Solar Energy Materials & Solar Cells 97 (2012) 83–88

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

High efficiency inverted polymeric bulk-heterojunction solar cells with hydrophilic conjugated polymers as cathode interlayer on ITO

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ARTICLE INFO

Available online 29 September 2011

Keywords:
Inverted solar cell
Hydrophilic conjugated polymer
Cathode interlayer polymer
Interface modification
Low band gap polycarbazole

ABSTRACT

In this work, alcohol-soluble 2,7-carbazole-1,4-phenylene copolymers PCP-NOH and PCP-EP, comprising surfactant-like diethanolamino and phosphonate end groups on the side chains, respectively, were utilized as cathode interlayer on ITO to construct inverted solar cells based on a low band gap poly(2,7-carbazole) (PCDTBT) as the polymer donor and [6,6]-phenyl C_{71}-butyric acid methyl ester ($PC_{71}BM$) as the acceptor. The work functions of ITO were shifted to −4.2 and −4.3 eV by PCP-NOH and PCP-EP, respectively, which can well match the LUMO level of $PC_{71}BM$ for good electron extraction. The power conversion efficiency (PCE) of the inverted solar cells without the cathode interlayer was only 1.63%, because of very low open-circuit voltage (V_{oc}, 0.48 V) and fill factor (FF, 36.9%). Using PCP-NOH and PCP-EP as cathode interlayers significantly improved V_{oc} to 0.88 V and FF to ~58%, giving PCEs of 5.39% and 5.48%, respectively. The increasing extents of PCEs by the interlayers are over 230%. The PCEs achieved by PCP-NOH and PCP-EP belong to the top device performances so far reported for the inverted PVCs with an organic cathode interlayer. Our results suggest that hydrophilic conjugated polymers are promising candidates as a cathode interlayer in high efficiency inverted solar cells through the modification of interface contacts.

1. Introduction

Polymeric photovoltaic cells (PVCs) have attracted considerable attention over the past several years due to their unique advantages of low cost, light weight, and great potential for realization of flexible and large area devices [1,2]. Typically, bulk heterojunction (BHJ) PVC, a promising device configuration for high power conversion efficiency (PCE), involves the use of a phase-separated blend of an electron-donating conjugated polymer and an electron-accepting fullerene derivative as the active layer [3–13]. In a typically conventional structure for BHJ PVCs, indium tin oxide (ITO)/poly (3,4-ethylenedioxythiophene:polystyrene sulfonate) (PEDOT:PSS) on a substrate works as the anode for hole collection while a deposited metal in vacuum is utilized as the cathode for electron collection. Recently, inverted BHJ PVCs with ITO as the cathode and a high work function metal as the anode have been demonstrated as a new device structure that can show higher device stability [14,15]. Tremendous efforts have been made for the development of electrode interlayers in the inverted PVCs so as to improve carrier collections at the anode and the cathode. MoO_3, V_2O_5, and PEDOT:PSS have been widely utilized as the anode interlayer [16–18]. Recently, CuO_x as the anode interlayer also exhibited good photovoltaic performance [19]. There are more approaches involving the development of cathode interlayer. Some inorganic interlayer materials on the ITO cathode, such as Cs_2CO_3 [16,20], metal oxides (ZnO, TiO_x, Al_2O_3) [18,21,22], metals (Ca, Mg, Al) [23,24], In_2S_3 [25], etc., have been studied and some of them can show good electron collection ability. Additional organic buffers on the metal oxide interlayer were also been reported [26,27].

Organic cathode interlayer materials, directed deposited on the ITO cathode, have also caught the attentions of researchers in the inverted PVCs. Vacuum-deposited small molecules [28], water-soluble poly(ethylene oxide) (PEO) [29], water-soluble cationic polythiophene polyelectrolyte modified PEDOT:PSS [30], alcohol-soluble conjugated polyfluorene polyelectrolyte with alkyl-amine salt on the side chains [31], self-propagating small molecule-based assemblies [32], and Langmuir–Blodgett (LB) deposited ferroelectric polymer [33] were proposed for the cathode interlayer materials, and the resulting poly(3-hexylthiophene) (P3HT)-based PVCs showed power conversion efficiencies (PCE) between 0.7% and 3.6%. Some of the organic interlayers showed remarkably improvements of open-circuit voltages (V_{oc}), thus power conversion efficiencies (PCE) of the inverted PVCs could be elevated [29,31–33].

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doi:10.1016/j.solmat.2011.09.030

An ideal organic interlayer needs a good adhesion capability to both ITO and the subsequently deposited active layer. Also the erosion of the organic interlayer by the solvent for deposition of the active layer should be greatly suppressed. An ideal organic interlayer should realize ohmic contact between the ITO cathode and the active layer.

Recently, hydrophilic conjugated polymers as the cathode interlayer in conventional PVCs have shown big potential to elevate their PCEs, and high efficiency PVCs with PCEs over 6% have been demonstrated [34–36]. For a low band gap poly(4,5-ethylene-2,7-carbazole) donor, a bilayer cathode based on a hydrophilic polyfluorene and Al could be superior to Ca/Al cathode that has been utilized in some high efficiency solar cells [35]. In this work, two hydrophilic conjugated 2,7-carbazole-1,4-phenylene alternating copolymers PCP-NOH and PCP-EP (Fig. 1a), soluble in methanol, were utilized as the cathode interlayer to construct inverted PVCs based on a low bandgap poly(2,7-carbazole) (PCDTBT) [37] as the polymer donor and [6,6]-phenyl C_{71}-butyric acid methyl ester ($PC_{71}BM$) as the acceptor (Fig. 1b). PCP-NOH and PCP-EP comprise surfactant-like diethanolamino and phosphonate end groups on the side chains of the both main chain blocks, respectively, which impart the alcohol solubilities of the two polymers [38]. In our previous work, PCP-NOH/Al and PCP-EP/Al displayed higher efficiency than

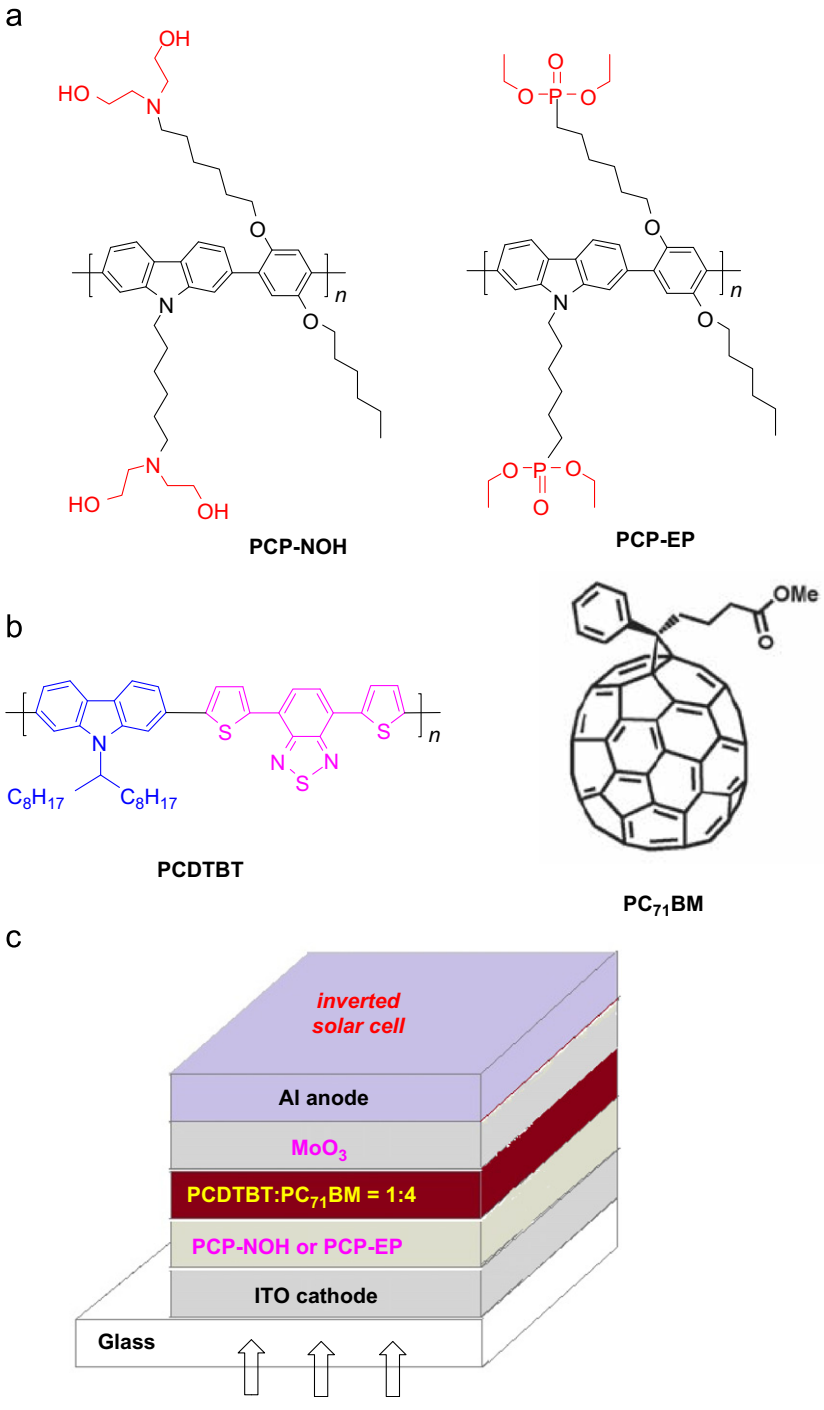

Fig. 1. (a) Chemical structures of interlayer polymers PCP-NOH and PCP-EP. (b) chemical structures of PCDTBT polycarbazole donor and $PC_{71}BM$ acceptor,and (c) the device configuration of the inverted solar cells.