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Multilayer encapsulation of plastic photovoltaic devices

Pallavi Madakasira [a], Kanzan Inoue [a], Ross Ulbricht [a], Sergey B. Lee [a], M. Zhou [b], John P. Ferraris [b], Anvar A. Zakhidov [a,*]

[a] *Nanotech Institute, University of Texas at Dallas, Richardson, TX, USA*
[b] *Department of Chemistry, University of Texas at Dallas, Richardson, TX, USA*

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Abstract

We report the first results on conformal deposition of parylene on plastic solar cells, and study the effects of protection on performance characteristics of polymer solar cell. We show that single parylene coating layer is not a very effective barrier even for thicknesses as large as 10 μm. Our results support the experimental observations that the main degradation processes in poly(3-hexylthiophene) are the oxygen-assisted photochemical reactions, such as photobleaching and chain scission. Multilayer barriers made of parylene and aluminum oxide coatings are very promising for full protection of organic solar cell from degradation even under intense AM1.5 solar light.
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1. Introduction

The power conversion efficiency of organic solar cells has been improved dramatically since the introduction of the concepts of a bulk-heterojunction and bi-continuous interpenetrating network of acceptor and donor materials [1]. The optimal nanoscale phase separation of the donor and acceptor into a bi-continuous network is critical for the performance of solar cells because of the short exciton diffusion length (∼10 nm) in organic materials. In our earlier papers [2] we have demonstrated that high efficiency solar cell can be made by using home-made fresh regio-regular poly(3-hexylthiophene) (RR-P3HT). Four percent efficiency was achieved in optimally processed Al/P3HT + PCBM/PEDOT:PSS/ITO solar cells, as compared to ∼3.5% efficiency using the RR-P3HT from commercial sources (e.g. American Dye Source Co.). The effect of the solution homogenization time on the performance of the device was also reported. Long stirring of freshly synthesised P3HT without special purification creates a short circuit current (I_{sc}) increase from a typical range of ∼10 to ∼15–20 mA/cm^2, but the filling factor decreases from 0.6 to 0.4.

There are extensive studies of degradation processes in organic light-emitting diodes (OLED). Several encapsulation methods have been developed for protecting OLED on plastic substrates from moisture and oxygen in ambient air [3,4]. However, the intrinsic problem of plastic solar cell degradation in ambient atmosphere under intensive light illumination still remains. Encapsulation methods using multilayer oxygen and moisture barrier films for plastic solar cells must be developed for future commercial applications.

The degradation of polymeric device in air under intense solar light AM1.5 is caused by the degradation of π-conjugation due to a photosensitised reaction of singlet oxygen to the thienyl-diene conjugated system via a Diels–Alder addition [5]. This degradation leads to the reduction of conjugation length, and hence, to polymer photobleaching and decrease of charge carrier mobility [5,6]. Photo chain scission can even occur in the presence of trace amounts of metal catalysts [5].

The oxidation and delamination of the reactive metal cathode is also very important factor in fast degradation of polymeric devices in presence of moisture and oxygen [7].

The [6,6]-phenyl-C61 butyric acid methyl ester (PCBM) is stable if stored in the dark (or in amber bottle) under nitrogen. It has been shown in literature that the presence of oxygen (air) will greatly decompose the material over a period as short as 3 months. PCBM is usually stored in a glove box or sealed under

* Corresponding author. Tel.: +1 972 883 6218; fax: +1 972 883 6529.
E-mail address: zakhidov@utdallas.edu (A.A. Zakhidov).

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nitrogen. The polymer degradation occurs much faster than C_{60} and PCBM [8]. However, in the mixture the degradation of conjugated polymers is much slower due to fast electron transfer from polymer to PCBM and triplet formation quenching. Thus, the energy transfer from triplet state in polymer to ground state in oxygen with formation of singlet molecular oxygen which serves as a reactive intermediate in the polymer photoxidation is strongly suppressed [8]. Nevertheless, the stability of plastic solar cell still needs to be improved significantly.

In the present paper, we report the first results on conformal deposition of parylene on flexible solar cells, and study the effects of protection on characteristics of polymer solar cell. Parylene provides pin-hole free coating which is unexcelled for corrosion resistance and dielectric protection. We show that single parylene coating layer is not a very effective moisture and oxygen barrier. We, therefore, present the results on multilayer barrier coatings based on repeating sandwiches of parylene and aluminum oxide films.

2. Experimental

ITO-coated glass substrates, <15 Ω/sq with ∼85% light transmission, were obtained from Delta Technologies Limited. OLED-grade PEDOT-PSS was purchased from Bayer AG. Regio-regular P3HT was synthesised by the standard synthetic procedure of McCullough [9–11], changing only the amount of reagents (regio-regularity is typically ≥95% HT couplings). A lower outcome from the reaction was obtained, as compared to published data.

PCBM was purchased from American Dye Source. All materials were used as received without further purification. The current–voltage characteristics were recorded with a Keithley 236 source-measure unit. A calibrated solar simulator (Spectra-Physics) was used as the light source for solar cell efficiency measurements. We fabricated four devices on each substrate, each having an area of 9 mm^2. The ITO-coated glass substrate is etched and cleaned before being plasma-treated for 5 min (90 s for flexible substrates) in O_2 gas. A layer of PEDOT:PSS is then spin-coated onto the substrate at 6100 rpm creating a 30–35 nm layer. The sample is then dried by being heated at ∼120 °C for 100 min (60 min at 110 °C for flexible substrates) in a glove box. The photoactive material solution is dispersed by a magnetic stirrer for days until is determined to be the best condition. The solution is then spin-coated onto the sample at 700 rpm creating a 50–60 nm layer using a toluene solution consisting of roughly 1:2 ratios of PCBM and RR-P3HT, respectively. The final layer is made up of 65% RR-P3HT and 35% PCBM. An aluminium cathode is then deposited under high vacuum (<10^{-6} Torr) at an initial deposition rate of 0.4 Å/s and gradually increasing to 1.0 Å/s with a 450 s ramp time to create a final thickness of 1000 Å. The device structure is shown in Fig. 1. A thin 6 Å LiF layer is deposited prior to aluminium deposition for flexible devices. A surface profiler (AMBIOS XP-1) was used to measure film thickness. The finalized device is then annealed on a hot plate in a glove box at the desired temperature for the desired amount of time.

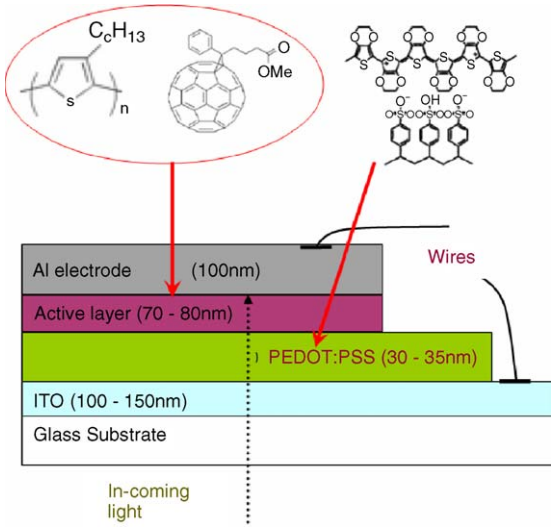

Fig. 1. Device structure.

Parylene coating is done in home-made chamber using Parylene C dimer from Specialty Coating Systems, Inc.

Magnetron sputtering of aluminium oxide is done at a pressure of 100 mTorr. The deposition process is turned on by setting the necessary parameters for oxygen and argon (8 and 48 mTorr, respectively). The power is set to 100 W. The ramp time is set to half a minute and the deposition time to 20 min. Using these settings, ∼350 Å thickness of aluminium oxide is deposited on the parylene-coated device.

All testing were done under clean room conditions in the presence of ambient oxygen and moisture.

3. Results and discussion

Fig. 2 shows the slight degradation of devices after keeping them in glove box for more than 12 h. Slight degradation occurs because testing of devices is done in ambient air. But strong degradation was observed after devices were moved out of glove box. The non-encapsulated devices are practically dead after about 8 h in air.

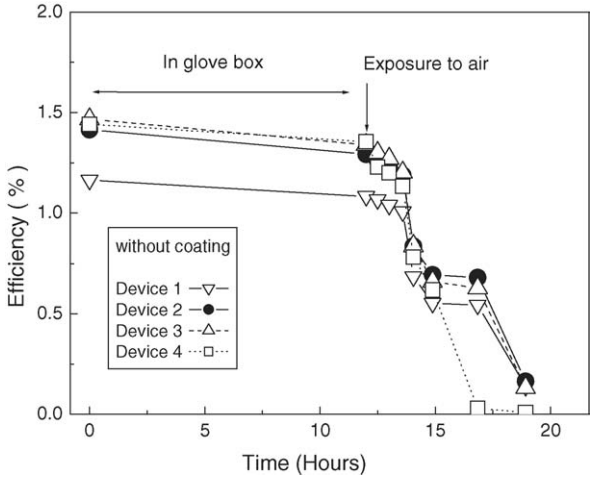

Fig. 2. Change of efficiency in unencapsulated solar cell in ambient conditions.

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