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"Solar tree": Exploring new form factors of organic solar cells

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ABSTRACT

Organic solar cells have great potential as a clean and renewable solar energy conversion system, due to their low cost materials, ease of production, and lack of harmful emissions. The rapid improvement in organic solar cell performance in recent years has triggered significant interests in developing organic solar cells for commercial applications. Harnessing the unique set of characteristics of organic solar cells, here we demonstrate a new form factor for organic solar cells, a "solar tree" or an electricity-generating artificial tree with organic solar cells as leaves. We first fabricated polymer:fullerene based organic solar cells on flexible plastic substrates that show similar performance to devices on rigid glass substrates using the inverted device structure. Large-area flexible devices were fabricated and cut into palm leaf shapes with an active device area of 6.5 cm^2 using a steel rule die. 12 leaf-shaped organic solar cells were then assembled to form a prototype "solar palm tree". Two different wiring configurations among the devices provided different power delivery modes: a low-voltage, high-current "fan mode" and a high voltage, low-current "LED mode".

1. Introduction

The search for clean and renewable energy sources has become one of the greatest challenges for our society, due to the rapid depletion of fossil fuels and increasing demand on energy supply. One of the most promising alternative energy sources is solar energy, which is clean, renewable, safe and abundant [1,2]. Using solar cells to directly convert sunlight to electricity is one of the major methods to utilize such an abundant energy source. Compared to inorganic semiconductors that are used in commercial solar modules, organic solar cells have several advantages such as the low material cost, easy tunability of material properties and compatibility with large-area and roll-to-roll manufacturing technologies [1–7]. The power conversion efficiency, η_P, now reaches over 10% with the recent advance in new active material and device architecture designs [8–14].

In addition to conventional applications of solar cells as power-generating sources, the light weight, high flexibility, and rich colors of organic semiconductors enable new form factors and unique applications of organic solar cells. For example, organic solar cells can be integrated into fabrics, such as jackets, handbags, and tents [15]. They can also be used in landscaping applications to substitute for natural grass, flowers, or trees. Such "solar plants" not only can preserve the aesthetic appearance of a location, but provide economic and environmental benefits as they avoid irrigation, application of pesticides/fertilizers, trimming/mowing, and other maintenance needs for natural plants and grass. This makes them very appealing for regions where obtaining sufficient water supply is at a premium, and at the same time minimizing potential adverse impact on the environment.

Here we demonstrate the viability of assembling a "solar palm tree" based on organic solar cells on flexible polyethylene terephthalate (PET) substrates. Using a poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl-C_{61}-butyric acid methyl ester (PCBM) film as the active layers, such flexible devices show a maximum power conversion efficiency $\eta_P = 2.7 \pm 0.1\%$, compared to $\eta_P = 3.0 \pm 0.1\%$ for similar devices on rigid glass substrates. The flexible devices show high flexibility and η_P was only decreased by ~12% after 1000 bending cycles with a bending radius of 1.2 cm. We also scaled up the device area to more than 6 cm^2 on flexible substrates, and demonstrated "solar palm leaves" by cutting the flexible organic solar cells into palm leave shapes using a steel rule die. 12 pieces of leaf-shape devices were then assembled together to construct a prototype "solar palm tree", in which two different wiring configurations among the devices provided two power delivery modes: a low-voltage, high-current "fan mode" and a high-voltage, low-current "LED mode".

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2. Experiment

2.1. Device fabrication

Comparative devices were fabricated on two types of substrates with different transparent conducting electrodes (TCE): glass substrates coated with a transparent indium tin oxide (ITO) electrode, and flexible PET substrates coated with a transparent In_2O_3/Au/Ag (IAA, Delta Technologies) electrode. The sheet resistance of ITO is $19 \pm 1\ \Omega/\square$, whereas the IAA electrodes have two different sheet resistances, $20 \pm 2\ \Omega/\square$ and $60 \pm 5\ \Omega/\square$ (denoted as IAA-L and IAA-H, respectively). All the substrates were successively sonicated in a solution of Liquinox, deionized water, acetone, and isopropanol, followed by 15 min treatment under UV-ozone prior to device fabrication. P3HT (purchased from Rieke Metal Inc.) and PCBM (purchased from Nano-C Inc.) were dissolved in chlorobenzene (1:0.8 weight ratio with a total concentration of 27 mg/mL) and stirred for 24 h before use. ZnO nanoparticles (NPs) were synthesized as reported previously and dispersed in ethanol [9,16,17]. Fig. 1 schematically shows two types of device structures studied here. For the "normal" device structure (Fig. 1(a)), a 40 nm thick poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) layer was first spin-coated from an aqueous solution and annealed in air at 150 °C for 15 min. The active layer was then spin-coated onto the PEDOT:PSS layer from the P3HT:PCBM solution at 1000 rpm for 1 min in a nitrogen-filled glove-box. The devices were completed by thermally evaporating a 100 nm thick Al layer, followed by a post-fabrication thermal annealing at 150 °C for 30 min in a N_2 atmosphere. For the "inverted" device structure (Fig. 1(b)), a 40 nm thick ZnO nanoparticle layer was first spin-coated onto the TCE, followed by spin-coating the P3HT:PCBM layer. The samples were then annealed at 150 °C for 30 min in a N_2 atmosphere. The "inverted" devices were completed by thermally evaporating a 5 nm thick layer of MoO_3 and a 100 nm thick Al layer on the organic layer. All the annealing temperature was reduced to 110 °C for devices on the PET substrates to avoid thermal damage to the PET films. For comparison, devices on glass substrate were also annealed at 110 °C. In the normal structures, the TCE serves as the anode for hole collection, whereas Al serves as the cathode. In the inverted devices, the low work function of the ZnO NP layer [18–21] and the high work function of the MoO_3 layer [22,23] lead to electron and hole extraction at the TCE and Al electrodes, respectively, thus inverting the polarity of the cells. The active device area for the small-area organic solar cells is 4 mm^2, and device performance was averaged over 16 devices. For leaf-shaped devices, the active device area is 6.5 mm^2.

2.2. Device characterization

The current–voltage (J–V) characteristics of the organic solar cells in the dark and under white light illumination were measured using an Agilent 4155C semiconductor parameter analyzer. An Oriel solar simulator equipped with a Xe-arc lamp was used to provide simulated AM 1.5G solar illumination. The light intensity was measured using a calibrated single-crystal silicon reference cell with a KG1 filter [24]. To measure the external quantum efficiency (*EQE*) of these devices, a monochromatic light with varying wavelength was generated from a tungsten lamp through an Oriel monochromator, and chopped at 400 Hz by a mechanical chopper prior to incident on solar cells. The photocurrent was measured using a Stanford Research System 830DPS lock-in amplifier and a Keithley 428 current amplifier. The optical transmittance of films was calculated from the incident, transmitted and reflected light intensities measured using the same setup as the *EQE* measurement.

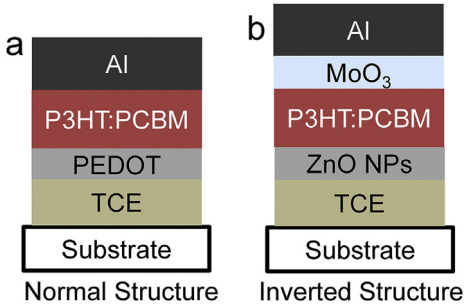

Fig. 1. Schematic illustration of organic solar cells with (a) normal device structure and (b) inverted device structure.

3. Result and discussion

3.1. Devices on rigid glass substrates

The J–V characteristics for the normal and inverted organic solar cells on glass substrates under 1 sun AM 1.5G illumination are shown in Fig. 2(a). All the device parameters are summarized in Table 1. The inverted device has a slightly higher open-circuit

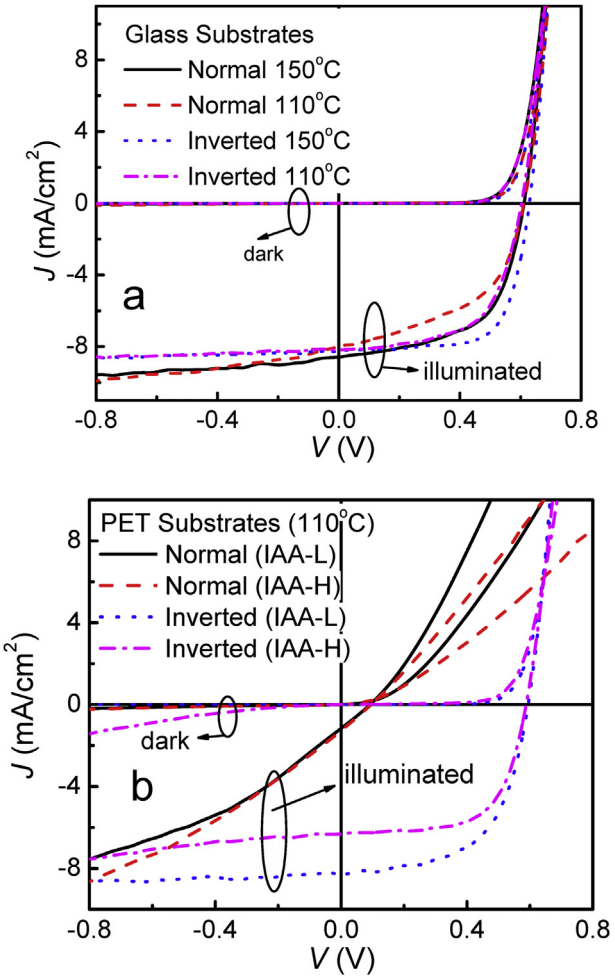

Fig. 2. Current density–voltage (J–V) characteristics of (a) normal and inverted P3HT:PCBM organic solar cells on glass substrates with different annealing temperature (110 °C and 150 °C) and (b) normal and inverted devices on PET substrates with different sheet resistance (annealing at 110 °C) in the dark and under simulated 1 sun AM 1.5 solar illumination.