



Efficient bifacial perovskite solar cell based on a highly transparent poly(3,4-ethylenedioxythiophene) as the p-type hole-transporting material



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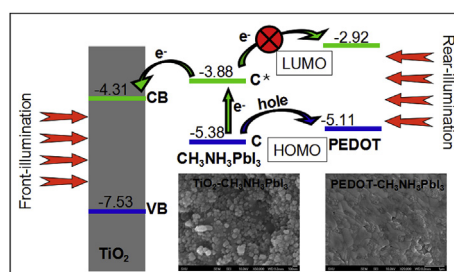
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HIGHLIGHTS

- Efficiently bifacial PSC is prepared based on the highly transparent PEDOT HTM.
- The bifacial PSC reaches 12.33% and 11.78% of the front and rear efficiencies.
- The front efficiency is only decreased by 4.46% to rear efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel bifacial perovskite solar cell (PSC) is devised and prepared by using a highly transparent poly(3,4-ethylenedioxythiophene) (PEDOT) electrode. The PEDOT is used as the p-type hole-transporting material (HTM) due to the well matched band positions for the charge separation and transport. Moreover, the PEDOT layer can play a role of electron blocking layer at the $\text{CH}_3\text{NH}_3\text{PbI}_3/\text{PEDOT}$ interface to reduce the electron recombination rate because of its LUMO level is higher than that of the perovskite sensitizer. As a result, the bifacial PSC based on the PEDOT HTM yields front and rear efficiencies of 12.33% and 11.78% respectively, which are higher than those of the PSC without the PEDOT HTM (8.67% and 8.27% of the front and rear efficiencies). And the front efficiency is only decreased by 4.46% to the rear efficiency. These promising results highlight the potential application of the PEDOT in the cost-effective and transparent PSC, which could be used in the bifacial solar cell and tandem solar cell.

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1. Introduction

In the past few years, the perovskite solar cell (PSC) has attracted

scientific and technological interest of researchers due to its clean, low-cost, high efficiency, good durability, and easy fabrication [1–14]. In a typical PSC, the high-cost Spiro-MeOTAD is generally used as the hole-transporting material (HTM) to promote the rate of hole transfer for the excited perovskite, which demonstrates low recombination rate and efficient charge transport improving device performance [1–4]. Polytriarylamine (PTAA) [15] and poly(3-hexyl-

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thiophene) (P3HT) [16] are also used as the HTMs. For the sake of low-cost, good stability, and simple easy preparation of controllable structures, the p-type conducting polymers, e.g., polypyrrole (PPy) [17], polyaniline (PANI) [18], and poly(3,4-ethylenedioxythiophene) (PEDOT) [19–21] have been successfully employed as cheaper HTMs in all-solid-state dye-sensitized solar cells (DSSCs). Recently, we developed a low-cost dual function PANI as the HTM and the synergistic sensitizer for use in the PSC, 7.34% of the PSC efficiency was achieved due to its unique optical and electronic properties [22]. Moreover, poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT: PSS) solution in water is widely used for the preparation of optoelectronic device [23], and PEDOT: PSS is known as the most promising candidate as a transparent electrode, as well as a HTM in both standard [9,24,25] and conductive oxide (such as FTO or ITO) free [26,27] architectures in photovoltaic devices.

Furthermore, enhancing the power-generating efficiency of the PSC is still an important issue [28]. The bifacial silicon heterojunction-perovskite organic-inorganic tandem solar cells [29] and bifacial DSSCs have been realized to enhance their efficiency [30,31], which collects sunlight from either of its two sides. Tai et al. reported on a bifacial DSSC with the transparent PANI CE yielding front and rear efficiencies of 6.54 and 4.26% respectively [30]. However, the rear efficiency is decreased by 34.86% to the front efficiency. Similar result (38.06% decreased [31]) by Wu et al. repeated owing to the dark color electrolyte based on high I_3^- concentrations was used in the bifacial DSSC. In the PSC field, no I_3^- based dark color electrolyte but light-colored HTMs can advantage to prepare the bifacial PSC. However, the non-transparent metal—such as Au, or Ag, or Al—back contact electrode in the PSC presents a significant obstacle to the bifacial PSC. Recently, You et al. reported the fabrication of semi-transparent PSCs by laminating stacked multi-layer graphene as transparent electrodes, the device showed the average efficiencies up to 12.02% and 11.65% when the device was illuminated from the FTO side and graphene side, respectively, and in this device a thin layer of PEDOT:PSS was used to improve the conductivity of graphene and also used as an adhesion layer to the perovskite active layer [32].

Here we devise a novel bifacial PSC based on a highly transparent PEDOT electrode, which is used as the HTM due to the well matched band positions for the charge separation and transport. Moreover, the PEDOT layer can play a role of electron blocking layer at the $CH_3NH_3PbI_3$ /PEDOT interface to reduce the electron recombination rate. Fig. 1 shows the device schematic diagram and energy level diagram of the bifacial PSC. The bifacial PSC based on the PEDOT HTM yields front and rear efficiencies of 12.33% and 11.78% respectively. The efficiency from the front illumination is only decreased by 4.46% to that from the rear illumination, the decrease is much lower than that of the bifacial DSSC.

2. Experimental

2.1. Materials

3,4-ethylenedioxythiophene monomer (EDOT) was purchased from Aldrich, USA. Sodium dodecyl sulfate (SDS), lithium perchlorate ($LiClO_4$), aqueous ammonia, isopropyl alcohol, methanol, ether, hydroiodic acid (45 wt.% in water), methylamine (30% in methanol), lead iodide (PbI_2), chlorobenzene, acetonitrile, tetrabutyl titanate, and Triton X-100 were purchased from Shanghai Chemical Agent Ltd., China (Analysis purity grade). γ -butyrolactone (>99.9%), tetrabutylammonium hexafluorophosphate (TBAPF₆, 98%), and ferrocene (>99.9%) were purchased from Aladdin. The above agents were used without further purification.

2.2. PEDOT electrode electropolymerization

The PEDOT was electrodeposited on the fluorinated tin oxide (FTO) glass substrate (NSG, $12 \Omega \text{ sq}^{-1}$) by the cyclic voltammetry (CV) method from an aqueous solution containing 2.0 mmol L^{-1} EDOT, 10 mmol L^{-1} SDS, and 10 mmol L^{-1} $LiClO_4$ [33], in which the SDS was used as the dispersion agent for the EDOT monomer being completely dispersed in water, and $LiClO_4$ was used as the supporting electrolyte for the CV electrodeposition. A three-electrode cell was used with a computer-controlled Autolab potentiostat (Type III) at ambient atmosphere, in which a Pt wire, a saturated silver/silver chloride (Ag/AgCl), and a cleaned FTO glass substrate were used as the counter electrode, the reference electrode, and the working electrode, respectively. Before the plating, FTO substrates ($1.5 \text{ cm} \times 2 \text{ cm}$) were cleaned with acetone and isopropyl alcohol, respectively. The potential range was set between -0.1 V and 1.2 V for 10 cycles for the PEDOT electropolymerization vs. Ag/AgCl at a scan rate of 0.05 V s^{-1} . The obtained PEDOT films were rinsed in distilled water and then immersed in an aqueous ammonia for 12 h to change their conductive state to semiconductor state. Finally, the samples were drying at $80 \text{ }^\circ\text{C}$ in a vacuum drying oven (Suzhou Jiangdong Precision Instrument Co., Ltd., China).

2.3. Perovskite sensitizer synthesis

The perovskite sensitizer $CH_3NH_3PbI_3/\gamma$ -butyrolactone solution was synthesized according to the reported procedure [15]. The CH_3NH_3I was prepared by reacting 20 mL hydroiodic acid (45 wt.% in water) and 20 mL methylamine (30% in methanol) in a 250 mL round-bottomed flask at $0 \text{ }^\circ\text{C}$ for 2 h with stirring. Then the resulting solution was evaporated at $50 \text{ }^\circ\text{C}$ for 1 h. The precipitate was washed three times with diethyl ether, dried at $60 \text{ }^\circ\text{C}$ under a vacuum oven for 24 h, and used without further purification. The synthesized CH_3NH_3I powder (0.395 g) was mixed with PbI_2

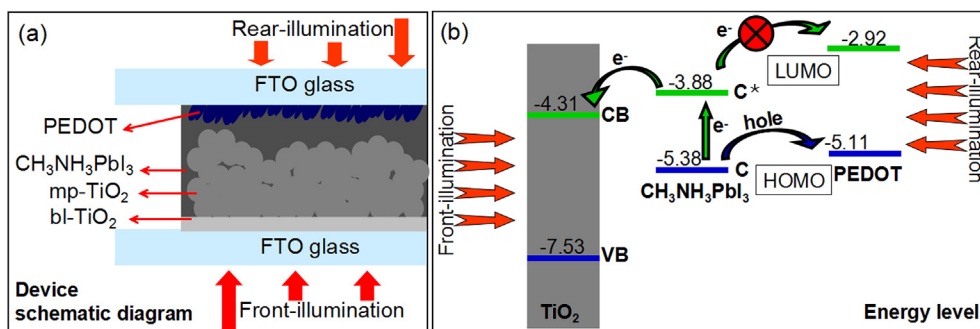


Fig. 1. Device schematic diagram and energy level diagram of the bifacial PSC.

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