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The use of polyurethane as encapsulating method for polymer solar cells—An inter laboratory study on outdoor stability in 8 countries

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ABSTRACT

A new encapsulation method for organic solar cells has been tested on flexible solar modules and cells embedded in polyurethane, sandwiched between a tempered glass plate and a polycarbonate plate. Panels, each containing 10 organic solar modules/cells, were fabricated and installed for outdoor exposure in eight different countries for 4½ months. In order to minimize potential deviations in procedures and equipment, one person was responsible for the fabrication, installation and initial and final *IV*-measurements of the panels using the same equipment for all measurements and calibrations. The encapsulated modules/cells showed significantly reduced degradation compared with previous studies, with final average efficiencies around 40% of the original after 4½ months outdoor exposure. Photodegradation was furthermore found not to be the primary source of degradation.

1. Introduction

Organic solar cells have in recent years seen great progress in lifetimes, reaching a level in stabilities where stability studies can be carried out in the more unpredictable outdoor conditions compared to the carefully controlled laboratory environment [1–4]. This calls for the development and testing of new methods on how to encapsulate the solar cells as they are still not stable enough to be left unprotected towards oxygen and water, which can diffuse freely within the organic solar cells causing them to degrade, if no measures are taken [5–7]. Katz et al. [2] performed an outdoor study in the Negev desert on organic solar cells on glass, sealed using glass fiber reinforced thermosetting epoxy (prepreg) by the procedure described by Krebs [8]. They found that the efficiency of P3HT/PCBM-cells dropped to approximately 10% after 32 day of outdoor exposure. An alternative approach was used by Hauch et al. [1], who used a transparent barrier film (WVTR rate of 0.03 g/(m^2 day) at 38 °C/100% rh) to encapsulate flexible P3HT:PCBM modules on PET. They experienced full retention and even a slight increase in efficiency after 14 months of outdoor rooftop exposure in Lowell, MA (USA), mainly due to an increase in the fill factor by 11%. Although an impressive result, changes clearly happens to the modules IV characteristics after exposing it to outdoor conditions, best illustrated by the final

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improved fill factor and by fact that the authors show that the power density increases to approximately 140% of the initial value within a few days. Unfortunately no comparison was made of the final efficiency and the efficiency of the module after reaching maximum power density.

In a recent inter-laboratory study by Gevorgyan et al. [4], flexible modules of P3HT:PCBM on PET were encapsulated by a barrier film from Amcor Flexibles and studied at different outdoor locations. Average efficiencies of approximately 40% of original were observed after approximately 1000 h (~42 day) of outdoor exposure.

As a final example, Medford et al. prepared large panels of P3HT/PCBM flexible modules in series, testing different encapsulation methods for outside conditions. The one that showed the best preservation properties involved pre-lamination of the freshly prepared cells with a ~100 μm thick PET gas barrier layer from Amcor Flexibles with a ~50 μm pressure-sensitive acrylic adhesive, which were further laminated between a 4 mm tempered glass window and black Tetlar foil, using two sheets of 0.5 mm thick ethylene vinyl acetate (EVA), which was heated to 150 °C for 30 min causing the EVA to liquefy. The panel having an active area of 9180 cm^2 showed 54% of the original efficiency after 6 months outdoor exposure. Also Krebs [9] has performed 'hot lamination' in the encapsulation of indium–tin-oxide free cells using EVA, but no outdoor test was performed.

When testing an encapsulant, properties like moisture ingress from the edges, adhesion at the interfaces and diffusion temperature dependence might influence the outcome [10,11]. In order to fully test the properties of an encapsulation method it is thus desirable to perform the experiment at a multitude of locations that differs in whether condition (ambient temperature, fluctuations in ambient temperature, humidity, hours of sunlight, etc.). This can be done by round robins (RR) and inter-laboratory studies (ILS), which are important and useful methods to reach consensus of solar cells properties and establishing standard procedures for their characterization. Previously performed RR and ILS [4,12], where organic solar cells were shipped to different locations to be mounted and measured, have shown that potential problems are related to this approach. First of all different people approach an assignment in different ways, and involving many persons often results in deviations from proscribed procedures—as the old proverb goes, "too many cooks spoils the broth". Just as important, different laboratories generally tend to have different types of equipment at their disposal, which makes it difficult to compare results afterwards. Ideally such studies should be performed by a single person to ensure that everything is done as similar as possible, using the same measuring equipment to rule out deviations.

We here present the use of polyurethane as encapsulation method in a study performed in 8 different countries, where one person has been responsible for the preparation and outdoor mounting of 8 panels, each containing 10 roll-to-roll processed polymer solar modules and solar cells encapsulated in polyurethane. The same person furthermore measured all cells after manufacturing of the panels at Risø DTU, at each test site before installing the panels, at each test site after a period of approximately 4½ months and finally again at Risø DTU after having taken down the panels and shipping them back. All measurements were done with the same equipment and the same reference for the measured light intensity was employed in all cases. In order to monitor the cells during the 4½ month period local personnel at each site performed continuous outdoor measurements of the short circuit current (I_{SC}) and the open circuit voltage (V_{OC}). The test site locations involved (shown in Fig. 1) were: Patras (by the Mediterranean Sea in Greece), Sede Boker (in the Negev desert of Israel), Barcelona (by the Mediterranean Sea in Spain), Petten (by the North sea in the Netherlands) Clermont-Ferrand (inland in the mountainous Massif Central in France), London (inland in the southern United Kingdom), Freiburg (inland in south west of Germany) and, finally Risø DTU in Roskilde (by a fjord in Denmark). The locations were chosen for their different geographical locations and diverse local weather conditions that differ on parameters that could have an influence on the outdoor stability, such as amount of sunlight, ambient temperature, moisture and amount of salt in the air. All preparations of the panels as well as initial and final measurements were performed at Risø DTU.

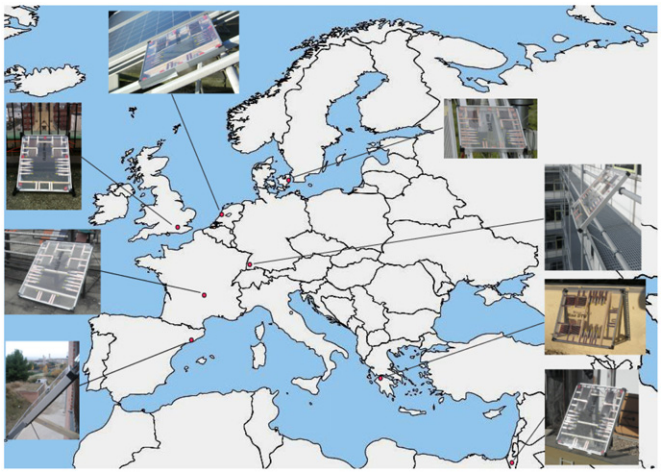

Fig. 1. Map showing the geographical locations of the mounted panels.

2. Experimental procedures and methodology

2.1. Types of cells used

The polymer solar modules and cells used in the study consisted of four types of geometries (see Fig. 2) and four types of active material inks. All were prepared with an inverted geometry on indium tin oxide (ITO) patterned PET substrates (PET|ITO|ZnO|active layer|PEDOT|Ag) using roll-to-roll (R2R) slot die coating for all layers except for the silver, which was screen printed using UV-curable silver paste [13]. The detailed procedures of manufacture have previously been published [14,15].

Each panel contained ten modules/single cells. Module **1–3** were P3HT:PCBM modules consisting of 16 cells in series with an active area of 35.5 cm^2 differing only in the geometry of the silver back electrode used. For module **1** a simple busbar was used, just connecting the ITO of one cell with the PEDOT of the next to make the series connection, but leaving the main part of the PEDOT uncovered. In module **2** the connecting busbar was supplied with a silver grid, in order to facilitate charge collection, and finally in module **3** the silver fully covered the part of the PEDOT that was over the active area.

Module **4** had the same geometry as module **1** but was prepared using the commercial ink PV2000 from Plextronics. The cells **5–10** were all single cells with an active area of 4.2 cm^2 and a grid patterned silver back electrode. In cells **5–8** the polymer employed was polymer **A** (see Fig. 3) and in cell **9** and **10** polymer **B** was used (Additional information on polymer **A** and **B** can be found in the supporting information).

All modules were prepared during a workshop in relation with the ISOS3 conference held at Risø in October 2010. The single cells were prepared just before assembling the panels in November 2010.