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A round robin study of polymer solar cells and small modules across China

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ABSTRACT

A round robin study across 15 laboratories in China was carried out using single junction devices with an active area of 1 cm^2 and differently sized small module with an active area of 20 and 24 cm^2 respectively. The devices represented the state of the art in terms of processing as they did not employ indium or vacuum and were prepared using only printing and coating techniques on flexible substrates. The devices were studied in their flexible form and thus approach the vision of what the polymer solar cell is. The main purpose of the work was to establish and chart geographic and cultural differences in what constitutes a competent *IV*-characterization procedure and also to establish the spread in measured data across the globe. The main finding is that efficiency data deviated up to 30% from the mean while an overall relative standard deviation of 12% was observed. Collating this spread with previous findings points toward a seemingly region-independent i.e. global observation of the uncertainty in the *IV*-characterization of a polymer solar cell. Finally, we highlight what might be done to improve the accuracy of the reported data.

1. Introduction

Organic photovoltaics (OPV), using either polymers [1] or oligomers [2] as light absorbing material, have now convincingly

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peaked beyond 10% power conversion efficiency (PCE) [3–5]. At the same time roll-to-roll (R2R) fabrication schemes have evolved toward encompassing true scalability, from gadgets to bulk energy production [6–9]. However, the average laboratory efficiencies, be it for either small area OPV prepared by spin coating or large area OPV prepared via R2R coating and printing methods, are still lacking significantly behind the record numbers. This has been shown neatly by Dang et al., taking a bird's eye view of selected data for the all-time favorite P3HT-PCBM blend system [10]. Thus it might seem a fact of life within the field of OPV that reproducibility is relatively poor. Two distinct factors can be said to contribute to this apparent reproducibility challenge: One is intrinsically inherent to the OPV device, coming from the myriad of parameters entering into the fabrication procedure as well as the synthesis of the materials composing the device. These variations are in a sense hidden variables due to a systematic neglect of statistics when presenting OPV efficiency data, as the current habit is that only the "hero" device is presented. The extent of the spread, however, becomes quite obvious when large PV data sets of similarly prepared devices are studied [11,12].

Another distinct factor which might be hampering the reproducibility can be said to be extrinsic. This extrinsic factor relates to the variations in the current–voltage (*IV*) characterization under simulated AM1.5G illumination conditions. Influential parameters on the extrinsic variability includes effects related to masking and defining the device active area [13], while also the type of solar simulator used, especially of course if the spectral mismatch factor is disregarded. But spectral variations might also have other unpredictable effects, depending on materials composition of interfacial layers and electrodes, such as the readily observed UV activation of ZnO [14–16]. While temporal variations in these extrinsic parameters might occur within each laboratory, the most significant variation must be inter-laboratory.

Perhaps the best way to investigate the inter-laboratory variations is through so-called round robin (RR) studies, where the same devices are measured in many laboratories. Where only a few exists for OPV [15,17], it is a technique often used within the field of inorganic PV [18–20].

In this study we employ the RR methodology to investigate the inter-laboratory variations among 14 laboratories in China and one laboratory in Denmark where the devices, a set of all roll-to-roll (R2R) -coated and -printed ITO-free devices, were fabricated [7,21]. As the number of publications on OPV coming from China today is among the highest for any country, this geographical boundary condition was an obvious choice as the high density of OPV laboratories enabled one operator to travel between each of the participating labs, ensuring that the measurements were conducted as similarly as possible, while keeping the total time of the experiment as low as possible, in order to minimize the effects of device degradation and failure.

2. Experimental

2.1. PV device preparation

The devices were prepared by R2R following the process earlier reported as "IOne" [7,21], and were based on a flexible ITO-free substrate (Flextrode [8]), upon which the inverted solar cell stack was completed, so that the entire stack was PET/Ag/PEDOT:PSS/ZnO/P3HT:PCBM/PEDOT:PSS/Ag. As shown in the schematic in Fig. 1, the devices consisted of serially connected stripes each with an active width of 1 cm. The devices were manually cut from the roll of solar cells, in three different sizes according to Table 1 and Fig. 2. Then each contact was reinforced by Cu tape. The devices were encapsulated; by manual placement of the device between two sheets of flexible Amcor® barrier foil applied with a UV-curable adhesive (DELO® LP655), then passing each device through the nip of a R2R machine ($<0.5\ \mathrm{m\ min^{-1}}$) enabling a homogeneous adhesive layer, and finally curing the devices under a UV-intense solar simulator for 5 min on each side. Electrical contacting through the encapsulation was made using nickel free button contacts [22]. Examples of the three types of final devices can be seen in Fig. 2.

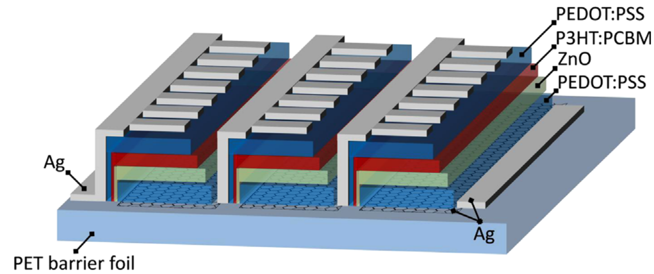

Fig. 1. A schematic drawing of the PV module stack used in this study. Three stripes in series are shown here.

Table 1
Relevant parameters of the three device types.

Device type	No. of stripes	Nom. active area (cm^2)	Cell outline
a	4	20	5-by-5 cm
b	4	24	5-by-6 cm
c	1	1	1-by-1 cm

2.2. Participating laboratories

The RR included 15 laboratories, 14 in China (one in Hong Kong), and DTU in Denmark. Details can be found in Table 2. Due to the nature of the study, all PV data will be presented anonymously.

2.3. The round robin procedure

The RR cycle was as follows: The devices were, once prepared, initially characterized at the OPV characterization lab (CLOP) at DTU. Next they were transported to China, where an operator brought them between laboratories by means of both land and air travel. At each laboratory, all the RR devices were tested according to a simple measurement protocol:

1. Each device is *IV* measured initially, keeping the illuminated time before measuring to a minimum.
2. A dark *IV* measurement is then performed.
3. The device is left under illumination for 5 min, and then a second *IV* measurement is performed
4. Followed by a final dark measurement.

Additionally, the spectrum of the solar simulator was recorded using a spectrometer (Avantes AvaSpec-3648).

At some laboratories, the size of the solar simulator only permitted correct measurement of the smaller sized **c-type** devices. The cycle was as shown in Table 3.

2.4. Long-term stability

At some laboratories a sub-study was carried out, designed to ascertain the long-term stability of the type of devices used in the RR. These laboratories have been highlighted in Table 2. In the experiments, one device was kept outdoors without exposure to