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Review

Fabrication and processing of polymer solar cells: A review of printing and coating techniques

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ABSTRACT

Polymer solar cells are reviewed in the context of the processing techniques leading to complete devices. A distinction is made between the film-forming techniques that are used currently such as spincoating, doctor blading and casting and the, from a processing point of view, more desirable film-forming techniques such as slot-die coating, gravure coating, knife-over-edge coating, off-set coating, spray coating and printing techniques such as ink jet printing, pad printing and screen printing. The former are used almost exclusively and are not suited for high-volume production whereas the latter are highly suited, but little explored in the context of polymer solar cells. A further distinction is made between printing and coating when a film is formed. The entire process leading to polymer solar cells is broken down into the individual steps and the available techniques and materials for each step are described with focus on the particular advantages and disadvantages associated with each case.

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1. Introduction

Why polymer solar cells? As a technology polymer solar cells are unrivalled in terms of processing cost, processing speed, processing simplicity and thermal budget. It is the only photovoltaic technology that potentially offers a convincing solution to the problem of a high cost commonly encountered for photovoltaic technologies. There are, however, unsolved problems of low power conversion efficiency, poor operational stability, materials cost and environmental impact.

1.1. A short history

The field of polymer and organic solar cells has been the subject of reviews [1–20], special issues [21–27] and books [28–32] on several occasions during the past 5 years and the definitions of polymer solar cells are quite broad spanning all-polymer solar cells, polymer fullerene solar cells, small molecule and hybrid solar cells. By far the most successful of them are the polymer–fullerene solar cells that comprise a mixture of the polymer, which exclusively is the donor material and typically a soluble fullerene derivative as the acceptor material. While research on polymer and organic solar cells date back to the 1980s [2] the first example of a polymer solar cell with a convincing underlying understanding of the physics and chemistry is the bilayer heterojunction between the soluble polymer 2-methoxy-5-(2-ethylhexyloxy)-polyphenylenevinylene (MEHPPV) and the Buckminsterfullerene C_{60} [33,34] where a power conversion efficiency of 0.04% was obtained using monochromatic light. It is reasonable to define this report as the prototypical example of a polymer solar cell from which all modern polymer solar cells stem. The next convincing step was the application of a dispersed bulk heterojunction of MEHPPV and C_{60} [35] and later soluble derivatives of C_{60} [36–38], which increased the power conversion efficiency to 2.5%. The third step that represents the state of the art today is the exemplification of the interplay between the morphology reached by processing of the active layer and the function of the device which allowed efficiencies of up to around 5% to be reached for mixtures of poly-3-hexylthiophene (P3HT) and phenyl-C61-butyric acid methyl ester ([60]PCBM) [39,40]. A lot of original research has detailed methods for improving the function through physics and chemistry. The most important physical means for improving performance are the use of a thin layer of an insulator between the active layer and the low work function metal electrode [41] and more recently also in inverted devices [42], the use of optical spacers [43–45], the understanding of how the open circuit voltage is obtained [46] and by these means deriving an efficient method for predicting performance of materials combinations based on measurable materials properties [47] and finally the use of various mixing and annealing methods to control the morphology of the active layer [48]. It should be mentioned that the latter methods are not generic and generally should be viewed as materials specific. Thermal annealing is a good example that will work well for some material combinations, but not others. Sometimes even the same material gives different results as in the case of P3HT where regioregularity and molecular weight plays a crucial role [17]. In terms of chemistry work has focussed on improving the properties of both donor and acceptor material. For the polymers (the donor materials), which in many of the reported devices are responsible for the light harvesting there has been special focus on obtaining a low band gap such that as much of the available energy from the Sun is harvested [5,11,18]. Many materials with low band gap have been prepared and while band gaps as low as 0.5 eV has been prepared it is remarkably few of the low band gap polymers that give devices that rival those obtained from materials with a larger band gap. The most successful fullerene (the acceptor material) is the derivative known as [60]PCBM [36]. In spite of intensive research for better fullerene derivatives (which would be a review topic of its own) there has been no derivatives being as performing as [60]PCBM except perhaps for the more difficultly accessible [70]PCBM [49] and the recent Bis[60]PCBM [50].

1.2. State of the art

Most improvements have been found through materials such as P3HT and the fullerenes [60]PCBM and [70]PCBM that represent the state–of-the-art well from a materials point of view. In terms of device structure efforts have been relatively limited for various reasons. Firstly, there is a considerable drive towards achieving high power conversion efficiency and this implies small devices and a high conductivity of the electrodes. Since the back electrode for "hero" cells is typically an evaporated metal electrode the limiting electrode in terms of conductivity is the necessarily transparent front electrode. The best performing transparent electrode material that combines high transparency over a broad range of wavelengths and high electrical conductivity is indium tin oxide (ITO). From the point of view of processing polymer solar cells on a large scale there are several impossibilities connected to the use of ITO but for the purpose of breaking power conversion efficiency records there are few. The reason that nearly all reported devices with any significant power conversion efficiency are prepared on ITO covered glass substrates is understandable. This has severely limited the evolution of both device geometry and processing techniques.

The most significant step is undoubtedly the stacking of both the high and the low band gap materials into a tandem solar cell with the highest reported power conversion efficiency of 6.5% [51]. In Fig. 1 an example of a tandem solar cell structure is shown along with examples of high and low band gap materials [52]. The tandem solar cell is a pleasing concept that itself has been subject to some