Detectivity analysis for organic photodetectors

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ABSTRACT

In this perspective letter, we report that there is a problem with a detectivity estimation method based on dark current measurement for organic photodiodes (OPDs). Based on dark current, calculated detectivity for fabricated OPD was 4.22×10^{13} cmHz$^{1/2}$/W at 520 nm. However, calculated detectivity for OPD based on measured noise current was 8.4×10^{10} cmHz$^{1/2}$/W at 520 nm. Therefore, we found that there are huge differences (more about 3 magnitudes of order) of detectivity calculations based on dark current measurement assumption and our noise measurement analysis. From the calculations of detectivities, it is concluded that noise current analysis should be addressed to clarify the organic photodiode characteristics.

1. Introduction

Organic polymer-based photodiodes (OPDs) are intensively studied for optical sensing and electro-optic applications [1]. They have intrinsic merits such as large-area photodetection, wide material selection opportunity and low-cost, low-temperature fabrication processing on flexible substrates [2]. One of the most important specifications of OPD is the detectivity, and it has been reported based on Gong's statement [3]. Gong et al., reported that 'If, as expected, the shot noise from the dark current is the major contribution, the detectivity can be expressed as

$$D^* = R/(2qJ_d)^{1/2} = (J_{ph} / L_{light})/(2qJ_d)^{1/2} \quad (1)$$

where q is the absolute value of electron charge (1.6×10^{-19} Coulombs), J_d is the dark current, J_{ph} is the photocurrent and L_{light} is the incident light intensity [3]. As Gong's statement, if shot noise is the dominant factor, it is the most desirable to reduce dark current for the enhancement of detectivity in the photodiode. However, the dark current-based assumption is not always true. From the report [3], the high-detectivity in PDDTT:PC$_{60}$BM OPD was achieved by suppressing dark current using the blocking layer between the photoactive layer and the metal electrodes. However, unfortunately, their postulate and calculation of detectivity did not appropriately consider the critical electro-optical phenomena of photodiodes. When light is absorbed in the photo-active layer of OPD, an electron-hole pair (EHP) is generated in the photo-active layer. Also, this EHP generation is related to wavelength and optical power of the light. During EHP generation process, three types of noise are involved such as flicker (1/f) noise, Johnson noise and shot noise. Among three types of noise, shot noise is related to the statistical fluctuation in both high-optical power (photocurrent) and very low-optical power (dark current) of light. Another type of noise can be generated by thermal fluctuation which is called Johnson or thermal noise. Also, while measuring shot and Johnson noise, flicker (1/f) noise can be seen at low frequencies. Therefore, the origin of noise in the photodiode should be analyzed to accurately express the detectivity. Moreover, several recent reports on OPDs are still following the Gong's postulate [4–9]. The figure-of-merit of the photodiode is the noise equivalent power (NEP) to distinguish between detected minimum optical power and the noise. However, recently published literature have not fully considered the advantages of the NEP properties for the detectivity calculation. To address this critical issue, we have calculated this detectivity for both OPD made from the conventional device architecture and a Si-based photodiode. We measured dark current density (J_d), noise current (i_n) and external quantum efficiency (EQE), then calculated detectivities and NEPs based on both J_d and i_{n}. In addition, a generalized transfer matrix method (GTMM) calculation results will be introduced to define the behavior of light absorption in the OPD structure [10,11].

2. Experimental details

In this study, OPD device was fabricated with a donor-acceptor blend of poly(3-hexylthiophene-2,5-diyl) (P3HT) and [6,6]-phenyl-C60-butyric-acid-methyl-ester (PC$_{60}$BM) for a planar photo-active

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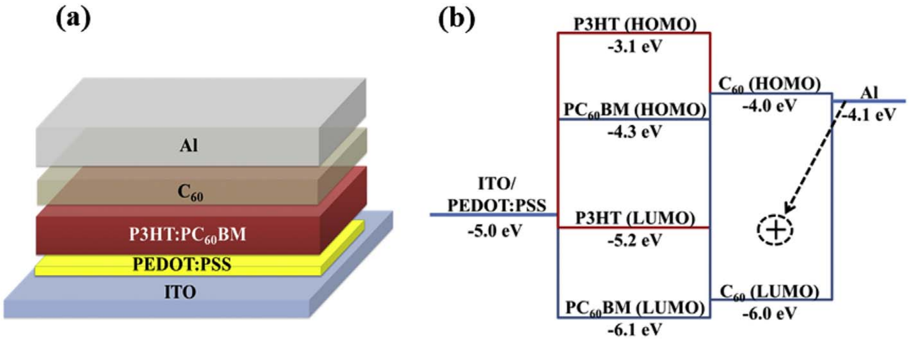

Fig. 1. a) Fabricated OPD structure, b) band diagram for fabricated OPD.

layered structure. P3HT and $PC_{60}BM$ were dissolved at 70 °C in 1,2-dichlorobenzene (DCB) and stirred for 12 h. A purchased (Kintec Company) indium tin oxide (ITO) coated glass substrate was cleaned sequentially by ultrasonic treatment in detergent, de-ionized water, acetone and isopropyl alcohol. A thin layer of PEDOT:PSS (20 nm) was deposited on top of the ITO-coated glass substrate by a spin-coating method with speed of 4000 rpm for 40 s. Then the P3HT:$PC_{60}BM$ bulk-heterojunction (BHJ) layer was spin-cast from the blended solution to form a thickness of 120 nm. The total concentration of P3HT: $PC_{60}BM$ blend was 30 mg/ml. Finally, a C_{60} (40 nm) hole-blocking layer (HBL) and Al (100 nm) electrode were deposited on top of the BHJ layer. The OPD surface area was 0.2 cm^2. Fig. 1 shows fabricated OPD structure and band diagram for detectivity evaluation. In the case of C_{60} layer, it has applied to reduce the dark current density level as reported [1]. All devices were annealed at 150 °C for 10 min in N_2 filled glove box. All OPD devices were electrically characterized in the air after encapsulation. A commercial characterization system for *J-V* and EQE was supplied by PV Measurement Inc. to acquire the data. The noise currents were measured with Agilent B1500A as reported by Kim et al. [12]. Si-PD (D214) was purchased from Hamamatsu. A GTMM simulation was accomplished to calculate the absorption fraction and charge generation rate in the multi-layered interface of OPD. To perform GTMM analysis, optical constants such as reflective index (n) and extinction coefficient (k) values were obtained after Ellipsometry measurements.

3. Results and discussion

Fig. 2 shows measured *J-V* results under the dark condition for both Si-PD and OPD. For Si-PD, measured dark current densities were 6.0×10^{-8} A/cm^2 at -1.0 V and 3.5×10^{-11} A/cm^2 at 0 V conditions, respectively. In the case of OPD, measured dark current densities were 1.6×10^{-8} A/cm^2 at -1.0 V and 8.1×10^{-11} A/cm^2 at 0 V conditions, respectively. Note that, dark current level of OPD in reverse bias condition is better than commercialized Si-PD and C_{60} HBL is effectively working.

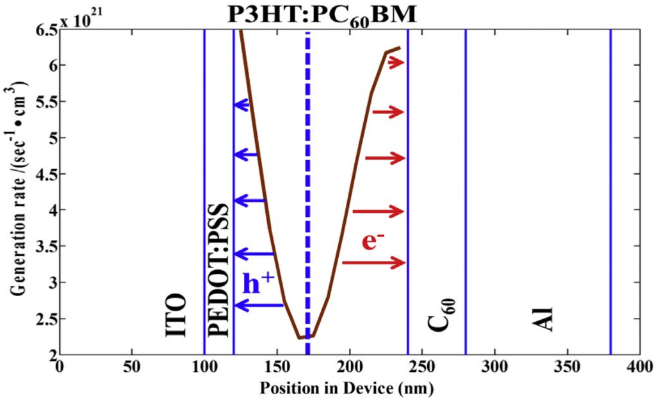

Fig. 3. Charge generation simulation result by generalized transfer matrix method (GTMM).

Fig. 3 confirms charge generation and extraction performance by GTMM calculation. In the bulk-heterojunction (BHJ) of P3HT:$PC_{60}BM$ blend, maximum charge generation is occurred near the interface of PEDOT:PSS and C_{60} layers, respectively. Then generated charges are extracted by built-in voltage potential for both anode and cathode electrodes before recombined [1].

Fig. 4 shows measured EQE results for both Si-PD and OPD at zero bias condition. As expected, the photo-response of Si-PD covers the spectral range up to 1100 nm. However, OPD has frail photo response after 700 nm wavelength.

Fig. 5 shows absorption and reflection simulation result in OPD obtained by GTMM. Note that, according to GTMM result, the absorption fraction of P3HT:$PC_{60}BM$ shows similar shape of EQE result in OPD. By comparing between EQE and GTMM results of P3HT:$PC_{60}BM$,

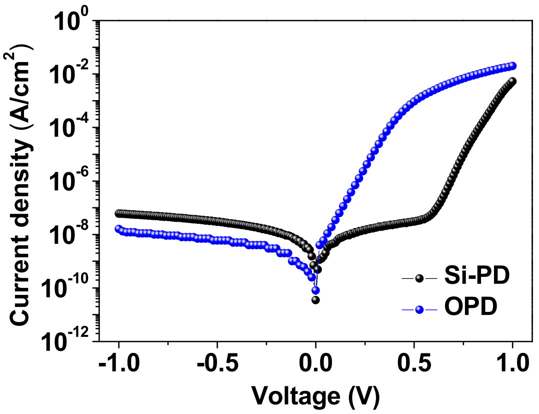

Fig. 2. Measured *J-V* results under the dark condition for Si-PD and OPD.

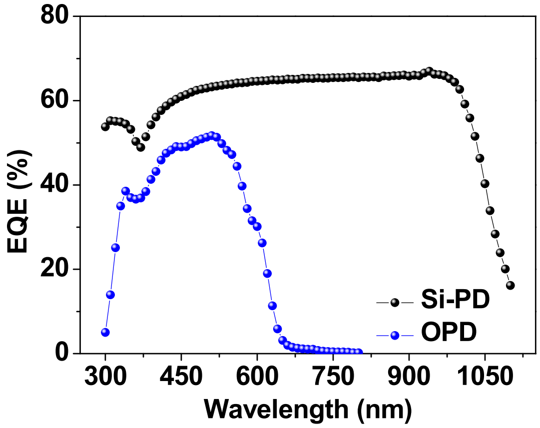

Fig. 4. Measured EQE results for Si-PD and OPD at zero bias voltage.