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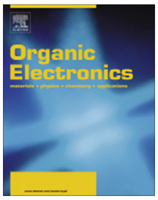

Performance characteristics of pentacene-based organic photovoltaic cells

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ABSTRACT

We demonstrate the maximum power conversion efficiency of 3.89% from organic photovoltaic cells using pentacene as a hole transport layer with PIN structure of ITO/poly(3,4-ethylenedioxythiophene)–poly(styrenesulfonate) (PEDOT:PSS)-glycerol/pentacene/pentacene:C_{60}/C_{60}/BCP (bathocuproine)/Al under standard AM 1.5 illumination (100 mW/cm^2). To achieve high power conversion efficiency, the optimization of thickness of pentacene and glycerol-doped poly(3,4-ethylenedioxy-thiophene)–poly(styrene sulfonate) (G-PEDOT:PSS) as well as pentacene:C_{60} (1:1) thin film as an active layer was accomplished. Our results show that the PIN structure with enlarged interface between pentacene and C_{60} thin films increases the power conversion efficiency of the devices than the PN devices. The morphology of pentacene thin film with various thicknesses and glycerol-doped PEDOT:PSS layers crucially affected the performance characteristics of pentacene-based photovoltaic cells.

1. Introduction

Organic photovoltaic cells (OPCs) have been extensively studied as a next generation renewable energy source because of their attractive properties such as low cost of fabrication, light weight and easy processing [1–3]. It was reported that the first potential OPCs have been achieved 1% power conversion efficiency and remained for long time by Tang [4]. At present, the performance of OPCs has been reported up to PCE of 10% and above [5,6]. However, the power conversion efficiency of OPCs is still low compared to the silicon-based photovoltaic cells [7].

Some organic materials have been confirmed as promising candidates for photovoltaic application, which include poly(3-hexylthiophene) (P3HT), methanofullerene [6,6]-phenyl C_{61} butyric acid methyl ester (PCBM), metal phthalocyanines (MPCs), buckminsterfullerene (C_{60}), poly (2-methoxy-5-(2′-ethyl-hexyloxy)-1,4-phenylene vinylene) (MEH-PPV). However, the performance of these photovoltaic cells has been limited due to the relatively short exciton diffusion lengths and low charge carrier mobility of the active layers [8–10].

Pentacene has been extensively studied as a p-type semiconductor in organic thin film transistors (OTFTs) [11–17] and the field-effect hole mobility of pentacene is reported to be about 1.5 cm^2/Vs, which is comparable to that of amorphous silicon [18–23]. In addition, pentacene has long exciton diffusion length and well suited absorption spectrum in the solar spectrum [24–27]. Various researchers reported on photovoltaic applications of pentacene as a dopant into hole transport layer [28], an interlayer for polymer bulk-heterojunction photovoltaic cells [29], and a donor material [24,30–42]. But pentacene-based photo voltaic cells have been reported with relatively minor photovoltaic response due to limitation of the general structures such as pentacene-C_{60} bilayer heterojunction.

In this study, pentacene-based photovoltaic cells have multi-layers with PIN structures to overcome relatively minor power conversion efficiency. The performance characteristics of OPCs using pentacene as a hole transport layer have been investigated with the dependency of the

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power conversion efficiency on thickness of pentacene layer and the effects of glycerol-doped poly(3,4-ethylenedioxythiophene)–poly(styrene sulfonate) (G-PEDOT:PSS) layer. The thickness of donor materials is the most important parameter in photovoltaic cells because photon absorption depends both on optical absorption coefficient and on the thickness of donor materials. The effects of morphology of pentacene thin film with various thicknesses and G-PEDOT:PSS layer on performance characteristics of OPCs will be mainly discussed.

2. Experimental

Pentacene (formula: $C_{22}H_{14}$, molecular weight: 278.35 g/mol, melting point: 372–374 °C) and C_{60} (formula: C_{60}, molecular weight: 720.64 g, melting point: >280 °C, Tg: 174 °C) were used as a donor and an acceptor, respectively. Twice sublimed pentacene (99.99%) and C_{60} (99.5%) were purchased from Sigma–Aldrich. PEDOT:PSS was purchased from Baytron P from H. C. Starck GmbH and was used as a hole conducting layer material. Glycerol (formula: $C_3H_8O_3$, molecular weight: 92.09 g/mol, melting point: 20 °C, boiling point: 182 °C, Sigma–Aldrich) was used as a dopant. As hole/exciton blocking layer material, bathocuproine (BCP, formula: $C_{26}H_{20}N_2$, molecular weight: 360.46 g/mol, melting point: 277–285 °C, Acros Organics) was used.

The patterned indium-tin-oxide (ITO) glass substrates (Samsung Corning, Korea) were cleaned with acetone, ethanol and isopropyl alcohol 1:1:1 mixture for 30 min by sonication, and then the samples were rinsed by ethanol. Pre-cleaned ITO surface was spin-coated with PEDOT:PSS solution. Before spin coating, PEDOT:PSS solution was filtered using a 0.45 μm Millipore polytetrafluoroethylene (PTFE) syringe filter. Spin-coated thin film was dried on the hot plate at 120 °C for 10 min in air. The thickness of PEDOT:PSS film was controlled to be 40 nm. Organic materials and Al cathode were deposited via thermal evaporation in a high vacuum chamber with a base pressure of $\sim 2 \times 10^{-7}$ torr and substrate temperature of 60 °C. Vacuum deposition technique by thermal evaporation was used to obtain a homogeneous layer with well-controlled thickness. Pentacene layer with various thicknesses in the range of 35–65 nm, 6 nm pentacene:C_{60} layer, 38 nm C_{60} layer, and 6 nm BCP layer were sequentially deposited onto the PEDOT:PSS thin film, followed by a 100 nm thick Al cathode, which was evaporated through a shadow mask. Post annealing was performed at 200 °C for 1 min in vacuum. The energy level diagram and the structure of pentacene-based photovoltaic cells are shown in Fig. 1.

The current density–voltage (J–V) characteristics were measured using a multi-source meter (KEITHLEY 2400) and a solar simulator (XES 301S, SAN-EL Electronics). The Xenon lamp (100 mW/cm^2) was used as a light source. The illumination intensity has been measured by a silicon photo-diode calibrated for an AM1.5 spectrum. The thicknesses of deposited organic and cathode materials were measured using a well calibrated quartz crystal thickness monitor (CRTM-600, ULVAC kiko Co. Ltd.) with thermal evaporator (VPC-260, ULVAC kiko Co. Ltd.). The crystallinity

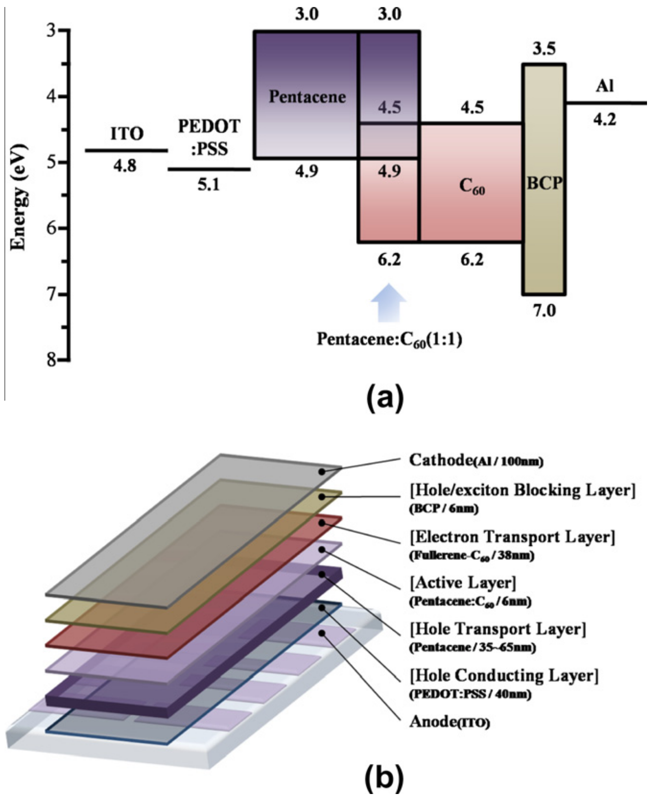

Fig. 1. Pentacene-based photovoltaic cells with PIN structure: (a) energy level diagram of a device and (b) schematic device structure.