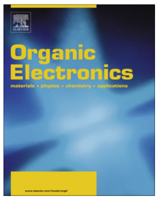
Organic Electronics xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Organic Electronics

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



ITO-free large-area flexible organic solar cells with an embedded metal grid

Seungkeun Choi, Yinhua Zhou, Wojciech Haske, Jae Won Shim, Canek Fuentes-Hernandez, Bernard Kippelen *

Center for Organic Photonics and Electronics, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

A R T I C L E I N F O

Article history:
Received 28 October 2014
Received in revised form 23 December 2014
Accepted 28 December 2014
Available online xxxx

Keywords:
ITO-free
Flexible
Large area
OPV
Embedded
Metal grid

A B S T R A C T

We report on ITO-free large-area flexible organic solar cells with embedded thick metal grids. Embedded thick metal grids on flexible substrates allow uniform spin coating of thin layers of PEDOT:PSS (PH1000) semitransparent electrodes and organic semiconductor layers. A transparent SU8 photo-patternable polymer is used as a flexible substrate. Electroplated copper metallic grids, up to 15 μm thick, defined by photolithography, produce a shadow area of 5.5% of the active area. Inverted solar cells with an active area of 9.3 ± 0.2 cm^2, exhibited a fill factor of 0.53 ± 0.06, and an open-circuit voltage of 808 ± 5 mV and a short-circuit current density of 5.5 ± 0.5 mA/cm^2, yielding a power conversion efficiency of 2.4 ± 0.4% under 100 mW/cm^2 air mass 1.5G illumination. The fill-factor and open circuit voltage values of large-area solar cells are comparable to values reported on small-area solar cells.

1. Introduction

Over the last decade, organic photovoltaics (OPV) have been extensively investigated for their potential to develop low-cost, flexible, and light-weight solar cells [1–3]. The power conversion efficiency (PCE) of OPV has rapidly improved during the past few years and now exceeds 10% [4,5]. These laboratory-scale OPVs are often demonstrated as individual cells, with a small active area (typically less than few cm^2), usually fabricated on rigid, or even flexible, substrates having indium-tin-oxide (ITO) transparent electrodes [1]. However, ITO is brittle and expensive, so the realization of mechanically stable large-area OPVs on flexible substrates will require developing alternative transparent electrodes that replace ITO [6,7].

Finding suitable replacements for ITO is still an important technical challenge. Two most widely used ITO alternatives are a highly conductive poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) [6,8,9] and thin semitransparent layers of metal or carbon nanotubes [10–12]. In order to obtain sheet resistance values comparable to those of ITO (10–15 Ω/sq.), PEDOT:PSS is often combined with silver nanowire or thin metallic grid manufactured with various processing techniques [10,11,13–21]. While all these efforts aim to develop a transparent electrode that can replace ITO, the performance of large-area OPVs is still significantly limited by parasitic series resistance effects even in solar cells that use ITO transparent electrodes (which display sheet resistance values that are at least two orders of magnitude lower than those reported for PEDOT:PSS) [22–25]. This is because the power loss due to series resistance is proportional to the square of the solar cell length. Furthermore, parasitic series resistances become a limiting factor when implementing OPV modules, forcing the use of the so-called stripe geometry wherein several cells consisting of narrow stripes are connected in series. This method is widely used in OPV

* Corresponding author.
E-mail address: Kippelen@ece.gatech.edu (B. Kippelen).

http://dx.doi.org/10.1016/j.orgel.2014.12.029
1566-1199/© 2015 Published by Elsevier B.V.

modules manufactured with roll-to-roll processes [3,26–30]. A disadvantage of this method is that the area used by the stripe-to-stripe connections reduces the overall active area of the module (typically around 20%), leading to a significant reduction of the power conversion efficiency in modules compared to small-area cells [31]. Hence a need exists to develop alternatives to ITO with higher conductivity and better mechanical properties for the realization of large-area OPV solar cells and modules.

We recently demonstrated the realization of bottom electrodes comprising thick metal grids and a highly conductive grade of PEDOT:PSS (Clevios PH 1000, H.C. Starck), which was used as a substitute for conventional ITO-coated substrates in large-area OPVs [22] and organic light-emitting diodes (OLEDs) [32,22,23,33]. The benefits of a thicker metal grid is obvious as it provides more conductive current paths compared to a thin film based metal grid [23]. In fact, it was shown that the thicker grid was essential to minimize resistive power loss from the grid itself [33]. Furthermore, it was proven that the same metal design can be applied to much larger areas without significantly increasing resistive power loss densities by using the same grid design with a thicker grid [23]. In such devices, the organic semiconductor layers were thermally evaporated rather than spin-coated. To facilitate solution processing, a better approach would be to have metal grids embedded in the substrate [34,35].

Herein, we report on the demonstration of ITO-free flexible large-area organic solar cells with an embedded metal grid fabricated on a SU8 substrate. Because the thick metal grid was embedded within the flexible substrate, layers of PEDOT:PSS (PH1000) and organic semiconductors were spin coated uniformly on top of a large-area substrate. An SU8 photo-patternable polymer was used as a flexible substrate as it has good optical transmittance in the visible wavelength. Copper was electroplated up to 15 μm creating embedded metal grids. The shadow area loss due to the metal grids is 5.5% of the active area. The completed device had an inverted structure of SU8/embedded-metal-grid/PEDOT:PSS(PH1000)/PEIE/P3HT:ICBA/MoO_3/Ag with an active area of 9.3 cm^2. The device exhibited a fill factor of 0.6, a short-circuit current density of 5.8 mA/cm^2, and an open-circuit voltage of 0.81 V, yielding a power conversion efficiency of 2.8% under 100 mW/cm^2 air mass 1.5G illumination.

2. Experimental section

2.1. Large-area flexible solar cells fabrication with an embedded metal grid

Metal grids embedded within a SU8 thin film were fabricated by first coating a glass substrate with a thin posi-

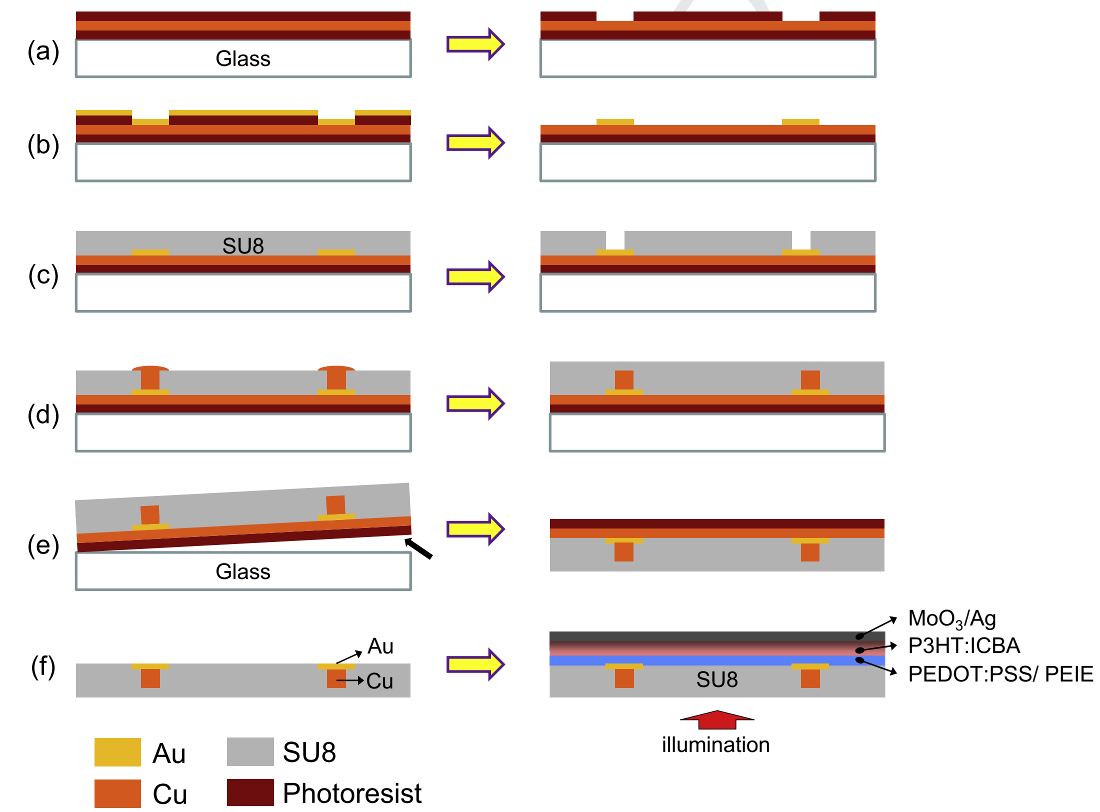


Fig. 1. Fabrication sequences for ITO-free large-area organic solar cell with embedded grids: (a) seed layer deposition and mold structure creation for Au grids, (b) Au deposition and lift-off, (c) SU8 spin coating and patterning; (d) copper grid electroplating, (e) peel-off the flexible substrate from the glass and (f) seed layer removal and OPV fabrication.