

Edge sealing for low cost stability enhancement of roll-to-roll processed flexible polymer solar cell modules

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ABSTRACT

Fully roll-to-roll processed polymer solar cell modules were prepared, characterized, and laminated. Cell modules were cut from the roll and matched pairs were selected, one module with exposed cut edges, the other laminated again with the same materials and adhesive sealing fully around the cut edges. The edge sealing rim was 10 mm wide. Cell modules were characterized by periodic measurements of IV curves over extended periods in a variety of conditions, as well as by a variety of spatial imaging techniques. Data show significant stability benefits of the edge sealing process. The results of the imaging experiments show that the ingress of atmospheric reactants from the edges leads to degradation. In the case of edge sealed devices the same effects are observed but significantly slowed down. In particular, the fast nonlinear degradation is eliminated.

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1. Introduction

Major advances are being made in the field of organic polymer photovoltaics [1]. Cell efficiencies of over 8% have been achieved [2,3] and cell manufacturing techniques have been developed to the level that industrial production of cells and modules is technically feasible with continually decreasing costs [4,5]. Stability of organic photovoltaic (OPV) devices has become a more active area for research as well [6–10]. While progress has been impressive in all three of these areas individually, the next challenge is to bring these research successes together in a single device structure. In this work we focus on two of these three areas, combining economically viable full roll-to-roll fabrication processes with enhanced cell module stability. The stability of polymer solar cells is affected by a complicated mixture of different processes that all result in device degradation. Degradation at interfaces and photochemical degradation are some of the most important mechanisms that involve atmospheric components such as oxygen and water [11]. Methods to improve stability of the polymer solar cells and modules not only include improvement of the inherent stability of the materials and interfaces [12], but also prevention of ingress of atmospheric

components through encapsulation [13,14] and reduction of the most reactive part of the electromagnetic spectrum through filtering UV-light [15]. It is of course possible to completely seal the device from the surroundings but the available methods are both tedious and not competitive in terms of cost and processing time. Ideally the encapsulation should be compatible with the manufacture of the solar cells and modules, which is through roll-to-roll processing. In the case of ProcessOne (described below) it is possible to seal the device in a fast roll-to-roll process although the seal is not complete at the edges of the device after it is cut from the roll [7]. In this case a second seal would be needed. In this work we thus aim at establishing the differences between the partially sealed (but easily accessible) device and the edge sealed device (that requires more processing time). Our approach is to look at the established ProcessOne fabrication method, which uses a polyethyleneterephthalate (PET) substrate coated with a transparent front electrode of indium-tin-oxide (ITO), an electron transport layer of ZnO, an active layer comprised of a blend of poly(3-hexylthiophene) (P3HT) as the donor and the phenyl-C61-butyric acid methyl ester (PCBM), a hole transport layer of poly(3,4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS) and a Ag back electrode all laminated on the roll with a UV filter and barrier film. Modules were prepared with (edge sealed) and without (control) a second level of lamination to form a barrier against diffusion through the cut edges of the devices. We characterize the devices by periodically measuring their IV curves and following their performance under a variety of illumination conditions over time.

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In addition we image the devices to spatially map their induced photocurrent [16,17], and induced temperature variations under forward and reverse bias [18,19].

2. Material and methods

Polymer solar cell modules were fabricated using ProcessOne by slot die coating in a fully roll-to-roll (R2R) process in an ambient laboratory environment as part of the ISOS-3 workshops held in October 2010 at Risø DTU. Each module consists of 16 individual cells in series. The active area of each module is nominally 35.5 cm². Each cell has an inverted architecture consisting of a transparent PET foil substrate coated by a layer stack of ITO/ZnO/P3HT:PCBM/PEDOT:PSS/Ag and laminated with a UV filter and barrier layer. The *inverted* architecture has light entering through the substrate and ITO, which serves as a collector for electrons from the active layer, while the holes are collected through the PEDOT:PSS to the Ag electrode. The advantages of this architecture include the elimination of reactive low work function metals used as the electron collector in the *normal* architecture and enhanced stability in the presence of water vapor. [7] A sputtered layer of 90 nm of ITO on a PET substrate was used as the anode. ZnO nanoparticles were prepared by caustic hydrolysis of Zn(OAc)₂·2H₂O as described previously [7,20,21] and were used for ink formulations using Acetone as a solvent. The ZnO ink was filtered through a 0.45 μm filter before coating. The ink for the active layer was prepared by dissolving P3HT (18–24 mg/mL) purchased from BASF (Sepiolid P200), and PCBM (16–22 mg/mL) purchased from Solenne B.V. in half the final volume of chlorobenzene at 120 °C for 3 h, followed by addition of the second half of the final volume of chloroform. The ratio between P3HT and PCBM was typically 10:9. PEDOT:PSS, was purchased as EL-P 5010 from Agfa and was diluted slowly with isopropanol using stirring until a viscosity of 270 mPa s was obtained. The silver ink employed, which is screen printable and UV curable was purchased from Toyo (FS18). Each cell has a full silver back electrode and series connection to adjacent cells, and large silver contacts for the anode and cathode contacts of the module. The adhesive for encapsulation was 467 MPF from 3 M and the barrier material was purchased from Amcor and has a UV filter with a cutoff at 380 nm. The barrier has a water vapor transmission rate $\sim 0.1 \text{ g m}^{-2} \text{ day}^{-1}$ [38 °C, 90%RH] and an oxygen transmission rate $< 0.01 \text{ cc/g m}^{-2} \text{ day}^{-1} \text{ bar}$ [23 °C, 50%RH] as reported by Amcor. The transmission rates for the adhesive are not reported, but are expected to be much higher. After the first level of lamination, modules were cut from the roll leaving open edges on the perimeter of the lamination, $\sim 1 \text{ cm}$ from the active cell region. Modules were fully characterized and matched pairs were made with similar performance, typically with a power conversion efficiency, *PCE*, from 1–2%, and pairs were selected with *PCE* values within 0.2%. Cu tape (3 M) was applied to the silver electrodes to extend the electrical contact away from the device region. The edge sealed samples (one from each pair of modules) were then laminated a second time with an adhesive seal $\sim 1 \text{ cm}$ wide around the perimeter of any edges. There is no evidence that the edge sealing lamination process changed initial module performance. Metal snap fasteners (#20) are used to pierce the Cu to form the electrical terminals (similar to a 9 V battery) on all the modules.

Electrical characterization was performed by collecting IV curves with a Keithley 2400 sourcemeter under illumination from a metal halide solar simulator (KHS Solar Constant 1200) calibrated for AM1.5G at 1000 W/m² with an automated roll-to-roll testing system for an initial screening, followed by an annealing soak (KHS Solar Constant 575) for 40 min to activate the ZnO

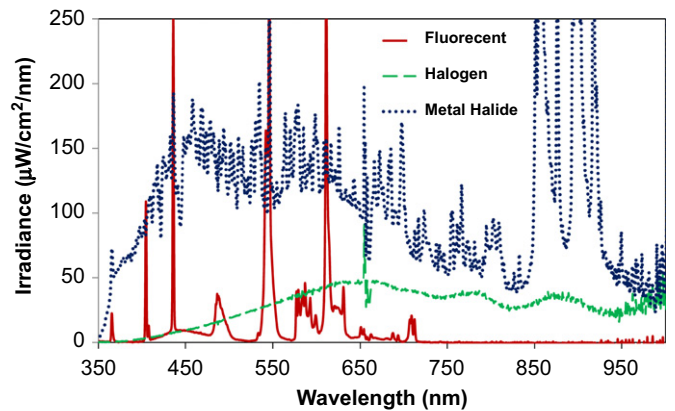


Fig. 1. Calibrated irradiance for the three light sources used in this study: metal halide (KHS Solar Constant 575), halogen lamp (Osram Halopar), and fluorescent lamp (Osram FQ Lumilux HO).

layer and maximize the module performance. Long term stability was measured under four illumination conditions: full sun (KHS Solar Constant 575, AM1.5G at 1000 W/m², $T \sim 55 \text{ }^\circ\text{C}$) halogen lamps (Osram Halopar 64845FL, 250 W/m², $T \sim 30 \text{ }^\circ\text{C}$), indoor fluorescent lighting (Osram FQ Lumilux HO, 100 W/m², $T \sim 45 \text{ }^\circ\text{C}$), and dark storage ($T \sim 20 \text{ }^\circ\text{C}$). The calibrated irradiance spectra of all three lighting conditions are shown in Fig. 1.

Photocurrent measurements were taken with a novel high speed light beam induced current (LBIC) system developed at Risø DTU. Adjustable gain and offset optimize visualization of patterns within each module image but absolute photocurrent cannot be compared across images. Spatial images of minute thermal fluctuations resulting from dark charge injection into the modules are measured by dark lock-in thermography (DLIT) and highlight ohmic power losses in the cell modules. [19] A high frame rate IR-camera combined with computer controlled charge injection and digital lock-in detection employed at TU Ilmenau enables measurement of thermal variation below 0.1 mK [18].

3. Results

The ZnO nanoparticles in ProcessOne modules require an initial activation, typically by exposure to UV [22]. Fig. 2 shows LBIC and IV characterizations of an edge sealed module before and after an initial 40 min soak to activate the ZnO. (The data is similar for the control module without the edge seal). The activation is not permanent, and is one way to see the effect of the edge sealing on the modules. A module with a full edge seal remained fully activated when stored in the dark for periods over 100 h, while the control module without an edge seal reverts to its initial deactivated state over the same period.

The effect of the edge sealing is most apparent on the samples under full sun illumination. Fig. 3 shows the degradation of a matched pair of modules over 800 h. The red curve represents the edge sealed module with a linear degradation, while the purple curve represents the control module and appears to have an exponential decay. LBIC images are shown at the end of the curves as insets. These modules also display significant visual differences in polymer bleaching and electrode oxidation as they degrade, as seen in Fig. 4, a photo taken after soaking the modules for over 900 h. The left image shows the edge sealed sample is visually unchanged from when it was sealed. There is no bleaching or oxidation apparent. The right image shows significant bleaching of the polymer near the open edges of the control module and along the top cell. A substantial darkening of the printed silver due to oxidation is also present, in marked contrast to its

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