Ageing of organic photovoltaic devices in Benin environment (South-Sudanese climate)

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ABSTRACT

This study compares the ageing processes of standard P3HT:PCBM bulk heterojunction solar cells upon exposure to a temperate (Belgium) and an equatorial (Benin) climate. Differences in degradation of non-encapsulated systems are attributed to humidity differences between the European and African environments. The decrease in the power efficiency is shown to be related to two processes: degradation of the optical absorption and charge transport in the active layer. The decrease of the absorption can be further accelerated upon light exposure. Rigid encapsulation tackles efficiently the degradation process under both climates. Devices fabricated in air yield almost similar performances that those fabricated in N_2, confirming that the fabrication process can be carried out in simple environmental conditions. This supports the development of low-cost sustainable photovoltaic technologies in countries with limited economic resources but abundant solar radiation.

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1. Introduction

Organic photovoltaic devices (OPV) are receiving growing interest in recent years due to the main advantages they offer: the materials are often solution-processable, so that inexpensive devices can in principle be fabricated on large and flexible surfaces. This opens wide perspectives for photovoltaic applications with low cost and large scale processes [1–4]. The ability to ensure low manufacturing costs through fabrication processes in standard environmental conditions (i.e., at room temperature and in ambient atmosphere) is clearly an asset for expanding the implementation of photovoltaic technologies in areas with limited economic resources, like the tropical countries (such as Benin), in which energy dependence production is critical and harvesting solar power is of great interest, because of the availability of abundant solar radiation. Performances now reaching up to 10% [5] make OPV technologies quite appealing and further development is in particular focused on the need of increased stability and lifetime for the devices [6,7]. According to the international consensus of stability testing protocols for organic photovoltaic

materials and devices, basic procedures (level 1) require minimum instrumentation and protocol requirements likely to be fulfilled in most places. For conditioning and testing in tropical countries, the ambient conditions are defined as 25 °C and 65% for the testing temperature and relative humidity (RH), respectively, according to ISO 291(2008): Plastics–Standard atmospheres. Electrical characterization for the determination of the power conversion of the devices simply requires a calibrated solar simulator. Temperature and RH can be ambient. Similar conditions are applied for laboratory weathering testing protocols [8].

In this context, this work is dedicated to the study of the degradation of standard poly(3-hexylthiophene): phenyl-C_{61}-butyric acid methyl ester (P3HT:PCBM)-based bulk-heterojunction OPVs in different climatic environments, through a collaboration between the University of Abomey-Calavi, Benin, and the University of Mons, Belgium, in order to assess the possibility of low-cost manufacturing processes in emerging countries. This paper aims therefore at analyzing the influence of the environmental conditions on the fabrication process, the device performances and the degradation mechanisms. Furthermore this work lies within current global approaches to sustain the lighting market in developing countries, with projects such as a prototype of the polymer solar lamp tested in Zambia with Lighting Africa Project [9], as a collaboration between the International Finance Corporation (IFC) and the International Bank for the Rebuilding and Development

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(IBRD), or IndiGo© initiated by Eight 19 as an affordable solar lighting and battery charging system [10] targeting the supply of low cost renewable energy to off-grid communities.

2. Experimental

The fabrication process of the devices is standard and has been carried out only in Belgium. Patterned ITO-coated glass substrates are cleaned by sonication steps in deionized water, acetone and isopropanol consecutively. Subsequently PEDOTS:PSS is spin coated to yield ~40 nm thick films. Samples are then annealed at 100 °C for 60 min to get rid of the remaining solvent. The 1:0.7 P3HT:PCBM active layer is obtained by spin coating a solution of chlorobenzene ($C_{P3HT} \approx 12.5$ g L^{-1}) to yield 100 nm thick films, in air for air-fabricated cells and in a glovebox for N$_2$-fabricated cells. The device fabrication is completed with thermal evaporation (200 nm) of an Yb/Al cathode. Annealing at 150 °C for 10 min is finally performed in the same environment (air or N$_2$) as the fabrication process. In Belgium, the current density–voltage (J–V) characteristics of the devices are obtained using a computer-controlled Keithley 2400 under a standard 1 sun illumination (100 mW cm^{-2}) provided by a ABET solar simulator equipped with an AM 1.5 filter and calibrated by a power source meter (Laser point model Plus SN 600540). In Benin, the J–V characteristics of the devices are measured using a computer-controlled Keithley 2700 under 1 sun illumination provided by a halogen tungsten lamp (500 W) with a broad continuous spectrum in the visible and IR range and initially calibrated with the same power source meter as used in Belgium.

Samples are then exposed to air and ambient light for increasing periods of time, to investigate the contribution of O$_2$, H$_2$O and light to the degradation mechanisms. UV–vis absorption spectra are recorded at different ageing times with a Perkin Elmer lambda 6505 spectrometer. Rigid encapsulation is obtained by applying a glass plate over the devices, with a resin (Nagase Chemtex Corporation) that is crosslinked upon 10 min UV exposure.

3. Results and discussion

3.1. Influence of the fabrication environment

Fig. 1 shows the typical J–V profiles recorded in the dark and upon illumination for two representative devices fabricated in N$_2$ and air environment, respectively. The average performances based on sets of eight devices and measured directly after fabrication are given in Table 1.
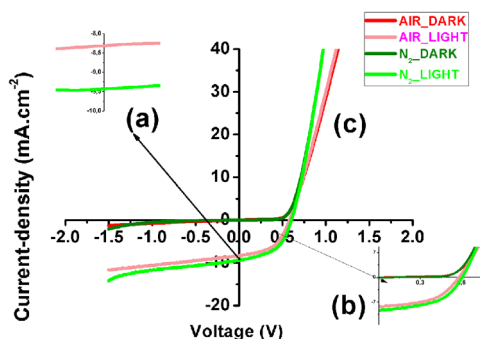
Fig. 1. Typical current density–voltage profile of 1:0.7 P3HT:PCBM solar cells fabricated in air (red) and N$_2$ (green) measured in the dark (deep color) and upon illumination (light color). Insets: influence of the fabrication environment on (a) the photocurrent; (b) the open-circuit voltage and the fill factor and (c) influence of the fabrication environment on the series resistance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Power conversion efficiencies (η) up to 2.5% and 3.1% are obtained for devices fabricated in air and N$_2$, respectively. This difference is relatively small (~20%) and indicates that a fabrication protocol in air is suitable for yielding acceptable performances, both for degradation studies and in the prospect of applications.

The data in Table 1 indicate that the differences between the efficiencies are related to a decrease of the short-circuit current density (J_{SC}) and an increase of the series resistance ($R_S A$) when changing the fabrication environment from N$_2$ to air. The open-circuit voltage (V_{OC}), the parallel resistance ($R_P A$) and the fill factor (FF) remain similar for both sets of devices.

J_{SC} depends both on the absorption of photons and the charge transport properties in the active layer. The 20% decrease of J_{SC} values observed from N$_2$ to air environment is therefore to be attributed to changes in these processes once the P3HT:PCBM active layer is exposed to air. Fig. 2 shows the absorption spectra of P3HT:PCBM films deposited either in N$_2$ (green) or air (red). The spectra recorded directly after deposition (full lines) are similar for both fabrication environments. The differences between the two spectra lie within $\pm$3% over the spectral range (400–900 nm). This suggests that the air exposure during fabrication does not affect the absorption of photons. The ~20% difference in J_{SC} values is therefore likely to be related to charge transport mechanisms. From Table 1, $R_S A$ is also shown to increase by about 50% from N$_2$ to air environment. $R_S A$ is solely related to charge transport processes in the device. These processes are shown to depend on the chemical structure of the materials, the mesoscopic morphological organization to form charge collection pathways and the electrical properties at the interfaces with the electrodes. As reported in literature, rapid chemical modifications of the P3HT:PCBM/Al interface can be observed once exposed to oxygen [11–13]. This oxidation of the interface is then likely to increase its resistance, hence to impact the device efficiency via both J_{SC} and $R_S A$. This mechanism is therefore expected to contribute to the observed decrease of J_{SC} and increase of $R_S A$. Quantitative analysis remains however difficult since the influence of the environment during the post-fabrication annealing must also be taken into account, as it significantly modifies the morphology of the blend. Let us notice that the influence of the fabrication environment is different for J_{SC} and $R_S A$: $R_S A$ increases by 50% whereas J_{SC} decreases by only 19% (Table 1). This can be related to the opposite directions of charge transport between the voltage ranges in which J_{SC} and $R_S A$ are measured. Depending on the voltage range, electrons (J_{SC}) or holes ($R_S A$) are collected at the P3HT:PCBM/Yb/Al interface. The chemical modifications upon air exposure can impact differently on the transport mechanism, depending on the nature of the charge collected.

3.2. Ageing in the dark

Fig. 3 compares the ageing of two sets of non-encapsulated devices fabricated either in N$_2$ or air, by examining the variations of J_{SC} and η over a 250 h period. The ageing process is passive, i.e. the samples are simply exposed to air in the dark at ambient temperature and humidity rate (48–59% in Belgium). Again, the samples fabricated in N$_2$ exhibit higher J_{SC} and η than those fabricated in air. J_{SC} and η decrease with time, indicating a degradation of the devices in those conditions. In contrast, but similarly to what observed at $t=0$ (Table 1), V_{OC}, $R_P A$ and FF remain constant whereas $R_S A$ is increasing for both sets of devices throughout the measurement period.

For devices fabricated in N$_2$, the η and J_{SC} values are reduced by about 8% and 5%, respectively, over 10 days while for those fabricated in air the corresponding reductions are only 4% and 1.2%, respectively. The degradation trend depicted on Fig. 3 can be explained on the basis of previous studies reporting about the existence of two stages in the degradation process: the first one