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Interlaboratory outdoor stability studies of flexible roll-to-roll coated organic photovoltaic modules: Stability over 10,000 h

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ABSTRACT

This work attempts to reveal the comparability issues related to outdoor testing procedures of organic photovoltaic (OPV) modules via studies of inter-laboratory long-term outdoor measurements of roll-to-roll coated flexible OPV modules (P3HT:PCBM, inverted architecture) in different geographic locations from both Southern and Northern hemispheres. The interpretation of the module degradation via sub-cell analyses is presented and the poor reproducibility of the module performance linked to the barrier properties of the encapsulation around the device terminals is addressed. We demonstrate that the modules' t_{80} lifetime may vary between a few hundred to over 10,000 h depending on how well the device terminals are sealed. We additionally demonstrate up to 17 months of stable performance for sub-cells within the modules. Furthermore, the effects of different geographical locations, weather conditions and measurement setups on the comparability of test results are analyzed. A strong link between the device temperature and performance is revealed, which is ascribed to the reaction of PEDOT:PSS layer with water. The estimation of the true performance of the modules by accommodation of variations in testing conditions is performed. Based on the results a set of recommendations from the ISOS-O guiding protocols are highlighted, which can help remove the factors that affect the comparability of the test results.

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1. Introduction

The field of organic photovoltaics (OPVs) continuously shows successful achievements not only in the photoconversion efficiency (PCE), but in recent years also in stability and large scale production [1]. As a result, OPVs are gradually entering the stage of industrialization. One of the issues hampering this process is the lack of standard protocols for testing and qualification of durability of OPV products. The aim of a standard protocol is to uncover the already known degradation or failure mechanisms of the product in the intended environment [2] and any such protocol is tailored to only address a certain set of degradation and failure mechanisms for certain type of products. Due to the multitude of degradation processes taking place in typical OPV devices [3] it is rather challenging to develop such rigid standards for OPV technology. The situation is additionally made complex due to the continuous developments of new materials and product designs used in OPVs, which introduce new degradation modes forcing constant readjustments in the testing procedures. This is especially reflected on accelerated aging experiments, where excessive amounts of stresses are applied on the specimen to accelerate certain degradation mechanisms followed by estimation of the real time performance using the acceleration factors [4–7]. Employing such an accelerated test for OPVs requires first understanding the degradation modes in the device during operation under real conditions [8,9]. The issue of standard testing protocols

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has been in constant focus of the working groups at the International Symposiums on OPV Stability (ISOS) in the past few years and as a result a set of ISOS guidelines for testing OPV device stability were published in 2011 [10]. These are expected to improve the comparability of OPV device stability testing and fortify the work towards establishing rigid standards for durability testing of OPVs.

Due to the lack of standard protocols, various custom procedures for measuring device stability have been employed throughout the history of OPVs. While this has generated field data and experience, which can aid in establishing standard testing protocols, the greatest drawback of the results is the poor comparability [11]. One of the most challenging tests in that regard is the outdoor exposure. While it is the most relevant in a sense that the testing is performed in an environment, where most of the OPV products will eventually be operating, the behavior of OPVs during outdoor testing is greatly affected by the dynamic nature of the testing environment, as has been shown earlier [11–13]. Since the testing conditions are constantly varying (daily and seasonal variations), it is hard to define whether the sample performance changes are caused by the variations in the conditions or by the inherent processes inside the samples. If this differentiation is not performed then the reported device lifetime will contain the imprint of the testing conditions defined by the season and location of the testing, questioning the comparability of the results.

The presented work addresses this issue by analyzing the measurements of OPV modules during long term outdoor exposure (more than 17 months) in six different geographic locations, which have been performed based on the recommendations of the earlier reported interlaboratory studies [11] and ISOS guiding protocols [10].

2. Experimental

2.1. Module preparation

As a part of the ISOS-3 workshops held in October 2010 at DTU (Denmark) roll-to-roll coated flexible modules based on serially connected solar cells of inverted device architecture with P3HT:PCBM active layer sandwiched between ITO/ZnOx and PEDOT:PSS/Ag-paste electrodes were produced according to *process one* described elsewhere [14]. PEDOT:PSS was purchased from Agfa (Orgacon EL-P 5010). Fig. 1 illustrates the module from the top and a cross section. The active layer pattern consisted of 16 serially connected solar cells with total active area of ~35.5 cm^2. The module encapsulation was performed using a UV filter/barrier (Amcor) with a pressure sensitive adhesive (467 MPF, 3M). The barrier performance was <0.01 cm^3 m^{-2} bar^{-1} day^{-1} with respect to oxygen (measured according to ASTM D 3985-81) and 0.04 g m^{-2} day^{-1} with respect to water vapor (measured according to ASTM F 372-78). The barrier foil thickness was 55 μm. The difference from the previously reported interlaboratory studies [11] was that an additional layer of barrier was applied in this case covering the entire module, as seen in Fig. 1, while only active area sealing was performed with electrodes exposed in the earlier studies. Such procedures significantly improve the stability of the modules, as was recently demonstrated for the same type of devices in another study [15]. Cu tape (3M) was applied to the terminals before the second encapsulation and metal snap fasteners were then applied onto the Cu tape over the barrier layer to create an electrical access to the module. A Hamamatsu photodiode was mounted on the modules for reference measurements.

2.2. Module measurements

The modules were distributed to 6 laboratories in 4 countries on May 2011 for performing outdoor lifetime tests. The laboratories were chosen from the list of the participants of the earlier interlaboratory lifetime studies [11] and from the attendees of ISOS-3 conference, who were able and willing to perform long-term outdoor testing of OPV samples. During the time period between production and distribution, the modules were stored in dark in room environment (for about 8 months). Each laboratory received two OPV modules. Table 1 shows the list of the laboratories together with the geographic coordinates and types of outdoor platforms used for the measurements. The experiments were started in June 2011 corresponding to the winter season in Australia and summer in all other locations. The samples were kept at open circuit for the periods between the *I–V* tests performed in outdoor conditions under natural sunlight. The results were reported to the coordinating laboratory in Denmark. For the analyses of the results the short circuit current (I_{sc}) and maximum power (P_{max}) values were linearly adjusted to the standard irradiance level of 1000 W/m^2.

After 17 months from the start of the measurements the samples were shipped back to the laboratory of origin in Denmark, where the modules were further analyzed by testing the performance of the individual subcells in the modules. Needle-contacts were used to penetrate through the encapsulation in order to individually access each solar cell. The measurements were

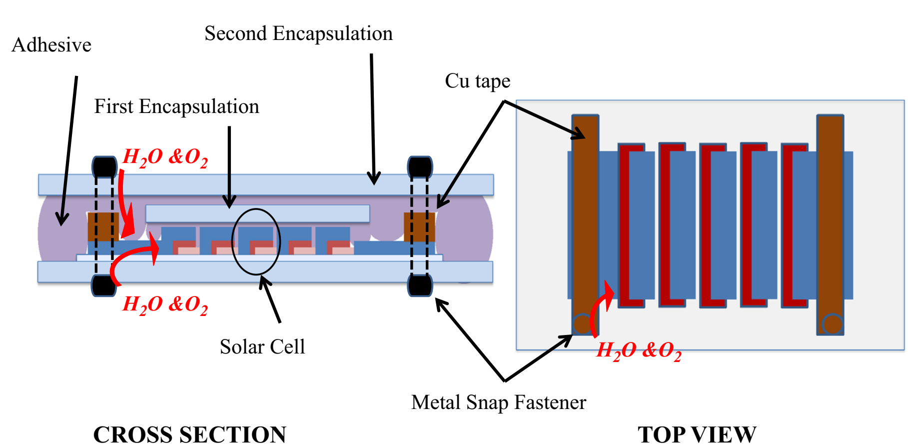

Fig. 1. Cross section (left) and top view (right) of the module outline illustrating the various components of the modules. The modules consist of 16 serially connected solar cells (the image illustrates only 5 solar cells for simplicity). Possible paths of H_2O and O_2 penetration are shown with red arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

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