A Green Antisolvent Strategy for Enhancing the Performance of Carbon-based CsPbIBr$_2$ Solar Cells

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Abstract

All-inorganic CsPbIBr$_2$ perovskite materials demonstrated to own a balanceable feature for its acceptable bandgap, good phase stability and excellent thermal stability. Herein, we introduce ethyl acetate (EA) and chlorobenzene (CB) as antisolvent to improve the quality of CsPbIBr$_2$ thin films. Compared with CB, EA is a good green antisolvent, and high-quality CsPbIBr$_2$ thin films with enlarged grain sizes, few grain boundaries as well as improved optical properties were obtained by optimizing EA as antisolvent. Based on a carbon-based and hole-free planar heterojunction structure of FTO/TiO$_2$/CsPbIBr$_2$/Carbon, an optimal power conversion efficiency (PCE) of 4.35% was achieved, 10% enhancement in PCE. This work contributes to selecting nontoxic solvent engineering for realizing the preparation of high-quality CsPbIBr$_2$ thin films and the improved performance of all-inorganic CsPbIBr$_2$ PSCs.

Keywords: perovskite solar cells; antisolvent; carbon electrode; performance.

1. Introduction

Since first reported in 2009, perovskite solar cells (PSCs) have attracted widespread attention due to their high power conversion efficiencies (PCE) and low fabrication costs. After eleven years’ rapid development, the efficiency record of organic-inorganic hybrid perovskite solar cells has reached up to 25.5%, which is almost comparable to traditional crystalline silicon cells[1]. However, in order to realize the potential commercialization applications, PSCs are still facing several challenges, mainly including the organic cations in organic-inorganic hybrid perovskite materials that have poor stability to heat, water and ultraviolet light, resulting in the decomposition of the hybrid perovskite materials and the reduction of the corresponding cells’ performance[2].

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What’s more, expensive organic hole transport layers (HTLs) and novel metal electrodes are commonly used in PSCs, which cause instability problems as well as the fabrication costs[3]. In contrast, all-inorganic perovskite materials have obvious advantages in terms of thermal stability and light stability, especially the all-inorganic CsPbIBr\textsubscript{2} perovskite, which demonstrates a balanceable feature for its acceptable bandgap, good phase stability and excellent thermal stability[4]. Therefore, the above advantages contribute to the rapid development of carbon-based and hole-free CsPbIBr\textsubscript{2} PSCs in recent years. However, the CsPbIBr\textsubscript{2} thin films deposited by the traditional solvent spin-coating method usually form poor film morphology, such as the appearance of many pinholes and small grains, which lead to the recombination of carriers in the perovskite films, thus having a negative effect on device performance[5]. To address the above problems, enormous efforts have been taken to improve CsPbIBr\textsubscript{2} films for device performance improvement, such as crystallization engineering, compositional engineering and interface engineering[6-8]. Zhu and his colleagues proposed an intermolecular exchange method to precisely control the growth and crystallinity of CsPbIBr\textsubscript{2} films, a high-performance device with a PCE of 9.16% was obtained[9]. And it was reported that Mn-doped CsPbIBr\textsubscript{2} film shows perfect crystallinity and morphology, alleviating the energy loss in hole transfer. As a result, the optimized Mn-doped CsPbIBr\textsubscript{2} PSC was boosted from 6.14% to 7.36%[10]. Liu and his colleagues introduced SmBr\textsubscript{3} to modify the interface between the electron transport layer (ETL) and CsPbIBr\textsubscript{2} perovskite layer, obtaining the improved crystallization and morphology of the CsPbIBr\textsubscript{2} perovskite layer with gradient energy band, thus reaching 30% increase in PCE[11]. At the same time, the antisolvent assistance strategy has been confirmed useful in improving the quality of perovskite films in typical organic-inorganic hybrid PSCs as well as all-inorganic CsPbI\textsubscript{3} and CsPbI\textsubscript{2}Br PSCs[12, 13]. These works inspire the application of antisolvent assistance strategy in the CsPbIBr\textsubscript{2} PSCs[14, 15]. However, conventional antisolvents like toluene, chlorobenzene, dichloromethane are high toxic solvent, which are harmful to experimental safety and natural environment. So it is vital for reducing the use of toxic antisolvents and employing more green antisolvents to carry out scientific experiments. In this work, we introduce ethyl acetate (EA) and chlorobenzene (CB) as antisolvent to improve the quality of CsPbIBr\textsubscript{2} films through the conventional one-step solution method. Compared with CB, EA is not only a good green antisolvent with low toxicity, but also helpful for the formation of high-quality CsPbIBr\textsubscript{2} films with enlarged grain sizes, few grain boundaries, improved optical properties as well as reduced charge carrier recombination. Consequently, we obtained a champion PCE value of 4.36% based on carbon-based and hole-free CsPbIBr\textsubscript{2} PSCs, 10% enhancement in PCE. Furthermore, the devices prepared through the antisolvent assistance strategy showed good repeatability.

2. Experimental

2.1 Fabrication of solar cells

All chemicals and reagents in this work were directly used without any further purification. Firstly, the cleaned FTO conductive glass was treated under oxygen plasma for 20 min. Then, 4.5 mL pure TiCl\textsubscript{4} (Titanium tetrachloride) precursor solvent was slowly dropped into the frozen water (200 mL), accompanying with the magnetic stirring to make the solution clear and colorless. Then placing the cleaned FTO conductive glass into the solution. After 70 °C and 30 min reaction time, cleaning the glass with deionized water followed by annealing at 450 °C for 30 min, then the TiO\textsubscript{2} electrode transport layer (ETL) was formed. Next, 1M CsPbIBr\textsubscript{2}...
perovskite precursor was spinning on the TiO$_2$ surface at 600 rpm 5 s and 3500 rpm 40 s. During this process, 200 uL CB or EA was added into the spinning films after 20 s of beginning of the second spinning stage, respectively. Meanwhile, these substrates were annealed at 240 °C for 10 min. Finally, the carbon back electrode was prepared through a doctor-blade method, followed by a heat treatment at 110 °C for 20 min.

2.2 Characterization

The analysis of phase structure was studied by X-ray Diffraction (XRD, Bruker) with Cu Kα radiation ($\lambda=1.5418$ Å). Top-view morphologies of perovskite films were conducted by cold field emission scanning electron microscopy (SEM, Hitachi). Steady-state photoluminescence spectra (PL) were performed using a fluorescence spectrometer (Hitachi). UV-visible (UV-vis) absorption spectra were obtained with a UV-vis NIR spectrophotometer (PerkinElmer). The short-circuit current with open-circuit voltage curves (J-V curves) and external quantum efficiency (EQE) measurements of the CsPbI$_2$Br$_2$ PSCs were obtained by a simulated sunlight system (Newport) and quantum efficiency measurement system (EnliTech), respectively.

3. Results and discussion

For convenience, the CsPbI$_2$Br$_2$ films or PSCs treated by CB and EA are marked as CB-CsPbI$_2$Br$_2$ and EA-CsPbI$_2$Br$_2$, respectively. Figure 1 presents the XRD patterns of CsPbI$_2$Br$_2$ films treated by two different antisolvents. The XRD peaks located at 14.85°, 21.10° and 30.03° correspond to the (100), (110) and (200) planes of cubic phase CsPbI$_2$Br$_2$ perovskite[16, 17]. No additional peaks appear in both two films, proving that no new phases were formed after antisolvent processes. The main peak intensities of (100) and (200) planes in EA-CsPbI$_2$Br$_2$ films are respectively higher than that of the CB-CsPbI$_2$Br$_2$ films, indicating the former has the enhanced crystallinity, which is helpful for light absorption.

![Figure 1: XRD patterns of CsPbI$_2$Br$_2$ films treated by CB and EA antisolvent.](image)

The effect of antisolvent processes on optical properties was investigated. All CB-CsPbI$_2$Br$_2$ films and EA-CsPbI$_2$Br$_2$ films were directly deposited on insulating glass substrates. Figure 2(a) firstly gives the ultraviolet-visible (UV-vis) absorption spectra of CB-CsPbI$_2$Br$_2$ films and EA-CsPbI$_2$Br$_2$ films. It can be seen that both two antisolvent processes did not cause obvious changes in the absorption edge in UV-vis absorption spectra. And
the identical absorption onset at approximately 610 nm, corresponding to the bandgap of ~ 2.05 eV calculated from the Tauc plots in Figure 2(b). Despite the unchanged bandgap, the EA-CsPbBr₂ films showed stronger absorption compared with the CB-CsPbBr₂ films, which helps to increase the light-harvest ability. In addition, the steady-state PL spectra of two different CsPbBr₂ films are displayed in Figure 2(c). Both the CB-CsPbBr₂ films and EA-CsPbBr₂ films exhibited a PL emission peak at ~ 605 nm. Notably, the PL intensity of EA-CsPbBr₂ films was higher than that of CB-CsPbBr₂ films, indicating the reduced nonradiative recombination process caused by defects in CsPbBr₂ films, which is ascribed to the improved morphology of EA-CsPbBr₂ films, such as the enlarged grain sizes with decreased grain boundaries.

**Figure 2:** (a) UV–vis absorption spectra, (b) the corresponding Tauc plots calculated from the UV–vis absorption spectra and (c) steady-state PL spectra of CB-CsPbBr₂ films and EA-CsPbBr₂ films deposited on insulating glass substrates, respectively.

**Figure 3(a-b)** displays the top-view SEM images of CsPbBr₂ films with two different antisolvents (CB and EA) on the TiO₂/FTO substrate. Both the CB-CsPbBr₂ films and EA-CsPbBr₂ films show full coverage and uniform morphology, and no obvious pinholes appeared. However, the top-view images of EA-CsPbBr₂ films exhibit quite high quality with the large grain size, the detailed grain sizes of statistical charts are shown in **Figure 3(c-d)**, in which the average grain sizes were ~ 320 nm and ~ 410 nm for CB-CsPbBr₂ films and EA-CsPbBr₂ films, respectively. The larger grain sizes with fewer grain boundaries of the perovskite morphology help to reduce the carriers nonradiative recombination process in perovskite films, which would have a positive role in optimizing the performance of all-inorganic perovskites solar cells[18, 19].
In order to investigate the potential improvement of different antisolvent treatments on the photovoltaic performance of all-inorganic CsPbBr₂ PSCs, the devices with a configuration of FTO/TiO₂/CsPbBr₂/Carbon was fabricated in the nitrogen glove box. Figure 4(a) is the schematic sketch of the carbon-based CsPbBr₂ PSCs, in which the carbon electrode is used as the anode and the hole transport layer (HTL). Figure 4(b) gives the current-voltage curves of CsPbBr₂ PSCs with two different antisolvents (CB and EA), all the detailed photovoltaic parameters such as short-circuit current (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and PCE, are listed in Table 1. The champion PCE values of the CB-CsPbBr₂ PSCs and the EA-CsPbBr₂ PSCs are 4.35% and 3.95% at the reverse scan directions, respectively. The improved PCE value of EA-CsPbBr₂ PSCs is mainly attributed to the optimized morphology with improved grain crystallinity and enlarged grain sizes, which lead to the slight enhancement in J_{sc}, V_{oc} and FF values. Indeed, we have also investigated the EQE spectra of the CB-CsPbBr₂ PSCs and the EA-CsPbBr₂ PSCs, the results are shown in Figure 4(c). The EA-CsPbBr₂ PSC owns higher EQE values than that of the CB-CsPbBr₂ PSCs within a spectral response range of 400-500 nm, indicating the enhanced light absorption ability in EA-CsPbBr₂ PSCs.
Figure 4: (a) Schematic sketch of the carbon-based CsPbIBr$_2$ PSC; (b), (c) and (d) are J-V curves, EQE spectra and PCE distribution histograms of CsPbIBr$_2$ PSCs with two different antisolvents (CB and EA), respectively.

Table 1: Photovoltaic parameters of CsPbIBr$_2$ PSCs with two antisolvents (CB and EA)

<table>
<thead>
<tr>
<th>Sample</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>$V_{oc}$ [V]</th>
<th>FF</th>
<th>PCE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB-CsPbIBr$_2$</td>
<td>8.54</td>
<td>0.96</td>
<td>0.48</td>
<td>3.95</td>
</tr>
<tr>
<td>EA-CsPbIBr$_2$</td>
<td>8.56</td>
<td>1.00</td>
<td>0.51</td>
<td>4.35</td>
</tr>
</tbody>
</table>

Besides, the integrated $J_{sc}$ calculated from the EQE spectrum are 8.05 mA/cm$^2$ and 8.16 mA/cm$^2$ for the CB-CsPbIBr$_2$ PSCs and the EA-CsPbIBr$_2$ PSCs, respectively, which are closed to the corresponding $J_{sc}$ values obtained in the J-V curves, implying the accuracy of the J-V measurements. Additionally, the statistical PCE distributions of CsPbIBr$_2$ PSCs with two different antisolvents (15 devices each) are compared and summarized in Figure 4(d). On the one hand, both two antisolvent processes showed good repeatability; on the other hand, the average PCE value of EA-CsPbIBr$_2$ PSCs are higher than that of the CB-CsPbIBr$_2$ PSCs, which mainly ascribed to the improved CsPbIBr$_2$ films including enlarged grain sizes with fewer grain boundaries, enhanced light absorption ability as well as reduced defects.

4. Conclusion

In summary, a green antisolvent strategy was introduced to improve the quality of CsPbIBr$_2$ films. We select EA and CB as antisolvents to prepare CsPbIBr$_2$ thin films and carbon-based CsPbIBr$_2$ PSCs with a structure of FTO/c-TiO$_2$/CsPbIBr$_2$/Carbon. Compared with the CB-CsPbIBr$_2$ films, our results demonstrated that the EA-CsPbIBr$_2$ films exhibited an enhanced crystallinity, larger grain sizes and fewer grain boundaries, enhanced UV-
visible light absorption intensity as well as reduced carrier nonradiative recombination. Thus the corresponding EA-CsPbIBr$_2$ PSC showed improved photovoltaic parameters, the optimal efficiency reached 4.35%, which was 3.95% for the CB-CsPbIBr$_2$ PSC, an increase of 10% in PCE. At the same time, the devices prepared through antisolvent methods showed good repeatability. This work contributes to selecting nontoxic solvent engineering for realizing the preparation of high-quality CsPbIBr$_2$ thin films and the improved performance of carbon-based all-inorganic CsPbIBr$_2$ PSCs.

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References


