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New barrier encapsulation and lifetime assessment of printed organic photovoltaic modules

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ABSTRACT

Organic photovoltaic (OPV) modules printed on plastic substrates are attracting worldwide attention due to advantages such as flexibility, large-scale printability, lightweight, and potential utility for new products. However, exposure to atmospheric oxygen and water vapour is known to cause rapid device degradation and OPV devices thus require encapsulation using materials having ultra-low permeability to these atmospheric constituents to achieve the required operational lifetimes for commercial applications. In this work, various encapsulation architectures using flexible barrier films and adhesives available from commercial suppliers are developed and the lifetime of encapsulated large-area (active area $\sim 50\ cm^2$) fully-printed OPV modules are assessed under ambient laboratory and outdoor conditions. New encapsulation architectures significantly enhance the durability of printed OPV modules, with results showing modules exhibiting a shelf-life of more than 5 years, and no evidence of degradation after 13 months' exposure under outdoor conditions.

1. Introduction

Organic photovoltaics (OPV) has attracted much attention in the field of photovoltaic research. Recent progress in the development of new materials and device structures has led to several reports of devices having power-conversion efficiencies exceeding 9% for laboratory-scale test devices [1–3], and a certified record efficiency of 11.5% [4]. A primary advantage of OPV technology is that all of the functional layers in an OPV module can be manufactured by eco-benign, scalable printing or coating technologies [5,6]. Furthermore, the ability to manufacture on flexible plastic substrates using high-speed roll-to-roll manufacturing lines enables significant potential cost benefits for OPV modules compared with other PV technologies [7–10]. Other features such as the flexibility and light-weight of printed OPV modules are attractive for a variety of diverse applications ranging from power sources for portable electronic devices to building-integrated power-generating PV systems. The potential commercial opportunities offered by printed OPV technology have prompted substantial research into methods for fabrication of modules using various large-scale continuous printing methods. However, the instability of printed OPV modules to environmental factors such as oxygen and water vapour remains a major limiting factor for the successful commercialisation of printed OPV technology [11,12].

The development of suitable encapsulation protocols using materials capable of providing extremely high barrier to the ingress of oxygen and water vapour into the modules is needed to improve the lifetime of printed OPV devices. Water vapour transmission rates (WVTRs) of the barrier films used for OPV encapsulation should, ideally, be less than around $10^{-3}\ g\ m^{-2}\ day^{-1}$ for extended outdoor applications [13,14]. A few barrier encapsulant layer materials satisfying these conditions have been reported [15,16] and some proprietary commercial and pre-commercial materials are available, although notably these films are not typically supplied with an integrated bonding/adhesive layer. Consequently, separate sealant materials need to be applied in order to complete the encapsulation process. The adhesive bonds the two encapsulation layer materials together and/or the encapsulation layer materials to the device. In previous work [17] we have shown that even trace levels of moisture retained within the barrier films and adhesive materials can cause significant reductions in the long-term stability of OPV devices, and highlighted the importance of pre-conditioning barrier materials prior to encapsulation. Flexible barrier encapsulation materials are capable of inhibiting the ingress of moisture and oxygen through the front and back surfaces of a device. The design of a suitable encapsulation architecture that also restricts

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lateral ingress of moisture and oxygen through the bonded edges and/or the electrical contacts of the device continue to present a significant scientific and technical challenge.

The OPV literature is dominated by research on new active materials and device structures aimed at improving the device efficiency, with relatively few studies reporting results of long-term outdoor stability tests and the development of suitable flexible encapsulation [18–25]. In the present study we have developed new encapsulation architectures and conducted extended lifetime testing for more than 1 year on large-area printed OPV modules under ambient laboratory conditions and upon outdoor exposure. It was found that adhesives used to bond the two barrier encapsulant layers and the electrical contact regions can provide a significant pathway for ingress of atmospheric moisture and oxygen into the encapsulated device. Therefore, effective encapsulation designs need to include a means to inhibit moisture and oxygen entering laterally through the edges of the laminated device, particularly around the electrical contacts. The durability results presented here provide unique information regarding the long-term stability behaviour of printed OPV modules encapsulated using different encapsulation architectures under typical indoor and outdoor conditions.

2. Experimental

2.1. Device fabrication and encapsulation

Printed OPV modules comprising five individual strip cells in a so-called "inverted" configuration (PET|ITO|ZnO|P3HT:PCBM|PEDOT:PSS|Ag) and connected electrically to each other in series were fabricated on ITO-coated PET substrates, following the work of Krebs et al. [26]. Details about the device structure, preparation of solutions for the printed layers, and substrate used in the present work are the same as described previously [10]. The ZnO nanoparticle solution was prepared as described by Sarasqueta et al. [27]. For the active layer, P3HT (15 mg/ml) and PCBM (15 mg/ml) in chlorobenzene:*o*-dichlorobenzene(3:1 v/v ratio) were stirred separately for 3 h at 70 °C. The two solutions were cooled to room temperature, mixed together, and then passed through a 0.45 μm syringe filter prior to use.

Modules were prepared by firstly printing ZnO colloidal solution onto cleaned ITO-coated PET by the reverse-gravure printing method using a Mino-Labo™ printer (MAHY-1310; Yasui Seiki Co. Ltd) followed by heating on-line at 140 °C for a few seconds to remove residual solvent. P3HT (SP001, Merck):PCBM (Tec. Grade, Solenne) and PEDOT:PSS (S315, Agfa) layers were applied by reverse-gravure printing, followed by a screen-printed Ag grid (PV416, DuPont) to enhance charge collection of the module and to connect the five cells in series [31]. Printed modules were pre-conditioned by storage under vacuum at room temperature for at least 12 h followed by storage in a N_2-filled glovebox until the encapsulation process was completed.

3M™ Ultra Barrier Solar Film was used as the plastic barrier encapsulant layer for the front and back sides of the device. According to the manufacturer, the water vapour transmission rate (WVTR) of this material is less than 5×10^{-4} g m^{-2} day^{-1}. The barrier layers were bonded onto the device using adhesive transfer tape (3M™ 467MP) or ethylene vinyl acetate (EVA) films (3M™), and the perimeter of some of the encapsulated modules was sealed using a moisture-barrier tape (HelioSeal® PVS 101, ADCO). As described previously [17], pre-conditioning of the encapsulation materials is essential for optimal device lifetime once removed from the glovebox. All the encapsulation materials were pre-conditioned under vacuum at 100 °C for at least 10 h. The encapsulation process was carried out by lamination at 130 °C in a N_2-filled glovebox maintained at moisture and oxygen levels of less than 1 ppm. It is important that the encapsulation materials and processes are not over-engineered for a given end-use application. Therefore, three encapsulation architectures were investigated in the present work, namely 'partial', 'perforated' and 'complete' (Fig. 1), with the complexity of the encapsulation materials and protocols increasing in that order. Electrical contact with each module was made by soldering a connecting wire onto an exposed region of the Cu tape in direct contact with electrodes of the encapsulated module. These external electrical connections were located at the backside of the module and therefore received some physical protection from the elements.

2.1.1. 'Partial' encapsulation

Transfer adhesive films, including their paper release-layer, were laminated onto the 3M™ Ultra Barrier Solar Film layers. After removing the paper release-layer, the barrier encapsulant 3M™ Ultra Barrier Solar Film layers were laminated directly onto the printed OPV modules, with the back-encapsulant film being slightly narrower than the module in order to enable electrical contact directly with the modules (Fig. 1(a)). This arrangement resembles the encapsulation architecture reported by Krebs et al. [9,28].

2.1.2. 'Perforated' encapsulation

As illustrated in Fig. 1(b), a 3M™ Ultra Barrier Solar Film layer slightly larger than the printed OPV module was laminated onto the front and back sides of the module. Electrical contact to the module is via the Cu tape (thickness: ~50 μm) connected to the module using conducting adhesive, where a small perforation was punched into the back encapsulant film over the region of the Cu tape.

2.1.3. 'Complete' encapsulation

This encapsulation architecture, shown in Fig. 1(c), consists of 3M™ Ultra Barrier Solar Film barrier encapsulant layers laminated onto the front and back faces of the printed module, together with an edge-sealing tape to provide additional moisture barrier. Pre-cut EVA sheets having a thickness of ~100 μm were used as interlayers to bond the barrier films to the front and back sides of the module. Electrical contact to the module is via Cu tape connected to the module using conducting adhesive, and where the Cu tape passes through edge-sealing material to limit moisture entering through the regions around the electrical contacts.

2.2. Module stability analysis

2.2.1. Shelf-life testing

Encapsulated modules and non-encapsulated control modules were stored at ambient laboratory conditions with the modules also exposed continuously to ambient laboratory lighting. The ambient laboratory temperature and relative humidity were in the range 21 ± 5 °C and 50 ± 30%, respectively. Current density-voltage (J-V) characteristics of the devices were measured using a solar simulator equipped with an AM 1.5 filter (Newport Oriel) and a Keithley 2400 source meter. J-V measurements were carried out in the 0–3 V range with a 50 mV s^{-1} scan rate from forward bias to short-circuit.

2.2.2. Outdoor testing

Outdoor durability tests were carried out by installing sets of triplicate modules encapsulated using either the 'partial' or 'complete' encapsulation architectures on a purpose-built solar cell assessment rig (Fig. 2). Electrical contact with each module was made by soldering a connecting wire onto an exposed region of the Cu tape in direct contact with an electrode of the