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Short Communication

A two-terminal all-inorganic perovskite/organic tandem solar cell

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A R T I C L E I N F O

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Organic-inorganic lead halide perovskite solar cells (PSCs) have been marching rapidly in recent years with power conversion efficiency (PCE) boosting from 3.8% to 24.2% (NREL Best Research-Cell Efficiency Chart, https://www.nrel.gov/pv/cell-efficiency.html, Accessed April 2019). However, these solar cells are not stable at high temperatures due to volatile organic cations [1]. All-inorganic perovskites with cesium cation like $CsPbI_{1-x}Br_x$ present high thermal stabilities [2]. By partially replacing I^- with Br^-, the bandgap for $CsPbI_{1-x}Br_x$ can be tuned from 1.73 to 2.36 eV. $CsPbI_2Br$ exhibits a bandgap of 1.92 eV, showing potential in tandem and semitransparent solar cell applications.

Two-terminal (2T) tandem solar cells based on Perovskite/Si [3], Perovskite/Cu(In,Ga)Se_2 (CIGS) [4], and Perovskite/Perovskite [5] were reported. Organic solar cell (OSC) with good solution processability can be combined with perovskite solar cell to build tandem solar cells. Zuo et al. [6] ever invented an integrated solar cell with a structure of ITO/PEDOT/$CH_3NH_3PbI_3$/(PDPP3T–$PC_{61}BM$)/Ca/Al. The low-bandgap polymer remarkably broadens the EQE spectrum of the perovskite solar cell. Later, Chen et al. [7] reported an organic-inorganic hybrid perovskite/organic tandem solar cell with a 10.2% PCE, in which the perovskite solar cell was used as the rear cell. However, the subsequent solvent erosion and high-temperature treatment from perovskite preparation might damage the organic active layer. Liu et al. [8] made a tandem solar cell consisting of organic-inorganic hybrid perovskite front cell and organic rear cell. But the absorption spectrum of perovskite front cell and that of organic rear cell overlap, and the absorption spectrum for this tandem solar cell only reaches 800 nm. It was noted that all-inorganic perovskites with wide-bandgap can be used in making tandem solar cells, but we find no reports. In this communication, an all-inorganic perovskite/organic tandem solar cell is demonstrated, with $CsPbI_2Br$ cell as the front cell and PTB7-Th:COi8DFIC:$PC_{71}BM$ ternary cell as the rear cell [9]. The wide-bandgap $CsPbI_2Br$ can absorb short-wavelength photons before 650 nm while the low-bandgap nonfullerene acceptor COi8DFIC in ternary solar cell can absorb long-wavelength photons until 1,050 nm.

The structure for the tandem solar cells is indium tin oxide (ITO)/SnO_2/$CsPbI_2Br$/PTAA/ interconnecting layers (ICL)/ZnO/PTB7-Th:COi8DFIC:$PC_{71}BM$/MoO_3/Ag (Fig. 1a and b). The MoO_3/Au ICL was made by thermal deposition. The holes generated from perovskite front cell and the electrons from organic rear cell recombine at Au layer. Owing to the island growth mode of metal film in thermal deposition, the thinner Au film has rougher surface with many pinholes [10]. The J-V curves for the tandem cells with 2 nm Au layer and without Au layer both exhibited "S" shape (Fig. S1 online), because of the non-Ohmic contact between MoO_3 and ZnO. 2 nm thick Au layer was not applicable due to the bad morphology. On the other hand, as Au film thickness increases, the transmittance decreases. Transmittance spectra for Au films with different thicknesses are given in Fig. S2 (online). 4 nm thick Au film was chosen to make the tandem cells. The all-inorganic perovskite front cell with ICL provides >50% transmittance at 700–1,100 nm wavelength, giving good irradiation to organic rear cell (Fig. 1c). The J-V curves for a single-junction $CsPbI_2Br$ cell, a single-junction organic cell and a 2T tandem cell are shown in Fig. 1d. The reverse scan of the best tandem cell delivered a 15.04% PCE with a V_{oc} of 1.71 V, a J_{sc} of 11.98 mA cm^{-2}, and a fill factor (FF) of 73.4%. The device performance data are listed in Table S1 (online). The hysteresis for the tandem cell originated from the hysteresis of perovskite front cell (Fig. S3 online). The EQE spectra are presented in Fig. 1e. The front cell showed high

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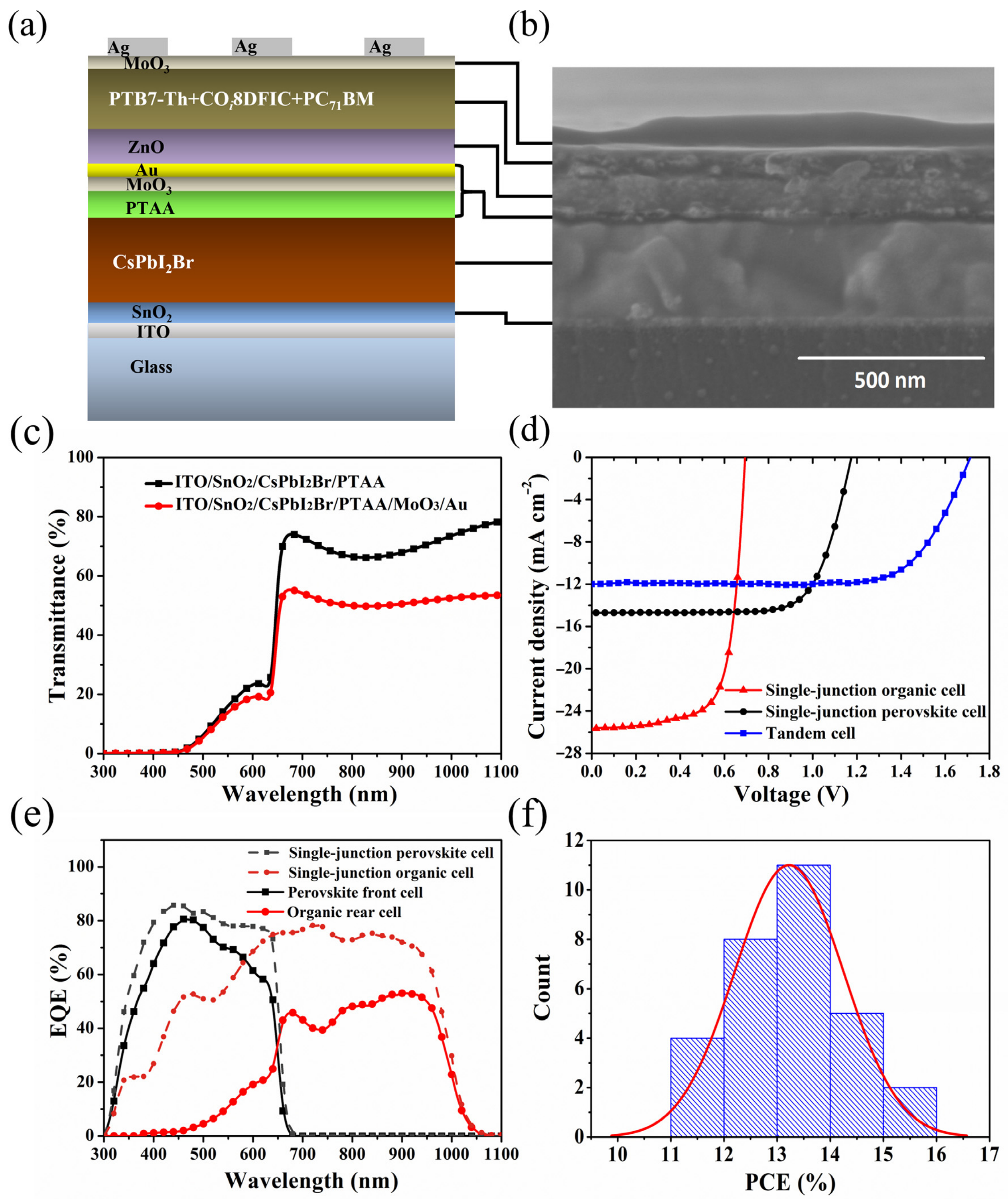

Fig. 1. 2T all-inorganic perovskite/organic tandem solar cell. (a) Schematic for 2T tandem solar cell; (b) the cross-section SEM image for a 2T tandem solar cell; (c) the transmittance spectra for all-inorganic perovskite front cell and all-inorganic perovskite front cell with ICL; (d) *J-V* curves for a single all-inorganic perovskite cell, a single organic cell and a 2T tandem cell; (e) EQE spectra for an all-inorganic perovskite front cell and an organic rear cell, operating in 2T tandem cell; (f) the PCE histogram for 30 cells.

response before 650 nm, corresponding to an integrated J_{sc} of 11.40 mA cm^{-2}. The rear cell mainly absorbed low-energy photons from 650 to 1,050 nm, corresponding to an integrated J_{sc} of 11.65 mA cm^{-2}. The photocurrent from both subcells matched well. But the photocurrent from the tandem cell was lower than both single-junction cells, especially much lower than that from single-junction organic cell. Since the front cell generated lower photocurrent, the maximum photocurrent from the tandem cell was limited by the front cell. More interfaces in the tandem cell could cause photocurrent loss. The PCE histogram is presented in Fig. 1f. After being stored in N_2 glovebox for 30 days, the tandem cells retained 96% of their initial PCEs (Fig. S4 online).

In summary, we successfully developed a 2T tandem solar cell consisting of $CsPbI_2Br$ front cell and organic rear cell, demonstrating a 15.04% PCE. There is still room for optimizing the partnership of the light-harvesting materials and those interfaces. Considering the good stability of all-inorganic perovskite solar cells, we believe all-inorganic perovskite/organic tandem solar cells deserve further efforts aiming to enhance the PCE. This exploration will stimulate more research on this device.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Qiang Zeng and Ling Liu performed the experiments. Zuo Xiao, Fangyang Liu, Yong Hua and Yongbo Yuan participated in the discussion on experimental results. Liming Ding directed this project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.05.015.

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