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MACl enhanced electron extraction in all-inorganic Cs₂AgBiBr₆ perovskite photovoltaics†

We present organic-halide treatment in advance to maximize electron extraction of $Cs_2AgBiBr_6$ double perovskite solar cells. Through optimizing the organic halide and concentration systematically, the best carbon-based $Cs_2AgBiBr_6$ perovskite solar cell fabricated in an airing chamber achieves a power conversion efficiency of 2.03% and shows excellent long-term stability in air over 30 days.

Halide perovskite materials have become one of the most competitive photovoltaic materials owing to their exceptional photoelectrical characteristics, such as large absorption coefficient, adjustable bandgap, high carrier mobility and long carrier diffusion length. Representative organic-inorganic hybrid perovskite solar cells (PeSCs) show outstanding photoelectric conversion ability. To date, the power conversion efficiency (PCE) has leapt to 25.8% (certified 25.5%). 1,2 Unfortunately hybrid PeSCs contain lead and organic ions, resulting in poor device stability and environmental toxicity, which seriously hinder large-scale production and commercialization of PeSCs. Inorganic cations replacing organic cations and two heterovalent cations taking over divalent lead ions have been proposed to enhance the inherent stability and decrease heavy metal toxicity.3-6 The concept of a fully inorganic lead-free double perovskite with the formula of A₂B⁺B^{/3+}X₆ conforms to this situation. According to the first principle calculation, Cs₂AgBiBr₆ is a double perovskite alternative to toxic and unstable hybrid PeSCs because of its high stability and long carrier lifetime.6-8

Slavney *et al.*⁹ presented that Cs₂AgBiBr₆ had terrible potential optical and physical properties, which motivated further exploration of double perovskites for photovoltaic applications. Greul *et al.* prepared Cs₂AgBiBr₆ films by a spin-coating

method and incorporated them into photovoltaic devices in 2017. The Cs₂AgBiBr₆-based PeSC showed PCE of 2.43% and open circuit voltage (V_{oc}) exceeding 1 V, which was the highest V_{oc} for perovskite containing bismuth at that time. This work pointed out a promising class of perovskites for the photovoltaic field. However, the efficiency of Cs2AgBiBr6 PeSCs was limited by their wide indirect bandgap and high inherent defects. Increasing the light capture and crystalline quality of Cs2AgBiBr6 film is a considerable challenge to further improve Cs2AgBiBr6 device performances. 10-13 Photosensitizers (such as dyes and organic materials) have been introduced to broaden the absorption spectrum and raise the device PCE of Cs₂AgBiBr₆ perovskite. 11-13 For example, Yang et al.11 used an N719 interlayer to broaden the absorption and heighten the PCE to 2.84%. Wang et al. 12 improved the light absorption of Cs2AgBiBr6 films by D149 dye treatment of the electron transport layer (ETL). Nevertheless, dye intermediates failed to improve the poor crystallinity of Cs2AgBiBr6 itself, and affect the internal resistance of the device, resulting in the decrease of the fill factor (FF).

In addition, expensive organic hole transport materials (HTMs) are very vulnerable to the migration of halide ions. ¹⁴ The carbon electrode materials replacing the HTM and metal electrode are relatively mature in related fields. Cs₂AgBiBr₆ PeSCs based on carbon electrodes have seen some attempts. ^{15,16} For example, Li *et al.* fabricated a Cs₂AgBiBr₆ PeSC with the efficiency of 2.57% and excellent high-temperature and air stability. ¹⁵ Li *et al.* ¹⁶ employed ionic liquids (ILs) to inhibit Br⁻ migration effectively, thereby reducing film defects and improving energy level matching. A carbon-based Cs₂AgBiBr₆ PeSC achieved a PCE of 2.22% and positive long-term stability. These provide convenient and efficient strategies to raise the efficiency and stability of environmentally friendly Cs₂AgBiBr₆-based photovoltaics.

Undesirable performances of Cs₂AgBiBr₆ photovoltaics are due to their deep electron defects. ^{15,17} The passivation for the ETL/perovskite interface by methylammonium chloride is an aid to improve the crystallization of Cs₂AgBiBr₆ film and electron extraction capability. ^{18,19} In this work, we introduce methylammonium halide (MAX) to ameliorate the ETL/perovskite

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interface and perovskite quality. Three MAXs are employed to explore systematically the role of charge transport and perovskite crystallization.

The concentration of the Cs₂AgBiBr₆ precursor solution is 0.5 M. After finishing the growth of TiO2 NRs, 0.25 M-MAX solution was spin-coated in advance on the TiO2 ETL followed by spin-coating the Cs₂AgBiBr₆ precursor. The entire preparation procedure of Cs₂AgBiBr₆ film was carried out in an airing chamber and drawn with a diagram in Fig. S1 (ESI†). Cs₂Ag-BiBr₆ films with uniform yellow appearance (optical image illustration is in Fig. S1, ESI†) were obtained after 280 °C annealing. Cs₂AgBiBr₆ film without pre-treatment was prepared as a reference sample. In order to verify the effect of MAX pretreatment on the morphologies of Cs₂AgBiBr₆ films, the surface of the samples was observed by a Scanning Electron Microscope (SEM). SEM images of Cs2AgBiBr6 films with MAX pretreatment (including the reference, MACl, MABr and MAI pretreatment) were exhibited in Fig. 1 using low magnification and high magnification. Cs₂AgBiBr₆ samples with MACl, MABr and MAI pre-treatment were named Cs₂AgBiBr₆-MACl, Cs₂AgBiBr₆-MABr and Cs₂AgBiBr₆-MAI, respectively. From SEM images, rather more regular grains were observed in Cs₂AgBiBr₆ films with MAX pre-treatment than reference Cs2AgBiBr6. Among four Cs₂AgBiBr₆ films, Cs₂AgBiBr₆-MACl has the smoothest surface and the most uniform grains. The pin-holes and/or cracks were marked by circles in other Cs₂AgBiBr₆ films.

In the X-ray diffraction (XRD) spectra of Fig. S2a (ESI†), all samples presented Cs₂AgBiBr₆ characteristic peaks.^{13,15} The full-width half-maximum (FWHM) of the reference, Cs2Ag-BiBr₆-MACl, Cs₂AgBiBr₆-MABr and Cs₂AgBiBr₆-MAI was 0.131°, 0.124°, 0.128° and 0.126° based on the (220) plane at ~22.12°. The narrow FWHM of Cs₂AgBiBr₆-MACl suggested its largest grain size among the four Cs₂AgBiBr₆ samples, ¹² which was in accordance with the SEM observation in Fig. 1. Fig. S2b (ESI†) displays the ultraviolet-visible (UV-vis) absorption spectra of the Cs₂AgBiBr₆ samples. The absorption peak was at \sim 439 nm for the Cs₂AgBiBr₆ samples. The absorption intensity followed the order: Cs₂AgBiBr₆-MACl > Cs₂AgBiBr₆-MAI > Cs₂AgBiBr₆-MABr > the reference. Cs₂AgBiBr₆-MACl had the highest absorption intensity and the broadest absorption edge. The bandgap energy calculation is shown in the Tauc diagram of Fig. S2b (ESI†). Cs₂AgBiBr₆-MACl had narrow direct and indirect bandgaps. Steady-state photoluminescence (PL) spectra in Fig. S2c (ESI†) showed that all Cs₂AgBiBr₆ samples had an

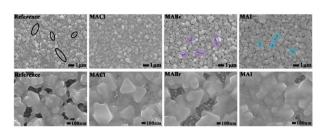


Fig. 1 SEM images of the reference and the samples pre-treated with

emission peak at \sim 520 nm, according to the direct bandgap. TiO2/Cs2AgBiBr6-MACl film had the lowest emission, which suggested its high crystalline quality and low defect density. 15,20 Fig. S2d (ESI†) exhibits the time resolved photoluminescence (TRPL) spectra of TiO2/Cs2AgBiBr6 films. The carrier recombination lifetime (τ) fitting data are displayed in Table S1 (ESI†). The lifetime of the reference, Cs₂AgBiBr₆-MACl, Cs₂AgBiBr₆-MABr and Cs₂AgBiBr₆-MAI samples was 59.46 ns, 42.53 ns, 48.53 ns and 45.0 ns, respectively. The smallest lifetime of Cs2AgBiBr6-MACl indicated its fast electron transfer and low trap recombination.21 To elucidate the chemical state of Cs₂AgBiBr₆ films, the X-ray photoelectron spectroscopy (XPS) spectra are shown in Fig. S3 and S4 (ESI†). The expected elements were found in scanning XPS measurement of the Cs₂AgBiBr₆ films.²⁰ The orbital binding energy of element Ag, Bi and Br for Cs₂AgBiBr₆-MACl shifted slightly towards the high binding energy direction, while the binding energy of Cs3d did not shift. The chemical bonding interaction of Cs-Br, Br-Bi and Br-Ag was enhanced for Cs₂AgBiBr₆-MACl, verified by Fourier transform infrared (FT-IR) measurement. This was beneficial to improving the stability of Cs₂AgBiBr₆ PeSCs.

HTM-free PeSCs using carbon as the top electrode were fabricated with the structure of FTO/TiO2/Cs2AgBiBr6/carbon. A typical diagrammatic sketch and cross-sectional image of the Cs₂AgBiBr₆-MACl device are shown in Fig. 2a. The J-V curves of the Cs₂AgBiBr₆ devices are depicted in Fig. 2b. The Cs₂AgBiBr₆-MACl PeSC had a significantly improved short-circuit current density (J_{sc}) of 3.04 mA cm⁻² and FF of 62% compared to the reference PeSC, resulting in the efficiency reaching 2.03%. The efficiency of the Cs2AgBiBr6 devices was in the order of Cs2Ag- $BiBr_6-MACl > Cs_2AgBiBr_6-MAI > Cs_2AgBiBr_6-MABr > the$ reference. The PCE of the Cs2AgBiBr6-MACl device is the highest, which is 68% higher than that of the reference PeSC. The best and average photovoltaic parameters of the Cs2AgBiBr6 devices are summarized in Table S2 (ESI†). As shown in Fig. 2c, the reverse and forward scanning (RE and FW) J-V curves were diagrammed for the champion devices. The hysteresis index (HI) was further quantified according to the formula²¹

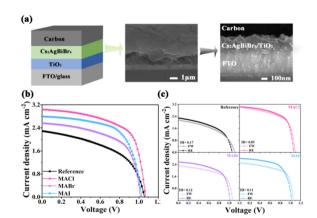


Fig. 2 (a) Scheme and SEM sectional images of the device structure. (b) J-V curves of the champion devices. (c) RE and FW J-V curves for the

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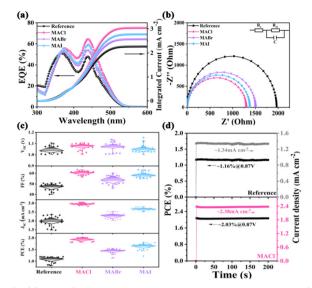


Fig. 3 (a) The EQE and integrated current density curves of the PSCs. (b) Nyquist EIS spectra (the inset is the equivalent circuit). (c) Box charts of $V_{\rm oc}$, FF, $J_{\rm sc}$ and PCE. (d) Steady-state power outputs at the maximum power point of the reference and Cs₂AgBiBr₆-MACl.

$$HI = [J_{RE}(0.8 \ V_{oc}) - J_{FW}(0.8 \ V_{oc})]/J_{FW}(0.8 \ V_{oc})$$
(1)

where $J_{\rm RE}(0.8\ V_{\rm oc})$ and $J_{\rm FW}(0.8\ V_{\rm oc})$ are the current-densities at $0.8 V_{oc}$ in reverse and forward scanning, respectively. The HI of the Cs₂AgBiBr₆-MACl device decreased to 0.05 from 0.17 for the reference PeSC.

Fig. 3a portrays the external quantum efficiency (EQE) spectra of the Cs₂AgBiBr₆ PeSCs. In the wavelength range of 350-550 nm, the Cs₂AgBiBr₆-MACl PeSC had the highest EQE value among the four Cs₂AgBiBr₆ cells. The EQE of the Cs₂Ag-BiBr₆-MACl PeSC was 65% at 440 nm, which was 15% more than that of the reference PeSC. The calculated integral current density was from 2.27 mA cm⁻² in the reference PeSC to 3.01 mA cm⁻² in the Cs₂AgBiBr₆-MACl device, which corresponded to the J-V results in Fig. 2b. The Cs₂AgBiBr₆-MACl device obtained the highest current density. To further explore the raised FF and J_{sc} related to charge transport at the interface and interior of the PeSCs, electrochemical impedance spectroscopy (EIS) tests were carried out. Nyquist spectra of four PeSCs were plotted in Fig. 3b and the corresponding equivalent circuit was illustrated. The fitted data are summarized in Table S3 (ESI \dagger), where R_s represents the series resistance of the devices, $R_{\rm ct}$ is the interfacial charge transport resistance and C refers to the capacitance. R_{ct} was arranged in the following order: the reference $> Cs_2AgBiBr_6-MABr > Cs_2AgBiBr_6-MAI > Cs_2Ag-$ BiBr₆-MACl. The $R_{\rm ct}$ values were calculated to be 1.99 k Ω , 1.51 k Ω , 1.36 k Ω and 1.27 k Ω , respectively. Significantly reduced $R_{\rm ct}$ indicates superior charge collection, rendering improved FF and diminished HI in the Cs2AgBiBr6-MACl and Cs2AgBiBr6-MAI devices. 12,16 Hence, Cs₂AgBiBr₆-MACl had the champion efficiency combined with the highest J_{sc} . The statistical photovoltaic parameters of the Cs2AgBiBr6 devices were summarized in Table S2 (ESI†) and Fig. 3c. The increase of $J_{\rm sc}$ and FF produced high PCE in the Cs2AgBiBr6-MACl devices. To verify

whether the PeSCs stabilize the output power under the irradiation of AM1.5G standard sunlight, the steady-state photocurrent and efficiency at the maximum power point (MPP) were further characterized in the air environment, as shown in Fig. 3d. The voltage at the maximum power point (V_{mpp}) of the Cs₂AgBiBr₆-MACl device was 0.87 V, and the steady J_{sc} and PCE are 2.38 mA cm⁻² and 2.03%, which were much higher than those of the reference device (1.34 mA cm⁻² and 1.16%). The photoelectric conversion curves of the MAX pre-treated devices under continuous light within 200s were smoother than that of the reference device, indicating better interface contact of ETL/perovskite in the PeSCs with MAX pre-treatment. The trap density (N_{trap}) was calculated by the space charge limited current (SCLC) model to be 1.468 \times $10^{15}\,$ $m^{-3}, \quad 9.737 \quad \times \quad 10^{14} \quad m^{-3}, \quad 1.312 \quad \times \quad 10^{15} \quad m^{-3} \quad and$ $1.27 \times 10^{15} \text{ m}^{-3}$ for the reference, Cs₂AgBiBr₆-MACl, Cs₂AgBiBr₆-MABr and Cs₂AgBiBr₆-MAI, respectively. The dark J-V curves were measured and plotted in Fig. S8 (ESI†) to unravel the working mechanism of the devices. The Cs2AgBiBr6-MACl PeSC had the lowest saturation current and relatively large shunt resistance $(R_{\rm sh})$ among the four Cs₂AgBiBr₆ devices, which suggested that the Cs₂AgBiBr₆-MACl PeSC had high electron extraction and low defect recombination. This was in line with the absorption, PL, EIS, defect and J-V results.

Based on these results, the mechanism of Cs₂AgBiBr₆-MACl was speculated. At the initial stage, MA⁺ and Cl⁻ ions participated in the double perovskite crystallization, producing the formation of $Cs_{2-x}MA_xAgBiBr_{6-y}Cl_y$ (0 < x < 1.0, 0 < y < 1.0) intermediate phase. With the volatilization of MA⁺ and Cl⁻ ions during heat treatment, the $Cs_{2-x}MA_xAgBiBr_{6-\nu}Cl_{\nu}$ intermediate phase transformed to the ultimate Cs₂AgBiBr₆. Adequate volatile additive can promote crystal growth, which resulted in superior film morphology by altering the activation energy of the perovskite crystallization. 22,23 Consequently, MACl delayed the crystallization progression of Cs₂AgBiBr₆ perovskites, resulting in large grain sizes and low trap density for Cs₂AgBiBr₆-MACl.

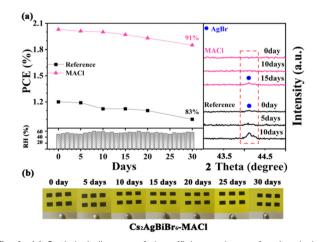


Fig. 4 (a) Statistical diagram of the efficiency change for the devices stored in the environment with a temperature of 28 $^{\circ}\text{C}$ and a relative humidity of 50-60% during 30 days. The right is the change of the XRD patterns of the devices. (b) Appearance change diagram of the Cs₂Ag-BiBr₆-MACl device within 30 days.

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Table 1 Recent progress of carbon-based Cs₂AgBiBr₆ PeSCs

Device structure	PCE	Fabrication	Long-term stability	Ref.
$\overline{\mathrm{FTO/m\text{-}TiO_2/Cs_{1.99}Li_{0.01}Cs_2AgBiBr_6/C}}$	2.57%	N2 glove box	80%, 25 °C, 5%RH, 90 days 80%, 85 °C, 0%RH, 60 days	15
$FTO/TiO_2NRs/Cs_2(Ag_{1-x}Zn_x)BiBr_6/C$	2.16%	N2 glove box	90%, 25 °C, 40%RH, 14 days in ambient air	21
FTO/TiO ₂ NRs/BMPyrCl/Cs ₂ AgBiBr ₆ /C	2.22%	N2 glove box	\sim 100%, 25 °C, 40% \pm 5%RH, 40 days in ambient air.	16
FTO/m-TiO ₂ /Cs ₂ AgBiBr ₆ /SnS QDs/C	1.95%	N2 glove box	90%, 42 h in ambient air.	23
FTO/TiO ₂ NRs/Cs ₂ AgBiBr ₆ -MACl/C	2.03%	Airing chamber	90%, 28 °C, 50%–60%RH, 30 days in ambient air	This work

Moreover, the strong MA+/TiO2 interaction compared to inorganic ion/TiO2 brought higher quality double perovskite film and faster electron extraction in the perovskite PeSC. 19 Impurity phase containing chlorine caused by excess MAX would hinder charge transport, which was confirmed by the inferior performance of Cs₂AgBiBr₆-0.5MACl (shown in Fig. S9, ESI†).

In order to investigate the effect of MACl pre-treatment on the performance stability of the PeSCs, the unpackaged reference and Cs₂AgBiBr₆-MACl samples were monitored by storing them under the air condition of 28 °C and relative humidity of 50-60% for 30 days. The PCE and XRD results are shown in Fig. 4a and Table S5 (ESI†). By tracking the PCE changes of the PeSCs, the Cs₂AgBiBr₆-MACl device maintained more than 90% of the initial PCE, while the reference device maintained 83% of the initial efficiency. AgBr miscellaneous phase was detected for the reference on the fifth day and aggravated on the tenth day by XRD monitoring in Fig. 4a, which was considered as an evil to deteriorate device performance. AgBr impure phase appeared after 15 days for the Cs₂AgBiBr₆-MACl device. No significant change of the Cs₂AgBiBr₆-MACl film was monitored in the appearance during preservation, which was displayed in photos of the samples during storing for 30 days. The Cs₂AgBiBr₆-MACl sample had better stability because of its higher perovskite crystalline degree than the reference sample. In addition, the hydrophobicity of the carbon electrode provides protection for the perovskite films, which further improves the environmental stability of the Cs2Ag-BiBr₆ PeSCs. The entire preparation process being completed in air widened the application fields of Cs₂AgBiBr₆ perovskite (Table 1).

In summary, we fabricated efficient and stable Cs₂AgBiBr₆ PeSCs by introducing MAX pre-treatment to modify the ETL/ Cs₂AgBiBr₆ interface and perovskite crystalline quality. The Cs₂AgBiBr₆ with three MAX pre-treatment was studied in an airing chamber systematically. The MACl modifier can bond with the ETL and perovskite and enhance perovskite crystallization. MACl modification facilitated electron extraction from the perovskite to the ETL, which reduced the trap-assisted recombination. As a result, the optimized PeSC with Cs2Ag- $BiBr_6$ -MACl achieved a PCE of 2.03% with slightly higher J_{sc} and FF than the reference device. Importantly, Cs₂AgBiBr₆-MACl exhibited better durability of the resultant PeSCs.

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Conflicts of interest

There are no conflicts to declare.

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