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Efficient bifacial semitransparent perovskite solar cells with silver thin film electrode



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ABSTRACT

Bifacial semi-transparent perovskite solar cells (PSCs) are highly attractive for improving the efficiency of tandem solar cells and extending bifacial photovoltaic applications. However, the further improvement of bifacial performance has always been limited by the semitransparent electrode. Here we report an efficient triplelayer cathode of polyethyleneimine ethoxylate/silver/molybdenum oxide (PEIE/Ag/MoOx) for hysteresis-free planar PSCs with an inverted device configuration. Firstly, the optimal thickness of Ag electrode (11 nm) is achieved by theoretical calculation, and the fabricated PSC achieves the PCE of 8.04% at indium-tin-oxide (ITO) side and 5.24% at Ag film side. Then, by introducing the MoO_x (10 nm) optical coupling layer and PEIE (10 nm) interfacial modifying layer, the resulted PSC shows an obviously increased PCEs of 13.55% (ITO side) and 8.41% (Ag side), which is 60% higher than that of Ag only PSCs. The optimized PSCs has a structure of Glass/ITO/Poly (3,4-ethylenedioxythiophene): poly(styrenesulfonate)/Methylammonium-Lead-Iodide (about 300 nm)/Phenyl- C_{61} -butyric-acid-methyl-ester/PEIE/Ag/MoO_x. It is thought that the enhanced Ag film transmittance by highrefractive-index MoOx and electron extraction ability by low-work-function PEIE contribute to the improved cathode property and bifacial PSC performance. Moreover, when a back-reflector is employed, the PCE of device could be further improved to 14.50% (ITO side) and 11.37% (Ag side).

1. Introduction

With the rapid development of photovoltaic technology, perovskite solar cell(PSC) has been one of the most promising photovoltaic devices due to the advantages of high absorption coefficient, broad absorption range, adjustable band gap, solution processing and particularly, costeffectiveness in organic – inorganic lead halide perovskites [1,2]. Since the first PSC appeared in 2009 [3], the photovoltaic performance and stability have acquired continuous improvement, and recently their highest PCE has exceeded 22% [4-6]. Thus the efficient PSCs with low cost have received widespread attention and found many promising potential applications such as photovoltaic curtains [7], building integrated photovoltaics [8,9], wearable electronics [10], and tandem cells [11,12]. To meet these demands, the bifacial semitransparent devices with comparable efficiency and low cost are desired to be systematically investigated.

As we know, to achieve highly efficient semitransparent PSCs which can absorb light from both sides, one of the main obstacles comes from contradiction the between transparency and conductivity

characteristics of transparent electrodes. Meanwhile the low cost and simple preparation process are also expected. Recently, many efforts have been carried out to find a quasi-ideal transparent electrode for semitransparent PSCs. Eperon et al. [13] reported the neutral-colored PSC based on Au transparent electrodes. Due to the poor average transmittance(< 30%) in visible region, the resulted device only obtained a PCE about 5.2%. Roldan et al. [14] reported that the semitransparent PSC with a higher PCE above 6% and a full device transparency of 30% have been achieved by implementing a thin perovskite layer and a simple foil compatible layout. However, the PCE was still too low and the high cost of Au was undesirable. Bryant et al. [15] fabricated the semitransparent devices with Ni mesh top electrodes and fluorine-doped tin, and the senior PCE of 13.3% (or 9.8%) in the FTO (or Ni mesh) side was acquired. But the high temperature processed TiO₂ (500 °C annealing) electrode transport layer and the serious hysteresis phenomenon [16,17] may limit their further applications. You et al. [18] reported that the efficient semitransparent PSC with graphene electrodes show the average PCEs up to 12.02% and 11.65% when they are illuminated from bottom (FTO side) and top (graphene

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side) electrodes. Nonetheless, the preparation processing of multilayer grapheme electrodes was relatively complex and time consuming, which is not expected for tandem cells fabrication.

In this work, as Ag has the lowest absorption in the visible region compared to the common Au, Cu, and Al films [19]. and relatively high conductivity, we investigated the bifacial semitransparent PSCs with the PEIE/Ag/MoO_x triple-layer cathode. At first the optimized Ag thickness of 11 nm is obtained by theoretical calculations and experiments, the corresponding device shows a better bifacial performance with the PCEs of 8.04% illuminated from ITO side and 5.24% from Ag film side. By introducing a high-refractive-index MoO_x optical coupling laver outer the Ag electrode, the device PCEs are increased to 10.40% (ITO side) and 6.54% (Ag side). By inserting a low-work-function PEIE modifying layer between PCBM and Ag, the PSCs obtain the further improved PCEs of 13.55% and 8.41%, and particularly, all devices exhibits the negligible photocurrent hysteresis. Additionally, when an external back reflector of plastic plate is added in the JV curve measurements, the PCE values are further improved to 14.50% and 11.37% for the same device illuminated from ITO and Ag film sides.

2. Methods and materials

The planar structure of bifacial semitransparent PSCs in this work is shown in Fig. 1, as well as the corresponding energy band diagram. For this inverted PSC, the $CH_3NH_3PbI_3$ perovskite film is employed as the light absorption layer, the poly(3,4-ethylenedioxythiophene): poly (styrenesulfonate)(PEDOT:PSS) acts as the hole transport layer and the phenyl-C₆₁-butyric acid methyl ester (PCBM) plays the role of electron transport layer, the ITO the anode and the Ag film is chosen as the semitransparent top cathode; the molybdenum oxide (MOO_x) optical coupling layer is used to adjust the transmission and reflection of Ag electrode; and the polyethyleneimine ethoxylate (PEIE) interfacial modifying layer is inserted to reduce the electron transport barrier at PCBM/Ag interface. Based on this geometric structure, the investigation is carried out from two aspects of theoretical calculation and device fabrication as following.

2.1. Theoretical calculation

To develop highly efficient semitransparent PSCs, the theoretical calculation based on the transfer matrix method [20,21] was carried out to investigate the maximum possible short circuit current density (J_{SC}) for PSCs vertically illuminated from ITO side and Ag film side. There includes many assumptions such as interfaces are parallel and flat compared to the wavelength of the light; the light incident at the device



can be described by plane waves [20] in the calculations. Here, the device has an optimized structure of Glass/ITO (180 nm) PEDOT: PSS (10 nm)/CH₃NH₃PbI₃(x nm)/PCBM(50 nm)/Ag(11 nm)/MoO_x(10 nm). The thickness of perovskite layer and Ag thin film were optimized to obtain best overall performance for bifacial semitransparent PSCs. It is noted that the selections of layer thickness is on the basis of previous experiments [22]; the optical constants of materials used in calculations are obtained from references [23,24]; and the calculation details and optical model could be referenced in our previous works and other reports [25–27].

2.2. Device fabrication

The planar heterojunction perovskite solar cells were fabricated as following. First, the ITO coated glass substrates were cleaned with detergent, DI water, acetone, alcohol for 15 min, respectively. And then they were treated by UV-OZONE for 15 min before the device fabrication. A layer of PEDOT: PSS (Clevios PVP Al 4083) was spun coated on ITO substrate at 7000 rpm for 40 s followed by annealing at 150 °C for 20 min on a hot plate. Then the substrates were transferred into a glove box filled with nitrogen. CH₃NH₃PbI₃ perovskite films were deposited by spin coating a solution containing 1.4 M PbI₂ (99.999%, Sigma) and 1.35 M CH₃NH₃I (99.8%, Dyesol) in co-solvent of DMSO: GBL (3:7 vol. ratio, Sigma). The spin-coater was started at a rotation speed of 1000 rpm for 15 s and 5000 rpm for another 25 s 350 µl toluene (99.8%, Sigma-Aldrich) was added quickly at 40 s after the start of spin coating process. The perovskite films were then annealed at 100 °C for 20 min and obtained a thickness about 300 nm [28]. Then, the 20 mg/ ml chlorobenzene (99.8%, Sigma)solution of PCBM (98%, Nano-C) was spin-coated at 2000 rpm for 40 s. The 10 nm PEIE (0.2 wt% in IPA) was coated at 5000 rpm for 40 s. Next, the samples were transferred into a metal evaporation chamber, the Ag film with different thicknesses was deposited under high vacuum ($< 4 \times 10^{-4}$ Pa). Finally, the 10 nm thick MoO_x (99.9%, Aldrich) was evaporated on the Ag electrode. The thicknesses of Ag and \mbox{MoO}_x were estimated in situ with a calibrated quartz crystal monitor. And the fabricated device shows an active area of 7 mm^2 .

2.3. Device characterization

The photovoltaic performances of PSCs were measured by using a Keithley 2400 source meter under the simulated AM 1.5 G (1 sun) illumination of 100 mW/cm² from a Class AAA sunlight simulator (Sanei Electric, XES-300T1). The illumination intensity was calibrated by a reference silicon solar cell verified by the National Renewable Energy

Fig. 1. Schematic of PSC structure and corresponding energy band diagrams. The work function of ITO is 4.7 eV; the Highest Occupied Molecular Orbital(HOMO) of PEDOT:PSS, $CH_3NH_3PbI_3$ (or MAPbI₃) and PCBM are 3.0 eV, 3.93 eV and 4.0 eV respectively; the Lowest Unoccupied Molecular Orbital (LUMO) of PEDOT:PSS, $CH_3NH_3PbI_3$ and PCBM are 5.2 eV, 5.5 eV and 6.2 eV respectively; the work functions of Ag are 3.77 eV and 4.62 eV with or without modifying of PEIE; the work function of MOO_x is 5.2 eV. Download English Version:

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