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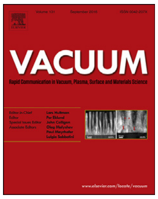

Fabricating high performance conventional and inverted polymer solar cells by spray coating in air

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ABSTRACT

We report bulk heterojunction organic solar cells utilising the electron-donating polymer PffBT4T-2OD blended with the fullerene acceptor $PC_{71}BM$, with cells explored based on both conventional and inverted architectures. As charge-transporting layers, we utilise the hole-transporting polymer poly (2, 3-dihydrothieno-1, 4-dioxin)-poly (styrenesulfonate) (PEDOT:PSS) in conventional device architectures, and zinc oxide (ZnO) electron-transport in inverted devices. Critically, all charge-transporting layers and the poly[(5,6-difluoro-2,1,3-benzothiadiazol-4,7-diyl)-alt- (3,3‴-di(2-octyldodecyl) 2,2’; 5′,2”; 5″,2‴ -quaterthiophen-5,5‴-diyl)] (PffBT4T-2OD): [6,6]-phenyl C71 butyric acid methyl ester ($PC_{71}BM$) active layer blend were spray coated in air. We demonstrate champion devices having a power conversion efficiency of 8.13% and 8.43% for conventional and inverted architectures respectively.

Organic photovoltaic devices (OPVs) represent a promising technology to convert solar energy to electricity, and can in principle be fabricated at low-cost on large area and flexible substrates [1–5]. In the past decade, the performance of OPVs has improved dramatically as a result of the development of new organic semiconductors and innovative processes for manufacture. Best devices now have a power conversion efficiency (PCE) exceeding 10% [6,7]; a value that has been considered as a milestone in the commercialisation of OPVs [8]. In order to advance the development of OPVs, it is still necessary to explore new, efficient semiconducting materials, together with innovative ways to fabricate devices.

Recently, a polymer namely PffBT4T-2OD has been synthesised and has attracted much interest [9,10]. When processed appropriately, PffBT4T-2OD:$PC_{71}BM$ blend films exhibit high crystallinity, high hole mobility and can form polymer domains having high purity; a combination of factors that allow this material to work in an efficient manner in an OPV device even when it is presented as a relatively thick layer (up to 300 nm). Using this material, OPVs have now been reported having a PCE up to 10.8% [10]. Although the efficiency is one of the highest yet reported for a polymer-based devices, the conditions used in thin-film deposition and device fabrication can influence the degree of polymer aggregation and crystallisation and thus can significantly affect device performance [9]. We note that the polymer PffBT4T-2OD has a tendency to aggregate in solution; a property that presents a significant obstacle during device fabrication.

Most reports of OPV fabrication using PffBT4T-2OD:$PC_{71}BM$ rely on the use of spin coating under a nitrogen atmosphere. Spin coating however cannot be used in a high volume fabrication process, and critically it is a wasteful process that requires the use of relatively high concentration solutions resulting in problems due to aggregation and loss of expensive material. In contrast, spray coating has been used in the fabrication of OPVs and is compatible with large area processing over flexible substrates [11–15]. Notably, most work on the development of spray cast OPVs have explored blend of the polymer poly (3-hexylthiophene) (P3HT) and (6, 6)-phenyl-C61 butyric acid methyl ester (PCBM). These materials are seen as being a prototypical OPV system, but are limited by relatively low PCE [16]. More recent work has however explored spray-cast blends of amorphous donor-acceptor co-polymers with fullerene-derivative electron acceptors, with improved device performance demonstrated [11,13,17,18].

Spray-coating has also been used to deposit the various charge transporting layers used in OPV devices [19]. In single junction OPV device based on a conventional architecture, the active layer is

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deposited onto a hole-transporting layer. Here, a widely used material is the polymer PEDOT:PSS which can be spray-cast from an aqueous solution in air [12]. In so-called inverted devices, the active-layer blend is instead deposited on an electron-transporting layer such as zinc oxide (ZnO). Here, ZnO can be easily processed from solution using a sol-gel method [20,21], with such materials also being compatible with deposition by spray coating [14,22]. We note that inverted devices can have significant advantages resulting from higher efficiencies and improved operational stability [23,24].

In this study, we fabricate PffBT4T:2OD:$PC_{71}BM$ based bulk heterojunction OPVs based on both conventional and inverted architectures. Here, the PffBT4T:2OD:$PC_{71}BM$ active layer, the PEDOT:PSS hole transport layer (HTL) and the ZnO electron transport layer (ETL) are all spray coated in air. By optimising the composition of the PffBT4T:2OD:$PC_{71}BM$ ink, conventional and inverted architecture OPVs were fabricated having champion efficiencies of 8.13% and 8.43% respectively.

The device architectures investigated in this work, together with the chemical structure of PffBT4T-2OD and $PC_{71}BM$ materials is shown in Fig. 1. Spray coating was conducted using a Prism 300 ultra-sonic spray coater (Ultrasonic Systems Inc.) that was operated in air under regular clean-room conditions with humidity of about 25%. This spray coater is a nozzle-less system, with the ultrasonic vibrating spray tip enabling the generation of a fine droplet mist; a crucial element in the creation of high-quality, uniform films [25]. To fabricate devices, our processes started with (20 mm × 15 mm) glass substrates coated with pre-patterned ITO electrodes (purchased from Ossila Ltd). Before use, the substrates were sequentially cleaned using an ultra-sonic bath containing Hellmanex solution, 2-propanol (IPA) and deionised water.

To prepare PEDOT:PSS ink for spray coating, PEDOT:PSS (Heraeus Clevios P VP AI 4083) was filtered through a 0.45 μm filter and then mixed with IPA and ethylene glycol (EG) according to a volume ratio of 1:8:1. Here, IPA and EG were used to tune the wetting property and viscosity of the ink to form a uniform film on the surface of the ITO [12]. During spray coating, the substrates were heated to 30 °C to facilitate the formation of a uniform film. During coating, a tip-substrate distance of 70 mm was maintained, with a lateral tip velocity of 80 mm/s used to create a film having a thickness of approximately 30 nm. The films deposited were then immediately annealed at 120 °C for 5 min before being ready for use.

The precursor gel used to fabricate the ZnO ETL was prepared by dissolving 110 mg zinc acetate dihydrate in 1 ml 2-methoxyethanol with 30 μl ethanolamine as stabiliser. The solution was then stirred for 12 h in air to form a transparent gel. Before spray coating, the resultant gel was diluted using methanol at a volume ratio of 1:8 to reduce its viscosity. For spray-coating, a tip-substrate distance was maintained at 45 mm, with a lateral tip velocity of 25 mm/s used to prepare films having a thickness of 25 nm. Here, films were sprayed onto substrates held at room temperature. The films were then annealed at 275 °C for 5 min to convert the precursor film to zinc oxide.

We have used an atomic force microscope (AFM) to evaluate the surface roughness of spray coated PEDOT:PSS and ZnO films as shown in Fig. 2. Here, parts (a) and (b) show spin- and spray-cast PEDOT:PSS, parts (c) and (d) shown spin- and spray-cast ZnO, whilst parts (e) and (f) show a spin- and spray cast PffBT4T-2OD:$PC_{71}BM$ blend. In these experiments, the films were spin/spray-cast onto a blank glass substrate.

We have used these images to assess the relative roughness of the films, and to compare films that have been spin- and spray cast. Comparing images (a) and (b) we determine a quadratic mean roughness (RMS) of spin-coated and spray-cast PEDOT:PSS to be 1.41 and 1.96 nm respectively. From images (c) and (d), we similarly find spin- and spray-cast ZnO have an RMS roughness of 1.16 and 1.35 nm respectively. We find therefore that the spray-cast charge extraction layers are in both cases slightly rougher than their spin-cast analogues, however we have previously found that such values are not detrimental OPV performance [13].

To coat the active layer, we prepared an ink consisting of 1:1.2 wt ratio of PffBT4T-2OD:$PC_{71}BM$ dissolved at 5 mg/ml into a mixture of the solvents chlorobenzene (CB) and 1, 2-dichlorobenzene (DCB) (volume ratio 1:1). The solvent mixture also contained a small (3%) volume concentration of 1, 8-diiodooctane (DIO) in order to optimise the micro nanostructure of the BHJ film [26,27]. Before use, the ink was stirred at 110 °C for 5 h to ensure the solids in the blend were fully solubilised. Notably, the relatively low concentration of solids used in this ink (formulated for spray-coating) effectively suppresses aggregation problems of PffBT4T-2OD that often occur in higher concentration solutions that have been optimized for spin-coating. The active

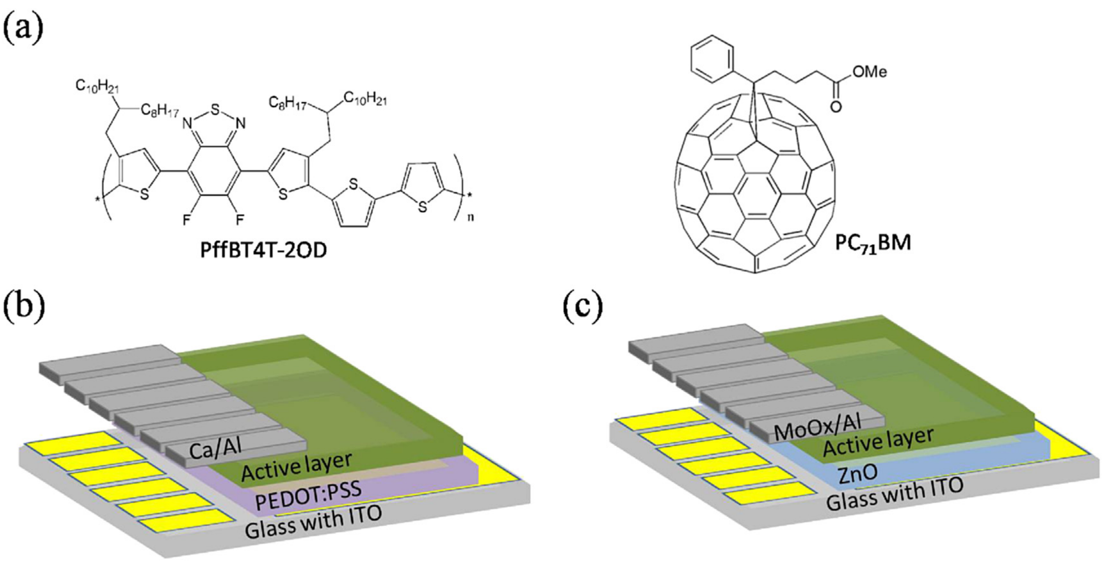

Fig. 1. (a) Molecular structure of PffBT4T-2OD and $PC_{71}BM$. Part (b) shows a conventional device, while part (c) shows an inverted OPV architecture.

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