Solar Energy Materials & Solar Cells 116 (2013) 219–223

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

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

Module structure for an organic photovoltaic device

Nam Su Kang [a], Byeong-Kwon Ju [a], Jae-Woong Yu [b,*]

[a] Display and Nanosystem Laboratory, College of Engineering, Korea University, Seoul 136-713, Republic of Korea
[b] Department of Advanced Materials Engineering for Information & Electronics, Kyung Hee University, 1732 Deogyeong-daro, Giheung-gu, Yongin, Gyeonggi 446-701, Republic of Korea

A R T I C L E I N F O

Article history:
Received 20 December 2012
Received in revised form
24 April 2013
Accepted 7 May 2013

Keywords:
Organic photovoltaic
Polymer solar cell
Module
Shunt resistance
Fill Factor

A B S T R A C T

The influence of module design on the performance of OPV modules was studied, especially longitudinal partition effects. Two different module designs were used, one with wider cells (8 mm) and one with narrower cells(3.7 mm).The narrow structure had a current extraction metal sub-electrode in the middle of the module, and a tandem series connection of 4 or 5 cells was used for a fixed total module area. The current density, fill factor, shunt resistance, and power conversion efficiency of the narrow cells were higher than those of the wide cells with a comparable length-to-width ratio. As the longitudinal partitioning of a cell increases, the performance of the device increases. However, the effective active area of the module decreases, so the total power output will decrease. The optimum length-to-width ratio of wide or narrow cells is between 16 and 18.

1. Introduction

Organic photovoltaics (OPVs) are attractive alternatives to conventional inorganic semiconductor-based photovoltaics, because they are light weight, mechanically flexible, compatible with flexible substrates, and large area device can be fabricated at low cost. Due to the strong demand for cheap, renewable energy, OPVs have been the subject of increasing developments over the last decade [1–8]. Recent rapid improvements in the power conversion efficiency (up to 10.6%) [4] have increased the anticipation for commercial OPV devices in the near future.

To deliver the electrical power needed for applications, a module structure with connections between each subcell is needed to increase the output power. Creating a series of connected modules is an easy way to increase power output. The first series connection in an OPV was a tandem cell consisting of phthalocyanine and perylenetetracarboxylic derivate, which approximately doubled the open circuit voltage compared to a single solar cell [9]. This study reports a series connection within a unit cell. Lungenschmied et al. [10] reported the first meaningful geometrical OPV modules, with square, broad-stripe, and narrow-stripe geometries. However, the dimensions were not practical for fabricating actual modules. Lyu et al. [11] reported an efficiency change according to the module structure using a theoretical power loss model. They used a series tandem structure module with 4 different widths (18.6, 11.6, 8.1, and 6.0 mm), and concluded that the optimum active cell was 13 mm wide. Many studies have assessed the effects of cell geometry on unit cell performance, but there have been relatively few studies on the effects of module geometry [10–17]. In a shading test of OPV modules, 10% shading shut down the whole module [17]. Therefore, optimum designs are critical to produce the maximum power output from a given module area. Krebs et al. reported several studies on the effects of module structure on the performance of roll-to-roll processed polymer solar cells [8,18–20]. The module structure of a polymer solar cell with a serially connected ITO stripe having different widths was studied. It was concluded that the width should be narrowest for a low series resistance, and widest for the active area [18]. They showed that the increased performance of OPV by narrowing the stripe width was quickly lost due to a loss in active area.

All of the module studies so far have concentrated only on the influence of the lateral direction, since charges have to traverse series connections to produce electricity. We investigated the influence of module design on the performance of OPV modules. In particular, we studied the influence of longitudinal partitions on module performance. We demonstrate that longitudinal partitioning is universally applicable to all organic photovoltaic modules.

2. Materials and methods

2.1. Fabrication of devices

A patterned ITO panel for cell testing was prepared by photolithography and cleaned by acetone, isopropyl alcohol, and

* Corresponding author. Tel.: +82 31 201 3325; fax: +82 31 204 8114.
E-mail address: jwyu@khu.ac.kr (J.-W. Yu).

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http://dx.doi.org/10.1016/j.solmat.2013.05.009

deionized water. Molybdenum oxide was deposited by thermal vapor deposition at 7×10^{-7} Torr and annealed at 250 °C in a nitrogen dry box for use as a hole transfer layer.

A typical organic solar cell module was prepared as follows: a blend containing 2.4 wt% P3HT (purchased from Rieke Metals, EE grade) and PCBM (purchased from Nano-C) with a 1:0.6 weight ratio was dissolved in anhydrous chlorobenzene and spin-coated at 2500 rpm for 40 s onto ITO glass coated with a molybdenum oxide layer. The resulting active layer was 140 nm thick, and was pre-annealed at 120 °C for 10 min. A 0.8 nm thick LiF layer was deposited as a buffer for electron extraction on top of the active layer, and a 150 nm thick aluminum layer was deposited by thermal vapor deposition at 10^{-6}–10^{-7} Torr. The prepared device was post-annealed at 120 °C for 10 min.

2.2. Fabrication of modules

A 10 cm × 10 cm piece of ITO glass with a sheet resistance of 8 Ω/□ was prepared from a large piece of ITO glass, and photolithography was used to create the desired pattern. The prepared ITO glass was then cleaned by rinsing with several solvents (acetone, isopropyl alcohol, and deionized water) and dried in a vacuum oven at a temperature of 200 °C. The ITO glass was treated with ozone for 15 min just before use. The hole transporting layer (MoO_x) was deposited at high vacuum (5×10^{-7} Torr) by thermal deposition (with a deposition rate of 1 Å/s). The 30 nm thick MoO_x layer was annealed for 30 min on a 250 °C hot plate inside a glove box with an N_2 atmosphere. The active layer stock solution (concentration: 2.5 wt%, with a donor acceptor ratio of 1:0.6) was spin coated at 900 rpm for 5 s inside a glove box, and also annealed on a hot plate at 120 °C for 30 min. A 150 nm thick aluminum layer was applied by thermal vapor deposition at 10^{-6}–10^{-7} Torr, and the prepared device was post-annealed at 120 °C for 10 min.

2.3. Characterizations

The thickness of the coated film was measured with a surface profiler (TENCOR®, P-10 α-step). The absorption spectra of the films were obtained using a photodiode array type UV–vis spectrometer (HP 8453). An Oriel Class A solar simulator (IEC 904) with an Oriel Reference Cell (calibrated data traceable to NREL) was used as a light source. All measurements were performed under a 1 sun condition (AM1.5 100 mW/cm²). Measurements were not corrected for reflection loss or light absorption in the ITO electrode. The *I–V* characteristics were determined with a Keithley 2400 source-measure unit.

3. Results and discussion

A MoO_x layer was used as a hole transporting layer instead of the typical conducting polymer film (PEDOT), since thermally evaporated MoO_x provides better smoothness and stability. Thermally evaporated MoO_x provides a more uniform thickness than spin-coated polymer films in 10 cm × 10 cm modules. Additionally, the acidity of PEDOT solution reduces the lifetime of organic photovoltaic devices [8,21,22]. The conductivity of MoO_x is lower than that of PEDOT film, but it can be improved by enhancing the oxygen vacancies, which is easy at relatively low temperature (250 °C) [23]. Fig. 1 shows the *I–V* characteristics of 2 mm × 2 mm devices with thermally treated MoO_x layers. The device performance was enhanced as the annealing temperature was increased. The reasons for these enhancements include the enhancement of the layer roughness by baking, and the creation of oxygen vacancies improving the electron and hole mobilities. As a result,

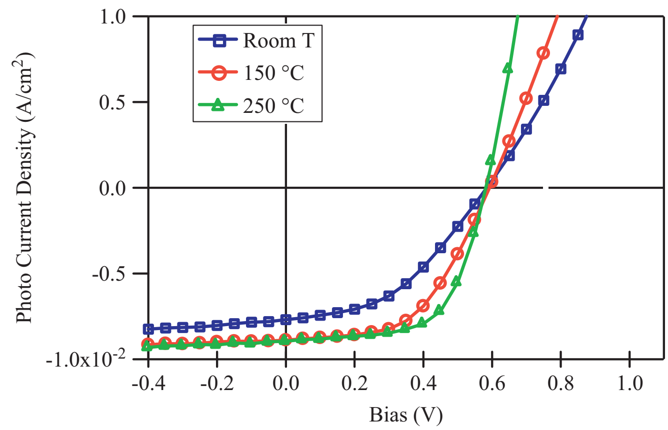

Fig. 1. *I–V* characteristics of thermally treated MoO_x layers.

Table 1
Performance of devices with annealed MoOx.

Annealing *T* (°C)	J_{sc} (mA/cm²)	V_{oc} (V)	FF	PCE (%)
Room T	7.69	0.58	0.44	1.96
150	8.87	0.59	0.52	2.76
250	9.06	0.58	0.65	3.41
PEDOT reference	8.86	0.59	0.65	3.40

the device prepared on a MoO_x layer annealed for 30 min at 250 °C had identical performance to a device prepared on PEDOT film, as summarized in Table 1. The annealed device showed markedly enhanced power performance compared to the as-prepared device (representing an enhancement in efficiency of about 70%, from 1.96 to 3.41).

Fig. 2 shows the module designs used in this study. We used two different designs: one with wider cells (8 mm) and one with narrower cells (3.7 mm). The module size was fixed at 10 cm × 10 cm. Using identical processing techniques (i.e., the same distance between cells), the wide-cell module has a higher effective cell area (22.8 and 21.6 cm²) than the narrow-cell module (18.6, 17.8, and 16.9 cm²). The wide-cell module has 5 cells connected in series to produce an open circuit voltage of about 2.6–2.7 V, while the narrow-cell module had 4 cells connected in series to produce about 2.4–2.5 V. The narrow structure has a current extraction metal sub-electrode in the middle of module to produce more current with a similar open circuit voltage compared to the wide structure (i.e. 4 cells connected in series with a current extraction metal sub-electrode in the middle).

Fig. 3(a) and (b) shows the *I–V* characteristics of the modules with wide and narrow cells, respectively. As the longitudinal partitioning of the cell increased (i.e., the length-to-width ratio decreased), the current density, fill factor, and shunt resistance increased. The results are summarized in Table 2. In the wide-cell module, as the length-to-width ratio decreased from 7.125 (57 mm long × 8 mm wide) to 3.375 (27 mm long × 8 mm wide), the series resistance did not change, and the fill factor increased slightly. However, the short circuit current density increased by about 6% and the shunt resistance increased by about 40%. As a result of these changes, the power conversion efficiency increased by about 13% (from 0.99 to 1.12). In the narrow-cell module, as the length-to-width ratio decreased from 17.027 (63 mm long × 3.7 mm wide) to 2.568 (9.5 mm long × 3.7 mm wide), all characteristics increased. The current density increased by 25%, the fill factor increased by 13%, the shunt resistance increased by 110%, the series resistance increased by 45%, and the power conversion efficiency increased by 45%. Comparing the analogous length-to-width ratios between