Organic-inorganic halide perovskite solar cell with CH₃NH₃PbI₂Br as hole conductor

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Abstract

Perovskite solar cells (PSCs) have attracted enormous interest as the most remarkably growing photovoltaic devices. With the power conversion efficiencies of PSCs exceeding 20%, great challenges have been focused on the issues of cost and long-term stability which are majorly related to the hole transport materials. In contrast, the PSCs without special hole conductors show great potential for commercial applications due to their cost-effective and fairly stable features. However, the inferior charge separation at the $\text{CH}_3\text{NH}_3\text{PbI}_3$ (MAPbI₃) and back electrode interface limits the cells for high efficiency. Our strategy is to arrange suitable energy band alignment at the interface to enhance the charge separation. We herein report a MAPbI₃/MAPbI₂Br cascade structured PSC with MAPbI₂Br majorly acting as a hole conductor. The conversion efficiency of the PSCs is greatly improved and a high efficiency of 15.83% is achieved. This new design of using organic-inorganic halide perovskites as hole conductors provides an efficient approach for improving the performance of low-cost PSCs.

Keywords: (perovskite solar cell; organic-inorganic halide perovskite; hole transport material; cascade structure)

1.Introduction

Recently, organic-inorganic halide perovskite solar cells (PSCs) as the most remarkably growing photovoltaic devices are attracting enormous attention due to the rapid increase of the power conversion efficiency [1-4]. The attractiveness of organic-inorganic halide perovskite ABX_3 , where A presents an organic cation (e.g. $CH_3NH_3^+$), B presents a metal cation (e.g. Pb^{2+}), and X is a halide anion, lies in their intense and broad light absorption and unique ambipolar charge transport characteristics. Several methods have been developed for producing high quality perovskite thin films, such as one-step spin coating [5], two-step sequential coating [6], vapor-assisted solution deposition [7], and dual-source evaporation deposition [8]. By far, the certified efficiency of 22.1% for PSCs with work area of 0.1 cm^2 [9] and 15% for PSCs with work area of 1 cm^2 have been reported [10].

Although the state-of-the-art PSCs have high enough efficiencies to meet commercial requirement [11], the inferior air stability is still a big issue. Especially, the PSCs based on $CH_3NH_3PbI_3$ ($MAPbI_3$) are very sensitive to ambient humidity and usually fabricated under extremely low humidity in glove box. A pioneer work was using solid state electrolyte such like 2,2',7,7'-tetrakis-(*N,N*-dimethoxyphenyl-amine)-9,9'-spirobifluorene (spiro-MeOTAD) as hole conductor to avoid decomposition of the perovskite by liquid electrolyte [12-14]. However, apart from the issue of expensive preparation cost, the lithium salts, such as lithium bis(trifluoromethanesulfonyl) imide (Li-TFSI) commonly used as p-type dopants to increase the conductivity of spiro-MeOTAD, are liable to aggravate the cell performance degradation due to their hygroscopy [15-17]. Therefore, it is necessary to develop low-cost and nondeliquescent hole conductors or alternatively to improve the performance of PSCs without a special hole conductor.

The PSC without a special hole conductor, so called “hole conductor-free” PSC, is much more cost-effective and the simple cell architecture also facilitates mass production. Etgar *et al.* firstly reported the hole conductor-free PSC with conversion efficiency of 5.5% by employing $MAPbI_3$ simultaneously as light absorber and hole conductor and TiO_2 nanosheets as electron collector [18]. Subsequently, they further improved the efficiency to 8.04% by deposition of a $MAPbI_3$ double-layer on a mesoporous TiO_2 film [19]. Nevertheless, the efficiency of such “hole conductor-free” PSC was still relatively low. The inferior cell performance was attributed to the bad interfacial contact between $MAPbI_3$ and Au back electrode. By improving the interface property, a higher efficiency of 10.49% was obtained [20]. However, comparing to their analogues with hole transport materials, “hole conductor-free” PSCs still suffer from inferior charge separation at the perovskite/Au interface. To

further improve the efficiency of such PSC, novel strategy is needed to efficiently enhance charge separation at the interface. Inspiringly, the energy band of perovskite ABX_3 is highly tunable by halogen substitution, providing much potential for achieving perfect energy band alignment at the interface to facilitate charge separation in the PSC. Our idea is to implant another perovskite thin layer between $MAPbI_3$ and the back electrode to force electrons injection into TiO_2 or block electrons transport from $MAPbI_3$ to the back electrode, and in the meantime to conduct holes to the back electrode. The candidate perovskite thus should have a broader band gap with conduction band edge and valence band edge higher than those of $MAPbI_3$. For $MAPbI_3$, the most frequently used sensitizer, the band gap was reported as 1.5 eV [5]. The conduction band edge and valence band edge are located at -3.93 eV and -5.43 eV vs. vacuum energy, respectively. We learned from recent reports that Br^- fully or partially substitution of I^- in $MAPbI_3$ usually led to an increase of the band gap [21-26]. Among the $MAPbI_{3-x}Br_x$ ($0 < x < 3$) perovskites, $MAPbI_2Br$ was reported with conduction band edge located at -3.62 eV and valence band edge located at -5.40 eV, respectively [26]. The much higher conduction band edge and slightly higher valence band edge of $MAPbI_2Br$ than $MAPbI_3$ is perfectly meet our anticipation.

In this work, we present a $MAPbI_3/MAPbI_2Br$ cascade structured PSC with $MAPbI_2Br$ majorly acting as a hole conductor. A perfect energy band alignment at the interface has been formed for efficient charge separation. To fabricate the $MAPbI_3/MAPbI_2Br$ cascade structured PSC, the $MAPbI_3$ film was formed by a two-step sequential deposition accompanying by a preheating treatment process. Subsequently, the $MAPbI_2Br$ thin film was coated on the top of $MAPbI_3$ layer by spraying deposition. As a result, the cascade structured PSC achieved a high efficiency of 15.83%.

2. Experimental

2.1 Materials

Lead iodide (PbI_2 , 99%), lead bromide ($PbBr_2$, $\geq 98\%$), copper iodide (CuI , 98%), titanium diisopropoxide bis(acetylacetonate) (75% in isopropanol), *N,N*-dimethylformamide (DMF) were purchased from Sigma-Aldrich. Methylammonium iodide (MAI) and Methylammonium bromide (MABr) were purchased from Dyesol Limited (Australia). All chemicals were used as received without any further purification.

The precursor solutions of PbI_2 for two-step sequential deposition of $MAPbI_3$ were prepared by dissolving 0.922 g PbI_2 in 2 mL DMF. Then the PbI_2 solutions were kept at

temperature range of 40–70 °C before using. To prepare precursor solutions for spray coating of MAPbI₂Br, PbI₂ and PbBr₂ were firstly mixed in DMF to form a solution with Pb²⁺ concentration of 0.1 mM and stirred for 1h. Then MAI with molar equivalent ratio of Pb element was added to the solution and keeping at 70 °C for 24 h with stirring. CuI was dissolved a mixture of propyl sulfide and chlorobenzene (1:39 in volume) to form a 0.1 M CuI solution and stirred overnight as the solution for deposition of CuI as hole transport layer.

2.2 Solar cells fabrication

Solar cells were fabricated in a glove box filled with Ar gas. Patterned fluorine-doped tin oxide conducting glass (Nippon Sheet Glass, with a sheet resistance of 8–10 ohm⁻²) was ultrasonically cleaned with detergent, purified water, and isopropanol sequentially. The substrate was further cleaned by UV-O₃ for 15 min. Then, 0.1 M titanium diisopropoxide bis(acetylacetonate) in butanol was spin-coated onto the substrate at 2000 rpm for 40 s and the sample was heated at 125 °C for 5 min. After cooling to room temperature, the same process was repeated again. Then the two-time coated sample was sintered at 525 °C for 30 min to form a uniform dense TiO₂ layer on the substrate. A mesoporous TiO₂ thin film was then deposited onto the sample by spin-coating at 2000 rpm for 40 s and then heating at 525 °C for 2 h. After cooling to room temperature, the sintered TiO₂ film was then coated with 0.15 M titanium diisopropoxide bis (acetylacetonate) as the same process mentioned above.

To obtain a suitable condition for forming uniform and dense perovskite films, the mesoporous TiO₂ films were preheated to a certain temperature of 40 °C, 55 °C, or 70 °C and infiltrated with the PbI₂ solution kept at the same temperature (40 °C, 55 °C, or 70 °C) by spin coating at 5000 rpm for 40 s and then heated up to 100 °C and keeping for 15 min. Then the PbI₂ film was immersed into 10 mg/mL MAI solution. Until color of the sample was completely changed to black, the sample was washed with isopropanol and dried by air blowing. After the sample was annealed at 100 °C for 10 min, the MAPbI₂Br precursor solution was spray-coated on the MAPbI₃ film at 100 °C. Then the sample was annealed again at 100 °C for 10 min. The CuI was deposited onto the MAPbI₃ film with a method similar to that reported [27]. For the back electrode, a 150-nm thick Au was deposited through a mask by thermal evaporation under ca. 1×10⁻⁶ torr vacuum condition.

2.3 Measurement and Characterization

Powder X-ray diffraction (XRD) patterns of the crystal structures of PbI₂ were recorded on a Bruker D8 diffractometer with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). Morphologies of the prepared films were examined by a field-emission scanning electron microscope (SEM, Quanta 250FEG). Absorption spectra of the prepared films were measured with a UV-vis-NIR spectrophotometer (UV-3600, Shimadzu). The photoelectron emission spectra of MAPbI₃ and MAPbI₂Br deposited on TiO₂ films were measured with a photoemission yield spectrometer (Riken Keiki AC-3). The current density-voltage (J - V) characteristics of the fabricated PSCs were measured under standard AM 1.5 sunlight (100 mW cm⁻², WXS-90L2, Wacom). The effective area of the cell was fixed as 0.09 cm² by using a non-reflective metal mask. Monochromatic incident-photon-to-current efficiency (IPCE) spectra were measured with a monochromatic incident light of 1×10^{16} photons/cm² in direct current mode (CEP-2000BX, Bunko-Keiki).

3. Results and Discussion

3.1 Characterizations of films

We adopted a two-step sequential deposition procedure for preparation of the MAPbI₃ films and followed by a spray-coating method for preparation of the MAPbI₂Br films, as shown in Fig. 1a. In the conventional two-step sequential deposition process [6], a thin film of PbI₂ was firstly formed by spin-coating of a warm PbI₂ solution (70 °C) onto the TiO₂ substrate at room temperature, after drying, then dipping in MAI solution to convert into MAPbI₃ film. We found that directly deposit warm PbI₂ solution onto TiO₂ films at room temperature tends to form big dendritic crystals, as see the morphology in Fig. S1 (Supporting Information). To form uniform and dense PbI₂ films, we hence modified the typical deposition procedure by preheating the TiO₂ films and the PbI₂ precursor solution at a same temperature and followed by annealing at 70 °C. XRD patterns of the PbI₂ films prepared at different preheating temperature are shown in Fig. 1b. As a control case, the PbI₂ film prepared at room temperature (RT) without preheating showed a very strong diffraction peak at 2θ of 12.6°, corresponding to a highly preferred orientation at the (001) lattice plane. Such highly preferred orientation is not good for forming a dense PbI₂ film, as shown in Fig. S1. The (001) preferred orientation growing was restrained when preheating the sample and solution at 40 °C and 55 °C. With increasing the preheating temperature to 70 °C, the strong (001) preferred orientation appeared again. We also measured the XRD patterns of PbI₂ films before and after annealing at 70 °C (Fig. S2). We found that when preheating the sample and

solution at 55 °C, even before annealing at 70 °C, the PbI₂ film already showed a very similar crystalline state with that of the PbI₂ film after annealing at 70 °C. This implied that the PbI₂ film formed at 55 °C before annealing already has good crystallinity and uniformity.

To gain further insight into the preheating process for preparing PbI₂ films affecting the final MAPbI₃ films, we also measured the XRD of the corresponding MAPbI₃ films. For clearly expression, the MAPbI₃ films are labeled as MAPbI₃-RT, MAPbI₃-40 °C, MAPbI₃-55 °C, and MAPbI₃-70 °C, according to the preheating temperature for preparing the PbI₂ films. As shown in Fig. 1c, the XRD patterns of MAPbI₃ films indicated typical (110), (220), and (330) peaks and no peak observable at 2θ of 12.6°, suggesting the PbI₂ was converted into MAPbI₃ completely. Among them, the MAPbI₃-55 °C and MAPbI₃-70 °C films showed similar crystalline phase with those reported in high efficient PSCs [5, 28].

Figure 1 (a) Schematic diagram of the fabrication process for preparing the MAPbI₃/MAPbI₂Br cascade film; and x-ray diffraction patterns of (b) PbI₂ films prepared at different preheating temperature, and (c) corresponding MAPbI₃ films.

The SEM images shown in Fig. 2a-c exhibit that the MAPbI₃-55 °C film has more dense and uniform morphology than either MAPbI₃-40 °C film or MAPbI₃-70 °C film. An average grain size of the MAPbI₃-55 °C film was estimated approximately as 400 nm from the SEM image, which was usually suitable for preparation of PSCs with high performance. Therefore,

we fixed the preheating temperature at 55 °C to prepare the MAPbI₃ films for the further study of MAPbI₃/MAPbI₂Br cascade structure. To prepare the MAPbI₃/MAPbI₂Br cascade structure, the upper MAPbI₂Br thin layer was coated on the MAPbI₃ film by a spray coating method. The surface morphology of the MAPbI₂Br thin layer was very similar to that of the film deposited directly on mesoporous TiO₂ film. As shown in Fig. 2d, the SEM image of the MAPbI₂Br film surface exhibits a dense and uniform morphology with grain sizes in the range of 100–400 nm.

Figure 2 SEM images of MAPbI₃ film converted from PbI₂ film deposited (a) 40 °C, (b) 55 °C, (c) 70 °C; and (d) SEM images of MAPbI₂Br thin layer on the top of MAPbI₃ film.

In consideration different halogen stoichiometry in the perovskite MAPbX₃ usually affecting the optical property, we measured the absorption and reflection spectra of the MAPbI₃, MAPbI₂Br, and MAPbI₃/MAPbI₂Br sensitized TiO₂ films using a UV-Vis spectrometer with an integrated sphere. Fig. 3 shows the absorbance spectra of the various perovskite compositions, respectively. The MAPbI₃ film shows a strong and broad absorption band in visible and near-infrared region with the onset of about 800 nm, which is in good agreement with those reported [5, 18, 26, 29]. The MAPbI₂Br film shows a stronger and

Figure 3 UV-vis absorption spectra of TiO_2 films sensitized by MAPbI_3 , MAPbI_2Br , and $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$.

sharper absorption band with onset clearly blue-shifted to 700 nm with respect to the MAPbI_3 film. For the $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$ cascade film, there is a slightly increase in light absorption over 340–700 nm with respect to the MAPbI_3 film, due to the contribution of MAPbI_2Br film. The optical band gaps of MAPbI_3 and MAPbI_2Br are calculated to be 1.5 eV and 1.77 eV from the diffuse reflectance spectra according to the method described in literature [5]. The photoelectron emission spectra of MAPbI_3 and MAPbI_2Br deposited on TiO_2 films were determined using a photoemission yield spectrometer. The excited-state oxidation potentials (valence band edges) of MAPbI_3 and MAPbI_2Br are measured as -5.43 and -5.39 eV, respectively (Fig. 3S), which are in accord with the reported values [5, 30]. The conduction band edges are calculated from the optical band gaps and the valence band edges of the perovskite materials. Based on these results, the energy band diagrams of MAPbI_3 and $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$ cascade films in contact with TiO_2 and Au electrode are established respectively, as represented in Fig. 4. The band positions of MAPbI_3 are well aligned for photoexcited electrons injection to TiO_2 and holes transport to Au (Fig. 4a). Nevertheless, the electrons in MAPbI_3 could transfer simultaneously “back” to the Au electrode and induce serious charge recombination with holes at the interface. By implanting a thin layer of MAPbI_2Br between MAPbI_3 and Au, the electron “back” transport can be blocked efficiently owing to the higher conduction band position of MAPbI_2Br than MAPbI_3 (Fig. 4b). Thus, the electrons and holes recombination can be greatly reduced and result in an improvement in cell performance. Additionally, the hole transport process also can be facilitated since the valence band of MAPbI_2Br is slightly higher than that of MAPbI_3 and the stepwisely elevating valence band alignment is of benefit to the hole transport.

Figure 4 Schematic energy level diagrams of (a) TiO₂, MAPbI₃, and Au in PSC based on MAPbI₃, and (b) TiO₂, MAPbI₃, MAPbI₂Br, and Au in MAPbI₃/MAPbI₂Br cascade structured PSC.

3.2 Characterizations of solar cells

The fabrication details of MAPbI₃/MAPbI₂Br cascade structured PSCs were described in the experimental section. The cross-section SEM image of the cell structure was showed in Fig. 4S. For comparison, PSCs based on MAPbI₃ single layer and with CuI as hole conductor were also prepared. The photovoltaic performances of the PSCs were characterized under standard AM 1.5 simulated solar irradiation (100 mW/cm²). Photovoltaic performances of the MAPbI₃ solar cells prepared at different preheating conditions were described in the Supporting Information. It should be mentioned that all of the MAPbI₃ cells prepared with preheating process (at 40 °C, 55 °C or 70 °C) showed higher efficiency in comparison with the cells without pretreatment, suggesting that the preheating process was of importance for fabrication of PSCs with high performance. The optimal preheating temperature was 55 °C under our experiment conditions.

The $J-V$ curves of the MAPbI₃/MAPbI₂Br cascade structured cells and corresponding MAPbI₃ cells are represented in Fig. 5a. As expected, the MAPbI₃/MAPbI₂Br cascade structured cell achieved a high efficiency of 15.83%, which was significantly higher than those of the MAPbI₃ cells without hole conductor (11.94%) and with CuI as hole conductor (13.53%). As a majorly increased parameter, the V_{oc} of MAPbI₃/MAPbI₂Br cell (1.05 V) was much higher than that of the MAPbI₃ cell without hole conductor (0.94 V). We consider this improvement was mainly attributed to effective suppression of charge recombination by the MAPbI₂Br thin layer.

Simultaneously, the J_{sc} was improved by 6.2 % from 20.57 to 21.85 mA cm⁻². This increase in J_{sc} was much higher than the value estimated from the contribution of the MAPbI₂Br thin layer in light absorption (Fig. 3), implying that the MAPbI₂Br was not merely as a co-sensitizer. In order to illustrate this in detail, we measured the IPCE spectra of the cells because J_{sc} and $IPCE$ values of a cell have the relation as shown in equation (1) [31].

$$IPCE (\%) = \frac{J (\lambda)}{q I_0 (\lambda)} = \frac{1240(\text{eV nm}) J_{sc}(\text{mA cm}^{-2})}{\lambda(\text{nm}) P_{in} (\text{mW cm}^{-2})} \times 100 \quad (1)$$

where λ is the excitation wavelength, $J (\lambda)$ is the photocurrent density, q is the elementary charge, $I_0 (\lambda)$ is the incident photon flux, and P_{in} is the incident light intensity. Since IPCE spectrum represents the light to current conversion efficiency as a function of light wavelength. The $IPCE (\lambda)$ at a certain wavelength also can be determined from three efficiencies, as shown in equation (2) [32].

$$IPCE (\lambda) = LHE(\lambda) \eta_{in} \eta_c \quad (2)$$

where $LHE (\lambda)$ is the light harvesting efficiency, η_{in} is the electron injection efficiency, and η_c is the electron collection efficiency. In the PSCs, the light harvesting efficiency is associated with absorption property of the sensitizer; the electron injection efficiency is affected by energy band gap between the sensitizer and TiO₂; and the electron collection efficiency is related to electron transport within the TiO₂ nanostructure network and the recombination of the injected electrons with holes. The IPCE spectra of MAPbI₃/MAPbI₂Br cascade structured cell and MAPbI₃ cell are shown in Fig. 5b. In comparison to the MAPbI₃ cell without hole conductor, the IPCE spectrum of MAPbI₃/MAPbI₂Br cell was slightly increased in the wavelength range of 400–500 nm, which was in accord with the increase of absorption spectrum at this region (Fig. 3). This confirmed that the MAPbI₂Br was working partly as a sensitizer. However, the major increase of IPCE was occurred in the region of 580–780 nm while the absorption spectrum was not so much improved in the corresponding region. It is reasonable that the improvement of IPCE in this region was owing to the increases in η_{in} or η_c . Since the conduction band of MAPbI₂Br is higher than those of MAPbI₃ and TiO₂, the driving force for the electron injection from perovskite materials to TiO₂ might be enhanced with the present of MAPbI₂Br, thus the MAPbI₂Br thin layer might slightly contribute to the increase of η_{in} . This slight increase of η_{in} was most likely occurred at short wavelength range rather than at long wavelength range, because MAPbI₂Br show higher light absorption than MAPbI₃ only at short wavelength range (Fig. 3). Therefore, the improvement of IPCE in the region of 580–780 nm could be mainly attributed to the enhancement of η_c .

Since we used the same batch of TiO_2 films in the $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$ cell and the MAPbI_3 cell, the effect of electron transport on η_c could be regarded as the same. The improvement η_c therefore could be considered primarily owing to the efficient charge separation. Thus, the increase of J_{SC} could be attributing majorly to the MAPbI_2Br thin layer blocking the electron transfer “back” from MAPbI_3 to Au and facilitating hole transfer to Au. These results confirmed that the efficiency of PSC without a special hole conductor could be greatly improved by employing another perovskite as hole conductor with considering a suitable energy band alignment at the interface.

Figure 5 (a) J - V characterizations of the best-performing PSCs with MAPbI_3 , $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$, and $\text{MAPbI}_3/\text{CuI}$. (b) IPCE spectra of PSCs sensitized by MAPbI_3 and $\text{MAPbI}_3/\text{MAPbI}_2\text{Br}$.

The statistics of cell performance parameters (Fig. 6) were performed by repeating the I - V measurements on 30 cells for each type, respectively. Comparing to the cells without hole conductor, the cells with MAPbI_2Br showed slight improvement in the standard deviations, suggesting the good reproducibility of cells with MAPbI_2Br as hole conductor. In contrast, the cells with CuI as hole conductor showed large deviations in the photovoltaic parameters. This may be because the complex fabrication process inducing

the big deviation in the cell performances. For the cells with MAPbI₂Br as hole conductor, half numbers of the tested cells show efficiency higher than 14.6%.

Figure 6 Statistics distribution of the photovoltaic parameters of 30 cells with MAPbI₃ (black), MAPbI₃/CuI (red), and MAPbI₃/MAPbI₂Br (blue), respectively.

4 Conclusion

In summary, we have demonstrated that conversion efficiency and long-term stability of “hole conductor-free” PSC could be improved by implanting a thin film of MAPbI₂Br between MAPbI₃ and Au electrode. The higher conduction band of MAPbI₂Br efficiently restrained electron transport from MAPbI₃ to the Au back electrode and meanwhile the slightly higher valence band of MAPbI₂Br could facilitate holes transport from MAPbI₃ to the back electrode. The strategy of suitable arrangement of the interfacial energy band alignment was verified to be beneficial to the enhancement of the charge separation in the PSCs. We also found that preheating the PbI₂ solution and TiO₂ films in a relative high temperature for spin-coating was important for fabrication of PSCs at ambient condition and the optimal temperature was about 55 °C under our experiment condition. Our work paves a way of using organic-inorganic halide perovskites as hole conductors in PSCs by carefully engineering the energy band alignment at the interface. We expect this strategy can accelerate the development of such kind of cost-effective perovskite solar cells.

Appendix A. Supplementary material

Supporting information associated with this article is available from the

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FIGURE CAPTIONS

Figure 1 (a) Schematic diagram of the fabrication process for preparing the MAPbI₃/MAPbI₂Br cascade film; and x-ray diffraction patterns of (b) PbI₂ films prepared at different preheating temperature, and (c) corresponding MAPbI₃ films.

Figure 2 SEM images of MAPbI₃ film converted from PbI₂ film deposited (a) 40 °C, (b) 55 °C, (c) 70 °C; and (d) SEM images of MAPbI₂Br thin layer on the top of MAPbI₃ film.

Figure 3 UV–vis absorption spectra of TiO₂ films sensitized by MAPbI₃, MAPbI₂Br, and MAPbI₃/MAPbI₂Br.

Figure 4 Schematic energy level diagrams of (a) TiO₂, MAPbI₃, and Au in PSC based on MAPbI₃, and (b) TiO₂, MAPbI₃, MAPbI₂Br, and Au in MAPbI₃/MAPbI₂Br cascade structured PSC.

Figure 5 (a) J - V characterizations of the best-performing PSCs with MAPbI₃, MAPbI₃/MAPbI₂Br, and MAPbI₃/CuI. (b) IPCE spectra of PSCs sensitized by MAPbI₃ and MAPbI₃/MAPbI₂Br.

Figure 6 Statistics distribution of the photovoltaic parameters of 30 cells with MAPbI₃ (black), MAPbI₃/CuI (red), and MAPbI₃/MAPbI₂Br (blue), respectively.