Composites Part B 147 (2018) 69–75

Contents lists available at ScienceDirect

Composites Part B

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

Experimental investigation of the mechanical robustness of a commercial module and membrane-printed functional layers for flexible organic solar cells

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ARTICLE INFO

Keywords:
Photovoltaic
Organic solar cell
Membrane
ETFE
Mechanical
Electrical characterization

ABSTRACT

A coupled mechanical and electrical characterization method to monitor the correlation of organic photovoltaic (OPV) electrode resistance and cell performance upon tensile strain and to verify the cause of deterioration and the effect of OPV performance under tensile stress has been developed. Both a commercial OPV module and ethylene tetrafluoroethylene (ETFE) membrane-printed OPV electrode layers have been tested by applying the method. The encapsulation layer strength has been found to be the mechanical bottleneck of the tested commercial OPV module. The decrease in the transparent electrode conductance has been found to be responsible for cell degradation upon tensile strain, with the threshold tensile strain at approximately 2%. A test results comparison between ETFE- and polyethylene terephthalate (PET)-printed OPV layers demonstrated that ETFE-printed electrodes are less brittle and sensitive to tensile strain owing to the network pattern response of ETFE-printed electrodes. In addition, the adoption of Ag/poly(3,4-ethylenedioxythiophene) (PEDOT) layering can improve the tensile strain threshold to almost double to maintaining 80% of the initial normalized layer conductance through the advantage of its “bridging effect”. Collectively, our results provide valuable information and illustrate a promising future for architectural membrane printed OPV.

1. Introduction

Organic photovoltaics (OPV) is a promising alternative to established crystalline silicon-based photovoltaic technologies owing to its higher flexibility and lower capital cost investments [1–3]. In particular, the high solution processability of its active materials enables the adoption of mass printing methods to manufacture high volumes in an effective way.

However, almost all current research of flexible OPV is carried out on common plastic substrates (PET, PEN, etc.) with inferior performance for architectural integration. Existing commercial OPV modules also neglect the application requirements as building integrated photovoltaic (BIPV) elements. Both can highly hinder their future applications in buildings.

Meanwhile, novel membrane materials, especially ethylene tetrafluoroethylene (ETFE), enjoy higher popularity as substitutes for glass in the contemporary architecture context, thanks to their extraordinary lightness, high transparency and flexibility [4,5].

The research integration of both can therefore help with the commercial application and market development of OPV while enhancing the versatility of architectural membrane products. Nevertheless, the great potential of an architectural membrane as a novel OPV printing substrate, based on its high performance properties, has never been explored.

This survey first explores the feasibility and applicability of OPV in the flexible architectural membrane integration scenarios. Because the membrane, the applied printing substrate of flexible PV in mainstream membrane products/structures (tensioned, pneumatic), is subjected to tensile stress through the application, the primary consideration of this integration scenario therefore becomes the strength and photovoltaic performance of the OPV layer/module under stress.

This study devised a novel experimental methodology based on coupled electrical characterization and uniaxial tensile tests to examine the mechanical robustness and electrical manifestations of membrane-integrated OPV upon stress.

In this research, the performance of an existing commercial OPV

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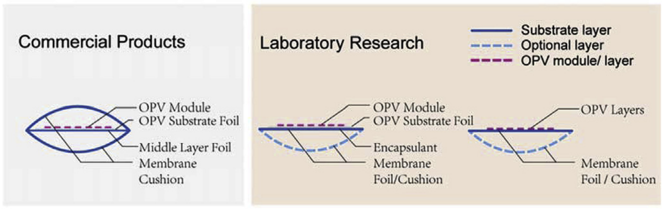
https://doi.org/10.1016/j.compositesb.2018.04.007
Received 25 May 2016; Received in revised form 14 August 2016; Accepted 3 April 2018



(a) (b) (c)

Fig. 1. Three strategies for membrane integrated flexible solar cells: (a) Mechanical integration; (b) Lamination; (c) Direct printing.

module under tensile stress is first reported to confirm its decay process and bottleneck limit of mechanical strength and electrical properties. Afterwards, this work uses the same method to examine the performance of functional OPV layers printed on an ETFE substrate under stress to explore the feasibility of architectural ETFE membrane-printed OPV layers, which can provide valuable knowledge for subsequent full OPV module printing on the ETFE membrane.

2. State of the art

Current OPV research has long focused on improving the power conversion efficiency and operational lifetime of the cell, whereas far less effort has been spent to optimize its integration for flexible building product development (and corresponding product performance).

Within the limited available research works concerning the OPV and even flexible PV integration onto/into architectural membrane foils/cushions, there are currently three main integration strategies (Fig. 1).

The first is to mechanically integrate flexible PV modules inside a cushion made of two or three membrane layers, with the edge fixed by either a mechanical or welding method (Fig. 1a). The embodied OPV module could be placed in either the upper or lower cavity.

An alternative process is to laminate the flexible PV module onto the membrane foil (Fig. 1b). This can be realized with suitable adhesive that can provide sufficient adhesion strength between the flexible PV module substrate and the membrane foil.

The most promising integration strategy is the direct printing of OPV modules onto the substrate foil, resulting in either single-layer membrane foil or integrated membrane cushion BIPV products (Fig. 1c).

All integration strategies require the incorporation of membrane substrate and functional OPV layers with distinct mechanical properties to form a composite product. Therefore, the mechanical properties of the OPV module and membrane, as well as their performance synergy, deserve investigation in detail. Meanwhile, the cell performance, with the functional layer in the condition of operational stress as integrated onto construction membranes, also must be verified. Both of the research topics lack relevant study.

To date, only limited work has been performed to understand the mechanical behaviour and electrical response under stress of OPV itself, and little has been reported about architectural membrane integrated OPV.

X. Chen and his co-workers investigated the mechanical behaviour of a commercially available OPV product from Konarka Technologies, Inc. through tensile testing [6,7]. With a uniaxial experiment, they obtained the nominal stress–strain curves for the full cell packaging and the individual layers, recorded the fracture sequence of each layer through the test, and showed that the two electrodes present in the stack are the short slab of the cell performance.

V. Brand et al. investigated the film stresses developed in polymer films and metal electrodes of P3HT and PCBM based bulk heterojunction organic solar cells [8]. They quantified the compressive stress in the PEDOT:PSS and Al electrode as well as the tensile stress in the BHJ layer. They also analysed the relationship between the deposition rate with the film stresses and cohesion among different layers. However, the effect of the stress on the layer and device performance has not been studied.

D. R. Cairns and his co-workers [9] noted the trade-off between thick layers of ITO to reduce resistivity and thin layers of ITO, which can withstand greater strain in the substrate.

Darren J. Lipomi and his group evaluated several different conjugated polymers with an effort to achieve a mechanically robust and intrinsically stretchable OPV [10–12]. They demonstrated the different responses upon tensile loads of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), poly-3-hexyl thiophene: phenyl-C61-butyric acid methyl ester (P3HT:PCBM), diketo pyrrolo-pyrrole moiety, thiophene, thienothiophene, and thiophene: phenyl-C61-butyric acid methyl ester (DPPT-TT:PCBM) fabricated on stretchable polydimethylsiloxane (PDMS) substrates. They also explored the crack and bulking effect through tensile tests, which are in favour of reversible stretchability. They have also investigated overall the stretchable, elastic and self-healing materials for OPV and electronic skins [13,14].

Toward the same endeavour, Kaltenbrunner, M et al. developed ultrathin and lightweight organic solar cells with high flexibility. They investigated the performance of their cells under extreme mechanical deformation and cyclic stretching tests. The performance of the tested solar cells was found to be able to withstand extreme mechanical deformations [15].

K. Leppanen et al. also studied the flexibility limit of ITO through bending tests [16]. The critical bending curvature and the correlation between the material conductivity and crack numbers were revealed.

However, the characterization of architectural membrane-printed OPV or its functional layers has not yet been started because no such cell structure has been fabricated. Even less work has been initialized with the mechanical flexibility of commercial polymer-printed OPV or its layers.

C. K. Cho, with his co-workers investigated the mechanical integrity of gravure printed PEDOT:PSS electrodes on the PET substrate through both bending and stretching tests [17]. They demonstrated that PEDOT:PSS film has superior stretchability relative to ITO electrodes. The same work group also tested the flexibility of a Ag nanowire (NW) network coated on a colourless polyimide CPI substrate peeled from a CPI/glass substrate sample [18]. The reported results also showed the higher flexibility of Ag NW over the ITO electrode. More recently, they tested the superior mechanical flexibility of transparent carbon nanotube (CNT) network electrodes prepared by a brush-painting method on PET for organic solar cells.

J. G. Tait et al. performed similar work to demonstrate that spray-coated PEDOT:PSS electrodes were able to withstand far greater mechanical deformation before failure than their ITO-based counterparts [19].

A. Iwan et al. further confirmed that ITO layers on PET foils are unsuitable for dynamic bending work conditions [20].

Meanwhile, S. Savagatrup et al. announced that P3HpT is an attractive potential replacement for P3HT in flexible, stretchable, and mechanically robust solar cells, as determined through tensile modulus comparison with P3HT and P3OT [21].

Some similar work has been performed with printed organic thin-film transistor (TFT)/light-emitting diodes (LEDs) or their electrode layers.

T. Sekine and his research group validated the adhesiveness importance of printed Ag electrodes on flexible plastic substrate for the mechanical durability and real performance of organic TFTs [22].

Z. Yu et al. developed and examined a highly stretchable electrode based on a carbon nanotube–polymer composite for their polymer light-emitting diodes [23]. The highly transparent electrode can be reversibly stretched by up to 50% strain with little change in sheet resistance.

Meanwhile, some research works have studied the performance response upon strain of amorphous silicon (a-si) solar cells and TFTs integrated on flexible substrates.